

## Aging Infrastructure: Evaluation, Repair, Improvement and Protection

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### INTRODUCTION

The US economy is supported by a vast network of infrastructure facilities in the form of the highways, railroads, waterways, transit ways, pipelines etc. According to several experts, the focus on securing the infrastructure from terrorist attacks during recent years has reduced attention on the need to maintain that same infrastructure, "We have been confronted with spectacular and tragic evidence of the inadequacy of these facilities in the failure of the levees in New Orleans and in the collapse of the I-35 bridge in Minneapolis," investment banker Felix Rohatyn and Everitt Erlich, a vice president for the Committee for Economic Development, wrote in a recent essay (Leggiere, HS Today, Oct. 2008). "The dangers of the nation's crumbling infrastructure to our economic health are as great as those posed by the current financial crisis.", Mr. David G. Mongan, President of ASCE wrote in his recent testimony before the committee on ways and means, U.S. House of Representatives. Some experts even presented the financing model for rebuilding nation's infrastructure called "National Infrastructure Bank" (Herman, 2008). The American Society of Civil Engineers' 2009 Report Card for America's Infrastructure assessed that the nation infrastructure failed to perform adequately in 15 categories it estimates that \$2.2 trillion is needed over a five-year period to bring the nation's infrastructure to a good condition (<http://www.asce.org/reportcard/2009/grades.cfm>). This has been an ongoing problem for years. Statistics from Federal Highway Administration in 1998 indicated that approximately 230,000 bridges are either functionally obsolete or structurally deficient and are in need for immediate rehabilitation requiring a total investment of \$70 billion (Wang et. al, 1998). In another study (FHWA) estimated that: nearly half of the bridge inventory is deficient due to either structural or traffic inadequacies; a \$90 billion backlog of bridge maintenance exists; traffic congestion wastes 1.4 billion gallons of gas and 1.2 billion person-hours each year; and transportation delays add \$7.6 billion annually to costs in the US (FHWA, 1993). It is estimated that \$78B will be spent over the next 20 years in major rehabilitation of bridges (McConnell,1996). However, this expenditure is only able to maintain the *status quo*, i.e., as many bridges become newly deficient as are refurbished (Prine, 1995). More than a third of the highways are in poor or mediocre condition. Increased traffic and larger trucks place greater loads on highways and bridges. It is estimated that inadequate roads will cost the economy \$67B per year ([http://findarticles.com/p/articles/mi\\_m3095/is\\_/ai\\_n27669436](http://findarticles.com/p/articles/mi_m3095/is_/ai_n27669436)).

2009 GRADES	
Aviation	D
Bridges	C
Dams	D
Drinking Water	D-
Energy	D+
Hazardous Waste	D
Inland Waterways	D-
Levees	D-
Public Parks & Recreation	C-
Rail	C-
Roads	D-
School	D
Solid Waste	C+
Transit	D
Wastewater	D-

**RAISING THE GRADES:  
5 KEY SOLUTIONS**

America's Infrastructure G.P.A. = D  
Total Investment Needs = \$2.2  
Trillion, (estimated 5 year need)

Consequently, the economic well-being of the nation, the safety of citizens, and the quality of life are all being adversely impacted. The US Federal Reserve Board has concluded

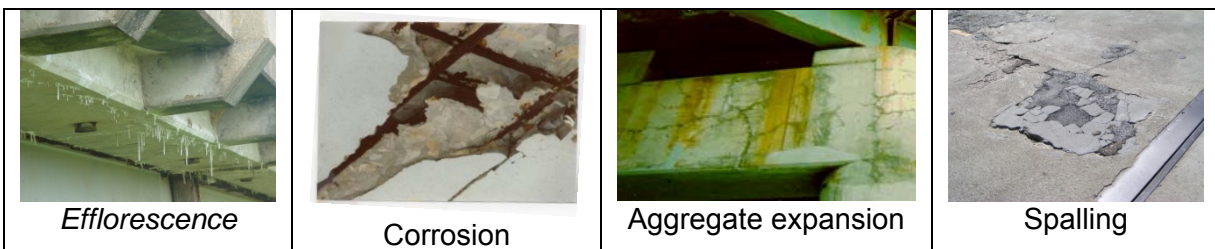
that the failure of civil infrastructure systems to perform at the expected level might reduce the national gross domestic product (GDP) by as much as 1%. Studies by the National Bureau of Standards (National Institute for Standards and Technology) estimated that overall corrosion costs in the United States are 4.2% of the Gross National Product (GNP).

Deterioration of concrete structures is a safety issue in addition to being an economic issue. Undetected or unheeded corrosion of bridges and other structures can cause catastrophic failure with loss of life. Two of the most well known corrosion-induced bridge collapses are the Point Pleasant (Silver) Bridge over the Ohio River in 1967 and the Mianus River Bridge on I-95 in Connecticut in 1983 (Kulicki et al. 1990). The Silver Bridge failed from corrosion cracks in an eye-bar while corrosion of a pin-and-hanger assembly caused the Mianus River Bridge collapse. Forty-seven people died during the Point Pleasant Bridge collapse. The cost in 1967 was \$175M; the cost of the same disaster today is estimated to be \$2.1-5.6 billion (Prine 1995). Example of other bridges that required emergency or accelerated repairs, closure, or traffic restrictions as a result of extensive corrosion, includes (Kulicki et al. 1990):

- Harvard Bridge in Cambridge, MA
- Yankee Doodle Bridge (I-95) in Norwalk, CT
- Southeastern Pennsylvania Transportation Authority (SEPTA) Bridge in Philadelphia
- Williamsburg Bridge in New York City
- I-35 W Bridge in Minneapolis
- Ben Franklin Bridge in Philadelphia
- Royal Gorge Bridge in Colorado
- Portsmouth Bridge over the Ohio River
- Tower Bridge in London
- Lake Maracaibo Bridge in Venezuela.

Aging manifests itself in many ways in civil infrastructure such as buildings, bridges, and dams. It occurs through:

- 1) Material degradation such as corrosion and wear occurring over long time scales (Fig. 1) Considerable expense in inspection, maintenance, and repair are consumed when this degradation occurs system wide on large volumes of material as occurs for highway pavements. These typically impair normal operations while they are conducted and incur further expense in indirect terms.



**Figure 1** Typical forms of deterioration (Al-Ostaz, 2005)

- 2) Sudden failures when latent design flaws reach critical loading condition such as occurred in the gusset plate connection of the I-35 steel bridge superstructure (Figure 2). These failures have both immediate impact in terms of loss of human life and service and again consume considerable expense during redesign, repair, or replacement phases.



