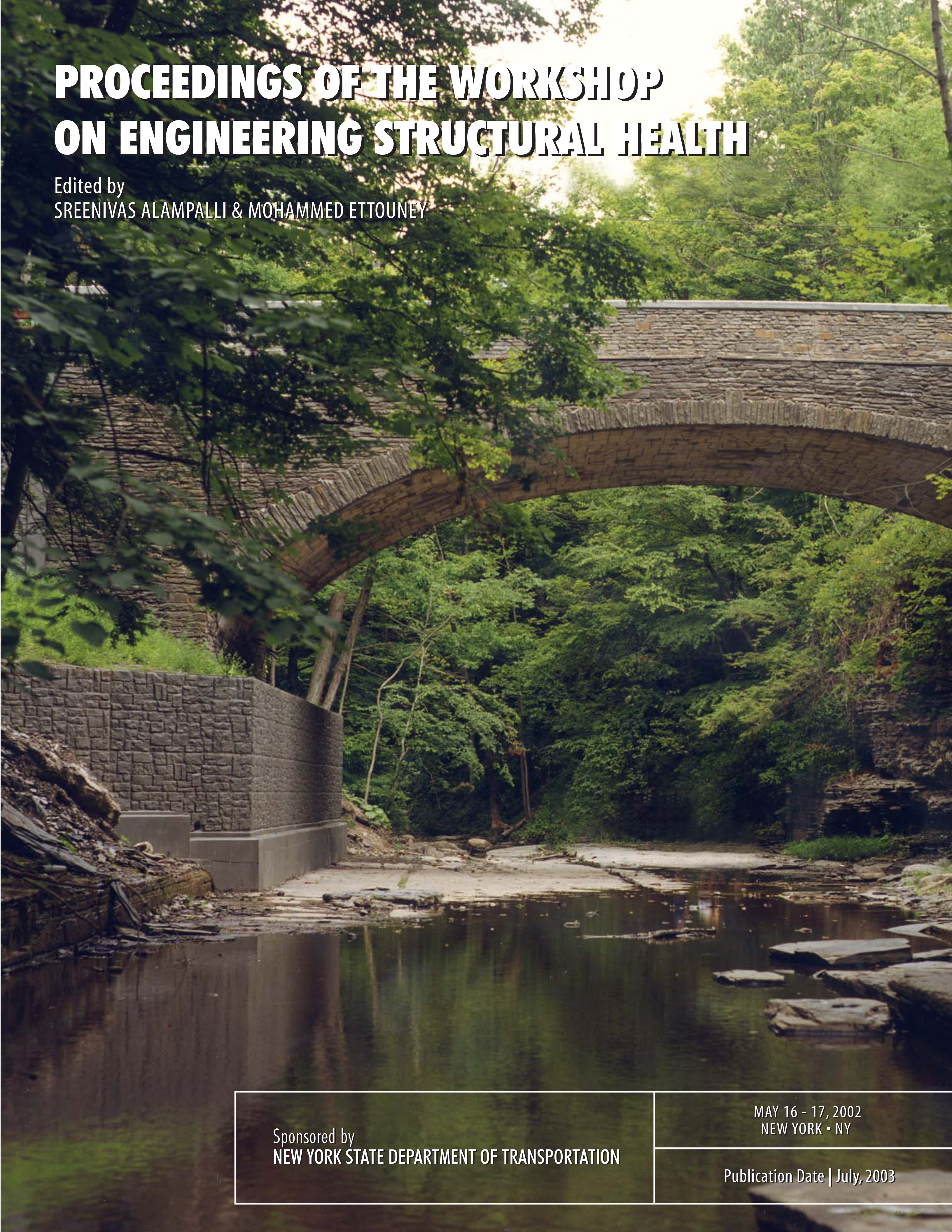
PROCEEDINGS OF THE WORKSHOP ON ENGINEERING STRUCTURAL HEALTH

Edited by
SREENIVAS ALAMPALLI & MOHAMMED ETTOUNEY



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Executive Summary

The *Engineering Structural Health* workshop brought representatives from infrastructure owners and government officials, practicing engineers, academia, and sensor/equipment manufacturers together to discuss the current state of structural health engineering. The goal of the workshop was to increase communication between the groups involved in this field as well as review necessary aspects of successful bridge infrastructure condition assessment.

