Application of Smart Materials/Technology at the Savannah River Site

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ABSTRACT

Large scale implementation of smart materials and smart technology to engineered structures in any particular location requires the demonstration of cost effective applicability to the construction, repairs/upgrades and in-service inspections required by that site. The potential for using smart materials/technology at the Savannah River Site (and within the DOE complex) can be demonstrated through the repair, upgrade and construction of two bridges. The design and construction philosophy for one of the bridges will incorporate smart materials and technologies while the other parallel bridge has already been constructed using standard construction practices. This demonstration of smart materials/technology at the Savannah River Site is still in the planning stage and will advance quickly as funding is acquired.

The Savannah River Site (SRS) has an ideal test bed to test the implementation of smart materials/technology in a real but controlled setting. Two bridges were selected to serve as this test bed. Each bridge handles one way traffic on either side of a divided road. One of the bridges, 72G, was built in August of 1996, while the other 71G, was built in the 1950's and is in need of repair. The older bridge will be upgraded with advanced materials and smart technologies and then monitored for performance. After the effectiveness of the repair has been demonstrated, the repaired bridge will be demolished and replaced with a new, smart bridge. Smart technology will be used to monitor and evaluate the demolition process. The newer conventional bridge (72G) may serve as a "control" structure to which the old bridge, the upgraded bridge, and the new, smart bridge may be compared. These comparisons will provide the technical basis to evaluate the use of advanced materials and smart technologies in facility upgrades and new construction at the Savannah River Site. This paper discusses the smart materials/technologies test bed at SRS and the development of an industry-university-laboratory team to support the SRS smart materials and technology demonstration.

Keywords: Application, Bridge, Design Philosophy, Smart Materials, Smart Structures, Smart Technology, Test Bed

INTRODUCTION

Smart materials/technologies are still in the beginning stages of the implementation phase even though they have undergone extensive research, especially during the last two decades. Smart materials/technologies exhibit numerous advantages over conventional materials/sensor technologies, and they are expected, by many, to become the new paradigm in construction. Some of the advantages for smart technologies include higher durability and system reliability and increased accuracy and sensitivity in health monitoring and sensing capabilities. To transfer smart materials/technologies from the laboratory to a commercial working structure, an initial application test bed is required. The ideal test bed should allow for comparison testing on a new conventional structure, an old structure, an upgraded structure, and a new smart structure. The structures and structural response to loading must also be modeled successfully and evaluated throughout the testing process.

Savannah River Site (SRS) has an ideal test bed where smart materials/technologies may be implemented into a semi-commercial setting. Two bridges will for the basis for this test bed. The two parallel bridges provide the opportunity to establish an excellent out-of-doors testing laboratory. Bridges 71G and 72G are located on site road B, handling one way traffic on either side of the divided road. One of the bridges, 72G, was completed in August of 1996, while the other, 71G, was built in the 1950’s and needs repair. The bridges are conveniently located for testing and chiefly handle shift change traffic. Because the bridges are on site, the traffic may be easily controlled and test loading can be conducted at regular intervals. The newer conventional bridge will serve as a “control” structure to which the old bridge, the upgraded bridge, and the replacement bridge will be compared. These conditions provide a golden opportunity to develop a working laboratory in a semi-commercial setting while also providing the opportunity for traffic control and the application of control loading at regular and/or selected times.

PARTICIPATION

Implementation of smart technologies to the two bridge test beds at the Savannah River Site will be through a smart structure team that includes government, laboratory, university, and industry participants. The vision is to use smart materials/technologies and construction techniques to build economical and safer facilities with longer life expectancies. Figure 1 is a visual representation of this team. Savannah River Technology Center (SRTC) will be the driving force for implementing smart materials/technologies into structures at Savannah River Site, while Central Services Works Engineering (CSWE) will provide support in the on-site infrastructure expertise. The University of South Carolina (USC) will provide modeling and laboratory support, including the degradation of materials under varying environmental conditions. The South Carolina Department of Transportation (SCDoT) currently funds USC for efforts in a related area and several other industries [Clark Shwebel, Riechhold, Chemicals Inc. Amoco, and Strain Monitoring Systems (SMS)] are willing to provide materials and in-kind support.

