LA-UR- 01-6573

Title: CONDITION/DAMAGE MONITORING METHODOLOGIES

Author(s):
Charles R. Farrar, LANL, ESA-WR
Hoon Sohn, LANL, ESA-WR

Submitted to:
The Consortium of Organizations for Strong-Motion Observations Systems (COSMOS)
Emeryville, CA
November 14-15, 2001

Los Alamos
NATIONAL LABORATORY

Invited Workshop on Strong-Motion Instrumentation of Buildings

Convened by

The Consortium of Organizations for Strong-Motion Observation Systems (COSMOS)

Marriott Courtyard Hotel, Emeryville, CA
November 14, 15, 2001

COSMOS, in cooperation with the Advanced National Seismic System (ANSS), is sponsoring an invited workshop entitled *Strong-Motion Instrumentation of Buildings*. The workshop is motivated by the need to obtain broad input from earthquake engineering professionals for the purpose of developing guidelines for strong motion instrumentation of buildings as part of the ANSS instrument installation effort. The ANSS has been authorized capital funding for 6,000 strong-motion instruments. It is expected that funding for purchase and installation of instruments will be appropriated over a period of several years. The instrument installations must meet multiple monitoring objectives including instrumentation of buildings of various types, urban reference stations, and emergency response and recovery actions. An important opportunity therefore, exists to comprehensively define strong-motion monitoring needs as an underpinning basis for developing guidelines for installation of this important monitoring system. This workshop will specifically address instrumentation of buildings.

The workshop has six objectives: 1) to document current practice for strong-motion instrumentation of buildings, 2) to define the types of building response measurements needed to respond to expanding uses of strong-motion data in earthquake engineering research and practice, emergency response practice, and building health evaluation following an earthquake, 3) to document developing instrumentation, communication, and monitoring system technologies, 4) to identify building types that require instrumentation and set priorities, 5) to evaluate national and regional priorities, and 6) to develop strategies and actions to engage private building owner and corporate participation. The workshop has been organized around four principal topics: current building instrumentation programs and guidelines, future needs for strong motion measurements in buildings, instrumentation technologies, and strategies for selecting buildings for strong motion instrumentation. The last of these topics will address national and regional priorities, priorities for selection of buildings, and mechanisms to encourage expansion of private participation in a coordinated national building instrumentation program.

Discussion papers in the form of an extended abstract with figures or summary paper with figures addressing the first three topics have been invited and will be distributed to workshop participants approximately one week prior to the workshop. The discussion papers will be presented in the first day. Twenty minutes have been allocated for presentation and discussion of each paper and 30 minutes have been allocated for general discussion. The second day of the workshop will be devoted to breakout discussions. Four breakout discussion topics have been identified: building priorities, National priorities, regional priorities, and encouraging private participation. The discussion papers together with consensus recommendations of the workshop will be published as an archival quality proceeding. It is intended that the proceeding will serve as a technical information base for separate development of program-specific guidelines for strong motion instrumentation of buildings.

Supporting organizations include the National Science Foundation U. S. Committee for Advancement of Strong Motion Programs, U. S. Geological Survey Advanced National Seismic System, COSMOS, and PEER.

CONDITION/DAMAGE MONITORING METHODOLOGIES

By

CHARLES R. FARRAR AND HOON SOHN

ENGINEERING SCIENCE AND APPLICATIONS DIVISION
LOS ALAMOS NATIONAL LABORATORY

INTRODUCTION TO STRUCTURAL HEALTH MONITORING

The process of implementing a condition/damage detection and monitoring strategy for aerospace, civil and mechanical engineering infrastructure is commonly referred to as *structural health monitoring (SHM)*. Here *damage* is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements and statistical analysis of these features to determine the current state of system health. For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure.

Current SHM methods are either visual[1,2,3] or localized experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiography, eddy-current methods and thermal field methods[4]. All of these experimental techniques require that the vicinity of the damage is known *a priori* and that the portion of the structure being inspected is readily accessible. The need for quantitative *global* damage detection methods that can be applied to complex structures has led to research into SHM methods that examine changes in the vibration characteristics of the structure. The basic premise of these global SHM methods is that damage will alter the stiffness, mass or energy dissipation properties of a system, which, in turn, alter the measured dynamic response of the system. Summaries of this research can be found in recent review articles.[5,6] In addition, there are several annual and biannual conferences dedicated to this

---

[1] Moore, M. et al, (2001) *Reliability of Visual Inspection for Highway Bridges, Volume 1: Final Report*, U.S. Department of Transportation report FHWA-RD-01-020.

