Smart Structures: Technology Changing the Opportunities and Responsibilities of the Modern Engineer

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1. Executive Summary

The fields of material science, signal processing, signal acquisition, and structural health monitoring have experienced explosive growth in the past two or three decades. Indeed the latter, structural health monitoring, is a field generally regarded as new with worldwide conferences on the subject area currently running on their 7th or 8th year. Despite exponential technological growth and progress in these areas, use of these new technologies is still extremely limited. Furthermore, capturing new technologies or the methodology of designing next generation structures in the classroom presents a unique challenge.

This paper starts by defining a "Smart Structure" and quickly traces some of the developments in Structural Health Monitoring to highlight why topic areas presented in this paper are timely now. The paper then presents research conducted by the authors in the areas of the development of a Statistical Based Damage Detection Method for structural systems, power harvesting for wireless sensor networks, and the usage of Shape Memory Alloys as passive control devices. The paper concludes with a look at potential military applications in two topic areas: 1) Improving vehicle operation and maintenance through real time data acquisition and 2) Presenting a solution for assessing critical structures and establishing a basecamp in a deployment scenario.

2. Introduction:

2.1 The Challenge of Maintenance & Inspection:

First and foremost if you are reading this, congratulations! You are part of the "mass-maintenance age" as termed by Yozo Fujino, a leading civil engineer from the University of Tokyo, Japan [1]. The "maintenance generation" engineers, being educated today, will be responsible for the explosion of infrastructural growth that occurred for the most part in a concentrated period between 1965-1985. What's the point? Most bridges, for example, were designed for a lifespan of 30-40 years. A casual drive to any New York City airport will highlight the need for repair, retrofit, and maintenance upon any of the tunnels, highways, and bridges along the journey. Upon reaching the airport, one is most likely to board an aircraft that was built in the 1980s with a design life in flight hours that typically equates to 25-30 years. The point is simply that much of the nation's infrastructure is entering the final phases of their design life.

As a bridge, skyscraper, or airplane ages, maintenance costs grow exponentially. Unfortunately, as a society, we are ill prepared for this challenge. Airline carriers, for example, find themselves struggling to meet service schedules during what may be the most difficult period in history for the industry. To continue with the example of infrastructural lines of communication, the nation's bridges are in disrepair. According to the National Federal Highway Association's website [2] and national bridge inspection program, there are currently 160,819 deficient bridges in the United States (last updated Dec 03) representing an incredible monetary shortfall/need. One must also consider that the cost of maintaining, repairing, or replacing a highway or bridge goes far beyond materials and labor but also extend into productivity and revenue since traffic flow and commerce may be impeded or stopped.

In a publication presented at Structural Health Monitoring 2003, Stanford CA [3], Steve Chase from the FHWA cites that although 10,000 bridges are being constructed or retrofitted each year at a cost of over $7 billion, the nation is still falling behind the deterioration rate because we are still using the same technologies, materials, and methods that were being used in construction over 20 years ago. This statement raises two challenges 1) Given limited resources to fix the nation's bridges (or any structure), how can the most critical bridges be identified and selected first? 2) What new technologies, materials, and methods can be employed to extend the life of existing and newly constructed bridges?

2.2 Reacting to and Preventing Tragedy

On November 2nd, 2002 an earthquake destroyed a small school in San Giuliano di Puglia, Italy killing 26 children and a schoolteacher. Built in the 1950s as a single story structure, a second floor was added a year prior to the tragedy, immediately raising questions concerning the design and construction of this addition. However, after the

anger, lawsuits, and liability involved, a very interesting 2nd order effect resulted. Parents across Italy demanded from their local officials "what about our school?" As a result, the Italian Government passed a law stating that every school and hospital would be inspected within 5 years to ensure public safety. There is interest in adopting this standard across the European Union. One requires a few moments of thought to appreciate the magnitude of this challenge. Countless schools, hospitals, and public facilities across Europe are hundreds of years old, have historic value, and are made of masonry, brick, and mortar. Although seismic codes are present to regulate future construction, what standard should be applied to existing structures? Who pays? What methods should be utilized? How do you inspect locations that you cannot access or see? These questions, and many others, are the subject of current research activities and conferences ongoing in Europe.

A similar type instance occurred in the United States when a piece of concrete tunnel roofing spalled, cracked, and fell on a passing vehicle that caused an accident killing the driver. The FHWA soon mandated that all tunnels needed to be tested at a cost approaching a billion dollars as inspectors tapped the roofs of tunnels with hammers amidst one-way traffic [1].

Common to the school and to the tunnel examples above is the age-old adage that an ounce of prevention, although it costs an ounce upfront, is worth much more in return considering the life of the structure. Moreover, the intent of this introduction is to inspire the questions "Could a tunnel be built with materials or devices to detect cracks and spalling?" "Could technology give us the ability to assess the condition, or health, of a school or hospital?" "Is it possible to monitor the performance of a bridge or aircraft to know when maintenance is required or how badly maintenance is needed?" The answer to all these questions is yes and is the motivation behind Smart Structures and the field of Structural Health Monitoring.

3. Smart Structure Defined and a Brief Historical Perspective

This paper defines a smart structure as any system exhibiting the following four characteristics.

- **Designed with a full life cycle management plan in mind**
- **Employs technology leveraged materials where appropriate**
- **Has active or passive controls against damage**
- **Has the ability to monitor its own health**

A representative example of a smart structure is the Wotton Bridge located in the municipality of Wotton (Quebec, Canada) [4, 5]. Constructed in a region where corrosion is of particular concern, the reinforced concrete deck is on one half of the span conventional steel, and on the other half of the span carbon and glass Fiber Reinforced Polymer (FRP) bars. Embedded fiber optic sensors (emplaced within the concrete) monitor temperature and strain readings of the reinforcement. Cables run under the

bridge to a 32 channel acquisition system that records and processes the readings. A modem transmits the data to engineers for analysis. Although the objectives of the Wotten Project are more directly linked to the implementation of FRP reinforcement and their comparison to steel reinforcement, looking at the project as a smart structure is even more fascinating. The structure was built with the idea and plan of self assessment. New technologies are leveraged. Engineers can study and monitor the performance (health) of the structure in real time and make comparisons over time. It is not hard to imagine that a code could be written to process this data and alert engineers to abnormal strain or temperature readings indicating possible damage.

