Preamble

A workshop on health monitoring (HM) of long-span bridges was held at Irvine on March 9, 2001. The workshop brought owners, operators and consulting engineers together with academic researchers and representatives from industries that offer advanced technology products and/or services that may be useful for HM. The workshop immediately followed the 2001 SPIE Conference on Smart Materials and Structures, and Nondestructive Evaluation and HM of Aging Infrastructure held during March 6-8 2001 at Newport Beach. The 2000 and 2001 SPIE Conferences have included a distinct program on the HM of Highway Transportation Infrastructure in addition to “Smart Highways and Bridges.”

The Workshop on HM of long-span bridges was the first of its kind in the US focusing on major, long-span bridges as an infrastructure component deserving of the pioneering applications of HM. Long-span bridge owners have already embraced various intelligent transportation systems (ITS) technologies that offer enhancement of operations. In Japan, Hong Kong and Europe, owners of new long-span bridges have installed instrumentation for structural HM whereas the first demonstration of this paradigm in the US is in progress on the Commodore John Barry Bridge operated by the Delaware River Port Authority of PA and NJ. Additional information about the Workshop participants, discussions and individual presentations is offered in the following Proceedings.

The following is an overview of state-of-the-art applications in HM of constructed systems, including major long-span highway bridges, synthesized from the recent SPIE 2001 Conference sessions and from the Workshop. Both the initial and lifecycle costs of major bridges, and the consequences of failure in any aspect of their operational or structural performance make them unique infrastructure components in terms of their societal impact. Most of the 1,100 major long-span bridges (those with spans of 100 meters or longer) in the US are over 50 years old, and several notable ones are over 100 years old (NBI, 1998). These bridges fall outside the Standard Specifications issued by AASHTO (1998), and there is little generic experience related to maintaining their performance especially after they age and/or following any damage. More than 800 of the long-span bridges in NBI are classified as fracture-critical. It follows that HM techniques may prove to be useful for maintaining and preserving this population of aging of long-span bridges.

Many long-span bridge owners have already adopted or are currently in the process of adopting various ITS technologies in order to enhance traffic flow or bridge operations such as toll collection. There are compelling benefits, in terms of the optimal management of long-span bridges, for expanding such ITS investments into a broader HM application for both operations and structural health. These will be discussed in the following. The integration of operational and structural HM will be demonstrated and the corresponding benefits will be quantified. Many owners have expressed strong interest in research for integrated operational and maintenance management of their infrastructure.

It is hoped that the following will stimulate additional discussion regarding the importance of HM as an emerging research area for both general infrastructure systems and long-span bridges. The Workshop was effective in presenting and obtaining valuable feedback on a national HM demonstration project that would be implemented for the new Woodrow Wilson Bridge in Washington, DC.
1. Health Monitoring: A New Paradigm for Constructed Systems

There is consensus on the importance of monitoring and managing the health of civil infrastructure systems (e.g. transportation, energy, water, environmental, building systems) that protect and sustain all other critical societal infrastructure systems such as health, telecom, cyberspace, manufacturing, finance, information, government, etc. The principal advantage expected from a new paradigm of infrastructure HM is to be able to proactively manage health just as the medical profession does. Diagnostic procedures will permit deterioration and damage to be detected at their initiation. Timely detection and effective response to operational incidents, accidents, and natural hazards and other emergencies may ultimately save lives and reduce downtime.

Presently, deterioration and damage are discovered by visually observing the signs they exhibit as they progress and take their toll on the structure’s reliability. In the case of long-span bridges, the effectiveness of visual inspection in reaching all of the critical locations and in finding all of the possible defects becomes somewhat questionable. The biannual visual inspection of a major bridge such as the Brooklyn Bridge in New York is reported to require over three months to perform and cost $1 Million. A recent study performed by the FHWA revealed that at least 56% of the average Condition Ratings derived from visual inspection were incorrect with a 95% probability (2001). It follows that if visual inspection were effectively coupled with advanced HM techniques, many of its present shortcomings could be mitigated. Such an improvement would help motivate bridge owners to take advantage of this paradigm.

At the workshop discussions following the SPIE conference many participants noted that HM requires and deserves a generalized theory and associated guidelines and standard specifications similar to those used in design and construction, irrespective of the specifics of the particular infrastructure systems or components that are considered. In general, HM of an entire infrastructure’s meta-system as opposed to its individual components is more meaningful and desirable, as this will permit an integrated, holistic and optimum management of the entire system’s health as opposed to just some of its components. Until this generalized theory is developed and demonstrated, highway bridges can be considered as critical system-wide nodes of the highway transportation system with the focus on component-level HM.