The major outcomes of the workshop were:

1. Increased understanding of owners' need to improve condition assessment of bridges.

2. Increased awareness of the problems that need addressing to understand and advance the structural health engineering field.

Significant observations and recommendations include:

1. General consensus of the infrastructure owners is that the "Engineering of Structural Health" field is still in its infancy.

2. There is a gap in perception, experience and knowledge between the engineering consultants, academia research staff and the sensor manufacturers.

3. In most situations, the current structural health monitoring systems on the market do not meet the owners' expectations.

4. Cost-benefit ratio is the most important issue to bridge owners.

5. Long-term continuous monitoring should be used as a last option in engineering structural health applications. Immediate and short term structural health issues are of higher importance levels.

6. National guidelines for bridge testing, structural health monitoring, and decision-making process are needed.

7. Owners, consultants, and academia feel that the failure/success of the project is the sole responsibility of the owners.

8. Peer Review is a valuable tool and should be used frequently in all stages of a structural health project.

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1 Introduction

1.1 Overview

Preserving the nation's infrastructure is dependent on the successful implementation of engineering structural health concepts. According to the workshop steering group, the concept of engineering structural health encompasses four distinct subsets: a) sensor allocation and measurements; b) structural identification; c) damage/degradation detection and evaluation, and d) decision making. Each of these subsets is a major topic by itself. However, for a successful health preservation program, all four should be considered simultaneously.

The integrated field of "Engineering of Structural Health" is still in its infancy. There have been numerous activities in different subsets of the field. However, many concepts still need further study; and the integrated field as a whole has not been studied and understood in full detail.

The objective of this workshop was to examine the four subsets of engineering structural health concepts and, more importantly, investigate the interaction and interdependence between those four subsets. An emphasis was placed on stronger and efficient integration of different aspects of engineering structural health.

The New York State Department of Transportation (NYSDOT) sponsored the workshop. The steering group for the workshop included Dr. Sreenivas Alampalli from NYSDOT and Dr. Mohammed Ettouney from Weidlinger Associates, Inc. (WAI).

1.2 Workshop Composition

The workshop was envisioned to have about 30 attendees representing all communities (stakeholders) interested in the field of engineering structural health. Four specific communities were identified as the main groups having direct/major interest in the Engineering Structural Health field. These communities are:

1. Infrastructure Owners and Government Officials: This group will be referred to as "owners" in the proceedings.
2. Practicing Engineers: This group will be referred to as "practitioners" in the proceedings.
3. Academic Community: This group will be referred to as "academicians" or "researchers" in the proceedings.
4. Manufacturers of Sensing Devices/Equipment: This group will be referred to as "manufacturers" in the proceedings.

The number of attendees from each group was almost equal, about seven to eight persons per group. The list of the Workshop attendees is included in Appendix A.

1.3 Workshop Layout and Agenda

The steering group identified four main topics in the field of engineering structural health, as indicated in an earlier section. Based on the expertise, involvement, industry, and vested interest, attendees were divided in to groups representing the four professional communities described in Section 1.2. In order to derive maximum benefit and foster effective discussions on all issues, the four groups met individually and together in a systematic fashion during various breakaway sessions (see Appendix B). In particular:

1. "Uniform" breakaway sessions were allocated for each group.
2. "Mixed" breakaway sessions were allocated for different combinations of groups.
3. The groups were encouraged to discuss one or more of the four engineering structural health topics.

The steering group thought that "mix and match" approach would be beneficial to the outcome of the workshop. In general, each individual community has its own way of addressing its problems, goals, perceptions about the other communities, and a course of action to advance the field. The exposure of each community to the thought process, goals, and perceptions of other communities would benefit everyone. The steering group envisioned, in particular, that this exposure is exactly what is needed to improve the integration of all four communities to advance the structural health engineering field.