**Figure 2** Damaged section of I-35 (www.enr.com)

- 3) Vulnerability to extreme loading such as occurs in above cases when unforeseen loadings occur or design loads are exceeded for any number of reasons. The vulnerabilities are exposed sometimes on massive scales during natural and manmade disasters such as the Northridge earthquake, the World Trade Center attacks, and Hurricane Katrina. These rare events place large inventories of civil infrastructure at risk which has been built up over time scales that span multiple design codes, standards of practice, and construction materials and technologies. Consider for example the reinforced concrete technology and associated design parameters identified for buildings in the bottom figure. Perfectly adequate designs and construction properly implemented may still fall victim if the designer or design code does not consider a particular load event (e.g. blast).

## NEED FOR FUTURE RESEARCH

At this moment, rebuilding nation's infrastructure is not an option; it should be the first one in the must-do list. In rebuilding these infrastructures, we propose three stage approach; (1) Innovative retrofitting techniques so that lightly damaged structures are repaired and have the extended service life. (2) Innovative design and construction techniques so that the new structures are resilient and cost effective. (3) A next generation real time monitoring and evaluation system which provides the information of the integrity of structures so that healthy structures can have longer service life but the unhealthy ones can be identified and retrofitted or rebuilt. These issues can be summarized in two main categories: use of advanced materials and evaluation methods.

### 1- Advanced Materials

The deterioration state of the nation's infrastructure has led the Civil Engineering Research Foundation to recommend the use of alternative materials that have attributed lower cost, lighter weight, reduced maintenance and enhance durability (ASCE, 1993). With increased concern of threats of attacks against our infrastructure, it is important to take this concept one step further into new generation of materials for building more resilience infrastructure that can withstand natural and manmade threats. This may include the new generation of nano structured materials, fiber reinforced polymer (FRP), polymer concrete and repair materials for live cracks (e.g. corrosion). The recent economic down turn emphasizes the need of using multifunctional materials. For example, applying polymeric materials reinforced with electrically conductive fibers may strength the aging structure, use as a sensor for health monitoring and be part of cathodic protection system.

- Nano-structured materials

With the increasing interest and remarkable progress in nano science, nano structured materials have emerged as potential construction and repair material considering the fact that their price is dropping steeply which make them economically viable. There is a need to develop physics-based models of nano materials in infrastructure applications.

Nano reinforcement can dramatically improve the structural and physical properties of engineering materials. Advances in nano science enabled engineers to understand and manipulate material properties more effectively. For example, the strength of cement is strongly influenced by the packing of the calcium-silica-hydrate gel at micro level. Hence, with the understanding of materials laws at the micro and nano level, it may be possible to design infrastructure materials such as green concrete, and building blast protection materials such as nano particle enhanced polymer spray on the wall. In addition, with the advent of nanotechnology, the use of innovative new nanomaterials such as POSS which has controllable and engineered structure, it is possible to improve soil properties, repair damaged concrete, and

restore structural integrity. The nation has the technology which can be quickly deployable and where reliable results may be obtained. Successful applications of nanomechanics in infrastructure applications are reported recently (Song et al. 2007, 2008, Al-Ostaz et al. 2008a, 2009b, Wu et al. 2008a, 2008b).

- Fiber Reinforced Polymers (FRP)

In spite of the successes of FRPs in structural rehabilitation and their promise for use in new construction, many concerns still remain regarding the long-term performance and durability of these “new” materials in the civil infrastructure environment. Although there is considerable information on the durability of FRPs at the material level, this data is generally disassociated from structural performance. Therefore, among the recognized needs are answers to questions about durability of FRP-strengthened structures. These answers can be provided through long-term health monitoring.

Several issues must be resolved before FRPs are widely deployed in the civil infrastructure. These include the development of:

- systems that take advantage of the inherent properties of FRPs
- fastening techniques
- appropriate design methodologies
- material and structural specifications
- construction specifications
- long-term (50-75 year) durability characterization
- non-destructive evaluation (NDE).

These issues may be characterized in the form of a pyramid, with widespread field implementation (the final realization) being the apex of the pyramid.

The American Concrete Institute (ACI) Subcommittee 440-D on research has conducted a survey with respect to needed research in the area of FRP composites. The area that received the highest priority in the survey was durability, and the issues of most concern were as follows:

- Alkali resistant resins/fibers
- Accelerated aging procedures
- Creep rupture of fibers
- Fiber orientation’s effect on strength
- De-icing chemical resistance
- Freeze/thaw performance
- Ultra-violet resistance
- Aging effects on bond length
- Aging effects on tensile/flexural strength

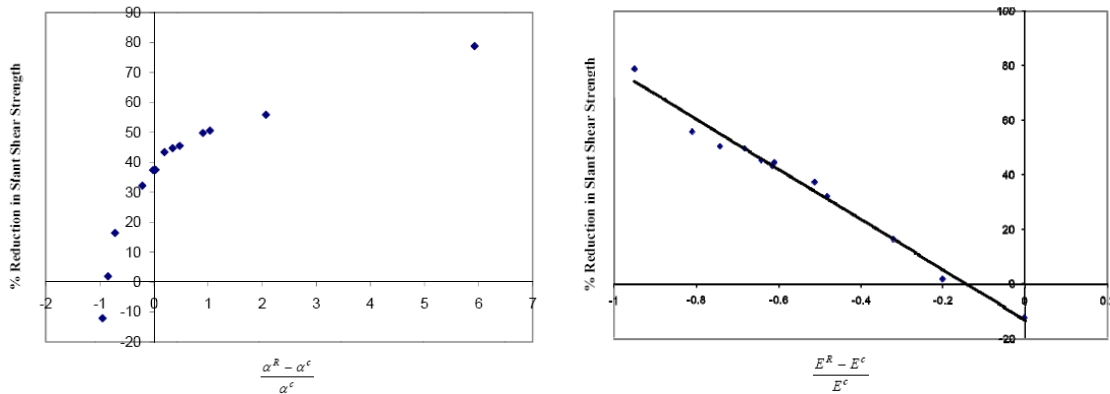
- Polymer Concrete

When the repair is carried out by the reinstatement of the cross section after removing the deteriorated concrete, the compatibility between the repair materials and the parent concrete becomes a major concern. This concern, however, is greatly magnified in climatic conditions where large fluctuations of temperature and thus of thermal expansion of repair material and parent concrete would cause differential thermal strain at the repair material - concrete interface resulting in possible damage to the bond and loss of adhesion at the repair joint. If the thermal stress exceeds the adhesion stress value, then debonding may occur. However, the low elastic modulus of the epoxy resin may reduce the effect of the thermal stress. Until recently, engineers were critical about the use of polymeric composite materials for the repair of concrete structures. When polymeric composites are used as a repair materials, advantages such as high performance, low strength, and high adhesion to concrete must be weighted against