2. Proposed Definitions of Health and Health Monitoring

Although there is no consensus definition for the “health” of an infrastructure system, the following may serve for discussion: “health is the maintenance of functional and structural reliabilities of a system at each of the utility, serviceability, safety and conditional limit-states.”

![Figure1: Critical Limit-States and Events Incorporated In Reliability Evaluation of Constructed Systems](image-url)
It follows that “health and performance are synonymous, and HM is the diagnosis and prognosis of performance.” Quantifying or bounding the functional and/or structural reliability of an infrastructure system or even just one bridge requires considerable data and knowledge (Figure 1). However, the concept of structural reliability (ASCE 1999, IFIP 1998), especially if both time and symptom-based formulations are integrated and extended to all the critical design and evaluation limit states, will serve as a powerful framework for describing “health of an infrastructure component or a system” (Yao and Yao, 1997).

Quantitative metrics for performance at each critical limit-state needs to be established to quantify reliability and health (Aktan for ASCE Committee, 2001). This will only become possible through a sufficient number of HM applications, collecting actual data on the long-term loading environments and actions that influence the onset of various limit-states, and the actual operational and structural behavior mechanisms that govern reliability at different limit-states. A generalized theory on HM can only be developed after a sufficient number of applications and demonstrations. In addition, by virtue of the definition and scope of HM, the structural damage detection problem (Chan, et al, 2001b, Fujino, et al, 2001, Lopes, et al, 2000b, Park, et al, 2001b, Sun, et al, 2001) and the nondestructive evaluation and controlled field-testing of structures (Chan, et al, 2001a, Schweginger, 2001, Wang, 2001) become subsets of the overall picture. HM offers a unified perspective of the entire realm of the performance and safety evaluation and management of existing constructed systems and also serves as a critical prerequisite for intelligent infrastructure systems.

3. Can We Monitor the Health of a System Without Conceptualizing?

There is debate on the importance of physics-based models and system-identification. To design and implement HM for an infrastructure system, the rational approach would be first to conduct system-identification and to conceptualize the system through a physics-based model. A physics-based model and other models that may be extracted from it by reduction would serve as a design basis for sensing and monitoring changes in the operational parameters and mechanical characteristics of the structure and materials. The various phenomena that may affect these operating and mechanical characteristics would need to be monitored to assist with the diagnosis and prognosis of performance. In cases where there are changes in the operation of the structure or to the structural systems, intermittent controlled tests would be performed and the system-identification process repeated as needed.

Many researchers have explored the use of numerical or neural models for HM of elements or local regions of structures (Shinozuka and Ghanem, 1995, Lopes, et al, 2000a, Livingston, et al, 2001, Marzougui, et al, 2001, Ni et al, 2001). In fact, HM has been described by Dr. Farrar as a “statistical pattern-recognition problem” (Sohn, et al, 2001). Such approaches are valid and useful; however, system-identification and conceptualization of a system through a physics-based model would be a necessary prelude to such efforts. Conceptualization of a system should remain a prerequisite for HM, especially in the case where systems and components have mechanical characteristics and operational and loading environments that are governed by significant uncertainty within large temporal-spatial scales.

4. Scenarios for Health Monitoring of Constructed Systems

Given the spatial and temporal extent of large populations of infrastructure systems and their components (e.g. 600,000 highway bridges in the US National Bridge Inventory), it is useful to describe various scenarios for helping to structure and classify HM applications. At one end of the spectrum HM of an entire regional highway transportation system can be envisioned. In order to monitor the operational and structural parameters of this system, various satellite, aircraft and land-based images (IASSAR, Shraishi and Shinozuka, 1998, Inaudi, et al, 2001, Park, et al, 2001a, Wang, et al, 2001, Tennyson, et al, 2001, Fujino, et al, 2001) and other types of sensor measurements (GPS, weigh-in-motion, weather stations, roadway temperature, strain, displacement) would be needed on-line and in real-time from highways and bridges (Figure 2). A HM application such as this would require an integrated information management system for legacy information on system design, maintenance and operational properties, archived data and various software engines for assisting managers to make operational decisions for improving traffic flow, response to incidents, manage emergencies, and, for an integrated maintenance and operational management of the entire transportation system. Further, this HM system would be in the realm of Supervisory Control and Data Acquisition (SCADA) systems that have been applied for process control in manufacturing, chemical, and power plants. Such SCADA systems are being explored today, offering great promise for infrastructure HM and management (Proceedings, MEDAT 2000 and Workshop, Kyoto, 2001).
Component level HM, such as for a long-span bridge, would represent the next level of HM applications. The Lantau Crossing bridges (Hong Kong), the Akashi Keikyo and Tatara Bridges (Japan), the Normandy Bridge (France) and the Great Belt Bridge (Denmark) are examples of long-span bridges that have been instrumented for structural monitoring and operational monitoring (Wong, et al, 2001, Ko, et al, 2001, Ni, et al, 2001, Sun, et al, 2001, Chan, et al, 2001a, Inaudi, et al, 2001, Sumitro, 2001, Mufti, et al, 2001). The George Washington Bridge, which is owned and operated by the NY-NJ Port Authority, is being equipped with a $25 Million system for operational monitoring (Rinaldi, Presentation during the Workshop). The Commodore Barry Bridge, which is owned and operated by the Delaware River Port Authority, is being equipped with a structural HM system by Drexel University. However, several challenges remain including determining how these applications may impact the maintenance and/or operational management of the instrumented bridges, and determining if the data obtained is contributing to state-of-knowledge. Many owners and operators are correctly questioning the benefit-cost ratio of a HM system at this time, and this issue will have to be debated for some time until conclusive results from current applications are obtained.