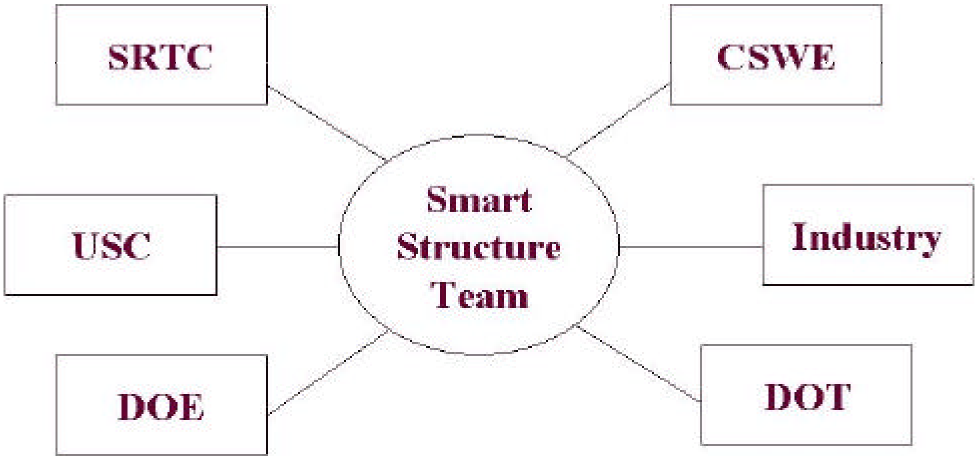

Figure 1 – Smart Materials/Technology Team

PROJECT OVERVIEW

The objective of the project is to reduce construction and repair costs, to reduce operation, inspection, and maintenance costs, and to increase the system reliability of civil structures built at the Savannah River Site. The incorporation of smart materials/technology into the design and construction philosophies of DOE will help achieve these objectives. In order to bring this vision into focus, the application and understanding of smart technologies must develop through three phases: assessment of current smart materials/technologies, in-situ testing of the selected smart materials/technologies on one type of structure, and transfer of the materials/technologies to other structures.

Phase 1 includes assessment. The current condition of the bridges in the SRS test bed must be assessed before any work can be done on them. Their surroundings, design, and load requirements must all be taken into consideration. In addition, market research must be conducted to determine which smart materials/technologies provide the optimum benefits for the project. Construction techniques must be evaluated and a plan must be developed and approved. The first of these phases will be coordinated through the University of South Carolina. At USC, the required laboratory experiments and literary research will be conducted to support this effort.

Phase 2 is divided into *four stages*. The load-response of a generic bridge will be modeled in the *first stage*. This model will provide a theoretical comparison for the old, new conventional, upgraded, and rebuilt bridges. The model will be based on the design of the bridges and will be able to include degradation that may have occurred since the construction of the bridges. The predicted behavior of the bridges during the testing will be based on this model. Since the model will be used to evaluate the conventional, old, upgraded and the new smart bridge, it is of great importance that the model is accurate. In the *second stage*, conventional and smart sensors will be applied to the conventional and old bridges and their load/response will be monitored and compared to the model. When the accuracy of the model and the smart sensors has been established, the third stage may begin. *The third stage* of the test bed is to upgrade the older structure. The upgrade will provide strengthening as well as health monitoring capabilities. Strengthening will be achieved using fiber reinforced polymeric (FRP) composite overlays. The sensors used in the second stage will be duplicated and combined with additional sensors to monitor the upgraded structure. Some additional sensors will be employed in this third stage to verify the expected improvements resulting from the upgrade and to evaluate the bridge during its destruction. The destruction process will involve intentional overloading, the use of controlled flaws and other activities to evaluate bridge failure processes. The *fourth stage* of this phase will be to construct a new bridge that incorporates embedded smart technologies and advanced materials and new construction practices and, ultimately, provide a fully operational advanced smart bridge. The behavior of this bridge will also be compared to the model.

Phase 3 provides for the transfer of smart construction materials/technology to other structural applications. After having designed, constructed, and tested the new smart bridge, the emerging smart technologies and advanced materials will be interfaced with ongoing plans to improve existing site structures, and to design and build new facilities. The completion of this phase will provide a technical basis for the economical use of advanced materials and smart technology in the upgrade and construction of civil structures at the Savannah River Site.

In addition, the successful incorporation of advanced materials and smart technologies into civil structures at SRS, coupled with the ongoing operation of the bridge test bed, will provide the demonstrations necessary to promote the use of smart materials/technology in other civil structures within the DOE complex. This effort will also support the advancement of smart materials/technology toward general use in any civil structures that require routine and or periodic inspection and maintenance processes.

A schematic of the project overview is shown in Figure 2. The three phases support the larger of large-scale implementation of smart materials and technologies to engineered structures. Although the goals are interrelated and imply a certain timeline, continual effort toward the completion of these phases will take place throughout the project.

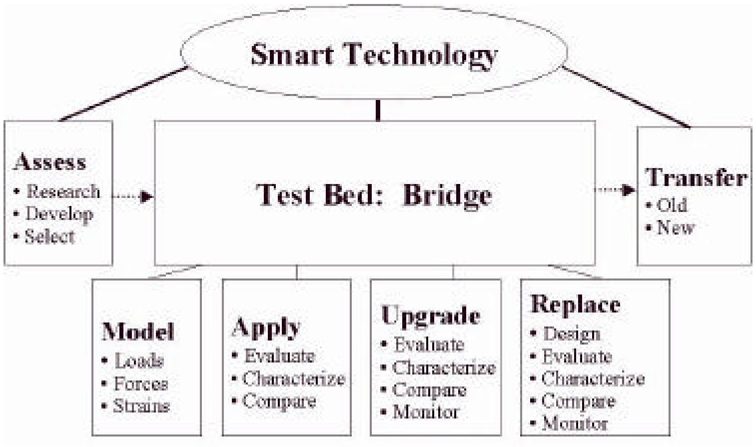

Figure 2 – Project Overview

PHASE I – ASSESSMENT

1.1. Bridges

The bridges differ in age and design, but their loading conditions and environmental conditions are nearly identical due to their location. The older bridge, 71G, completed in the 1950’s, has 40-ft. wooden pilings that support concrete pile caps, girders, and deck. The newer bridge, 72G, completed in August of 1996, has 60-ft. pre-stressed concrete pilings. Figure 3 shows a picture of both bridges, 72G is shown on the right and 71G is shown on the left.