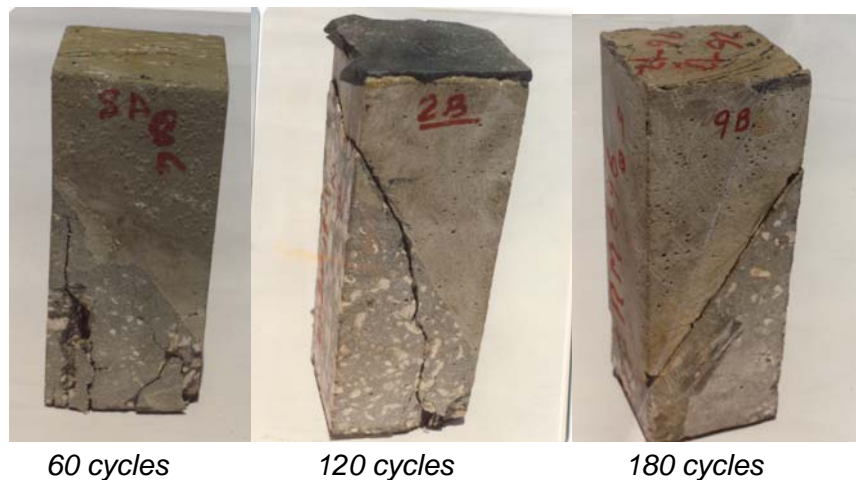
potential disadvantages such as the tendency of the repaired section to deteriorate under thermal cycling and / or wet- dry cycling due to a mismatch between the elastic and thermal properties of the repair material and those of parent concrete.

In terms of evaluating the bond between the parent concrete and the repair materials under cyclic heating and cooling, Schupach (1989) stated that “a single high thermal shock sometimes can degrade the composite, as can any of the various cyclic changes over a period of time”. He states that it is apparent, without even making any calculation, that the change in volume or shape of an epoxy due to changes in temperature, wetting and drying, freezing and thawing, or loads is likely to be very different from that of concrete to which it is attached. These differences can cause high stress at the bond line which may lead to failure.

Al-Ostaz et al (2009) investigated, the deterioration of bond between repair material and concrete due to thermal incompatibility. In that study the effect of thermal incompatibility between a parent concrete and a range of repair materials. Five resinous and six cementitious materials were used to repair fractured specimens by re-instatement of a section. Typical reduction in slant shear strength due to thermal is shown in Fig. 3. Also the modes of failure for various number of cycles are shown in Fig. 4.

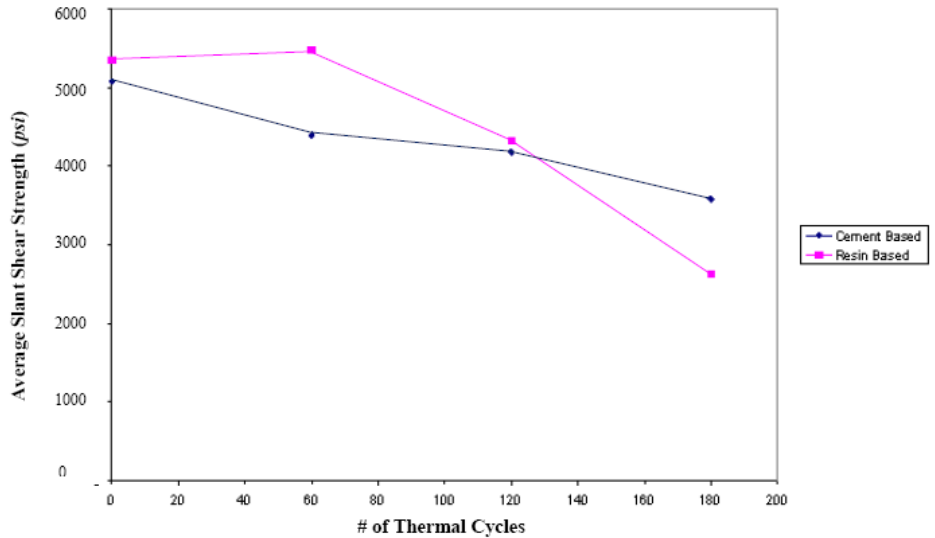


**Figure 3** Effect of elastic properties of repair materials on the reduction of slant shear strength of repaired specimens subjected to 180 thermal cycles before being tested in compression (Al-Ostaz et al., 2009).



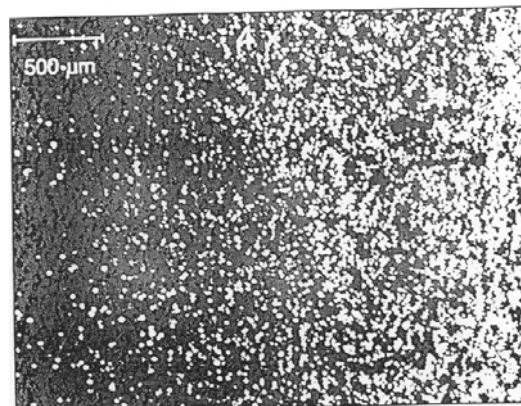
**Figure 4** Mode of failure of three test specimens repaired with epoxy mortar and subjected to various number of thermal cycles then subjected to mechanical loading (Al-Ostaz et al 2009).

On average, it was found that concrete specimens repaired with resin-based materials which showed higher bond strength at static room temperature exhibited higher reduction in strength when subjected to an increased number of thermal cycles as compare to those repaired using cement-based materials (Figure 5).



**Figure 5** Effect of heat cycling on reduction of slant shear strength (Al-Ostaz et al, 2009)

It is believed that the use of functionally graded material (FGM) between parent concrete and repair material will improve both the short term and the long term durability of repaired structures. By definition FGMs (Fig. 6) are used to produce components featuring engineering gradual transitions in microstructure and / or composition. This, usually, is motivated by functional performance requirements that vary with location within the part, these requirements are met in a manner that optimises the overall performance of the component. The introduction of spatial gradations in the composition, phase mix and microstructure offers the possibility to tailor the properties of materials for a broad range of applications.



**Figure 6.** Typical FGM

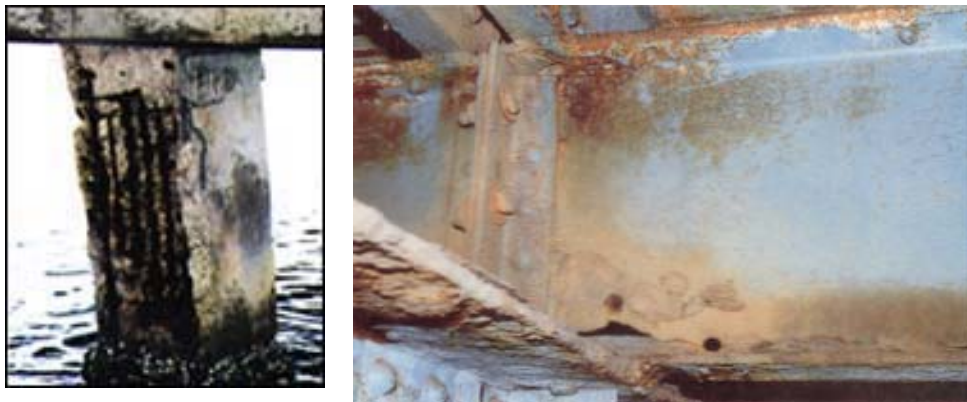
In short , while the main advantages of resinous materials are of high tensile and flexural strengths and their good adhesion to both concrete and reinforcement bars, the effective strength of the repaired section may be lower when the joint peels apart under loading due to

deterioration of bond between the composite repair material composite and parent concrete. The strength can be enhanced further by improving the compatibility between the repair material and concrete. The challenge here is to control and reduce the deterioration of bond between the repair material and concrete. This can be achieved by using a Functionally Graded Material (FGM, which will be the main thrust of this research.