A total of ten sessions were held during the workshop. The workshop started with an introductory session, which was attended by all the attendees. One or more groups attended the eight sessions that followed, in a systematic predefined manner. Some of these sessions constituted concurrent breakaway meetings. Session details and topics of discussions are shown in the workshop agenda (Appendix B). All the workshop assembly again attended the tenth and final session, designed as a "Closing Remarks" session, and each of the attendees described their summary of experiences.

1.4 Format of this Proceedings

The main points discussed in each of the sessions are described in the following sections. Whenever possible, each of the sections of this document will include:

1. Pertinent quotes from the attendees
2. Specific problems the attendees discussed
3. Specific "wish lists" of the attendees
4. Interaction and integration issues

The format and composition of each section varied according to the flow of the deliberations in that particular session. While editing this document, little or no omissions were made, in order to preserve the feel and content of the deliberations. However, the following rules were observed while editing this document:

1. Remove all specific references to names of individuals and bridges and/or any other infrastructure projects.
2. Rely, as much as possible, on a bulleted presentation style. This eliminated the need for extensive rewriting, and helped making the discussion points concise and easy to follow.

1.5 Acknowledgements

This workshop was sponsored by the New York State Department of Transportation. Weidlinger Associate, Inc. provided the location and the necessary logistics.

This document was made possible by the dedicated record-keeping efforts of all workshop attendees. The material provided in the following sections is an assemblage of all the notes that were taken during the deliberations in the breakaway sessions by record keepers and all other attendees. Their dedicated effort is gratefully acknowledged.

Editors acknowledge the assistance provided by Sharada Alampalli and Jonathan Kunin in preparing these proceedings. Editors also thank American Society of Civil Engineers for giving permission to include two of the papers, previously published in ASCE Structures Congress Proceedings, in Appendices of this document.

All the views represented in these proceedings are those of the attendees and the Steering Group, and not necessarily of the organizations they represent.

2 Introductory Session

This first session started with self-introductions of all the attendees followed by opening remarks from NYSDOT and WAI. This was followed by a presentation by Dr. Sreenivas Alampalli of the NYSDOT giving an introduction to general issues pertaining to *Engineering of Structural Health* (see Appendix C for the slides). The presentation introduced topics to be discussed, and stressed the importance of interdependence and integration between the different topics. He also discussed the scope, format, and logistics of the workshop. In addition to the introductions and the keynote presentation, the following technical papers related to Engineering Structural Health were handed out to the attendees.

Ettouney, M.M. and Alampalli, S. "Engineering Structural Health," ASCE Structures Congress 2000, Philadelphia, PA, May 2000.

Ettouney, M.M. and Alampalli, S. "Overview of Structural Health Engineering." ASCE Structures Congress and Exposition 2002, Denver, CO, April 2002.

These documents are included in Appendix D and E.

3 Session 2

In Session 2, individual groups representing their communities met separately to discuss their views on engineering structural health, health monitoring, and the issues facing them. This section summarizes their discussions.

3.1 Owners

Specific comments from participants are listed in this section followed by the summary/general observations of the session.

- **Participant 1**

  - What needs do we (owners) have? Do bridges require monitoring?

  - Things that were very difficult to monitor in the past are now feasible. We want to design bridges such that we don't need monitoring. New tools come from manufacturers and academia, and get used by practitioners.

  - Need to bring probabilistic methods to make deterministic decisions, which alone can not help. Probabilistic methods can eliminate unnecessary margins. These safety margins are very important; and perfecting design should not reduce factors of safety. In many cases, we may not necessarily know the factor of safety.

  - Quantification of structural response is useful and required. We as engineers have to make qualitative decisions. There is a huge gap between qualitative and quantitative. Any amount of measurement is not going to help us. Analysis is semi-probabilistic, and so we cannot eliminate engineering judgment.