Figure 1. Pictures of the Wotton Bridge, Quebec, embedded fiber optic sensors, and data acquisition system.

The idea of monitoring is certainly not new. One could readily point to the tachometer or fuel gage of a vehicle as an example of a real-time feedback mechanism, or to the Army Oil & Analysis Program (AOAP) as an example of a health monitoring. Indeed, these are fine examples and the exciting next step is applying these same concepts into structural systems such as bridges, tunnels, or buildings. This idea was first applied to the in the 1960s and 1970s to assess the health and performance of nuclear facilities and off-shore oil platforms [6]. For nuclear structures, structural integrity for containment was paramount; for off-shore platforms, continuous cyclic loading of the structure (waves) presented the risk of fatigue or connection failure. A monitoring system was operated for six years by the British Petroleum, and the result was that the structure was designed too conservatively. Subsequent structures were therefore designed less conservatively with consistent cost savings.

At its most basic level, engineers sought to identify changes in the vibrational characteristics of the structure, with the idea that damage would change the global stiffness and vibrational response of the structure. The method most commonly utilized to analyze the vibrational characteristics of an object, member, or structure was taken from the aerospace industry, modal analysis.

3.1 Modal Analysis:

Figure 2. Conceptual Representation of Modal Analysis

At its most basic level, modal analysis seeks to identify the relationship between some type of load (input) and the structural response (output). The idea is that the characteristics of a system (physical domain) or signal (time and frequency domain) can be broken into basic building blocks. In the time or frequency domains, any signal can be broken into a series of sine and cosine functions and reconstructed through superposition of these two basic building blocks. In the physical domain, these building blocks are called modes with corresponding mode shapes. Each successive mode occurs at higher frequencies. Modes are system dependent. In other words, every structure in existence has its own unique modes and mode shapes. Once modes and mode shapes are determined, any structural response can be modeled as a linear combination of these mode shapes. Mathematically, data is processed between the time and frequency domains via the Fourier transform, and the natural frequencies are the eigenvalue solutions of a system's characteristic equation. For a complex system (any structure), characteristics are obtained from correlating a system's response to known input forces across a range of frequencies in matrix form, called a Frequency Response Function. A schematic that briefly outlines this process is presented in Figure 3 below [7].

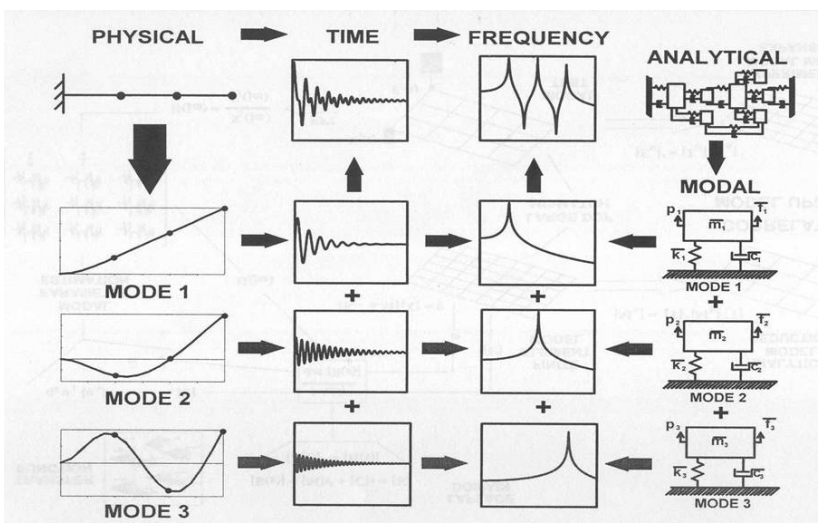


Figure 3. Schematic Representation of the Physical, Time, Frequency, and Analytical Domains of Modal Analysis

Modal analysis is a fairly mature field (50-60 years old) that has traditionally and effectively been utilized for two purposes: 1) Determination of natural frequencies and 2) Validation and improvement of Finite Element Models. Natural frequencies are the cornerstone of vibrations engineering since loading at or near one of a structure's natural frequencies can result in resonance and subsequent failure. The occurrence of torsion

modes coupled at or near natural bending vibration modes is termed “flutter” in the aerospace industry and can result in the near immediate implosion of wing structures. The classic example for structural engineers remains the Tacoma Narrow’s bridge which collapsed when wind loading of 42 mph caused resonance resulting in huge oscillations of the bridge deck. An exciting part of modal analysis is that it is based off of experiments that collect data from an actual structure. Hence, this data can be utilized to remove, improve, or validate many of the assumption necessary in finite element modeling. Hence, modal analysis can add a degree of confidence before using a FE model to predict system responses to new load cases.

3.2 Applicability of Modal Analysis to Structural Health Monitoring

Although a champion when applied to the field of vibrations engineering, is modal analysis appropriate for the field of Structural Health Monitoring? First, the objectives of structural health monitoring must be considered. The following four levels of damage assessment have been adopted as the standard across the field [8]:

- Is damage present? (detection)
- Where is the damage located? (localization)
- How severe is the damage? (diagnosis)
- How much longer can the structure perform? (prognosis)

The immediate answer to the question at hand (is modal analysis the best method?) is sometimes and maybe. For a specific application, focused on an individual member, with the objective of determining if damage is present, modal analysis can work. However, applied to a structure of thousands of elements, the question is much harder to answer. Another look at the process provides more insight. A load/input time domain signal and measured time domain response are utilized to generate a frequency domain function by using FFT. Modes are represented by the peaks on the frequency response function. Damage is indicated by the movement of these peaks (change in modal frequencies) at a different point in time (figure 4). Localization is best determined through the use of a finite element model used to compute numerical mode shapes and structural response.