Thus we propose to evaluate the effect of introducing a functionally graded material at the repair material-concrete interface on the durability of the repaired structures under, heating-cooling, freezing-thawing, and wetting-drying cycles. The FGM interface can be engineered using nano materials.

- Repair of live cracks

A major contribution factor to this deterioration is the reinforcing steel corrosion. It was reported that several thousand bridges in North America are suffering from the effects of corrosion. Excessive corrosion leads to the subsequent delamination and spalling of concrete. These cracks are a typical form of progressive / growing cracks (Figure 7). Corrosion of reinforcement results in the formulation of expansion products at the steel - concrete interface which leads to cracking of concrete parallel to the reinforcement. Such cracks, typically, are live cracks which grow in width with time as the corrosion progresses and corrosion products build up with time at the steel - concrete interface. Other possible forms of live cracks are related to cracks due to alkali-silica reactivity and surface attack.



**Figure 7.** Examples of severe corrosion on bridges (Davis et al, 1998)

Whereas, the repair of dead cracks is relatively simple, the repair of live cracks poses considerable problems. If the movements are very small, crack injection sealing materials may accommodate these small movements through their extensibility without reopening the same or an adjacent crack. However, when cracks move 5 % or more due to applied loads or due to internally expansive forces such as those created by the mechanical pressure of the corrosion products formed on reinforcement surface, then most materials will have great difficulty in accommodating such movement. This would result in re-cracking very shortly after the completion of crack repairs if repair is executed by the use of rich cement grout; polymer modified grout or the usually adopted pure resin formulations of rigid epoxies or polyesters.

Sealing live corrosion cracks would not only conceal the crack by adopting attendant proper cosmetic treatments subsequent to repair, but would also protect the reinforcement by preventing penetration of moisture, oxygen and other aggressive media, thereby providing conditions akin to combating, at least to some extent, future deterioration. Even then, the possibility of continued corrosion of reinforcement cannot be discounted. In fact, this is most

likely to happen if concrete is contaminated by chlorides inducted through constituent materials such as aggregates and mix water at the time of mixing, or from the brackish curing water immediately after placement and finishing, or due to subsequent ingress of chlorides through sea water in marine concrete or deicing salts in bridge decks. In such situations, the progressive corrosion will reopen the sealed crack at the repair - concrete interface or at a location close to the initial sealed crack. Also, if one doesn't fill the finest cracks and voids, the repaired section may not provide the maximum soundness and integrity ( Al-Ostaz and Bader, 1999).

An alternative technique for crack injection repair is the use of vacuum impregnation technique. By using the vacuum impregnation process a partial vacuum is introduced to the crack section to remove both air and moisture within the interconnecting cracks and voids prior to filling the crack. Thus the repair resin can seal all and create a thin layer of coating around the reinforcement which will reduce the chances of further corrosion. However the effectiveness of this method is highly influenced by the viscosity of the resin used.

- **Quick/Permanent Repair of Earthen Levees**

With frequent visits of unexpected weather conditions, the necessity of quickly deployable levee retrofitting technique is urgently increased. Grouting technique is one of the most popular retrofitting techniques for geotechnical structures worldwide, because it is proven to be effective, versatile and economic. It can improve the strength, water tightness, and both. But the success rate of the grouting techniques in US is quite low because it heavily depends on the empiricism. One of the typical troubles of ill designed/constructed grouting technique is the long term degradation of materials properties and environmental issues.

Analytical methods of grouting techniques is quite difficult because it includes the complicated physico-chemical interactions of chemicals and soils, which has never been easy. At this moment, we have strong nanomechanics analysis tools which are based on the emerging nanotechnology. With nanotechnology, new grout materials with designed properties can be manufactured, and field characteristics can be predicted. Successful applications of nanomechanics for characterization of geomaterials are reported recently (Song et al. 2007, 2008, Al-Ostaz et al. 2008, Wu et al. 2008a, 2008b).

## **2. Health monitoring**

The continued non-destructive evaluation of new and hybrid (new design or rehabilitated) FRP civil structures must recognize the constraints of cost and procedure speed (to minimize use disruptions) while addressing the needs to evaluate both global and local structural performance.

Highway agencies are unwilling to use FRPs for bridge applications without having effective technologies for evaluating the structural integrity and establishing a true measure of durability of FRP or FRP-strengthened systems. FRP-strengthened systems typically rely on the bonding of FRP to concrete or steel, and the strength and stiffness of the composite system is critically dependent on the integrity of the bond. All-FRP structures also may experience damage due to delamination and bond deterioration at connections. Due to their general inexperience with FRPs as a construction material, highway engineers are very wary of damage that is difficult to detect through standard bridge inspection practices. The availability of NDE methods to inspect bridges utilizing FRPs is therefore critically needed if FRPs are to be widely used.

Numerous NDE techniques have been developed for a variety of applications. Some of these are global methods that characterize the effect of degradation on the entire system, while others detect highly localized types of distress. Most investigators working on NDE methods for assessing bridges with FRPs adopt an existing NDE technique, typically a localized method.

This is problematic. The physical lengths associated with bridges make many of the localized methods ineffective for detecting damage over a significant part of the structure.

A systematic effort is required to assess the effectiveness of NDE methods that have been developed for other applications, and select and enhance a set of techniques that will be effective for bridge and other civil infrastructure systems that use FRPs.

A universally practical method that can effectively and economically characterize various types of defects in structures deployed in the field has yet to be developed. Review of common practice and scientific literature indicates that practitioners typically learn about one or two techniques, purchase the equipment, and then try to apply it to all problems. The failures of this approach are noteworthy in two ways. The first is that serious structural defects are often missed or overlooked?. The second is that users come away disillusioned because of the cost (time and money) spent for limited results. This is especially true in the composites field because many traditional NDE techniques cannot be effectively used on materials that are inhomogenous, anisotropic, and have poor thermal and electrical conductivity.

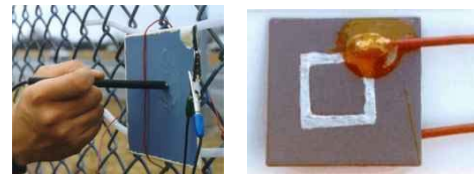
Given the urgency of the need, especially in critical structural applications such as bridges, a comprehensive approach that uses several different techniques in a systematic decision-making hierarchy is warranted. Such an approach would likely use rapid technologies for initial screening and call upon more involved methods for detailed defect characterization that would facilitate final decision-making as to the need for repair and for the evaluation of repairs. This concept and a limited sample application are described by Cloud, *et al*, 1999. Eventually, this process could be highly automated, and artificial intelligence could be incorporated.