The guardrails must be replaced on the older bridge if its use is to continue. The guardrail replacement will not be a part of the upgrade since degradation of the wooden pilings will ultimately result in the decommission of the bridge, if no upgrades are made. Traffic over the two bridges has decreased significantly because of recent changes in SRS operation goals; thus there were no plans to rebuild a bridge in place of 71G if the inspection reveals that its use should be terminated. The traffic on site road B is predominantly shift change traffic, and it has been shown that if bridge 71G was no longer fit for everyday use, that traffic would be diverted to bridge 72G. Because plans have already been developed to handle possible traffic problems that could arise in the event that 71G became inoperable, traffic problems during upgrading, destroying, reconstructing, and testing are not anticipated.

Figure 3 - Bridges 71G and 72G

1.2. Materials

1.2.1. Smart Sensing Technology

Conventional and smart sensing technologies will be employed in these structures. The sensing materials and technologies that will be used include strain gauges, piezoelectric materials, fiber optics, and TRIP technologies, Table 1 and 2.

Strain gauges will be used to monitor the strain in all of the bridge elements. Because these sensors have been used extensively for many years, they will serve as a basis for comparison in order to monitor and evaluate the performance of the smart sensors. Although strain gauges are not as sensitive, nor as accurate as piezoelectric sensors, the expected strains will be large and the strain gauges will be sufficient.

Piezoelectric materials may be used passively as sensors, or actively as actuators[i]. The piezoelectric sensors that will be used on this bridge include the PZT (lead-zirconate-titanate), a ceramic sensor, and PVDF (polyvinylidene fluoride), a polymeric sensor. The PZT's are extremely sensitive and very accurate, but due to their brittle nature, PZT's are restricted to being point sensors. Likewise, PVDF's are also very sensitive and accurate. However, PVDF's are not as brittle and may be integrated to perform distributed measurements. Therefore, PZT's will be located primarily in critical areas, whereas the PVDF's will be located along side the strain gauges.

Fiber optic sensors will also be used to measure both strain and moisture. Fiber optic sensors do not exhibit hysteresis, creep, or drift, and may be easily integrated into a distributed measuring device. Fiber optic sensors will be used along the bridge deck and around the pilings. The TRIP technologies will be used to establish maximum strains at selected, critical locations.

1.2.2. Smart Constructing Materials

The upgraded bridge will not require the replacement of any of the structural components in the bridge. Added strength will be gained by placing fiber reinforced polymeric (FRP) composite overlays on the wooden pilings and bridge deck. High performance prestressed and precast concrete, (conventional materials), polymeric concrete and FRP rebar in addition to FRP composite reinforcement will be used in the replacement bridge.

	Strain Gauge	**Polymeric Piezoelectric Sensors**	**Ceramic Piezoelectric Sensors**	**Fiber Optic Sensors**
Distributed Measurement Possible	No	Possible	No	Yes
Multiplexing Feasibility	Difficult	Can be integrated into film layout	Difficult	Can be integrated into fiber design
Technical Maturity	Excellent	Good	Good	Good
Sensitivity	30 V/ε or ~2με	10,000 V/ε	20,000 V/ε	0.11 μ strain per fiber
Accuracy	Fair	Good	Good/excellent	Very accurate
Maximum Temperature	300 to 400°C	Range is -40°C to 80°C	200°C	Variable (~300°C)
Linearity	Good	Good	Good	Good
Hysteresis	Good	Poor	Poor to Good	None
Creep	Poor	Fair	Fair	None
Chemical Compatibility	Poor	Good	Good	Excellent
Ruggedness	Fair	Excellent	Poor	Good
Weight		1.78 x 103 kg/m3	5 to 7 x 103 kg/m3	~9lb/1000ft
Cost	Low	Low to Moderate	Moderate	Moderate

Table 1 - Table of Sensors

Sensor	*Location*
Conventional Strain Gauge	Bridge deck, piles, pile-caps, girders
PVDF	Bridge deck, piles, pile-caps, girders
PZT	Critical areas
Optical Fiber	Bridge deck, piles
TRIP Technology	Bridge deck

Table 2 - Table of Sensors and Their Locations

PHASE II - TEST BED

1.3. Model

The load/response curve of both the new conventional and the old bridge will be modeled. This model, coupled with the emerging test data, will serve as a basis for comparison. Proper modeling of the bridges will rely on the cooperation between SRTC and USC. The upgraded bridge and the replacement bridge must also both be modeled for comparison. In addition, the anticipated bridge behavior during the destruction process will be established. The developed, accurate models will be used to predict the value added by upgrades to other applications and to determine the expected life extension due to upgrades and enhance the understanding of bridge failure processes.