- **Participant 2**

  - As owners, we make decisions based on the available information. Factors of safety are built into bridges and they help us in the long run. This also avoids constant maintenance. With little maintenance, the 100-yr bridges remained in service, due to these safety factors. Money really doesn't matter in this picture.

  - Knowing the bridge to the finest detail is great, but is it required? In practice, it is not possible to get complete data/information on a bridge. Health monitoring, if it can avoid the two-year bridge inspection, will be great. Can we do it?

  - The reality is that money does matter. Why we want to do it? Why can't we afford not to do this? What is health monitoring? Who did accomplish the heath monitoring successfully so far? Was it useful? These should be looked into.

- Fatigue analysis/limits may be useful to get and monitoring is useful there.

- Tidal Scour: Is there anyway to find the condition? Some bridges were lost due to tidal scouring. Can we detect removal of soil due to scour? Want to know before failure.

- **Participant 3**

  - Pure academic research monitoring programs are not needed. Lack of practical engineering judgment in these cases is very important to notice.

  - We had a bad experience in collecting data. We were promised great data! But, managing data proved to be a big problem. Maintaining the system is a very important problem. Sometimes we need a quick answer. Academia gives complicated answers that cannot be used directly. This is a big problem.

  - For example: For a deck deterioration survey, one needs to set specifications clearly. Results should be verified with field data. Specific needs of various test methods should be checked. "Are they (i.e. these methods) any good" is an important issue?

- **Participant 4**

  - Building bridges without monitoring is great! It will be nice if we could get by without maintenance! Minimize need for monitoring.

  - Different complexities that need monitoring and degrees of monitoring should be categorized. FHWA has a program for 2-yr monitoring that can be stretched out to 4-years on some bridges. Inspection itself is monitoring and can be stretched out to 4 years on some bridges.

- **Participant 5**

  - Agree with others. Cost-benefit is an issue. Analysis, data collection, etc. are expensive.

  - For example: Cathodic protection needs personnel time, etc., for long-term maintenance/monitoring. We cannot afford to do this. Management of data should be considered.

  - Monitoring is desirable, but we want to monitor only when we have no other choice. In that case, we need practices, procedures, and etc. to follow.

  - It all depends on cost-benefit analysis.

- Theory vs. Practice is important. False alarms are important. Practical reasons on why monitoring doesn't work should be considered. If it is the last option, then use it.

- What should be monitored should be well thought out. For example, monitoring corrosion progress may be more important than cable breaks.

- **Participant 6**

  - Need periodic checking of data etc. Standardization tests are needed. Passive is better. Look for passive monitoring.

  - Certain areas need lifetime monitoring and certain other areas don't need any. Categorize those areas and then the owner should decide what to do (structural response measurements or restricting loads or type of maintenance, etc.).

- **Participant 7**

  - Other countries experiences with health monitoring: Lack of knowledge and no national agenda are the reasons for the demise of heath monitoring in those countries.

  - Budget might be there to do continuous monitoring. National guidelines (to address what is monitoring etc.) are being developed. FHWA guidelines are in preparation. Monitoring applications should start with critical bridges.

- **Participant 8**

  - It is great to build bridges requiring no maintenance or monitoring. But, we need to make decisions as the time passes, as unanticipated things happen during a bridge's life.

  - Monitoring (continuous, periodic, or one-shot) is another tool in the process to help us make decisions. We have been very successful using this to answer specific questions – fatigue, load rating, material durability, etc.

  - "Just for research purposes" is not good reason for long-term monitoring. The purpose, budget, etc. needs to be set based on what we want, and then it boils down to a cost-benefit analysis.

The general consensus of the group representing the "Infrastructures Owners and Government Officials" at the workshop was that the integrated field of "Engineering of Structural Health" is still in its infancy. There is a gap of experience and knowledge between the engineering consultants, academia and manufacturers. Additionally, the current Structural Health Monitoring systems on the market provided by the group of engineering consultants, academia and manufacturers does not meet the owners' expectations.