A different application scenario would be HM of large populations of shorter-span bridges such as steel-stringer, RC slab, RC arch, PC box-girder bridges that are governed by similar loading and behavior mechanisms. Statistical sampling and clustering concepts have not been yet fully explored to take advantage of the potential in a “type-specific or fleet monitoring” approach for bridges that
make up most of the population. Once the common loading and behavior mechanisms of a bridge family are established by research on a properly selected statistical sample, it would be possible to develop practical experiments that may be applied during biannual inspections and associated analytical tools that may serve for objective HM of the entire population (Aktan et al 1998; Catbas, et al, 2001). The challenge in such an approach is to identify and group the critical parameters affecting “health” that will serve as the basis of statistical sampling and to represent all the critical behavior and failure modes of a large population by a smaller, manageable number of bridges that maybe feasibly monitored and studied. Recognizing the mechanisms of large uncertainty and variability in the mechanical characteristics and behavior of constructed facilities, especially after aging, the challenges in proper statistical sampling become apparent.

5. Temporal, Spatial, and Content Spectra of Data

Sensing is clearly a very critical aspect for HM. Sensing design requires obtaining a clear and conceptual understanding of the phenomena that should be measured during the system-identification study. The spatial resolution or sensor density, as well as the duration and frequency of measurements for HM would be dictated by the characteristics of the facility and of the phenomena that need to be measured. In general, continuous measurements at low frequencies (e.g. hourly) and that may have to extend as long as a decade would be needed to capture the trends in climate and weather related inputs such as wind, temperature and solar radiation together with the corresponding changes in ground and soil, the movements of the foundations and superstructure, and the intrinsic forces.

Programmed as well as triggered intermittent measurements would be needed for shorter durations and at higher frequencies for capturing operational and the corresponding structural parameters. For example, continuous real-time monitoring of weather, roadway and traffic may be envisioned for the operational control and incident detection on a long-span bridge. Streaming video and other measurements would be evaluated by the system for incident detection, and for alerting bridge operators and drivers in real-time, but these would not necessarily need to be stored and archived.

As a further example, an overweight vehicle may trigger a weigh-in-motion device located at the entrance to a bridge. The vehicle characteristics and identity would be captured and its positions would be monitored as it moves along the bridge, together with the corresponding critical structural responses. Such measurements may require capturing and storing streaming video along with high-speed sensor measurements (100 Hz or greater) for several minutes.

In the case of “local sentry” applications continuous scanning of an array of sensors at very high frequencies may be required. For example, to capture the initiation of a fatigue crack at a critical weld, it would be necessary to continuously scan with an array of acoustic sensors at frequencies in the MHz range require local signal-processing and diagnostics and overwriting a buffer until an event is detected.

Peak-events would need to be captured with passive sensors that would be interrogated only occasionally, say biannually, in conjunction with controlled tests. This would be accomplished by applying forced-excitation or by testing the bridge with special vehicles at crawl-speeds in order to calibrate the health of the structure and to monitor certain structural parameters with greater accuracy than would be afforded by passive monitoring.

These examples illustrate the temporal, spatial and content spectra of the many possible measurement modes and data by a HM system. It follows that both sensing and information technology (IT) are critical and challenging components of HM and they have yet to receive the attention they deserve by the current HM research community.