[2] (1994) *Procedures for PostEarthquake Safety Evaluation of Buildings*, Applied Technology Council report ATC-20, Redwood City, CA

[3] (1988) *Rapid Visual Screening of Buildings for Potential Seismic Hazards*, Applied Technology Council report ATC-21, Redwood City, CA

[4] Doherty, J. E. (1987) "Nondestructive Evaluation," Chapter 12 in *Handbook on Experimental Mechanics*, A. S. Kobayashi Edt., Society for Experimental Mechanics, Inc.

[5] Doebling, S. W., et al., (1998) "A Review of Damage Identification Methods that Examine Changes in Dynamic Properties," *Shock and Vibration Digest* **30** (2), pp. 91-105.

topic.[7,8,9] To date, most global SHM techniques proposed in these references examine changes in modal properties (resonant frequencies, mode shapes), or changes in quantities derived from modal properties. Drawbacks of these investigations include:

1. The use of relatively expensive off-the-shelf, wired instrumentation and data processing hardware not designed specifically for SHM. The relative expense of these sensing systems currently dictates that a structure is sparsely instrumented.
2. Excitation has, in general, been from ambient sources inherent to the operating environment. These ambient sources typically excite the system's lower frequency global modes that are insensitive to local damage.
3. When identifying damage sensitive features from the measured responses, data reduction is usually based on classical linear modal analysis. Therefore, most studies assume that the structure can be modeled as a linear system before and after damage.
4. Trending and threshold detection are the primary tools used to determine when a system change has occurred. Statistical methods have not been used to quantify when changes in the dynamic response are significant and caused by damage. Varying environmental and operational conditions produce changes in the system's dynamic response that can be easily mistaken for damage.

Taken as a whole, the aforementioned characteristics place serious limitations on the practical use of existing methodologies. Indeed, with the exception of applications to rotating machinery[10], there are no examples of reliable strategies for SHM that are robust enough to be of practical use.

HEALTH MONITORING OF STRUCTURES SUBJECTED TO SEISMIC LOADING

To the author's knowledge, formal procedures for structural health monitoring have not been applied to civil engineering infrastructure subjected to damaging seismic events. Most damage studies associated with seismic loading involve the visual observation that the structure has been damaged. As an example, visible distortion of a structure led to the discovery of moment-resisting welded-steel-joint damage after the Northridge earthquake[11]. Then an inverse modeling procedure is developed where a damage process is postulated and the structural model is subjected to a measured input. The model is used to generate time histories that are compared to the time-history responses measured on the structure with a typically sparse array of sensors[12,13].

---

[6] Housner, G.W., et al., (1997) "Structural Control: Past, Present and Future," (Section 7, Health Monitoring) *Journal of Engineering Mechanics*, ASCE, **123** (9), pp. 897-971.

[7] The 3rd International Structural Health Monitoring Workshop, Palo Alto, CA, 2001.

[8] The 6th International Symposium on Nondestructive Evaluation of Aging Infrastructure, Newport Beach, CA. 2001.

[9] The 3rd International Conference on Damage Assessment of Structures, Dublin, Ireland, 1999.

[10] Mitchell, J. S. (1992) *Introduction to Machinery Analysis and Monitoring*, PenWel Books, Tulsa.

[11] Bertero, V. V., J. C. Anderson, H. Krawinkler (1994) *Performance of steel building structures during the Northridge earthquake*, Earthquake Engineering Research Center, University of California, Report UCB/EERC-94/09

[12] Wilson, J. C. (1986) "Analysis of the Observed Seismic Response of a Highway Bridge," *Earthquake Engineering*

If the model predictions "agree" with the measured response, the assumption is made that the postulated damage process is, in fact, the correct one. Figure 1 conceptually illustrates drawback of this approach. A very limited sensor array (e.g. the 20-story Universal Studios Sheraton Hotel has only 13 sensors) provides minimal information regarding the damage evolution process. The arrows in Figure 1 indicate that there are possibly several deterioration paths that the structure could have experienced to reach the end state. Without a much denser array of sensors, it will be very difficult to demonstrate that the postulated damage process is correct and unique. Also, if the damage is not severe, it may not be detected with such a sparse array of sensors. This lack of early detection is particularly troublesome because a successful damage detection strategy must identify damage at an early state if it is to be useful. Such early detection will allow for the safe and timely return to service of critical infrastructure and, hence, help to mitigate the economic impact of a large seismic event.

