



**NORTH AMERICAN EURO-PACIFIC WORKSHOP
FOR
SENSING ISSUES IN CIVIL STRUCTURAL HEALTH MONITORING**

NOVEMBER 10-13, 2004 OAHU, HAWAII

EXECUTIVE SUMMARY

The first Civil Structural Health Monitoring (CSHM) workshop was held in November 2004 at the Royal Hawaiian Hotel in Honolulu, Hawaii. The aim of this workshop was to establish an international forum to discuss issues related to sensors in CSHM. The workshop entitled as the, “North American Euro-Pacific Workshop for Sensing Issues in Civil Structural Health Monitoring,” was organized by an international committee. The following individuals comprised members of the international organizing committee:

- **Farhad Ansari**, University of Illinois, Chicago, USA
- **Alessandro De Stefano**, Politecnico di Torino, Italy
- **Wolfgang Habel**, BAM, Germany
- **Hyun-Moo Koh**, Seoul National University, Korea
- **Sung Kon Kim**, Seoul National University of Technology, Korea
- **Aftab Mufti**, ISIS Canada, University of Manitoba, Canada
- **JinPing Ou**, Harbin Institute of Technology, China
- **Zhishen Wu**, Ibaraki University, Japan

This document is synthesis of the work of the three committees of the workshop with their recommendations to further research and development of sensors for CSHM. The three committees and their chairs are listed below:

Committee - 1 – Sensor Attributes and Placement Issues. Chaired by Dr. Baidar Bakht (Canada), and Professor Kazuro Kageyama (Japan)

Committee - 2 – Sensor Reliability for long term monitoring. Chaired by Professors Emin Aktan (USA) and Soheil Nazarian (USA)

Committee - 3 – Standards and Specifications. Chaired by Dr. Masoud Motavalli (Switzerland)

Chairs of the committees were responsible for development of the report for their respective committees based on the consensus of the committee members. A steering committee comprised of government decision makers, engineers, scientists and academicians took the responsibility for coordination of the activities of the technical committees of the workshop. Their participation assured that the research plans were steered towards relevant civil engineering applications. Members of the steering





committee worked with the three technical committees to provide input, review the reports of the technical committees, and make recommendations to the international organizing committee. The following individuals served in the steering committee:

- Prof. Perumalsamy N. Balaguru**, Steering Committee Chair, Rutgers University, USA
- Dr. Yukio Adachi**, Hanshin Expressway Public Corporation, Japan
- Dr. Steven Chase**, Federal Highway Administration, USA
- Dr. Hamid Ghasemi**, Federal Highway Administration, USA
- Prof. Dr.-Ing. Bernd Hillemeier**, Technical University of Berlin, Germany
- Mr. Andrew Horosko**, Ministry of Transportation, Canada
- Prof. Sun Kon Kim**, Seoul National University, Korea
- Prof. Qingbin Li**, Tsinghua University, China
- Dr. Bojidar Yanev**, New York City Department of Transportation, USA

The three technical committees of the workshop and their members are listed in the following table:

COMMITTEE - 1 SENSOR ATTRIBUTES AND PLACEMENT ISSUES	COMMITTEE - 2 SENSOR RELIABILITY FOR LONG TERM MONITORING	COMMITTEE - 3 STANDARDS AND SPECIFICATIONS
CO-CHAIRS: B. BAKHT AND K. KAGEYAMA	CO-CHAIRS E. AKTAN AND S. NAZARIAN	CO-CHAIRS M. MOTAVELLI
LOREN CARD GAUR P. JOHNSON MOHSEN A. ISSA FRITZ BRUNNER KARA PETERS CHANGSEN SUN K. TATEISHI SUMITRO SONARYO SAIID SAIDI TAKASHI MATSUMOTO DE STEFANO A. PIERRE LABOSSIÈRE	JINPING OU VISTASP M. KARBHARI WOLFGANG R. HABEL ALEXIS MENDEZ ZHIJUN ZHANG K. YOKOYAMA AKIRA TODOROKI MING L. WANG HIROSHI KOBAYASHI PETER CHANG NABIL F. GRACE GAMIL TADROS	IAN N. ROBERTSON, KONRAD BERGMEISTER INADA HIROSHI QINGBIN LI KAZUO HOTATE SOHEIL NAZARIAN HIROSHI INADA AHMAD SHUAIB BERND HILLEMIEIER ZHISHEN WU PAOLO CLEMENTE AFTAB A. MUFTI
YUKIO ADACHI BOJIDAR YANEV ROGER CHENG	J.F. CHOO SUNGKON KIM FRITZ K. BRUNNER	STEVEN B. CHASE JUNGWHEE LEE J.H. JANG