6. Differences and Potential Synergy Between Manufactured vs. Constructed Systems

Recently, there has been significant attention for generic research on HM of engineered systems, especially in the aerospace and automotive industries (Chang, Stanford Workshops, 1997, 1999). Members of the civil engineering community have also participated in these Workshops. However, in order to take advantage of the synergy in cross-disciplinary research on health monitoring, there is a need to address the distinctions between “constructed” and “manufactured” engineering systems:

The size, cost and lifecycle, and, variability in material properties of even prefabricated or shop-fabricated elements and in constructed systems far exceed those of common manufactured components and systems. In constructed systems, a 30% variation of a critical
property determined by testing three material samples is often considered acceptable as long as the mean is above the minimum expected value. The complete as-constructed mechanical (and electro-chemical) properties of constructed systems are unknown and cannot be estimated with any reasonable confidence unless an extensive effort for system-identification of a physics-based model (geometric model based on finite elements as opposed to mathematical, numerical or neural models) is carried out. Boundary conditions and connection rigidities of constructed systems are highly uncertain, nonlinear, and, non-stationary, affected by temperature, wind, etc. It would be highly satisfactory to be able to predict global properties of a constructed system with a FE model within a 100% discrepancy range and local characteristics within 300% discrepancy range. System-identification may improve this lack of confidence but it may be impossible to ever attain the confidence that can be attained with a mechanical system.

The operating and loading environment of constructed systems are very uncertain, there is little understanding about the critical regions and failure modes especially after aging. There is little knowledge about the interaction of constructed systems with the natural environment (climate cycles, soil-ground movements, daily cycles of temperature and radiation, rain, humidity wind, etc.) as well as the constructed systems and their users/operations. In addition, design, construction, operation and maintenance are often disconnected. There are often significant gaps in data and information transfer between design and construction, and no established mechanism for data and information transfer between construction, and, operation and maintenance. Case-based experience and the related heuristics are essential for designing and constructing successful civil infrastructure systems.

The payoff or at least the quantification of benefits from HM of manufactured versus constructed systems may require significantly different approaches as well. After all, HM generates quantitative and timely data and information about a system. There would be different benefits for HM depending on the financing mechanisms for initial and lifecycle costs, the consequences of a lack of performance or failure, the mechanisms that may be built-in for mitigating unacceptable consequences of failure, and the state-of-the-practice related to the operation, maintenance and lifecycle management of a system. Further, different design and implementation strategies may be need for manufactured versus constructed systems in order for the owners and users to accept and adopt a new health management paradigm.

In spite of such distinctions between manufactured and constructed systems, if the problem is approached in a sufficiently general sense, there should be a generic process and many similar HM algorithms and technologies that would serve both types of systems. The issue in a multidisciplinary approach to the problem is to identify those processes, technologies and algorithms that would be suitable for manufactured products but would be questionable for civil infrastructure system applications.

7. Challenges and Opportunities in HM of Constructed Systems

The civil engineering community recognizes that HM of constructed systems for health management is a new paradigm and a distinct research area. Civil engineers have been conducting visual inspections, proof-tests, controlled load-tests, nondestructive evaluations, and recordings of ground-motions and structural responses for a long time. In fact, exploring the structural health of offshore platforms by remote monitoring of their responses was a favorite research topic in the 1970’s (Coppolino and Rubin, 1980). However, these early applications did not involve system-identification, continuous and long-term data collection and timely interpretation in conjunction with a proactive health-management approach.

Current health assessment applications typically permit an engineer only to react to a lack of operational, serviceability, durability, damageability and/or ultimate limit-state performances. Efforts to diagnose the causative mechanisms and structural conditions in a forensic mode can be incomplete and are definitely not considered pro-active. There are no documented instances of a constructed facility that has subjected to a complete system-identification effort and continuous monitoring of the full spectrum of critical loading events and structural responses to diagnose the possible circumstances that may lead to deterioration or damage.

During the last five years, experiments on infrastructure systems such as gas and water distribution networks and long-span bridges for exploring the concept supervisory control and data acquisition (SCADA) systems for HM and/or emergency management have been reported (MEDAT, 2000; Kyoto, 2000, Wells, and Travis, 1997). Furthermore, certain sub-sets of HM have been applied for operational monitoring of highways, bridges or tunnels in the realm of ITS. However, it is unlikely that a full integration of operational and structural performance management for a large bridge, tunnel, dam or building, with the data content, spatial distribution, frequency and duration spectrums that were described in the earlier sections has yet been accomplished. The IT requirements for meaningful HM of large bridges or similar infrastructure components are overwhelming, and current experiments have not yet tackled the issues of: on-line, real-time sensing and management of data; data quality assurance; data processing, archival and integration with legacy data; data fusion, analysis, display and interpretation; integration of data-based
information and case-based experience to generate knowledge, intelligent infrastructure systems serving as partners to human operators and users, and, decision-making for management.