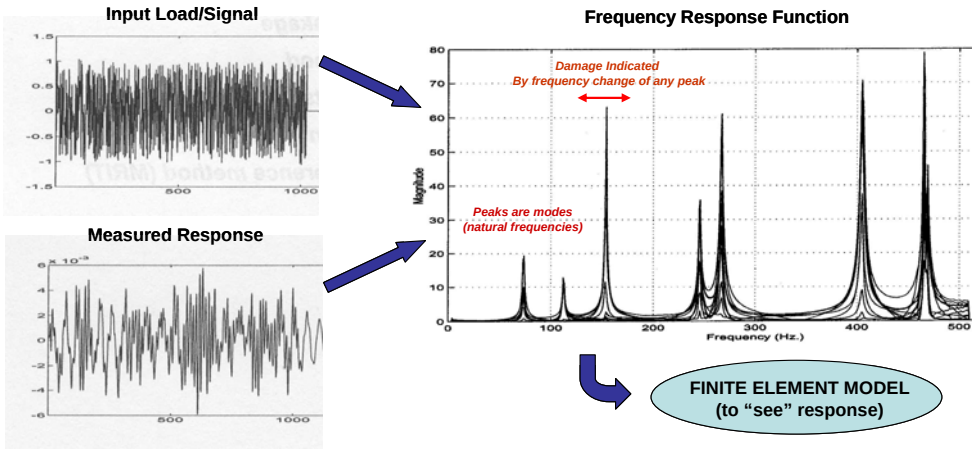


Figure 4. Interpreting the Frequency Response Function

Literally, thousands of papers have been written and hundreds of methods developed to optimize this process for particular structures of interest [8]. Data acquisition and signal processing have become fields within themselves. This paper does not aim to critique any particular method but seeks to highlight and address challenges common to modal analysis:

- **High processing demands**: Best results require knowledge of the input and output. After the FRF is generated, a Finite Element model is required to localize the damage. Noise in the signals is of concern. All of this means *high energy, size, and computing requirements.*
- **Careful and robust sensor placement**: Mode shapes require that sensors be placed where modes can be seen/captured. In a complex structure, this means many sensors at the right places.
- **Lack of sensitivity to damage**: Perhaps the largest concern. Damage to an individual member may cause almost no change to the global stiffness. Structures are most often robust and redundant. In many cases, one could even remove a column and see little vibrational change in the system. Successful damage detection is often represented by a 2-4% shift of modal peaks.
- **Extreme sensitivity to environmental Effects**: Temperature effects often impact modal parameters more than acceptable levels of damage [8]. As a result, damage can easily be lost within this change or falsely reported. Methods have been presented to factor out environmental effects but again require more computing, power, and are case by case dependent.

Due to the limitations discussed above, Structural Health Monitoring is still largely a laboratory exercise. This is not to say that particular applications have not proven successful, but that general practices and procedures still have to make their way into industry and practice.

4. Research Conducted: Statistical Response Surface Approximation Using the ASCE Benchmark

The author had the opportunity to conduct research with Sara Casciati of the University of Pavia, Italy, on a new approach to damage detection, response surface approximation [9]. The method is based upon a statistical approximation of the relationship between the structural responses recorded at different locations on the structure compared at different periods in time. The motivation for this research is twofold: 1) To develop a method that overcomes the limitations of modal analysis, and 2) To develop an efficient, simple, low power consuming damage detection algorithm that allows for continuous, wireless monitoring of a structure. The method was developed and applied to the benchmark problem developed by the ASCE Task Group on Structural Health Monitoring [10]. This work is focused on the first and fourth components of a smart structure, design of a structure with a plan for life cycle management and the ability for self assessment.

The method performs a statistical comparison of the response time histories collected at different periods of the structure's lifetime, one of which is known to be undamaged. By considering only the structural response data, this method is independent of the structure's internal characteristics and does not require a finite element model. As such, the computations are simple enough to be carried out on the microprocessor of a smart sensor, thus allowing the deployment of a distributed computational architecture which prevents the transmission of overwhelming amount of information from the sensor to the central CPU. This low power solution makes a wireless network feasible. The absence of cables decreases the installation and maintenance costs of a monitoring system so that the monitoring can be applied to any common type of structure, and it can be carried out in a continuous manner throughout the life-time of the structure.

4.1 Description of the Method

Let NS the number of sensors placed on the monitored structure. The sensors measure the time histories of the quantity of interest (acceleration, strain, etc.) at different locations on the structure, for given duration T, sampling frequency Df, and total number of points NP = T Df. Each time history is considered as a set of clusters of experiments by dividing it into *nset* successive segments of length $p = \alpha$ NS, where α is an integer assigned by the user. Therefore, *nset* = int(NP/*p*).

For simplicity of notation, consider a structure with four sensors, hence NS = 4 (e.g., a one-story, one-bay building with a sensor at each corner). Each time history segment of sensor 1, for example, is a function of the corresponding segments recorded by the other NS-1=3 sensors on the structure. Since the underlying mechanism is unknown, the experimenter must approximate the unknown function with an appropriate empirical model. For sensor 1

$$\mathbf{x}_1 = \mathbf{y} = f(\mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4) + \boldsymbol{\varepsilon} \tag{1}$$

where the $p \times 1$ vector $\mathbf{y}$ is the response variable, while the $p \times 1$ vectors $\mathbf{x}_j$, $j = 2,3,4$, are considered as the of the predictors. The function $f(.)$ is the response surface approximation, i.e., it is approximated relationship between the response variable (cluster of measurements recorded by the sensor under consideration) and the predictors (corresponding clusters measured by the other sensors). The error term $\boldsymbol{\varepsilon}$, which is also a $p \times 1$ vector, accounts for the pure randomness inherent to any experiment, and for the lack of fit due to the form assumed for $f(.)$.

Usually a low-order polynomial is used for $f(.)$. If a first order polynomial is selected, Equation (1) becomes

$$\mathbf{x}_1 = \mathbf{y} = \beta_1 + \beta_2 x_2 + \beta_3 \mathbf{x}_3 + \beta_4 \mathbf{x}_4 + \boldsymbol{\varepsilon} \tag{2}$$

In matrix form

$$y = X\beta + \varepsilon \tag{3}$$

where $\mathbf{X} = [\mathbf{1}\ \mathbf{x}_2\ \mathbf{x}_3\ \mathbf{x}_4]$ is the NP × NS matrix of the predictors, and $\boldsymbol{\beta} = [\beta_1\ \beta_2\ \beta_3\ \beta_4]^T$ is the NS × 1 (4 × 1 in this case) vector of the unknown linear regression coefficients.

Assume that the error $\boldsymbol{\varepsilon}$ is a vector of uncorrelated, normally distributed random variables of mean zero and same variance σ^2. To estimate the variance of the error, the linear regression analysis and the successive analysis of variance are performed.