1.4. Smart Technology Application

Conventional and smart sensors will be applied to the bridges. The chart, shown in Table 2, indicates a generalized location for the sensors on the bridges. Technologies chosen for the old bridge will be duplicated on the upgraded bridge.

1.4.1. Evaluation

The bridges will be monitored after the sensors have been positioned in the bridge, as described in Table 2. Data will be collected on a continuous basis as vehicles drive over the bridges. The measured load/response curve will be plotted for each sensor and the strains in each element of the bridge will be measured. From this data, and data obtained through test loadings, the structural health of the bridge and each bridge element will be assessed.

1.4.2. Comparison

There will be several bases for comparison at this stage in Phase II. First, the data collected from the different sensors will be compared to each other. Second, the load/response curves for the two bridges will be compared. And third, the load/response curves derived from the measurements will be compared to the modeled curve. The value, applicability and accuracy of the sensors will be reviewed before moving to the next stage in Phase II.

1.5. Upgrade

1.5.1. Construction

Bridge 71G is shown in Figure 4. Both a side view and a view from below the bridge are shown. Some degradation of the pilings is apparent in the view from the side of the bridge. This old bridge will be upgraded using FRP composite overlays as represented in Figure 5. The composite will be wrapped around the pilings and affixed to the underside of the bridge deck. These wrapped pilings will be able to carry greater loads possibly introduced by an earthquake. The composite adds lateral strength in compression by confining the pile and by carrying the brunt of the tensile load. The bridge deck carrying capacity will also be increased. A vehicle puts a positive moment on the bridge deck. The tensile face of the bridge is, therefore, on the underside. Because the composite is affixed to the deck on the tensile side, the tensile stress is transferred to the composite, which can carry a much higher tensile load than concrete.

Sensors will be placed as before, or merely left where they were, for the Upgraded Bridge. Placement will be coordinated through data gathered in the earlier stages of this project. Placement will include sensors at the locations described in Table 2; PZT sensors will be placed between the FRP composite overlays and the concrete in order to monitor adhesion and the transfer of load.

Figure 4 - Bridge 71G

1.5.2. Evaluation

The next stage in this phase is the evaluation of the materials, structural and sensory, that were used in the upgrade. This is necessary to determine the applicability of these smart materials/technologies to other structures at Savannah River Site. The evaluation will include the condition of the materials and the ruggedness, durability, sensitivity, and/or accuracy. The evaluation is both qualitative and quantitative and applies to all the structural parts as well as the sensors.

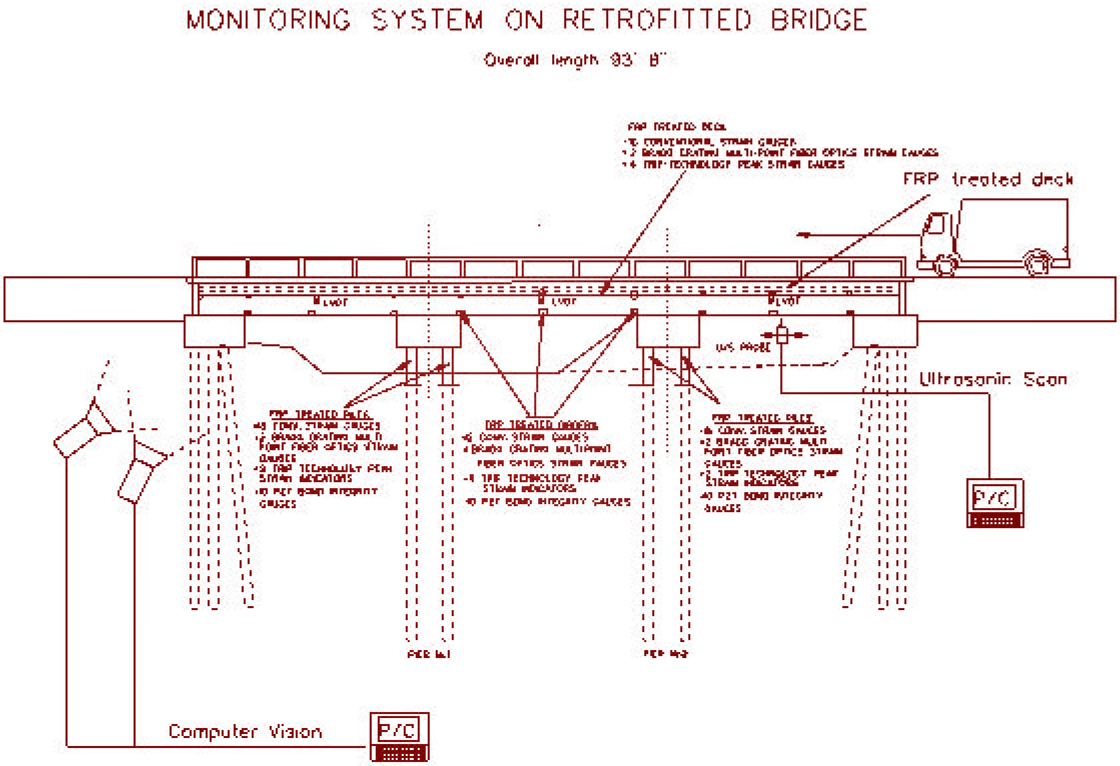

Figure 5 – Monitoring System on Upgraded Bridge

1.5.3. Characterization

Characterization of the upgraded bridge will include an analysis of the bridge's response to controlled loads. Measurements made by the smart sensors as well as traditional sensors will provide the basis for characterization. This characterization applies, primarily, to the bridge, not to the individual structural elements of the bridge.