Once the above listed challenges, especially in the realm of IT are resolved, HM can be expected to serve as a paradigm that may enable the following innovations:

- Generate knowledge on the as-built properties of infrastructure systems and components, how aging, deterioration and damage may affect these properties, relationships (or lack of) between infrastructure design, construction, operation and maintenance systems, as well as the interactions between constructed, natural and social systems and their influence on infrastructure performance;
- Pro-active health management (detect and mitigate circumstances that may eventually lead to unsafe operation, deterioration, damage);
- Enable innovation that is not yet commonly used and codified, such as deployment of new materials, protection measures, construction systems, adaptive systems, etc;
- Effective design and timely validation of the effectiveness of maintenance, repair and retrofit, especially in terms of early understanding of the root mechanisms leading to deterioration;
- Integrate operational and maintenance management for improved safety of operation, performance and revenue, especially by clearly understanding and mitigating the adverse impacts of climate, weather and ambient conditions on operational and structural performance;
- Manage emergencies during/following occasional accidents that may affect operation, serviceability and safety, as well as conditional limit-state events such as very rare disasters by effective data and information collection and management tools afforded by health monitoring;

8. An Action Agenda For Health Monitoring and Management of Critical Infrastructure Systems

Given the importance of infrastructure HM as a new paradigm for pro-active management of the health and performance of constructed systems, and the important role of infrastructure systems in sustaining the health of a society, it would be beneficial if federal agencies, state and local governments and private infrastructure owners invest in focused research, development and demonstrations in this area until this paradigm is established with a general theory, model guidelines and standard specifications.

Effective HM research and development require the participation of owners and operators within academe, government and industry partnerships. Without the active encouragement and participation of owners and operators, research on actual operating infrastructure is not possible. In addition, many engineering and science disciplines need to participate to contribute in an integrated, coordinated manner. The creation and sustenance of a community of infrastructure HM stakeholders that includes owners, operators and practicing engineers in addition to researchers is therefore necessary to advance this discipline.

The Stanford Workshops, SPIE Conferences, the International and European Structural Control Conferences, and the Workshop on Present and Future of Health Monitoring held at Bauhaus University in Germany were valuable platforms that brought researchers together. The March 9, 2001 Workshop on HM of long-span bridges brought owners, operators and consulting engineers together with researchers. Mechanisms for maintaining and strengthening this community should be created.

Infrastructure HM requires the integration of technologies and skills that are distributed among various engineering disciplines in a product-oriented (as opposed to a process-oriented) manner. If any of the individual components of complete constructed system does not perform, there will not be any use for the final product. For this reason the entire multi-spatial and multi-temporal-scale systems of sensing, data acquisition, transfer, quality-assurance and processing, management and archival, together with the diagnostics and prognostics of health should be designed, developed, customized, implemented, validated and optimized in an integrated and iterative manner.

Meanwhile there is little experience in closely coordinated integrated research by civil, mechanical, electrical and materials engineers and computer scientists on operating infrastructure. Organizing and coordinating such integrative research is an experiment by itself. A good mechanism for dealing with the challenges may be the organization of a National Center on Infrastructure Health Monitoring. This would be geographically distributed, linking different types of infrastructure systems and constructed facilities that would be instrumented for health monitoring. Data that would be collected and synthesized by such a center could potentially influence the
The entire practice of civil engineering and infrastructure management.

The value of research programs on innovative sensors, HM algorithms, analytical or experimental tools that may not be as integrated as discussed above cannot be ignored. There is also great value in continuing to bring together researchers interested in HM of manufactured systems with those interested in HM of constructed systems, as well as others interested in various aspects of smart materials and structures. However, the issues and concerns, the societal impacts, and the population of stakeholders affected by infrastructure health and performance are so encompassing that infrastructure HM deserves its own dedicated research. Those dedicated to customizing information technology to infrastructure applications are especially critical and rare.

A unique challenge in developing an agenda for infrastructure HM research, development and demonstrations is the lack of objective data and understanding regarding the impacts of interactions between natural, social and constructed systems. There is little documentation on the level and variation of intrinsic responses. Typical fields, magnitudes and long-term time-histories of strains, displacements and slips due to fabrication and construction, solar radiation, hourly, daily and seasonal changes in temperature, changes in environmental and operational conditions, long-term climate trends and their impacts on soil and water, etc. have not been adequately measured and documented. There is little understanding of the impacts of weather and environmental conditions as well as operational actions on the user’s behavior. Therefore, until a related knowledge base accumulates, HM applications would need to include an aspect of scientific exploration into the measurement of known and unknown natural phenomena. This makes infrastructure HM especially challenging and exciting, and may serve as a feature to attract additional interest.

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