This report is disseminated to the public through the National Science Foundation. The financial support of the National Science Foundation (NSF) for this workshop is greatly acknowledged. I am indebted to a number of organizations for their support and sponsorship of the workshop. These organizations include the American Concrete Institute (ACI), Canadian network of excellence, Intelligent Sensing for Innovative Structures (ISIS Canada), National Natural Sciences Foundation of China (NNSFC), and





the newly formed International Society for Health Monitoring of Intelligent Infrastructure (ISHMII). The primary goal of ISHMII is to advance the understanding and the application of Structural Health Monitoring (SHM) in civil engineering infrastructure. In this respect, ISHMII provides the desirable forum for exchange of ideas. One of the recommendations of the workshop steering committee pertained to future sponsorships of the CSHM workshops by ISHMII. It takes motivated engineers to further the state-of-the-art in CSHM and I am sure that we are on the right path towards advancing our goals.

Respectfully submitted,

A handwritten signature in black ink, which appears to read 'Farhad Ansari', is placed over a light blue rectangular background.

Farhad Ansari,
Professor &
Chair of CSHM workshop

March 2005





**NORTH AMERICAN EURO-PACIFIC WORKSHOP
FOR
SENSING ISSUES IN CIVIL STRUCTURAL HEALTH MONITORING**

NOVEMBER 10-13, 2004 OAHU, HAWAII

INTRODUCTION

Structural health monitoring (SHM) is emerging as an important element in managing the public works infrastructure systems such as bridges, tunnels, buildings, dams, and power plants. To a greater extent, infrastructure has become more reliant on SHM due to the increased costs associated with the safety, and security issues as well as the construction, maintenance, and the need for effective post disaster condition surveys. A successful structural health-monitoring (SHM) program involves selection and placement of sensors suitable for measurement of key parameters that influence the performance and health of the structural system. Survey of literature reveals development of a number of novel sensors for this purpose including optical fibers, MEMS and PZT based as well as magnetic and magnetostrictive type sensors. Integrated sensing systems are capable of monitoring and detecting numerous structural perturbations including cracks, strains, deformations, pressures, moisture ingress, corrosion, and delaminations.

Despite recent developments in the engineering of innovative sensors a number of issues have limited their applications to civil engineering structures. Civil structures are inherently large in dimension, geometrically complex with different elements and joints, and composed of different materials. Myriads of perturbations influence the behavior and the response of various elements of the structural system and therefore the measurements of interest are not limited to strains and vibrations. For instance, measurement of importance in cable stays is force and the condition of strands, i.e. rupturing of the strands. Whereas detection of cracks and corrosion in reinforcing bars is important in concrete elements and structural systems. Moreover, a number of major application areas in civil structures such as post seismic and disaster monitoring have received very little attention. It turns out that many of the novel sensor systems that have been developed over the past decade have the potential for effective health monitoring of civil structures. In certain instances, the advanced sensory systems have been effectively employed for health monitoring of structural systems. However, in the majority of cases these successes have been sporadic mainly due to issues involved in practical adaptation of the new technologies in civil structural systems. The primary technological challenges that need to be resolved prior to full adaptation of the sensor systems for SHM of civil structures are highlighted below:





- Configuring the sensor for sensing parameters of relevance, i.e. cracks, forces, stress, corrosion, deflections, etc.
- Sensor packaging for a diverse set of materials and structural elements such as concrete decks, rebars, steel cables, structural steel, FRP sheets and tendons
- Installation problems due to harsh construction environment
- Calibration and referencing for long term sensing
- Sensor packaging, durability and survivability of sensor components
- Long-term stability and reliability
- Multiplexing and distributed sensing
- Dynamic range, resolution and sensitivity
- Data acquisition, analysis, and management (software-supported)
- Cabling, leads in and out of the structure
- Sensor calibration and referencing for permanently embedded sensors