1.5.4. Comparison

The upgraded bridge must be compared to the old 71G bridge and to the newer conventional bridge, 72G when the characterization is completed. In order to transfer these upgrading technologies to other facilities, on or off site, it is necessary to know how much improvement should be expected. This comparison will answer the question, "Do the gains outweigh the investment?"

1.5.5. Monitor

The Upgraded Bridge must be monitored for a period of time to assure the continuing health of the materials. Monitoring the bridge will also provide continuous data concerning the health of the bridge, the wear of the upgrading materials, and the performance of selected advanced materials and smart technologies.

1.5.6. Destruction

Destruction of the upgraded bridge will provide an excellent opportunity to evaluate the behavior of the structure during overload conditions. Additionally, controlled flaws will be placed in the piling and/or bridge deck and the response of these flaws to a wide variety of loads will be measured and compared to model behavior. It is anticipated that during both the monitoring and destruction processes that the bridge will be opened to a number of investigations to test new and emerging smart sensor technologies as well as evaluate various models of structural behavior.

1.6. Replacement

1.6.1. Design

A new bridge will be designed to replace the upgraded bridge. This stage includes embedding sensors and the application of other technologies, to make the bridge a truly smart structure. Figure 6 represents a schematic of a new steel-free bridge. The sensors incorporated into the bridge will make this a smart design. However, the evaluation of new construction techniques and advanced materials is also essential to technological progress. Therefore, this smart bridge will incorporate the cutting edge technologies in civil applications. This includes a composite deck with polymeric concrete, high strength concrete piles and pile caps and girders reinforced with FRP composite rods. These FRP composite rods have the advantage of being non-corrosive as well as providing great strength.

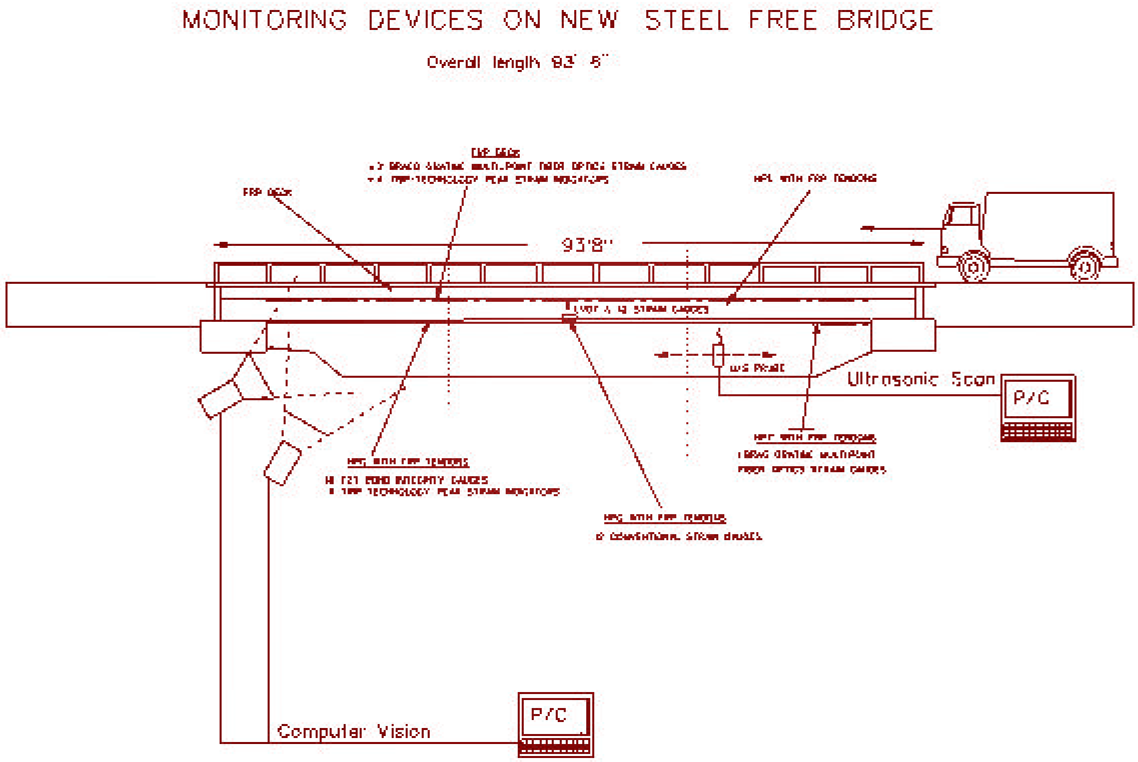

Figure 6 – Monitoring Devices on New Steel Free Bridge

1.6.2. Characterization

The embedded sensors will be used to characterize the performance of the new smart bridge. Vehicles will be driven over the bridge at known speeds and loads and the bridge's response will be recorded. Inspections will also be conducted to ensure the accuracy and reliability of the embedded sensors.