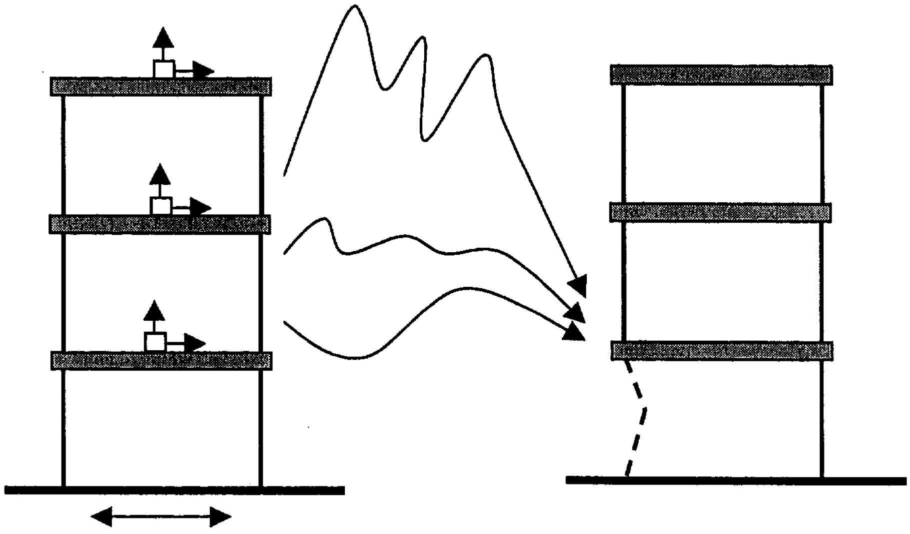

Figure 1 Simply having knowledge of the structure's end state and sparse measurements will not allow one to uniquely define the damage evolution.

Some of the primary missions for strong motion instrumentation placed in civil engineering infrastructure are to: 1. In some manner assess damage to the structure after a significant seismic event has occurred; 2. Shut down hazardous operations if excitation levels exceed some critical threshold; 3. Quantify inputs to equipment mounted in the structure; 4. Check the validity of assumptions used in the design process; and 5. Verify the accuracy of models used to predict the seismic response of the structure including soil-structure interaction effects. However, the authors feel that a major drawback to current strong motion instrumentation procedures, particularly when they are used for mission 1 above, is that these instruments are placed in the structure without a specific plan for the post-seismic data reduction and analysis.

---

and Structural Dynamics, **14**, 339-354.

[13] Werner, S. D., J. L. Beck and B. Levine (1987) "Seismic Response Evaluation of Meloland Road Overpass Using 1979 Imperial Valley Earthquake Records," *Earthquake Engineering and Structural Dynamics*, **15**, 249-274.

This presentation will focus on issues associated with the data acquisition for structural health monitoring of infrastructure subjected to seismic excitation. Some of these issues are generic in nature and must be considered for almost all SHM applications. Other issues are more specific to civil engineering infrastructure applications. The tact taken herein is to first provide a formal framework with which to view any SHM problem. Next, various issues associated with the data acquisition portion of the SHM process are identified with specific application to structural systems subjected to damage from seismic events. This presentation will conclude by suggesting some new approaches to seismic monitoring that are more focused on SHM issues.

A STATISTICAL PATTERN RECOGNITION PARADIGM FOR STRUCTURAL HEALTH MONITORING

The group of engineers at Los Alamos National Laboratory working in the area of Structural Health Monitoring views this problem in terms of a statistical pattern recognition paradigm. This paradigm can be described as a four-part process: 1.) Operational evaluation, 2.) Data acquisition & cleansing, 3.) Feature extraction & data reduction, and 4.) Statistical model development for feature discrimination. The authors believe that this four-step paradigm outlined must be implemented in an integrated manner where approaches to the data acquisition, feature extraction and statistical modeling portions of the process are developed in close coordination.

Operational evaluation answers four questions regarding the implementation of a structural health monitoring system: 1.) How is damage defined for the system being monitored?, 2.) What are the conditions, both operational and environmental, under which the system to be monitored functions?, 3.) What are the limitations on acquiring data in the operational environment?, and 4.) What are the economic and/or life safety motives for performing the monitoring? Operational evaluation begins to define why the monitoring is to be done and begins to tailor the monitoring to unique aspects of the system and unique features of the damage that is to be detected.