A linear regression analysis consists of determining the unknown coefficients β's in Equation (2). For this purpose, the least square method is applied, i.e., the coefficients that minimize the sum of the square of the error $\boldsymbol{\varepsilon}$ are computed. These coefficients are said the least square estimators and they are collected in a NS × 1 (4 × 1) vector **b** that results given by[1]

$$\mathrm{b} = (\mathrm{X}^T\mathrm{X})^{-1}\mathrm{X}^T\,\mathrm{y} \tag{5}$$

The fitted regression model is

$$\hat{\mathbf{y}} = \mathbf{Xb} \tag{6}$$

The difference between the observations **y** and the fitted values $\hat{\mathbf{y}}$ is the p × 1 vector of the residuals

$$\mathbf{e} = \mathbf{y} - \hat{\mathbf{y}} \tag{7}$$

Finally the analysis of variance is performed by computing the following sum of the squares:

$$SSY = \mathrm{y}^T\mathrm{y} \qquad \text{(Total sum of squares)} \tag{8}$$

$$SSR = \hat{\mathbf{y}}^T\hat{\mathbf{y}} \qquad \text{(Regression sum of squares)} \tag{9}$$

$$SSE = SSY - SSR \qquad \text{(Residual sum of squares)} \tag{10}$$

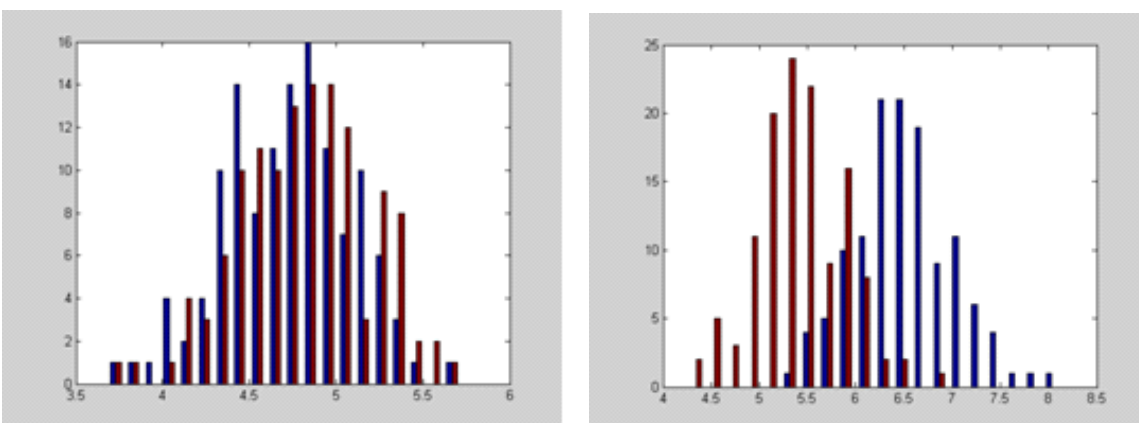
Dividing the *SSE* by the associated p - NS number of degrees of freedom provides an estimate for the variance of the error, σ^2.

By repeating the above procedure for all the *nset* clusters contained in the response time history of sensor 1, a histogram of *SSE*-values can be built in the corresponding location. This histogram shows different ranges of the *SSE*-values on the abscissa axis, and the number of occurrences of *SSE*-values that fall into these ranges on the ordinates axis. It

represents the empirical probability distribution of the variance of the error in the response surface model.

The described method is applied to two different sets of measurement taken during different periods of life of the structure: 1) the first is known to be associated to an undamaged state of the structure and it provides the reference *SSE*-histogram (blue); 2) the other is the mixed set of measurements from the undamaged structure and from a successive unknown state of the structure. The histogram provided by the latter analysis is therefore denoted by mixed-*SSE* (red). The two obtained histograms can be plotted together and compared, after simply multiplying by two the *SSE* one. If the histograms are adjacent to each other, then the state of the structure is still undamaged. Instead, if the histograms are shifted, then a structural change occurred and the presence of damage is detected.

The damage can also be located by permuting the sensor whose response time history segments are considered as response variable **y**, and repeating the analyses until all the NS(= 4) sensors are considered. In this way a histograms comparison can be built at each sensor location. Damage, if present, will be located close to the sensors where the largest shifts between the histograms are observed.



Undamaged Damaged

Figure 5: Damage Indicated by a Shift of the Probability Density Function of the Variance of Error

4.2 Application and Results to the ASCE Benchmark Problem

The ASCE SHM Task Group benchmark problem described in [10] was used to test the capability of the method to detect and locate damage. In brief, the test structure under consideration is a 2-bay by 2-bay, 4-story scaled steel frame. A data generation program (datagen.m) can be downloaded at wusceel.cive.wustl.edu/asce.shm/ to numerically compute the response of the structure to different types of excitation loads. A 120 d.o.f. analytical model of the structure was considered to account for the modeling error effect on the damage detection method performance. The selected excitation force is applied at

each floor in the y-direction to represent the wind load. The acceleration time histories are computed in 16 nodes, 4 on each floor. In two of the four nodes the acceleration in the x-direction is provided, while in the other two nodes it is computed along the y direction. The different d.o.f. are analyzed separately, so that NS was set equal to 8 in each analysis. The total number of points of each acceleration time history is NP = 40001. The proposed damage detection method was applied assigning an input parameter α equal to 40. Therefore, the response time histories were divided into clusters of $p = \alpha$NS = 320 points each, and the number of clusters is *nset* = int(NP/*p*) = 125 clusters each.

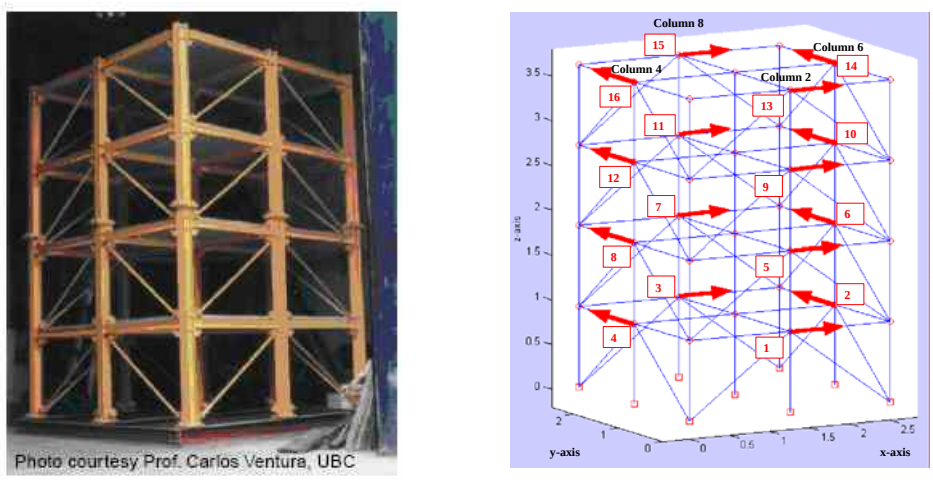


Figure 6: The ASCE Structural Health Monitoring Benchmark Problem

Damage was introduced by removing all braces at the first and third floors of the structure (Damage Pattern 2) and the program was run. The data was then processed by the method described above and histograms were generated for each sensor of the structure. Of note, the removal of this bracing does represent a significant change in structural stiffness and response.