The methods available for systematic NDE include optical techniques (digital speckle interferometry (DSI) and digital speckle shearography (DSS)), vibration testing (modal analysis), electrochemical impedance monitoring, thermal scanning, ultrasound (c-scan), eddy current, acoustic emission, x-ray, and others. These methods include some that can detect damage, or its impact, on a global (structural) scale, and others that can detect damage on a local scale. The investigators have detailed knowledge and some implementation experience with several of these techniques.

In practice, a rapid and simple technique, such as digital speckle interferometry or vibration testing, will be first used to scan a structural component for anomalies that suggest flaws such as disbonds or cracks. Based on findings, a decision is made to use another technique, such as thermal imaging or dielectric measurement, to obtain more data about the anomaly. These data, taken together, might indicate that the anomaly might be safely ignored, should be repaired, or that more data, such as from localized ultrasound scanning, might be required.

We propose to use four methods to evaluate bonding between FRP and concrete. : Namely: (i) Electrochemical Impedance Spectroscopy (ii) Dynamic Impedance, and (iii) Optics and use of ubiquitous/ambient intelligence

- Electrochemical Impedance Spectroscopy  
Electrochemical Impedance Spectroscopy (EIS) is an established laboratory technique for the investigation of coating deterioration and substrate corrosion (Scully, 1989, 1990; Tait, 1989; Murry and Hack, 1990; Mansfeld, 1982; Al-Ostaz et al, 2007).



**Figure 8** Top) Permanent In-situ sensor on laboratory test coupon. Bottom) Handheld sensor.

Very good correlation has been reported between short-term EIS data (such as low frequency impedance) and long-term coating performance in sea water immersion or other exposures, demonstrating the technique's predictive capabilities. Traditionally, the technique requires a specimen to be immersed into an electrolyte along with counter and reference electrodes. Such procedures are not suitable for detecting corrosion on structures in the field and would not be suitable for studying adhesive bonds even in the laboratory. The patented DACCO SCI *in-situ* sensor removes this limitation and allows EIS measurements to be taken under ambient conditions without remote electrodes (Davis, et al, 1995, 1999, 2000). It allows paint deterioration or substrate corrosion to be detected in its early stages with identical measurements to those obtained with conventional EIS. A similar approach is suitable for composites and concrete. The sensor electrode on the surface acts as both the reference and counter electrode with the substrate being the working electrode. The impedance across the paint, adhesive, or composite is measured.

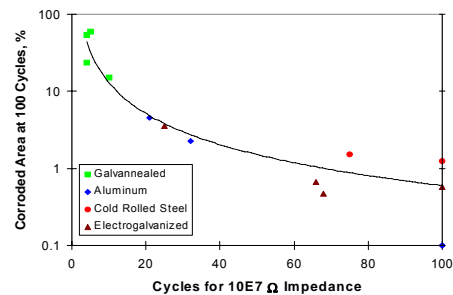
Two versions of the *in-situ* sensor being developed are suitable for monitoring materials (Figure 8). One is an incorporated electrode that is permanently attached to the structure. This version is especially useful for inaccessible locations. Wires are routed to a convenient connection point. The other is a hand-held electrode that is pressed against the structure during the measurement. This version could be used whenever a permanent electrode had not been incorporated into the structure or is not desired for appearance or aerodynamic reasons. The two sensor versions give identical results.

#### Use of In-situ Sensor to Monitor Degradation of Bond Between Metals and Polymeric Coatings

In EIS, a small AC voltage is applied between the sample and the reference electrode and the induced current is measured between the sample and the counter electrode. A complex impedance spectrum is obtained as a function of frequency. The metal/coating system is often modeled with an electric circuit such.

Initially, the coating resistance is very high so that the system acts as a capacitor with a log impedance-frequency slope of -1 (Figure 9). As the coating degrades and substrate corrosion occurs, the resistance of the coating decreases and the lower branch of the circuit becomes important at low frequencies. The low-frequency impedance then becomes independent of frequency.

The low-frequency region of the impedance spectrum can be used to determine the stage of degradation of a polymer/metal structure as illustrated in Figure 8. In this experiment, an aluminum panel was coated with an epoxy adhesive and was immersed in hot water. There are definite degradation stages corresponding to water uptake by the epoxy, incubation of hydration/corrosion, and intense hydration/corrosion of the adherend. It is during this third stage that the hydration/corrosion products, which occupy greater volume than the original oxide, disrupt the bond between the polymer and the metal. In a coated metal, this promotes coating failure and further attack of the substrate. In an adhesive bond, this promotes crack propagation to accommodate the increased volume of material. This experiment conclusively proved that hydration of an aluminum adherend occurs *prior* to crack propagation (Davis, et al, 2000).

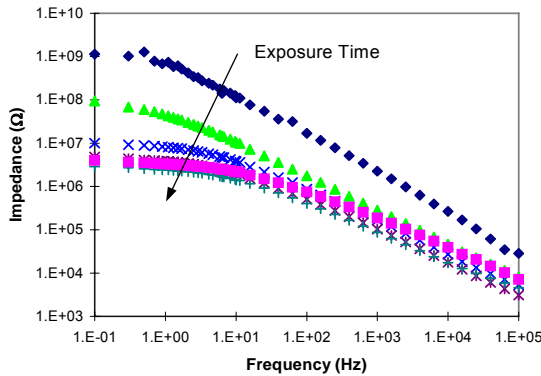


**Figure 11** Corroded area after 100 cycles of a cyclic corrosion test as a function of time for the low frequency impedance to drop to  $10^7 \Omega$ .

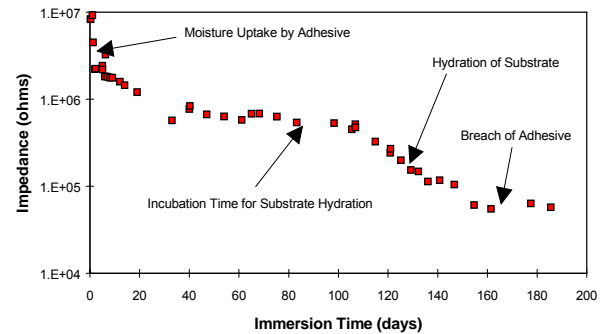
The predictive ability of the sensor is illustrated in Figure 10. A variety of different coatings and substrates were exposed to cyclic immersion/drying /humidity conditions that have been correlated with service conditions. An excellent correlation has been obtained between the time required for the low-frequency impedance, as measured by a sensor, to decrease to  $10^7 \Omega$  and the amount of corroded area on the specimen (Figure 11).