1.6.3. Monitor

The bridge will continue to be monitored indefinitely and can serve as a test bed for newly emerging sensor technologies. Because the sensors were embedded into the structure, "on-line" health assessment is possible, as the use of "remote" monitoring processes will be evaluated. Periodic inspections will be necessary during the first three years to ensure the accuracy and reliability of the internal health monitoring system.

1.6.4. Evaluation

After the bridge has been characterized and monitored, its behavior must be evaluated. The performance will be compared with the model behavior and the new conventional bridge. The complete evaluation of this new bridge will take into consideration all aspects of the design, construction, and life of the bridge including materials usage, time and labor, maintenance, and life expectancy to evaluate life cycle costs and the advantages of smart technologies.

PHASE III - SMART TECHNOLOGY TRANSFER

1.7. Application to Existing Structures

SRTC has selected several facilities on site that could benefit from the materials used in upgrading bridge 71G. These structures include the Defense Waste Processing Facility (DWPF), the canyons, and the tank farms. FRP composite overlays may be used to increase strength and provide protection from seismic activity and smart sensors may be used to monitor the structural health.

1.8. Incorporation into New Structures and Technology Transfer

There are also facilities still in the design stages of development that could benefit by incorporating these technologies. These facilities include Accelerator Production of Tritium (APT), fuel storage, and plutonium storage. By using new materials such as those in the replacement bridge, these structures may be lighter and have an extended life. They will require less materials and maintenance. In addition, they will have the health monitoring capabilities of the new smart bridge, which will increase the safety of the facility. The successful incorporation of advanced materials and smart technologies into civil structures at SRS, coupled with the ongoing operation of the bridge test bed, will provide the demonstrations necessary to promote the use of smart technologies in appropriate civil structures within the DOE complex. Additionally, this effort will support the advancement of smart technologies toward general use in civil structures that require routine and or periodic inspection and maintenance processes. The test bed will be available to the DOE complex as well as commercial industry as a working laboratory for future testing in support further understanding advanced materials and smart technologies.

CONCURRENT SMART MATERIALS ACTIVITIES AT THE UNIVERSITY OF SOUTH CAROLINA

1.9. High Frequency Electro-Mechanical (E/M) Impedance Analysis

The high-frequency electro-mechanical impedance method is a powerful tool for structural health monitoring, damage detection and NDE (Rogers and Giurgiutiu, 1997). A piezo-electric transducer in intimate contact with a structure sends and receives high-frequency elastic waves through its sensor/actuator functions. The drive-point mechanical impedance, $Z_{str}(w) = iwm_e(w) + c_e(w) - ik_e(w)/w$, of the structure (Figure 7) interacts with the internal impedance of the transducer, Z_{PZT} , and generates a combined impedance response, $Z(w)$, as shown in Equation (1). Thus, the drive-point mechanical impedance of the structure (itself dependent on the state of structural damage) is reflected into the electrical impedance as seen at the transducer terminals.

$$Z(w) = \left[iwC \left(1 - k_{31}^2 \frac{Z_{str}(w)}{Z_{PZT}(w) + Z_{str}(w)} \right) \right]^{-1} . \qquad (1.)$$

In Equation (1), $Z(w)$ is the equivalent electro-mechanical admittance as seen at the PZT transducer terminals, C is the zero-load capacitance of the PZT transducer, and k_{31} is the electro-mechanical cross coupling coefficient of the PZT transducer ($k_{31} = d_{13}/\sqrt{\bar{s}_{11}\bar{e}_{33}}$). The electro-mechanical impedance method is applied by scanning a predetermined frequency range in the hundreds of kHz band and recording the complex impedance spectrum. By comparing the impedance spectra taken at various times during the service life of a structure, meaningful information can be extracted pertinent to structural degradation and the appearance of incipient damage. It must be noted that the frequency range must be high enough for the signal wavelength to be compatible with the defect size. Several experiments have proven the ability of the E/M impedance technique to detect damage and localize its position in a variety of applications, as described next.

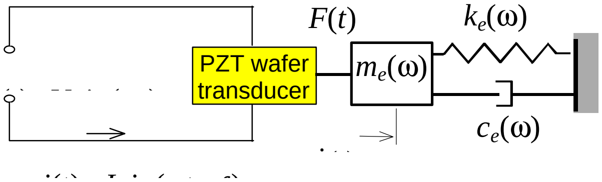

Figure 7 - Electro-mechanical coupling between the PZT transducer and the structure.

1.10. *High-frequency electro-mechanical impedance health monitoring testing of bolted joints*

The successful performing of damage detection experiments encounter, as a major challenge, the need to create controlled damage specimens. Generally, the creation of damage is an irreversible process that needs to be performed with utmost care. However, a special situation arises in the case of bolted joints. In bolted joints, damage can be created and eliminated by modifying the bolted joint parameters, such as the tension in the bolt, or the presence/absence of stiffening washers. Figure 8 presents experiments performed to correlate the E/M impedance readings with the presence of damage in the most common structural joint – the bolted joint. Results of these investigations are shown in Figure 9.