This list is not exhaustive, but it serves to illustrate some of the characteristic problems that need to be addressed prior to practical implementation of advanced sensing technologies to large structural systems. In essence, addressing these issues requires:

- 1) Synthesis of available sensing technologies and verification of their relevance to structural systems
- 2) Determination of the developmental stage of the technologies
- 3) Evaluation of the barriers that prevent implementation
- 4) Development of timelines for a coordinated R&D plan
- 5) Identify appropriate test beds for demonstration projects

While it was not possible to address all of these issues in a single workshop, the participants were able to develop a road map for implementation of R&D plans. The broad-spectrum of issues that was addressed in the workshop through presentations of the state-of-the-art and the work of the three committees included:

1. Sensor types, materials, and instrumentation suitable for civil construction materials use.
2. Methodologies for reliable processing of signals, and interpretation of real-time data acquired from sensors.
3. Determination of sensor integrity under structural loads, construction processes, and exposure to chemical and ambient conditions.
4. Development of sensor packages for distributed measurements of cracking, deformations, strains, force, weight in motion and corrosion in bridge and other structural systems.
5. Development of the calibration and measurement methodologies, guidelines and standardization of the developed methodologies through working with appropriate organizations (NIST, ASTM, IEC).
6. Implementation of field demonstration projects through full-scale tests of bridges.





REPORTS OF THE TECHNICAL COMMITTEES OF THE WORKSHOP

The products of the workshop are presented in the form of a state-of-the-art proceedings volume based on the presentation of the papers on the subject matter, and the reports of the technical committees presented here. The proceedings will be published in mid April 2005. The proceedings will be beneficial as a source of current information on CSHM; a benchmark to assess the progress of CSHM research in future (i.e. three years from now at the 2008 Workshop); and a valuable source of information for research and practice of CSHM.

The reports of the three committees of the workshop are given next in this document. These reports are not necessarily conclusive on the subjects and they are open for further details and additions by researchers and practicing engineers. In other words, these reports were prepared with the notion that they are work in progress.

The work of committee – 1 is synthesized in a table identifying the events and the measurable entities associated with those events. The research needs section of the table is based both on the urgency and need for sensors as well as realistic potential for success in development of such technologies. The panel in committee-2 addressed that the reliability must be dealt with in two fronts: (1) improving the reliability of the sensor system; and (2) Improving the reliability of the data.

As obvious from the deliberations of committee-3, at this point in time, CSHM is still at a stage of infancy, and for this reason, standards and specifications are basically nonexistent. Such specifications require processing of the state-of-the-art information by an expert forum with specific focus in structural health monitoring of civil structures. It turns out that ISHMII because of its constitution and sole devotion to structural health monitoring of civil structures is in a position to take on the challenge as outlined by the members of the panel in committee-3. In addition, education and training of personnel is an important factor in furthering successful practice of CSHM. Although, the educational aspects of CSHM were not discussed at this workshop, it is envisioned that ISHMII will be able to take on this mission through its special task force for education and training.

Again, my sincere thanks to all the participants as this report and the proceedings volume to follow is a result of their hard work. I am looking forward with great optimism to learn of our progress during the next CSHM workshop in 2008.

Farhad Ansari,
March 2005





REPORT OF COMMITTEE – 1

SENSOR ATTRIBUTES AND PLACEMENT ISSUES

CO-CHAIRS: DR. BAIDAR BAKHT, AND PROFESSOR KAZURO KAGEYAMA

In order to avoid the impossible task of discussing all problems related to the attributes and placing of sensors for structural health monitoring, the committee decided to develop a matrix in which a relationship is developed between ‘events’ which affect the safety of structures and the attributes of structures that could be measured by available sensors. For simplicity, traffic loads, structural fatigue and dead loads have been placed in the category of ‘events’.