Use of Sensors to Detect the Joint Effect of Debonding and Moisture Level

Al-Ostaz et al (2008) used EIS to detect debonding and moisture uptake of bonded joints. Two methods of analyzing the impedance spectra are common. The first method is to simply compare the raw impedance spectra. An impedance spectrum can be plotted in different ways. The conventional presentations are the Bode magnitude and phase plot, Nyquist plot, and real and imaginary impedance plots. The impedance magnitude, phase angle, real or imaginary impedance are compared over the entire frequency range or over specific frequencies. The second method is to analyze the impedance spectra using a lumped parameter equivalent circuit model. In this method, the parameters of an electrical circuit which has theoretical impedance similar to that of the measured impedance are estimated, and spectra are compared



**Figure 9.** Impedance spectrum for painted aluminum following immersion for different periods in salt water.

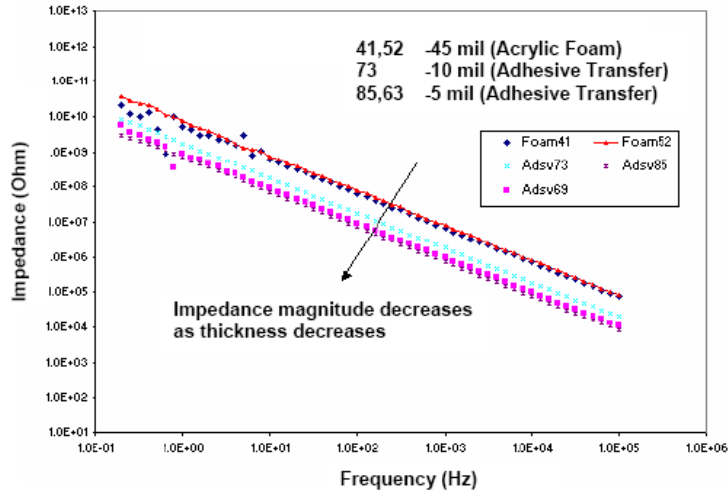


**Figure 10.** Impedance versus immersion time for an FPL-etched aluminum - epoxy adhesive half joint immersed in hot water.

based on the differences in the estimated parameters.

The effect of various circuit parameters i.e. impedance, capacitance, resistance and constant phase element were studied for both the single-lap joint and ENF specimens subjected to freeze-thaw cycling and heat-cool aging over 21 days. The capacitance  $C$  of the circuit is of particular interest because it can be analytically derived from analytical expressions.

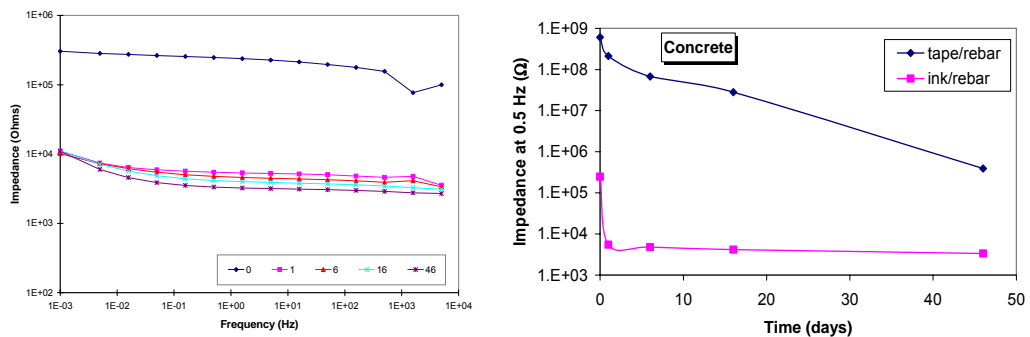
where  $\epsilon$  is the dielectric constant of the adhesive joint which is dependent on the moisture level,  $\epsilon_0$  is the permittivity of free space,  $A$  is the bonded area and,  $d$  is the thickness of adhesive material. Figure 12 shows the effect of adhesive thickness on impedance magnitude for dry samples. It shows an increase in impedance over the entire frequency range as the adhesive thickness increases. Thickness is inversely proportional to capacitance, and capacitance is inversely proportional to the impedance ( $C = \epsilon\epsilon_0 A / d$ ;  $Z_C = 1 / j\omega C$ ).



**Figure 12** Impedance as a function of single-lap joint adhesive thickness.

Use of In-Situ Impedance Sensors in Concrete

Whereas the Electrochemical Impedance Spectroscopy (EIS) was verified to work well for detecting damage between metallic polymeric and metallic materials, its use in concrete structure remains an open question. To validate use of the *in-situ* sensor for concrete, two types of sensors were installed on a concrete block that was then immersed in water. One sensor was the permanent ink-type sensor. The other was an adhesive tape-type sensor. The EIS signal was obtained between the sensor and one of the reinforcing bars in the concrete. The impedance spectra from the ink sensor and those from uncoated metals show a reduction in impedance with exposure time. Figure 13 also indicates that the concrete readily allows conduction between the external sensor and the internal reinforcing bar. There is a decrease of more than an order of magnitude when moisture is first introduced to the concrete block. There is an additional decrease of ~25% as additional moisture is absorbed by the block. The tape sensor behaves differently with a much higher impedance initially and a slower, but continual decrease of several orders of magnitude, reflecting a slower absorption of moisture. This behavior is likely to be dominated by the adhesive used to apply the sensor. In the proposed program, the adhesive can be chosen so that the concrete dominates the signal or the adhesive could be chosen to be a sensitive indicator of the amount of moisture reaching the interface.

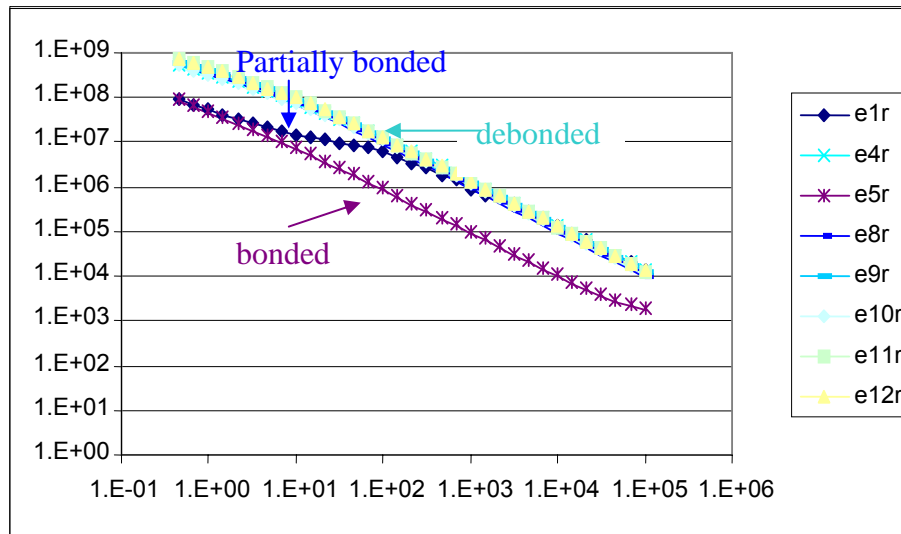


**Figure 13** Left) Impedance spectra between an ink sensor and rebar of a concrete block immersed in water. Right) Impedance at 0.5 Hz as a function of immersion time for the ink and tape sensors.