One Infrastructure Owner indicated that his agency's long term Structural Health Monitoring system, which was designed and installed by an academic research team, only provides the raw data such as the strain and acceleration of many structural members. The storage of the raw data, management of the large data base, and long-term maintenance of the hardware and software of the Structural Health Monitoring system have become a burden for the owner. The cost effectiveness of the long term Structural Health Monitoring system is questionable. He strongly recommended avoiding long term Structural Health Monitoring system unless there is a definite need. He recommended that Structural Health Monitoring systems be used only for short-term monitoring with the scope and the objectives of the monitoring system well planned and specifically defined.

Another Infrastructure Owner expressed that he'd like to receive a quick method of identifying the location of deficient structural members from a Structural Health Monitoring system. He does not like to get involved with the complicated process and evaluation of the raw data obtained from Structural Health Monitoring systems. And the Structural Health Monitoring systems would be used as the last resort when there are no better or more economical methods for structural health evaluation.

Two Infrastructure Owners indicated that their agencies had bad experiences in deck evaluation and delamination detection using couple of recently commercialized nondestructive test methods. The deck delamination predicted by the consultant gave poor correlations when compared with the field verification. It is recommended to hold the consultant and the parties, who perform such surveys and data processing, liable for the quality of the non-destructive test results by including penalty clauses in the specification when the survey results does not match well with the field verification during construction.

3.2 Manufacturers

Topics discussed, specific comments made, and thoughts expressed during the "Manufacturers" discussions are listed in this section.

- Where are we currently, in regards to sensors (acoustics, electromagnetic NDE/NDT, vibration, ultrasonic NDE/NDT, corrosion sensors)?

- Before buying and applying sensors, owners/consultants should be clearer about their needs. Provide better problem identification and communication to the manufacturer so that correct tools can be recommended/purchased.

- Currently visual inspection is the primary inspection method for bridges.

- Bridge scour is a problem that reduces stability and is relatively difficult to detect, although some methods exist.

- Biggest current need is to determine what properties to measure and/or test.

- Large jump from current knowledge levels to the ability to measure phenomena and relate that to a specific condition of a structure.

- We have the ability to measure virtually anything, but the need is to find a way to relate all of that data to a condition in order to make the information meaningful to the decision maker.

- Need to determine what parameters to measure and what the results mean in terms of corrosion, fatigue, and structural health. Can't measure everything and must be selective in building measurement plans.

- Develop correlation between measurements and structural health.

- Strategy – Joint programs with owners, researchers, and consultants. No testing plan should be put into service unless there is a bottom line cost benefit to the owners. Need to show what the benefits are, even in terms of potential cost avoidances due to structural problems or failures.

3.3 Researchers

The researchers group initially focused on pre-instrumentation analysis and the needs of owners. Then important issues facing their group were discussed.

- **Pre-instrumentation Analysis**

  - Before planning the instrumentation, pre-engineering analyses should be done to identify problems that must be addressed. The monitoring planning should address those problems identified.

- **What do the Owners Want?**

  - What may compel an owner to ask for help?
  - Inspection leading to unexpected discovery.
  - Rating of bridges.
  - Need more efficiency, sensors not fully utilized.
  - Too much data!! Owners may want specific data.

- **An academician can measure anything that is required. What are the important issues?**

  - Understanding the matrix of bridges, owners' vision, and typical problems is important.
  - Apply knowledge and technical know-how where it is important.
  - Importance of socio-cultural issue.
  - Technology is to be factored in.

3.4 Practitioners

The practitioners group agreed that their group is perhaps the major link that binds all communities in the structural health field together. As such, their responsibilities in ensuring a successful structural health program are paramount. Among important aspects of this are:

- Advise the owner of cost-benefit issues.
- Ensure that the bottom line goal of the project is well defined.
- Engage sensor and equipment manufacturers as early as possible.
- Help academicians to streamline research issues into practical and cost effective tools.