The results in figure 8 show representative sensor histograms from each floor of the structure. The histograms shift occurs on the floors where damage was incurred (braces removed). No changes are present at the other floors. A separate experiment was conducted (not pictured) by removing the braces only at the first floor. Again, the damage was correctly identified and located by a shift in the histograms at the first floor alone.

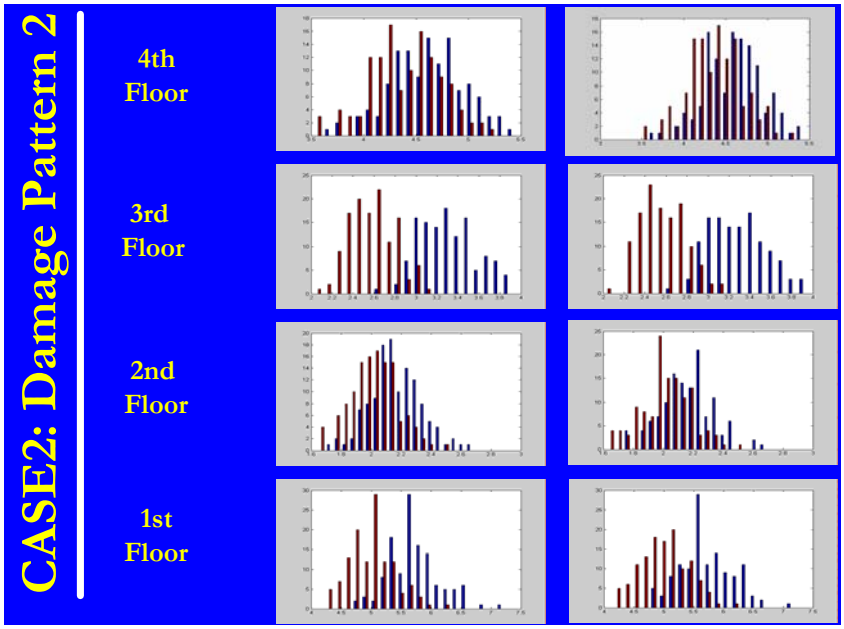


Figure 7. Histogram Shifts of the Damaged Floors for the ASCE Benchmark Program

Although extremely encouraging, future work needs to be conducted to better determine the sensitivity of the method to different levels of damage. This information would be utilized to achieve levels three and four of Structural Health Monitoring (diagnosis and prognosis). Another exciting and equally powerful aspect of this method is that since it is independent of actual structural characteristics, it theoretically should be insensitive to temperature effects that pose such extreme difficulties to modal analysis when applied to structures. This possibility, coupled with less demanding calculations, makes the method an attractive candidate in the development of wireless monitoring solutions.

5. Research Conducted: Vibrational Power Harvesting

Focusing upon the first component of a smart structure, i.e., the design of a structure with the considerations of health monitoring in mind, the author had the opportunity to participate in research focused upon vibrational power harvesting [11]. The goal of the research is the implementation of a self-powered wireless structural health monitoring sensor network. The network architecture under development consists of self powered accelerometers (s) that transmit short distances to computational nodes (C), which then transmit further distances to a centralized data server.

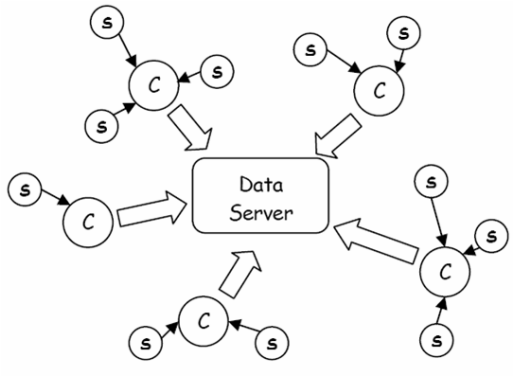


Figure 8. Concept of a Wireless Sensor Network

The benefits of such a network would include cost savings due to no cabling, ease of installation and the ability to drop a new sensor into the network at any time. The largest challenge of such a network is power. The requirement to routinely change batteries would make the wireless solution expensive and maintenance intensive (undesirable). Current state of the art for power harvesting includes the well established field of Solar Harvesting and the emerging field of Vibrational Harvesting.

The research conducted involved a simple spring mass type system that allows a small magnet to pass through a coil of 10000 wraps of copper wire. Power is created by magnetic induction. The idea is that such a system could be tuned such that its resonant frequency would match the most common response frequency generated by the structure. In turn this would generate the largest possible amplitude and frequency of movement of the magnet through the coil. For the apparatus constructed, the resonant frequency was 9.27 Hz.