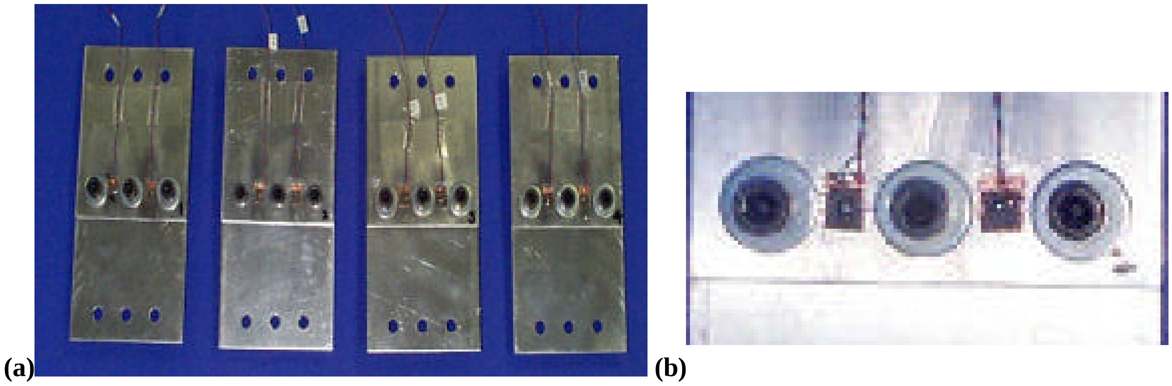

Figure 8 - High-frequency electro-mechanical impedance health monitoring testing of bolted joints: (a) Four shear lap joint tension specimens. (b) Close-up view of tone of the joints showing bolt-heads, washers, and the placement of two PZT active sensors (Giurgiutiu, Turner, and Rogers, 1999)

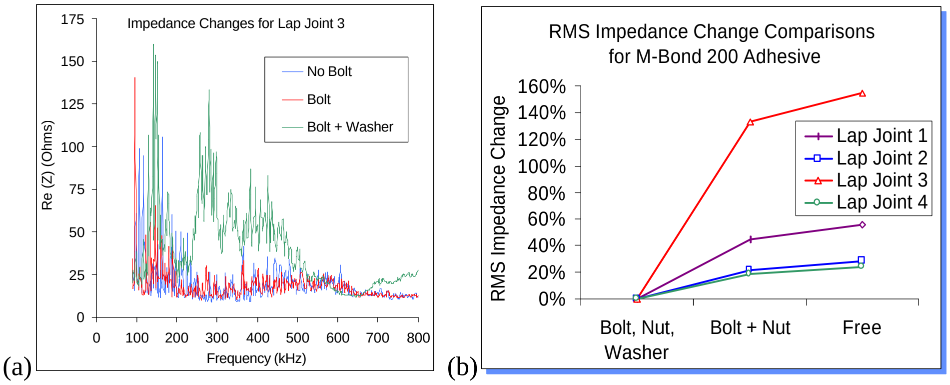

Figure 9 - Results of the high-frequency electro-mechanical impedance health monitoring testing of bolted joints: (a) electro-mechanical impedance signatures for three structural health situations: *no damage* (bolt+washer); *partial damage* (bolt only); *extensive damage* (no bolt). (b) Correlation between RMS impedance change and specimen structural health (damage progression). (Giurgiutiu, Turner, and Rogers, 1999)

1.11. *High-frequency electro-mechanical impedance health monitoring testing of composite overlays on concrete substrates (civil infrastructure repairs/strengthening/rehabilitation)*

Composite overlays are thin sheets of fiber reinforced polymeric material (1/8-in to 1/4-in) adhesively bonded to conventional construction engineering materials. Candidate polymeric systems include polyester, vinylester, epoxy and phenolic. Fibers can be glass, carbon, Kevlar, or combinations thereof. Glass and Kevlar fibers come in a variety of forms including weaves and non-woven fabrics. Carbon fibers can be woven, but common usage relies on unidirectional prepregs. The composite may be applied as (a) wet lay-up (b) precured panels or (c) partially cured prepregs. For wet lay-up and prepreg systems, the adhesive is the polymeric resin itself. For precured rigid panels, separate adhesive material needs to be used. Structural upgrades with composite overlays offer considerable advantages in terms of weight, volume, labor cost, specific strength, etc.

However, one critical issue raised by the structural engineers concerning the use of composites in infrastructure projects is the still unknown in-service durability of these new material systems. Their ability to safely perform after prolonged exposure to service loads and environmental factors must be determined before wide acceptance in the construction engineering community is attained. The E/M impedance technique has been evaluated as a potential health monitoring method for the composite overlay repairs, strengthening, upgrade and rehabilitation of the nation's aging infrastructure. Figure 10 shows the type of specimen used to correlate the E/M impedance readings with crack propagation in the bond between a composite overlay and a concrete infrastructure substrate.