4 Sessions 3 and 5

Four groups were formed to discuss instrumentation, damage detection, structural identification, and decision making issues. Each group consisted of members representing all four communities, and was asked to discuss two of the four aspects of structural health monitoring presented to them during the introductory session. A moderator and a note taker were designated by each group and this section presents their summaries.

4.1 Instrumentation Issues

Some direct quotes regarding the measurement and instrumentation are presented below.

- Passive monitoring is important. Read at defined points. Owners do monitoring only when needed. Reliability and false alarms are a problem and should be addressed.

- When do you monitor? Accept that there is a need to monitor.

- In general, the technology is there. But, they are quite general. Manufacturers always want to know what should be measured.

- Active and/or automatic monitoring? Where are we now? We have a long way to go!!

One of the owners, in the group discussing the instrumentation issues made the following comments, summarizing the owners' perspective on instrumentation, to assist the general discussion on instrumentation issues:

> "The owners voiced their hesitation concerning instrumentation, primarily due to their previous attempts to utilize sensors. By their description, the technology was oversold to them and not implemented properly or the evaluation of data was too difficult. Manufacturers need to work closely to understand the specific needs before pushing a product. Owners need to work closely with manufacturers to identify the problem by being very specific about needs and expectations. This would seem obvious to me personally but it was an area that definitely needed more focus."

4.1.1 Discussion on Instrumentation

The discussions covered several issues including instrumentation issues that can be divided into general instrumentation items, and specific issues related to bridge monitoring, corrosion, and fatigue. These are briefly summarized in this sub-section.

- General Instrumentation Issues

  - Structural identification: Global identification of the structure is needed.

  - Is it a key asset? This is an important question. Most of the work has been on large structures. Monitoring may be very useful for essential bridges. The monitoring may be of great use to important assets (economically or critical to social-impact).

  - Maybe what we are talking about covers only 5% of the bridges. Bottom line does matter. Budget optimization is the key.

  - Humans can say if he/she has a problem, but bridges cannot. This is the key difference in comparing health monitoring of humans and bridges.

  - The quests of owners, researchers, manufacturers, and consultants are different.

  - Proven technology: Proprietary issues are problematic for universities and manufacturers working together. Working relations and procurement methods also play a key role.

  - 5 to 10 years: Change is coming. Owners/managers are beginning to understand and are open to ideas. Monitoring is a fraction of the cost when compared to other items such as analysis, etc. Engineers are becoming more pro-active and are looking into investing now rather than worrying in the future.

  - Defining the problem clearly is of utmost importance.

  - Standardization/standards are acceptable. Proving the technology once and not worrying later is important for manufacturers. Standardization is great. Give a benchmark for manufacturers to prove their technology. They don't want to keep validating several times, as money and resources are limited in any industry.

  - Standardization of sensor technologies is very important and should be examined.

  - Owners should set standards as it is in the realm of the owners.

  - Consultants should make the decisions and not manufacturers. So, they should work together.

  - Knowledge of data interpretation is very important in civil structures and is not well founded yet.

  - Analysis is a good diagnostic tool and shows what is vulnerable. It plays a very important role. It will help direct all other stuff.

- Criteria should be laid down for analysis as well as measurement. Archiving etc should also be defined/explained and then these will become manufacturers' responsibility.

- Practical Issues on Bridge Monitoring
  - Advantages of monitoring for real motions under wind and traffic loads.
  - Large capital costs for large bridges. A certain large bridge had a zero rating. Approximately $1 billion is required to bring that bridge to code.
  - Make bridges accessible to instrumentation: Install instrumentation ports during the construction.

- Specific Monitoring Problems for Corrosion and Fatigue
  - Can it be associated to voids and lack of grout in addition to other sources?
  - Time Domain Reflectometry (TDR) is good for monitoring corrosion in concrete. How much impedance would one get for small corrosion?