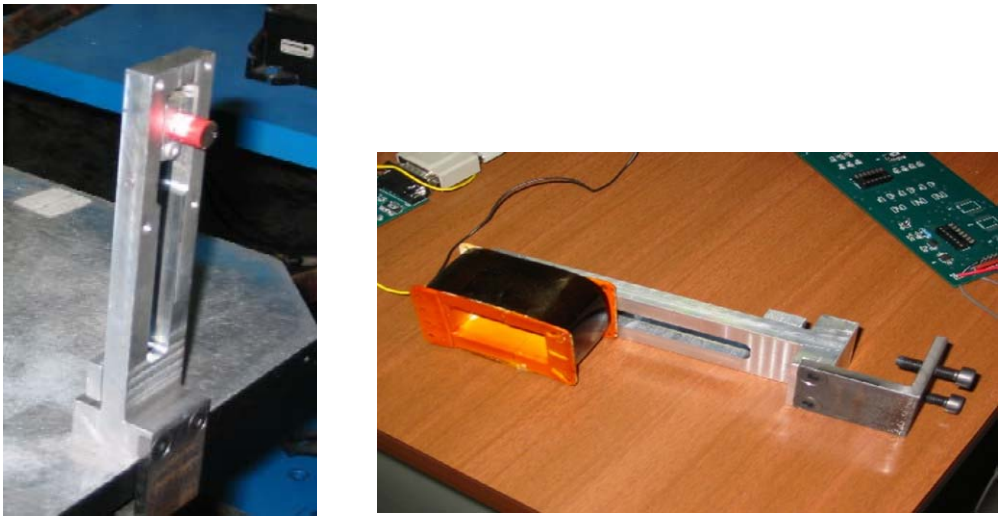


Figure 9. Vibration Power Harvester

The apparatus was attached to a shaking table and was tested at various frequencies and forcing functions (amplitudes). Results at the resonant frequency of 9.27 Hz and for 8 Hz are summarized below.

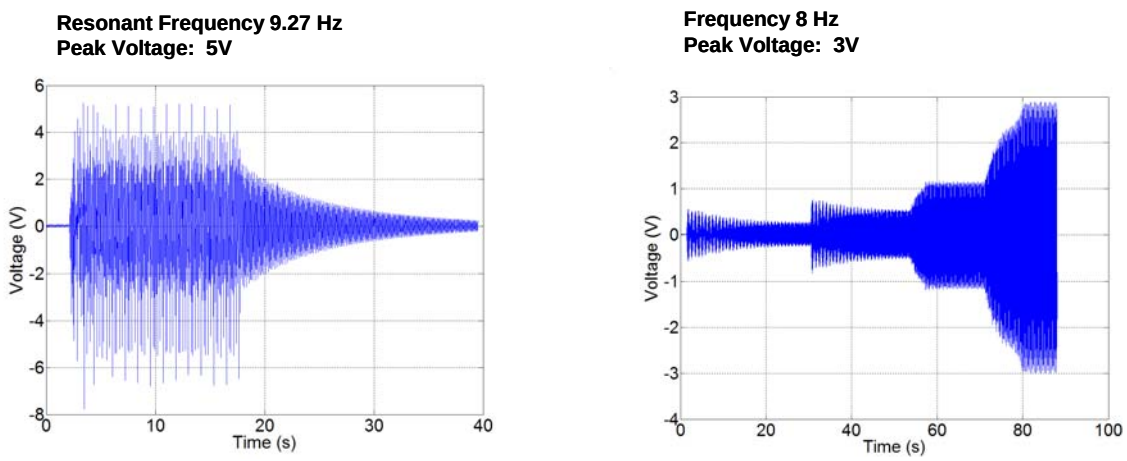


Figure 10: Voltage Generated at Varying Frequencies and Amplitudes

In the two examples above voltages range from 0.5V to 5V representing a power ranging from 40μW to 4mW. Understanding what can be done with this amount of power depends upon sampling rate, bandwidth of transmission, and distance of transmission. However, it must be stated that this is not a lot of power. Typical off the shelf accelerometers have an average power draw of 20mW. 2mW dual-axis MEMS (Micro Electro Mechanical Systems) accelerometers are available but require a board/microprocessor for transmission (transceiver) that ranges from 1mW to 20mW depending on the over the air bit rate. Using such an accelerometric station, at peak voltage 5V) and power capacity 4mW the station could obtain and transmit data at 25 Hz (25 samples per second). However, at 40μW the station would be limited to 0.25 Hz (one sample every four seconds). This sampling rate would not be acceptable.

The feasibility of utilizing vibrational power harvesting would be largely dependent on the structure of interest. Most likely, this method would need to be combined with solar harvesting and together these techniques could result in smaller backup batteries.

6. Research Conducted: Utilizing Copper based Shape Memory Alloy as a Passive Control Device

Focusing on the second and third components of a smart structure, i.e., leveraging new materials and employing active or passive controls against damage, research that explores the use of Shape Memory Alloy (SMA) as a passive control device is presented. The intent of this research is to show how Cu based SMA could serve the dual role of bracing a structure and providing a damper (passive control) in the event of unexpected loading.

Smart materials have defined the last two decades of material science engineering. These materials are able to vary their behavior in response to deformations, damage, or loads by changing their shape, position, stiffness, damping, viscosity or natural frequency by thermal or magnetic field changes. Electrorheological, magnetorehological fluids, piezo-electric and magnetorestrictive materials, and shape memory alloys are the most common smart materials [12].

Shape memory alloys exhibit two properties that can occur independently or concurrently:

- **Martensite:** When deformed below a certain temperature (T1), the material can recover its undeformed shape when heated.
- **Austenite:** When deformed above a certain temperature (T2), when the load is removed, it recovers its original shape up to about 8% strain.

These properties are termed the "Shape Memory Effect" and "Superelasticity" respectively. A look at two possible stress-strain curves for a shape memory alloy highlights these properties. It is also extremely important to point out that the area under these curves represents the dissipation of energy.

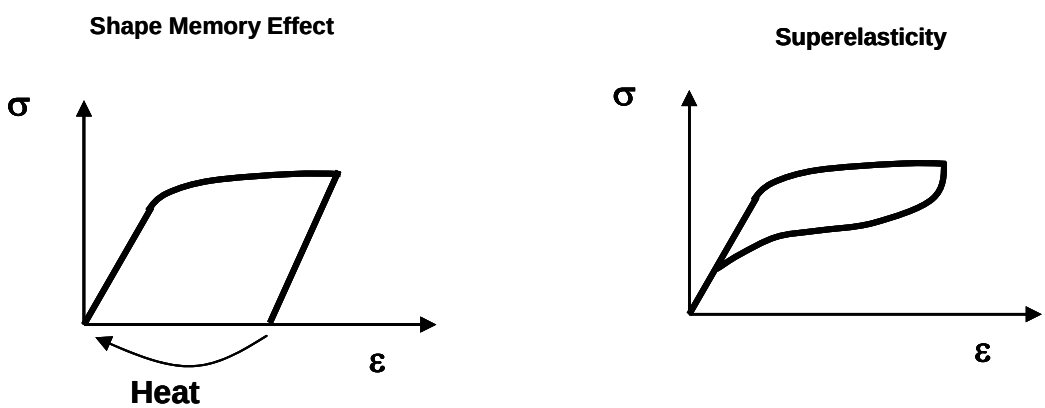


Figure 11. Possible Shape Memory Alloy (SMA) Stress Strain Curves

Currently, shape memory alloys are utilized mostly in the medical, aerospace and mechanical engineering fields. Common examples include force actuators, over-temperature shutoff valves, fractured bone mending, hydraulic couplings, eyeglass frames, and dental arches. SMAs have not been widely adopted in the structural community due to several challenges associated with the material: 1) SMAs are mostly produced only in wires and small plates, 2) Material Properties can be nonlinear over a span of loading and over time, 3) Material properties are extremely sensitive to changes in material composition and to the thermal process in which the material is prepared.