The data acquisition portion of the structural health monitoring process involves selecting the types of sensors to be used, the locations where the sensors should be placed, the number of sensors to be used, and the data acquisition/storage/transmittal hardware. Other considerations that must be addressed include how often the data should be collected, how to normalize the data, and how to quantify the variability in the measurement process. Data cleansing is the process of selectively choosing data to accept for, or reject from, the feature selection process. Various forms of signal conditioning such as filtering and data decimation can be viewed as data cleansing procedures.

The area of the structural health monitoring that receives the most attention in the technical literature is feature extraction. Feature extraction is the process of the identifying damage-sensitive properties, derived from the measured dynamic response, which allows one to distinguish between the undamaged and damaged structure. Almost all feature extraction procedures inherently perform some form of data compression. Data compression into feature vectors of small dimension is necessary if accurate estimates of the feature's statistical distribution are to be obtained.

Statistical model development is concerned with the implementation of the algorithms that analyze the distribution of extracted features in an effort to determine the damage state of the structure. The algorithms used in statistical model development fall into the three general categories: 1. Group Classification, 2. Regression Analysis, and 3. Outlier Detection. The appropriate algorithm to use will depend on the ability to perform *supervised* or *unsupervised* learning. Here, supervised learning refers to the case where examples of data from damaged and undamaged structures are available. Unsupervised learning refers to the case where data are only available from the undamaged structure[14]. Almost all structural health monitoring activities related to civil engineering infrastructure involved an unsupervised learning approach as data from the structure in known damage conditions are rarely, if ever, available.

The statistical models are used to quantify the damage state of a system, which can be described as a five-step process that answers the following questions: 1. Is there damage in the system (existence)?; 2. Where is the damage in the system (location)?; 3. What kind of damage is present (type)?; 4. How severe is the damage (extent)?; and 5. How much useful life remains (prediction)? Answers to these questions in the order presented represents increasing knowledge of the damage state. Experimental structural dynamics techniques can be used to address the first two questions in either a supervised or unsupervised learning mode. To identify the type of damage, data from structures with the specific types of damage must be available for correlation with the measured features implying that this question must be addressed in a supervised learning mode. Analytical models are usually needed to answer the fourth and fifth questions unless examples of data are available from the system (or a similar system) when it exhibits varying damage levels and suggests that a supervised leaning approach must be taken.

Finally, an important part of the statistical model development process is the testing of these models on actual data to establish the sensitivity of the selected features to damage and to study the possibility of false indications of damage. False indications of damage fall into two categories: 1.) False-positive damage indication (indication of damage when none is present), and 2). False-negative damage indications (no indication of damage when damage is present).

ISSUES FOR STRUCTURAL HEALTH MONITORING DATA ACQUISITION

The data acquisition portion of the structural health monitoring process must address: 1. Excitation; 2.Sensing; 3. Data storage and transmission; 4. Analog-to-digital conversion and Signal conditioning; 5. Data fusion; and 6. System power. Note that signal conditioning and data

---

[14] Bishop, C. M., (1995) *Neural Networks for Pattern Recognition*, Oxford University Press, New York.

fusion are also addressed through software applications as part of the feature extraction and statistical modeling portions of the paradigm. The optimal choices for hardware to address these various issues will be application specific and will be dependent on the specific definition of damage that is to be detected. Economic considerations play a major role in these hardware selection decisions. This discussion will focus on excitation and sensing issues for structural health monitoring applications associated with seismic damage to civil engineering infrastructure.

Some data acquisition choices will be dictated by the ability to deploy the sensing system on new construction as opposed to deploying the sensing system in a retrofit mode. An issue that will have significant influence on the choice of sensing hardware to be deployed is the decision to continue to perform sparse global monitoring as opposed to monitoring the more local response that the author's feel is more appropriate for SHM studies. Another issue that will dictate specific data acquisition requirements is the need to normalize data for varying operational and environmental condition. Finally, a choice must be made to address the data acquisition portion of the SHM process with either an optimal or redundant approach. The optimal approach typically will be more cost effective, but suffers from sensitivity to a single-point failure.

Excitation

The size of most civil engineering infrastructure dictates that ambient excitation provided by the natural environment (e.g. wind, wave motion, or ground motion) or excitation caused by operational conditions (e.g. traffic, machinery) is the only economically feasible means of exciting the structure. While the use of ambient excitation is a necessary choice, this type of excitation has many difficulties associated with it when used for SHM purposes. The primary concern is the non-stationary nature of most ambient vibration sources. This non-stationary property necessitates the development of data normalization procedures that can account for varying amplitude and frequency content of the excitation. Because there is no measure of the ambient excitation, questions will arise regarding the ability of that input to excite proper frequency ranges and to provide sufficient levels of input for the proper identification of the damage-sensitive features.