In order to assess the usability of electrochemical impedance spectroscopy in evaluating damage in FRP repaired concrete structures, a 6 x 6 x 12 concrete specimen was wrapped with FRP (carbon-epoxy). Debonding was generated at locations by inserting layers of Teflon at the concrete surface after installing the internal sensors but before applying the FRP (Figure 14).

Results from trial specimen reveal that

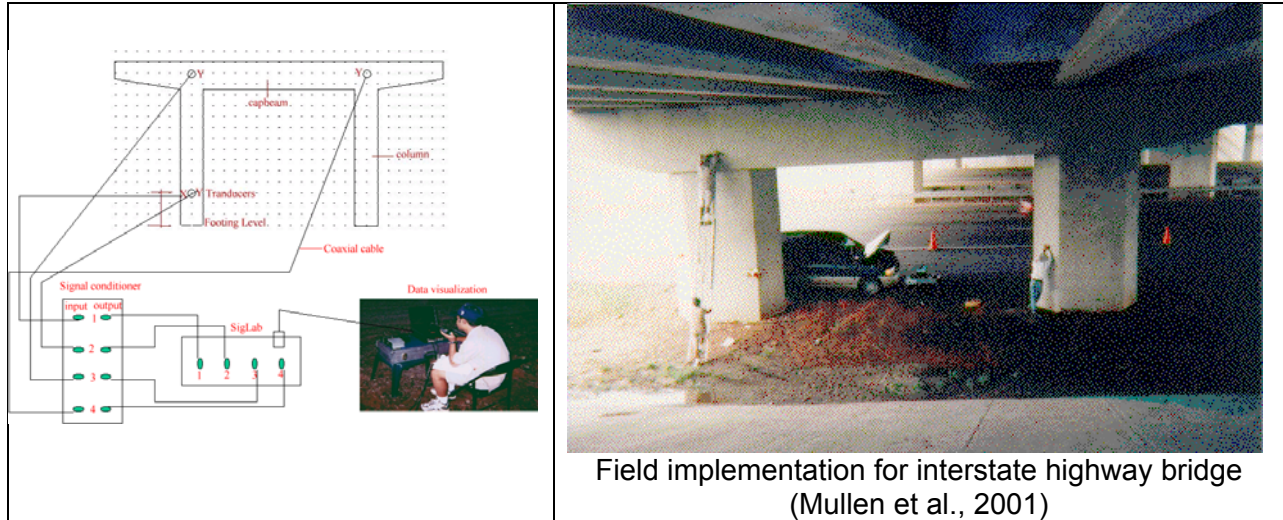
- 1- Reinforcing bar may be used effectively as an internal sensor to assess debonding between FRP and concrete.
- 2- There was a clear difference in the impedance value between the external sensor and the rebar whether the external sensor is locating in top of bonded or debonded area.
- 3- Localized damage may be measured using the impedance spectroscopy technique.



**Figure 14** Typical impedance measurement from the trial specimen

- **DYNAMIC IMPEDANCE**

Experience gained from recent field tests conducted under operating conditions (Mullen et al., 2001) as part of a research project sponsored by the Mississippi Department of Transportation's Bridge Division will guide the design of the procedures to be used for measuring dynamic impedance. The left part of Figure 15 shows a schematic arrangement of a four-channel system (SigLab Users Manual, 1996), which permits simultaneous recording of an input accelerometer such as a hammer, shaker, or reference response and up to three output accelerometers. The right part of Figure 15 shows a field implementation of such a portable array on the pier of an interstate highway bridge.

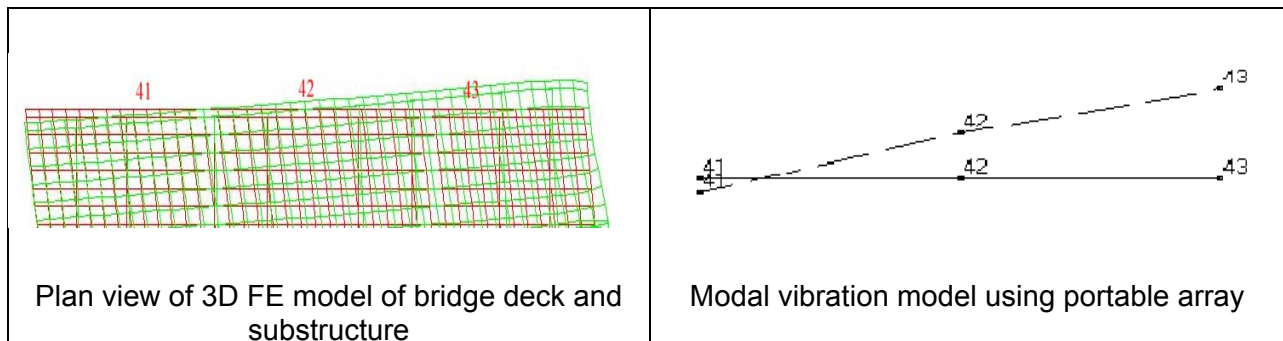


**Figure 15** Typical dynamic impedance measurement configuration

The time taken to set up and record data in each new configuration in this demanding environment was about 3 hours. Cable requirements involved up to 250 ft long spools to reach from each accelerometer placement to the centrally located signal conditioner. Additional 250 ft long spools were needed to bring the signals to the data acquisition unit which was required to be located nearest one of the intermediate bents for safety reasons.

For dynamic impedance measurements, particularly in damage detection applications, it is critical to have a well-calibrated reference finite element (FE) model to enrich the understanding of the modal vibration model and to guide the assessment of sensitivities to damage detection. In the case study, a three-dimensional (3D) FE model shown in the left part of Figure 16, was used to predict system modes of vibration, and the modal vibration model is depicted by the snapshot of an animation shown in the right part of Figure 16.

An initial model used beam and shell elements with fixed boundary conditions at the column footing levels and obtained less than 10 percent error with respect to the modal vibration model for the response mode of interest. The mode frequency of interest in this case was measured to be 3 Hz, and the corresponding mode shape is The modal model was extracted using polynomial curve fitting of peaks of the frequency response functions obtained at the three response points using commercial software (StarModal Users Manual, 1996). The final model shown in the left part of Figure B used continuum and infinite elements to represent the dynamic impedance of the soil down to a depth of 100 ft. These improvements reduced the error to less than 1 percent.



**Figure 16.** Typical dynamic impedance measurement results

In the field tests an attempt was made to excite the structural system using an instrumented sledge hammer capable of delivering up to 5 kN force, but this proved impossible because of the extremely high dynamic impedance. For the system identification, therefore, a reference input location was selected on the top of the deck and ambient vibrations triggered by heavy truck traffic were recorded. The reference input and portable array procedure, when tuned to target frequencies identified by the FE modeling, proved highly effective in this case as the results in Figure 16 indicate.