Despite these challenges, SMAs present excellent potential in civil engineering applications due to their ability to dissipate energy yet return to their undeformed shape. The first structural application of SMAs occurred recently in the retrofit of two historical

structures damaged by earthquakes, the San Giorgio Bell Tower in Trignano, Italy and the lateral tympani of the upper basilica in the San Francesco Church in Assisi. In both cases SMA based anti-seismic devices have the double task to improve the stability of the structure and to dissipate energy by reducing but not eliminating relative displacements [13].

The goal of the research conducted was to explore the usage of a copper-based shape memory alloy to increase the stability, stiffness, and damping of a structure. Currently, Nickel Titanium (Ni-Ti) is fairly well characterized, but are expensive and extremely sensitive to temperature changes with respect to its hysteretic cycle.

For the experiment, 1mm diameter Cu-Al-Be alloy wires [14] were selected and produced by a French manufacturer. Thermal preparation of the samples included heating for 1 minute at 850°C, cooling to the ambient temperature of 22°C then immersion in boiling water for 120 minutes. This process (or similar) is common to all SMAs and is critical to the molecular alignment (and function) of the samples. The wires were then utilized as the first floor bracing in a three story braced frame structure installed on a shaking table.

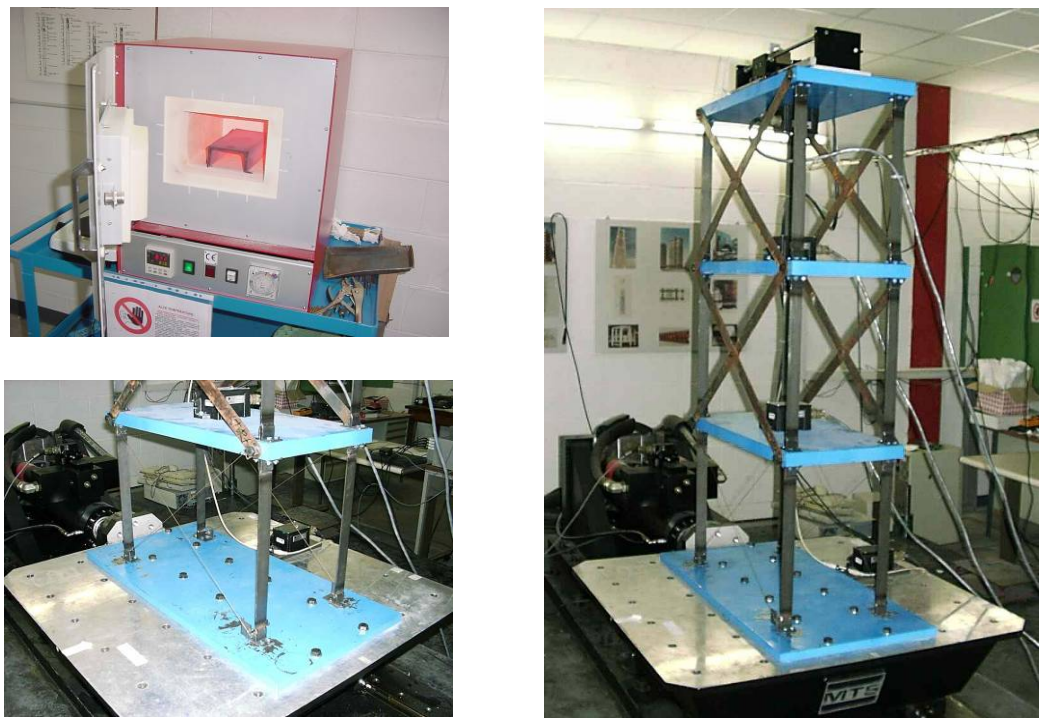


Figure 12. Thermal Treatment of Copper Based SMA Wires and use of the SMA Wires as Bracing in a Three Story Frame Structure.

Two configurations of the bracing were tested. One, pictured above, utilized the SMA wire for the entire length of each brace. The second utilized a 1/3 steel, 1/3 SMA, and 1/3 steel configuration secured by clamps such that the total length of SMA wire was 1/3

of the brace. In both cases, the results confirm what was expected from the experiment. First, the SMA bracing increases the stiffness and stability of the structure. This change of stiffness can be seen below by a shift in the first fundamental frequency (first mode) of the structure. This can be seen by the peak shifting to the right indicating a higher excitation frequency (more energy). Secondly, the SMA bracing provides a dramatic damping effect on the structure. This can be seen in the figure below comparing the oscillatory response of the structure with and without the SMA wires.

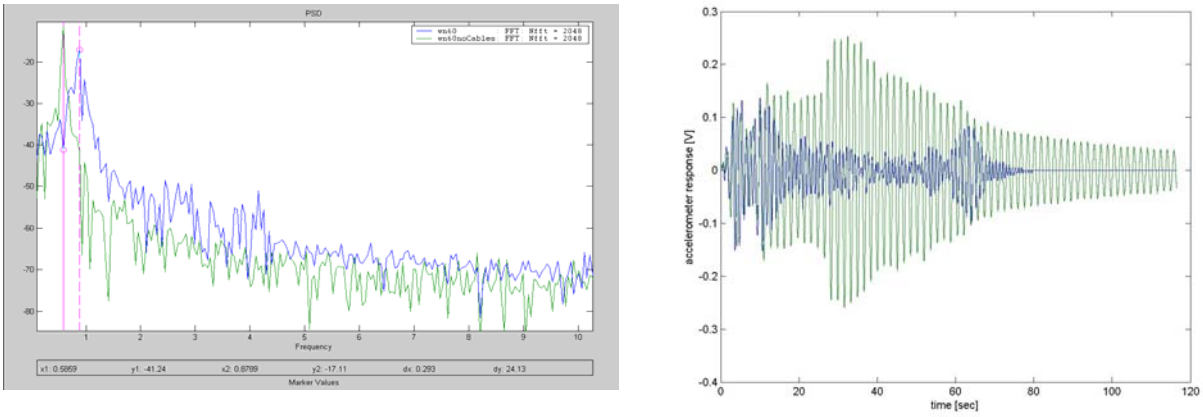


Figure 13. First Mode Frequency Shift and Damping Effect Utilizing the SMA Wire Bracing