To alleviate the difficulties posed for SHM by the use of ambient excitation, the possibility of local excitation is being explored. The excitation can possibly be provided with devices such as PZT actuators or combustion driven thrusters[15] developed for robotics applications. This approach has the advantage of tailoring the waveform to the specific SHM application, but it requires a well-defined damage location. Given the candidate damage locations, detailed numerical simulations can be used to aid in defining the bandwidth, amplitude and waveform needed to best identify the structural deterioration. The primary limitation of such a system is the amplitude of excitations that can be provided by these actuators. However, if the damage location is well defined (e.g welded moment resisting connections or bridge bearing seats), low-level excitations in the proper bandwidth may be desirable for damage detection, as this excitation will only be significant at the location of interest.

Sensing

---

[15] See http://www.sandia.gov/isrc/Hoppers.html

impact if it can be used expedite the return to service of commercial buildings and prevent the reoccupation of buildings that would be susceptible to severe damage during aftershocks.

The authors feel strongly that the current approaches to strong motion monitoring are not optimal for SHM studies. The instrumentation philosophy must shift from a sparsely distributed array of sensors monitoring lower frequency response to a dense array of local sensors monitoring bandwidths that have been predetermined to be sensitive to the postulated damage scenarios. A key element of this approach is to have very specific definitions of the damage that is to be detected and to develop and deploy the sensing system based on this definition. Also, the sensing system must be developed integrally with the other portions of the SHM paradigm and, in particular, the feature extraction and statistical modeling portions of the process.

As a suggestion, the authors feel that those in charge of distributing strong motion sensors should consider allocating 10-20% of their instrumentation budget to deploying new sensing and data processing systems such as the one being developed at Stanford[17] and Berkeley[18] and specifically designate these systems for structural health monitoring applications.

---

[17] Lynch, J. P., et al. (2001) "The Design of a Wireless Sensing Unit for Structural Health Monitoring," in *Proceedings of the 3rd International Workshop on Structural Health Monitoring*, Stanford, CA.

[18] see http://www.ce.berkeley.edu/~sglaser/CUREe.pdf

There are many issues that must be addressed with respect to sensing including: selecting the types of sensors to be used, selecting the location where the sensors should be placed; determining the number of sensors to be used (optimal versus redundant); determining the appropriate sensor dynamic range and bandwidth; determining the long-term stability, reliability and environmental ruggedness of the sensors; and establishing the noise floor of the sensing system. Currently, sensors that measure kinematic quantities (strain and acceleration) along with sensors to measure environmental quantities such a temperature are most commonly used for SHM applications.

Because data will be measured under varying operational and environmental conditions, the ability to normalize the data becomes very important to the damage detection process. This need can dictate additional sensing requirements as illustrated in Figures 2 and 3. Figure 2 shows the case when it is necessary to have a measure of the variability source. In Figure 2 the change in the distribution of damage sensitive features caused by some source of variability produces changes similar to those caused by damage. For this case a measure of the variability source will, most likely, be necessary. In Figure 3 damage produces a change in the feature distribution that is in someway orthogonal to the change caused by the environmental or operational variability. In this case it may be possible to distinguish changes in the feature distribution caused by damage from the changes caused by the sources of variability without a measure of the operational or environmental variability.