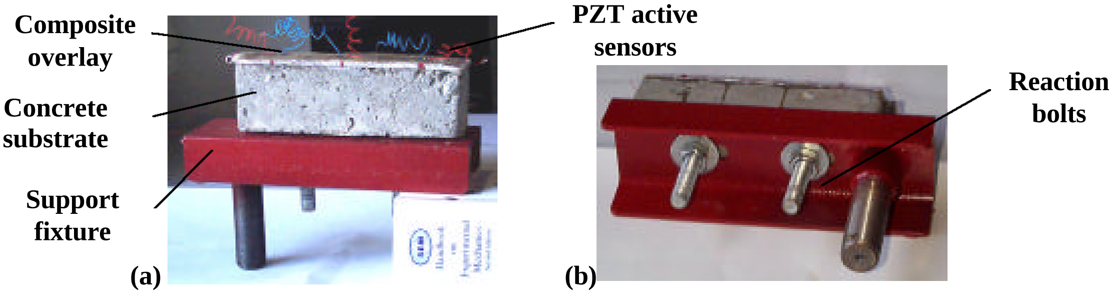

Figure 10 - Test specimen developed at USC for testing de-bond using the E/M impedance technique and piezoelectric active sensors: (a) side view showing support fixture, concrete brick and composite overlay; (b) bottom view showing retention bolts (Giurgiutiu, Whitley, and Rogers, 1999).

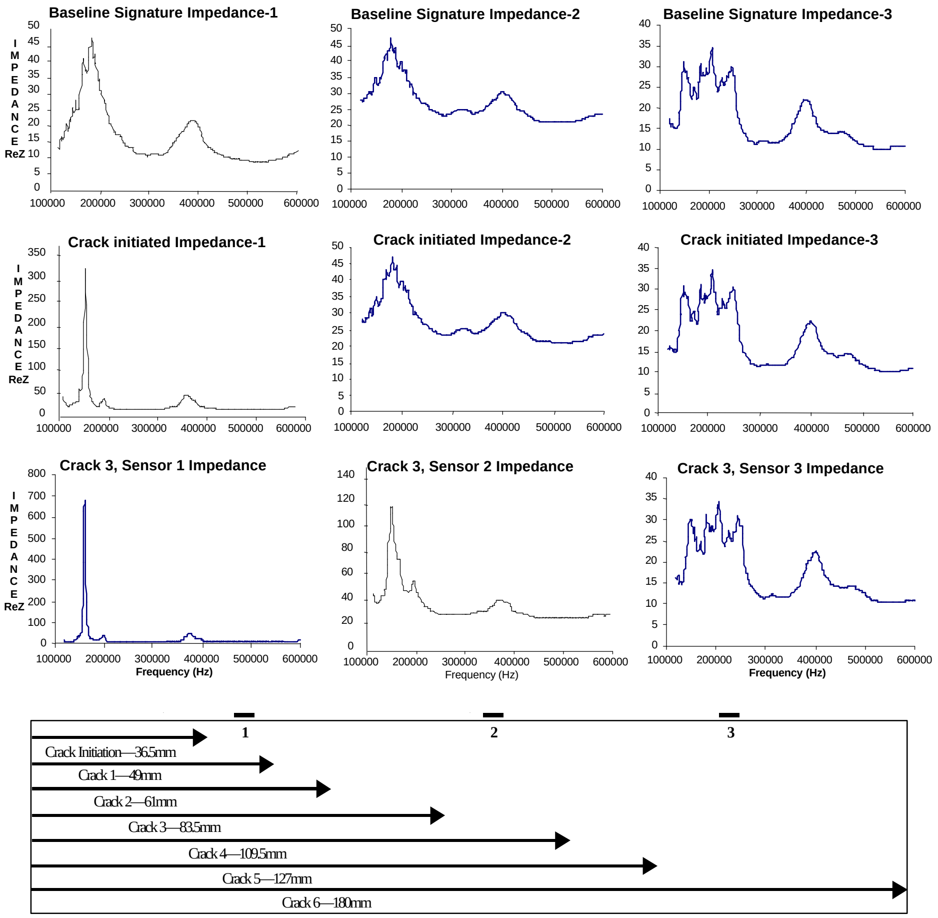

Figure 11 - High-frequency electro-mechanical impedance health monitoring testing of composite overlay. Indicate a direct correlation between the crack position and the E/M impedance spectrum. E/M impedance spectra arranged in three columns, corresponding to the active sensors 1, 2, and 3, (shown on the specimen sketch). As the crack advances from 1 to 6, the sensor E/M spectra changes accordingly (Giurgiutiu, Whitley, and Rogers, 1999).

Figure 11 illustrates the correlation between crack propagation and E/M impedance reading as measured during these experiments. The specimen underwent controlled amounts of cracking in a DCB-type test performed in an MTS universal testing machines. A number of cracks of increasing length were generated (Figure 11b). The high-frequency E/M impedance spectrum (Figure 11a), as measure by the active transducers placed on the composite overlay, remained undisturbed until the crack front came into the very proximity of the transducer. The changes in the E/M impedance spectrum clearly detected the presence of the crack. As the crack progressed, the E/M impedance spectrum of the sensors left behind the crack front remained, again, unchanged, while the sensors ahead of the crack tip became sensitive to the approaching front.

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