Implementation of this type of measurement scheme will require some enhancements in order to heighten sensitivity to more localized damage such as delamination regions. The importance of model calibration, portability of equipment, and accessibility to the structure for sensor installation must be kept in mind in any strategy that is to be practical, however. Access becomes especially critical when damage is located on girders that extend over operating traffic as was the case in the field tests.

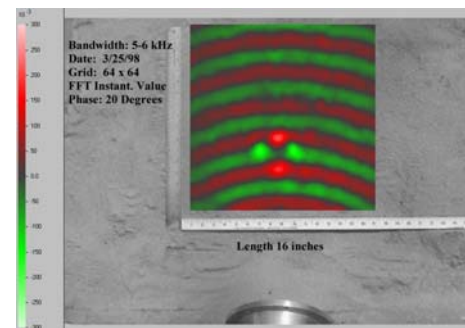
- OPTICS

Electronic Speckle Pattern Interferometry (ESPI) is an electronic version of holographic interferometry that uses DDC camera instead of a photographic film. EISPI, which uses phase shifting techniques, is a whole field noncontact optical method for the measurement of displacement components at an object's surface. High resolution, high sensitivity, speed and ease of use are the main advantage of ESPI, and they make this technique well suited for the study of strain field in a case of high strain gradient. The calculation of the strain map from the displacement map is always a challenging part of this type of analysis. Least squares surface fitting of the phase map representing displacement components is usually used for strain calculations.

Digital speckle interferometries (DSI and DSS) uses data contained in the speckle pattern that is seen when objects are illuminated with laser light (Cloud, 1995). For NDI applications, the approach measures anomalies in the surface displacement field that are produced by subsurface flaws such as disbonds. The chief advantages of these optical approaches for displacement/strain analysis and NDE are that they are whole-field, fast, non-contacting, flexible, sensitive, and, now, relatively inexpensive (e.g. Nokes and Cloud, 1993; Lanza di Scela, et al, 1998; and Cloud, 2000).

Another class of mechanical measurements is of the non-contact variety. The recent improvements in lasers in the last few decades have led to dramatic improvements in the NDE/NDT community. Non-contact laser measurements provided by a laser Doppler velocimeter (LDV) can provide measurements similar to standard pulse echo devices, but as the name implies, in a non-contact manner. Furthermore, it should be possible to scan the laser (Khan et. Al., 2001) to provide a more rapid measurement of the test specimen. There may be some logistical issues in scaling up such a test from laboratory to field sizes but they can be investigated as part of the proof of concept. An example of the fine scale, point by point measurement envisioned to identify a defect is presented in Figure 17.

In this example, from research currently underway at the University of Mississippi National Center for Physical Acoustics (NCPA), sound is being generated by a speaker and is passing over sandy ground in which a circular disk is buried a few centimeters below the surface. The LDV system is



**Figure 17:** Vibration data from LDV scan of sandy ground with buried object (Khan et.al., 2001).

measuring the velocity of the ground and the curved rings represent the amplitude of the vertical ground motion induced by the passing acoustic wave. The disk, which imitates a defect for our purposes, distorts this sound wave and is easily identified. Such a configuration could be used for detecting defects in bridges whether they are excited by acoustic waves in the air or structural (vibrational) waves in the bridge. Non-contact laser measurements are more expensive than the traditional pulse echo measurements due to the capital cost of the laser, which is typically \$200,000, but savings may occur from the reduced labor costs of measurements.

Other optical methods which may be used to evaluate both strain and stress fields include Moiré interferometry and photoelasticity. Whenever debonding between FRP and concrete takes place, this will affect both stress and strain fields which may quantitatively be evaluated using any of the optical methods mentioned above.

- *Ubiquitous/AMBIENT Intelligence*

Extending the service life of existing structures is as important as building new structures. To evaluate the service life of existing structures, a complete monitoring system with real time analysis system combined with the smart materials and Ambient Intelligence is essential. Monitoring data provide the integrity of structures, and engineers can utilize the infrastructure up to their life time limit. The proposed monitoring system is not just the duplication of traditional localized monitoring system. Variety of sensors is installed for critical structures, data are collected by wireless communication, real time analysis is performed, and real time information is provided to classified users. This system is called "Ubiquitous Intelligence" or "Ambient Intelligence". Using the Ubiquitous/Ambient Intelligence technology, healthy structures can be used for longer time while under-performing structures can be replaced. With the aid of self healing smart materials, the lightly damaged structures can also be self healed. In this way, tax payers' money will be most smartly spent.

Ubiquitous/Ambient Intelligence is different from the current monitoring system; it is in fact a much bigger concept than the current monitoring system. It actually includes the current monitoring system as one of its components. Using the example scenario in Wikipedia ([http://en.wikipedia.org/wiki/Ambient\\_intelligence](http://en.wikipedia.org/wiki/Ambient_intelligence)), an application scenario for the nation's infrastructure can be recomposed as follows to clearly show the potential of ubiquitous/ambient intelligence;

John travels back home after a long business trip. At I-95, he was recognized by an intelligent surveillance camera, the gates to fastlanes are automatically open, and the toll booths unlock and open. When he switched to I-85 to through his usual way, he was alarmed and the navigation map indicates that a bridge ahead of his route is overloaded. The GPS based navigation system connected to the Ambient Intelligence automatically found the shortest detour route and showed it on the screen. In the mean time, the Ambient Intelligence notifies John's family that he may be delayed 5 minutes because of the detour. A built in computer in his vehicle in turn collects all the sensor signals using RFID technology along his past routes and send them to Ambient Intelligence. Simultaneously the Ambient Intelligence outputs stresses and other mechanical information to the maintenance office for further analysis....

The critical technologies needed for this ubiquitous/ambient intelligence is GPS/Digital Map/Wireless Communication/Wired and Wireless Sensors. With the advent of modern MEMS (Micro-Electro-Mechanical System, most needed technologies are already developed. The application of this technology is actually considered in a smaller scale in space science area in US and some countries for the development of new subdivision. A rendering of Ubiquitous/Ambient intelligence system for a shopping mall (searching for an item, price, shop location and checking the shuttle bus schedule) is shown in Figure 18.



**Figure 18** Rendering of Ubiquitous/Ambient intelligence system for shopping in a mall (searching for an item, price, shop location and checking the shuttle bus schedule), [http://www.ercim.org/publication/Ercim\\_News/enw66/banatre.html](http://www.ercim.org/publication/Ercim_News/enw66/banatre.html)

The advantage of the system is that (1) it includes the existing monitoring system so that the past investment is still valid, (2) it is shown in several SF movies including Matrix series and most people are already aware of that, (3) the technology was not available in the past, but it is available now, and (4) the best time to apply this technique is when the new paradigm of the infrastructure is established, and this is the time.

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