The attached table represents the efforts of the committee, and should only be regarded as a work in progress. An empty cell in the table generally indicates that the effects of a given event cannot be, or have not been, predicted by the measurable entity. ‘Y’ in a cell indicates ‘yes’.

An important outcome of the committee’s deliberations is the ‘Research needed’ column in the attached table, which indicates whether research is required to predict the effect of an event by means of structural health monitoring. Areas of high priority indicated in this column refer not only to the importance of event, but also to the likelihood of success. Research related to an event is given high priority if chances of success are good. It is expected that the conducting of research indicated in the table will both advance the science and have a large and beneficial impact on the society.



Table 1. Relationship between effects of events on structural safety and measurable attributes of structures

EVENTS	2. MEASURABLE ENTITIES											Research needed
	Strain	Deformation	Acceleration	Temperature	Geometry	Image	Electric potential	Acoustic emission or attenuation	Chemicals, including moisture	Magnetic properties		
Fire	FAIR	FAIR	POOR	GOOD		1		2	FAIR		Y	
Explosion			POOR GOOD			Y FAIR ¹					High priority	
Collision to Girders and columns	Y FAIR	POOR ¹				POOR ²					Y	
Earthquake	Y FAIR ²	Y POOR ¹	Y GOOD			Y FAIR					Y	
Scour	3						4				High priority	
Traffic loads	6, 5	5	Y GOOD	Y GOOD	7						Y for Especially WIM	
Wind	Y GOOD	Y FAIR	Y GOOD	Y GOOD							Y	
Corrosion									Y FAIR	Y FAIR	High priority for corrosion of prestressing tendons, current methods make indirect measurements only	
Structural fatigue	Y FAIR										Y for fatigue of bridge deck slabs	
Dead Load	Y GOOD		8	Y GOOD								

Notes: Outlined in the following page





Table Notes:

1. Important, but difficult to measure
2. Current method too tedious
3. Change in column strains can detect effects of scour
4. Ultrasonic imaging has been used to map erosion due to scour
5. Laser vibrometer and tiltmeters can be used to monitor traffic
6. Weigh-in-motion (WIM)
7. Laser scanner can be used to detect change in geometry due to traffic
8. Forces in cables of cable stayed bridges have been obtained from their vibration characteristics







REPORT OF COMMITTEE – 2

SENSOR RELIABILITY FOR LONG TERM MONITORING

CO-CHAIRS: Professors Emin Aktan and Soheil Nazarian

The ultimate objective in any sensing application is to reliably interpret the data. This is not possible unless the data is reliable or at least the confidence in the data is acceptable. There are many sources of aleoric (due to variance errors and random nature of a measured quantity) and epistemic (due to bias errors and incomplete knowledge of the causative effects) uncertainty that affect measured data in a real experiment. The epistemic uncertainty may be dominant in field measurements, especially when measurements are taken over a large area (meters to kilometers) and over a long-term (years to decades) while exposed to the natural and operating environment.

Given the above, the reliability of a sensor should be considered in a global context, recognizing the systems nature of sensor, experiment, structure and environment that interact and affect each other in known and unknown ways. The reliability of the data from the best designed and best manufactured sensor will rely on many other mechanisms and parameters additional to the properties of the sensor itself. Before the issues related to the reliability of sensors can be addressed, the entire system that controls the integrity and usefulness of data should be defined.

A reliable data can be broadly defined as a set of values obtained with a sensor to either experimentally observe a phenomenon, or to verify or validate a model, or to diagnose the potential problems with a structure through pre-determined empirical or theoretical thresholds. The degree at which this goal is achieved can define the reliability of the sensor system.

When data is collected with a sensor, the useful measurements associated with the response of the structure are also contaminated with several other items. These include: random (variance) errors, systematic (bias) errors, intrinsic changes in the material properties and boundary conditions of the structure (and the sensor itself), and any unknown errors due to simplifying assumptions made in the characterization of the response of the sensor system. The goal is then to eliminate or minimize these errors and maximize the data component related to the structural response that is being sought.