Either of these effects can be obtained in isolation by other means. For example, a base isolation system can reduce the forces loaded on a structure due to an earthquake and thereby reduce displacements, braces can increase structural stiffness, and shock absorber dampers can provide structural damping. The encouraging aspect of utilizing SMA solutions is that these effects can be obtained simultaneously. It is even conceivable that if a structure was loaded such that the SMA device underwent greater than 8% strain, that this strain could be recovered back to the undeformed shape through the application of heat (electricity) if the material was designed properly.

7. Military Applications and Future Research

The author has been fortunate to attend several conferences on the topics of Structural Health Monitoring and Modal Analysis. It seems that representation from the Air Force is quite common and representation from the other services is less common. With the average age of DoD's aircraft being 25 years of age, the Air Force is very interested in aircraft availability and readiness. However, all services, systems, and maintenance procedures would benefit from reconsideration with respect to emerging technologies, materials, and monitoring capabilities. With a background of having commanded a construction company and through involvement in Basecamp Conferences at West Point, the author picked up upon and has interest in the following with respect to the field of smart structures.

7.1 Sensor Technology & the Army Oil Analysis Program (AOAP)

As a platoon leader, maintenance officer, and commander, I witnessed the investment of countless man-hours, saw many vehicles damaged due to improper sampling procedures, and saw large quantities of fluids and oils wasted and spilled. One day, vehicles will possess the ability to conduct on board emissions and fluids analysis. It is very likely that this capability already exists and could be implemented on those fleets that are the largest cost drivers of AOAP. We may just be waiting for someone to make the connection.

7.2 Critical Component Management

Although applying structural health monitoring to a complex structure is still largely an academic exercise, the monitoring of a single component is often very simple and the monitoring community is extremely good at it. A look at the following link from WNBC News http://www.wnbc.com/news/3269249/detail.html depicts a helicopter that crashes due to an apparent tail rotor shaft failure. Is it likely that the vibrational characteristics of this shaft, or the entire rear segment of the aircraft changed prior to the accident? Is it likely that these changes could have been detected alerting the pilot to necessary maintenance or impending failure? The answer to both questions is most likely yes. Applied to the military, if critical components, or components with a high maintenance costs that damage other components upon failure, could be identified, solutions are available today to monitor the health and performance of these components.

Another interesting example comes from minerals industry. In a keynote presentation at Structural Health Monitoring 2004 in Munich, Germany [15], Dr. John Rucinski from Australia outlined his company's work to prevent catastrophic failure of tagline cranes. Tagline cranes are very large and are the workhorse of a mining operation. The more dirt an operator can bring up with each bucket, the more material the plant can process and produce. When a crane becomes non-operational, profits are lost. On occasion, operators overload the crane causing failure of the lower members in the crane assembly. Dr. Rucinski's goal is to develop an on-board indicator to allow the operator to see when boom components reach a critical stress level. The operator could then take immediate corrective action and prevent damage to the crane. This same concept has many applications across military construction equipment as young operators learning the equipment can easily ask too much of the equipment. An immediate example that comes to mind are the actuator bags in the M9 Armored Combat Earthmover (ACE). When these bags rupture, which they often do, the vehicle becomes useless, an environmental nightmare has just arrived, and the maintenance shop is in for a long night. An on-board indicator, or kill switch, would be a very welcome addition to the ACE's capabilities.

7.3 Structural Assessment in a Deployment Scenario

A challenge identified and currently being investigated by the Engineering Research and Development Center (ERDC) is how to select and assess critical structures in a theatre of

operations. Who performs the function and how? Typically, locations for hospitals and command headquarters must be selected off of satellite imagery or by non engineer human intelligence. Even once on the ground, how does one assess an existing and possibly damaged structure without accurate knowledge of the materials or construction method originally utilized?

An interesting solution presents itself in the work of arsenal research from Vienna, Austria who are working on the challenge of assessing existing hospitals constructed of generally of unreinforced masonry, reinforced concrete and compressed unreinforced concrete that are located in seismic regions. The cornerstone of their work is a mobile, trailer mounted mass exciter named VICTORIA [16, 17].

Figure 14. VICTORIA being utilized to collect structural data and soil data

VICTORIA is essentially a 7000lb hydraulic piston that goes up and down at an adjustable rate. This piston gives VICTORIA the capability to provide a known loading into the soil around the trailer, or to attach to any structure of interest and shake it with up to roughly 5000lbs of force. With instrumentation and sensors, engineers can than record the response of a structure due to a known loading at various points and obtain soil data to enable modeling of the soil to structure interface. This real time structural data is then utilized to validate and improve a finite element model of the structure (FEM). A risk mapping is then generated to identify which parts of the structure are most vulnerable to damage.

The VICTORIA concept seems very well suited to address the challenge of assessing unknown and possibly damaged structures quickly. Durable, mobile, and fairly easy to operate, this piece of equipment could be utilized to collect data which could be immediately transmitted via satellite to technical labs and research centers in the United States. Technical experts would then be able to identify how a structure moves, see if it

is broken, and pinpoint which areas are most critical for repair and retrofit. Reasonable finite element models could be quickly developed and validated.

8. Conclusion

This paper has provided a small insight into the rapidly developing field of smart structures and structural health monitoring by looking at some of the motivation for and work done in these areas. Several areas of research the author had the opportunity to participate in are presented. Results in all areas of research are promising, but more work is required to put these ideas and methods into practice. However, materials, sensors, and other technologies are ready today that could benefit military platforms and systems. Embedded in this paper is the notion military educators, leaders, and officers have the responsibility to seek out and to make the best usage of emerging technologies for the protection of lives, resources, and equipment.

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