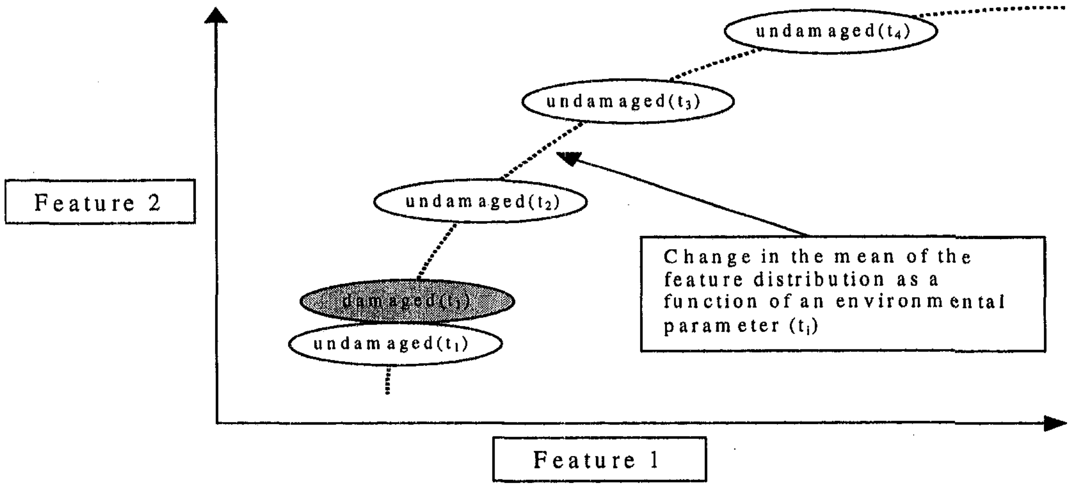

Figure 2 A hypothetical case where damage produces a change in the feature distribution that is similar to the change caused by the environmental variability.

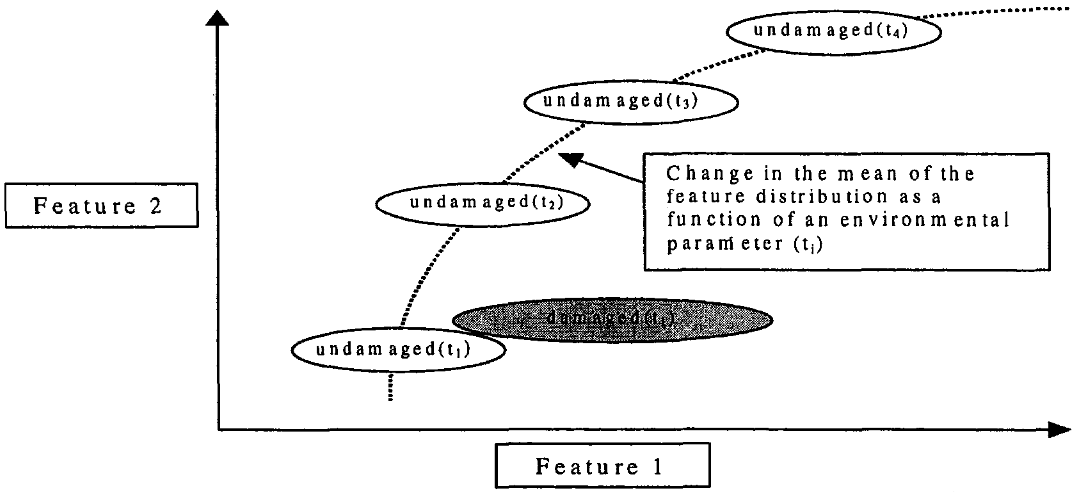

Figure 3 A hypothetical case where damage produces a change in the feature distribution that is in some manner orthogonal to changes caused by the environmental variability.

Two emerging sensing technologies that hold promise for SHM applications are micro-electromechanicsl systems (MEMS) sensors and fiber optic sensors. MEMS sensor prove flexibility in their design such that they can be optimized for the specific SHM activity. Also, the manufacturing process for MEMS sensors, which is similar to that employed for computer chip manufacturing, offers the potential to mass produce a particular sensor in a cost effective manner. As an example, the MEMS accelerometers used by the automotive industry to trigger airbag deployment cost approximately $1 per unit when bought in quantity.

Fiber optic strain sensors offer the advantages that they can measure strains at two-to-three orders of magnitude better resolution than conventional electrical resistance strain gages. Also, these sensors are immune to electromagnetic interference and therefore may be applicable for monitoring electric power transmission equipment. Fiber optic strain sensors are not a spark source so they are well suited for monitoring structures such as petroleum storage tanks. Recently, there have been numerous applications of fiber optic sensing technology to civil engineering infrastructure.[16]

SUMMARY

This presentation has attempted to first define a general paradigm for approaching structural health monitoring problems. The data acquisition portion of this paradigm was then addressed with particular attention to excitation and sensing issues associated with health monitoring of civil engineering infrastructure subjected to damaging seismic events. A key aspect of SHM for seismic events is that this technology is most useful when it can detect the onset of damage as opposed to severe damage. In particular, this technology will have a significant economic

---

[16] Todd, M., et al. (1999) " Civil Infrastructure Monitoring with Fiber Bragg Grating Sensor Arrays," in *Structural Health Monitoring 2000*, F-K Chang Edt. Technomic Publishing Co.,Lancaster, PA.