In this context, the following general items should be considered in any project dealing with the use of a sensor (Fig.1)





1. Objectives: The decision on the use of a particular sensor should be justified by ensuring that it provides data that can assist in meeting the objectives of the project.
2. Operational and Natural Environment: The sensor system should then be able to meet the environmental and operational requirements of the project for as long as necessary to support the objectives.
3. Nature of Structure: The specifications of the sensor system should be such that it can be readily installed on the structure under consideration with minimal interruption to the normal operation of the structure.
4. Based on the objectives, an experimental design should be carried out to ensure the adequacy of the sensor system, the frequency of data collection, the best way to monitor, store and archive the data, and the method to ensure the integrity of the data being generated by the sensor system.

The panel feels that these items should be addressed in two fronts:

- (1) Improving the Reliability of the Sensor System, and
- (2) Improving the Reliability of Data.

Strategies to improve these two factors through research and development are listed in the two Tables presented below. The panel understands that the strategies enumerated can fall under three categories:

- (1) Basic Research that can be pursued through agencies like NSF
- (2) Applied Research that can be pursued through governmental and private agencies such as FHWA and state transportation agencies.
- (3) Institutional and Cultural Modifications that can be addressed by either Federal Agencies (such as FHWA) or Trade groups (such as ISHMII).



SYSTEMS MODEL FOR DATA RELIABILITY

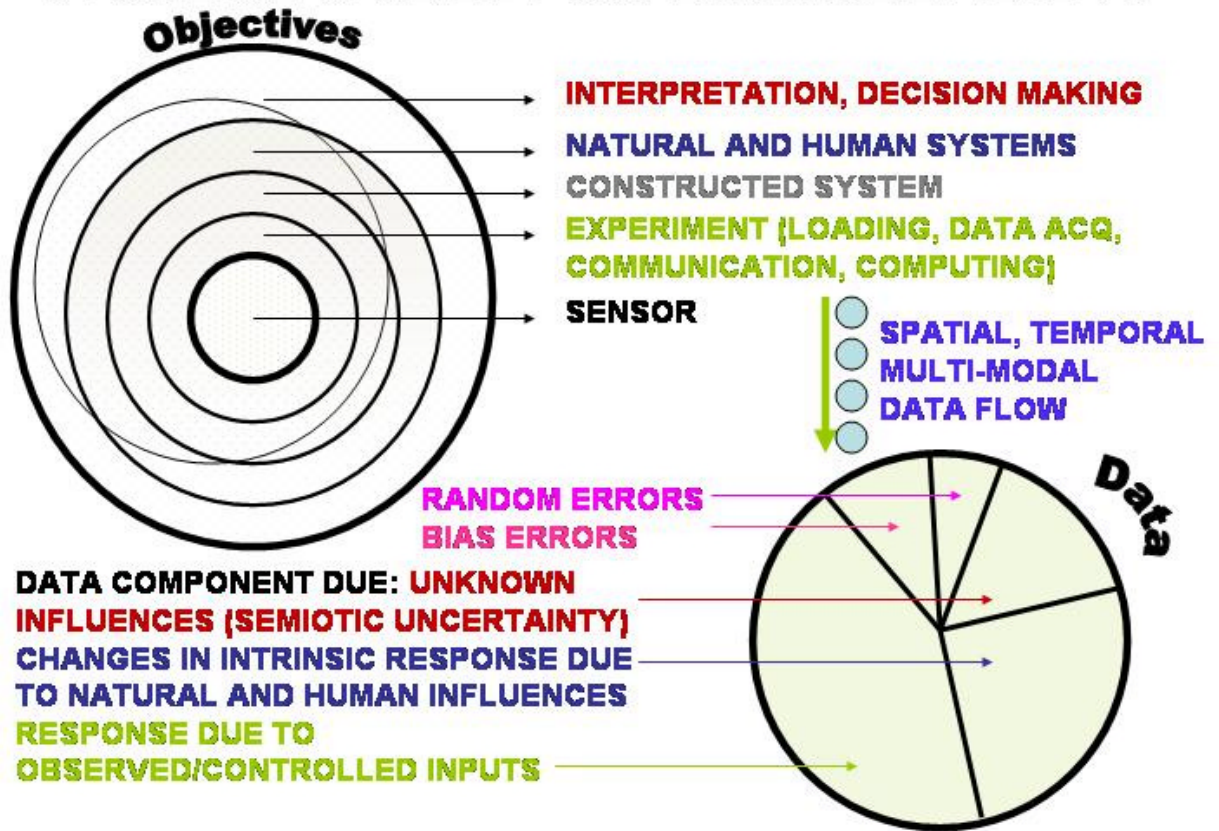


Fig. 1 Systems Model for Phenomena/Parameters Affecting Data Reliability



Table 1 - Strategies for Sensor reliability

No.	Proposed Strategy
1	Incorporate Redundancy due to changes in sensor materials
2	Need for calibration with time
3	Model sensor behavior under realistic conditions
4	Use sensors that are proven with time with new sensors use sensors that are proven
5	Develop self-calibrating and smart distributed network to self-correct
6	Minimize exposure to environment by design
7	Place sensors using well-designed programs
8	Develop a metrics for assessing the reliability of sensors
9	Develop sensor based on performance-based to maximize reliability
10	Database of successes and failures (especially failures)
11	Develop standard tests for verification
12	Validate the process and sensor system as a whole
13	Need for a well-recognized federally-funded to validate sensors using international standards
14	FHWA and NIST should advocate use of sensors through legislation
15	Develop a federally-managed networks
16	Resolve community resistance to new technology
17	Encourage performance-based construction to encourage innovation by construction industry
18	Need innovative means of installing and replacing sensors
19	Sensors for Geotechnical and Geotechnical Earthquake Engineering





Table 2 Data-Related Strategies

No.	Proposed Strategy
1	Need to understand intrinsic performance of sensor system (including sensing materials and packaging and wiring)
2	Need to understand environmental effects on deterioration of sensor
3	Need to validate/assess data streams
4	Need for developing self-calibration
5	Need for audit trail (type stamp, rate of sampling, calibration at time of data collection, etc.) for data
6	Need for standardization of data collection and archive format
7	Need to address the transportability of data once sensor becomes obsolete
8	Need to determine the integrity of data
9	Need to ensure the integrity of system components
10	Need for interface to display and visualize results
11	Need for effective data management with large stream of data
12	Need to make global measurements for effective interpretation for local data
13	Need to check response with time for reliability of interpretation of extreme events
14	Need to determine the environmental effects on structure as well as sensor system
15	Need for clear understanding of data requirements
16	Need for analytical prediction for selecting sensor types, sensor locations and data requirements
17	Need for sensor for real time material characterization in conjunction with health monitoring
18	Need for audit trail for reported interpreted data (i.e., transparency from the raw data to reported results).





REPORT OF COMMITTEE – 3

STANDARDS AND SPECIFICATIONS

Chaired by Dr. Masoud Motavalli

A guideline is essential to simplify and speed-up the planning and implementation of a monitoring sensor system at sustainable costs. In the meeting following points were discussed:

- Type of applied materials, such as concrete, steel, masonry etc. that would need sensors for their monitoring.
- Type of structures, such as bridges, high rise buildings, dams, historical buildings, etc.
- Worldwide available guidelines and specifications for sensors in civil structures.
- Worldwide ongoing projects related to our topic, such as European SAMCO project, ACI, etc.
- Activities of ISHMII related to our topic.

Based on the discussion following items are recommended to the steering committee:

1. Organize the next workshop before 2008: ISHMII to take the lead in organizing the workshop.
2. ISHMII to produce a pre-proposal (4-5 pages) to justify developing a proposal for the next workshop.
3. ISHMII to develop collection of information on SHM technology worldwide by March 2005 (next ISHMII meeting).
4. CSHM workshop steering committee together with ISHMII to provide networking platform for attendees of CSHM 2004 (photographs, areas of specialties, organization, e-mail)
5. It is recommended that:
 - Committee 1 develop a draft document on sensor attributes and placement issues by March 2006 and submit to Committee 3.
 - Committee 2 develop a draft document focusing on sensor reliability for long-term monitoring by March 2006 and submit to Committee 3.
 - Committee 3 to utilize the draft document of Committee 1 and 2 and to develop the draft guidelines for CSHM by June 2007 before the next CSHM workshop.