- Fatigue issues
  - Problem with older bridges, newer bridges may not have this problem.
  - A diagnostic problem, not a monitoring issue.
  - Remaining fatigue life can be determined by the measurement of crack size on passive gages.
  - Knowing real stress field will be valuable.
  - Monitoring can be useful to track over-loading.
  - Instrumentation will let you know the stress environment on diagnostic basis.

4.1.2 Current State of the Art: Instrumentation

The groups also discussed the state-of-the-art, the perspective of each community on current state-of-the-practices, and state-of-the-art of instrumentation's role in engineering structural health.

- **General**
  - We can measure anything that we want.
  - Lots of technologies are available.
  - Wireless data acquisition.
  - We don't know what do we do with these technologies?
  - Structural models are not adequate.
  - No need for emphasis to develop new devices.
- **Owners Perspective**
  - Owners feel they will have to monitor at some point in time. However, they prefer not to have to monitor.
  - Owners are interested in setting a criterion as to when monitoring should start. Example: Fatigue history of a steel bridge would be very useful.
  - Apparently, there is a big gap between instruments and analysis tools.
  - Owners don't see a need for measurements: Cultural Gap.
  - In order to use measurements, owners need to be convinced. The monitoring programs need involved owners.
  - Owners need to understand the impact.
  - Owners still want to inspect bridges manually, even though a measurement based approach may be available. For example, disconnect between owners and researchers, sufficiency rating affecting federal dollars, and resistance to change make better detail and construction preferred to monitoring. However, we may still need measurements.
- **Practitioners Perspective**
  - Traditionally, consultants are involved with inspections and offering solutions. A regulated health monitoring technique would be very effective.
  - Consultants are concerned with different mechanisms of deterioration, such as corrosion and ways to monitor its initiation and growth.

- **Manufacturers' Perspective**
  - Manufacturers feel that there are solutions to many concerns.
  - Parameters have to be identified by owners and consultants.
  - Some form of standards or criteria would allow for production of cost effective systems.
  - Constantly spending significant amounts of funding on validations and testing of sensors and techniques should be avoided.

4.1.3 Wish List: Instrumentation

The group discussed the wish list for instrumentation needs assuming no technology and cost barriers. The wish list is given below:

- Low cost, hand-held, and easy to use systems.
- Set criteria for structural and global identification.
- Key structures should be identified, so that monitoring can be targeted.
- Production of cost-benefit analysis on typical structures could ease some of the funding difficulties.
- Manufacturers to manage and store data to allow continuity of monitoring system due to possible changes in the owners/consultants staff.
- Knowledge of the fatigue history would be desirable. This would provide a prediction of the remaining service life. This is currently a knowledge gap.
- Need for standards for sensors and data management.
- Industry standards would make it easier for the bridge owners and vendors to interact.
- Significant knowledge gap exists in correlating measurements with the condition of structural health.
- The NCHRP project on cable reliability is looking to find the strength of cables through NDT. There is lack of technology to find the strength of cable through NDT to determine cable reliability. The same is true about pre-stressed concrete. There is a need for new instrumentation in this area.
- Devices required for local measurements.

- Instrument reliability and maintenance is an issue.
- Corrosion in embedded steel
- Loss of pre-stress or flaws in pre-stressing
- A lot of technology exists. We don't know how to use it or we need better tools.
- Majority of bridge failures are due to scour. Tools such as drop rods, talking rocks, sonar, etc. are available. But, instrumentation for reliable monitoring of bridges for scour is needed.
- Real-time data on the web is desirable.
- Streamline sensor info and put it on the web.

4.1.4 Miscellaneous Comments

- Federal and NY State Bridge inspection rating scales are different: Federal 0 to 9, and New York State 1 to 7.
- Need practical method for health measurement.
- Technical need for global deflection measurements over long spans – up to a mile.
- Current structural rating compared to "as built" condition.
- Current technology CANNOT replace visual inspection by an experienced inspector, but it would be nice to have a system to minimize onsite inspections.
- Instrumentation has its purpose if utilized correctly.
- Need for monitoring devices on things which cannot be seen (pre-stressed concrete, segmental, pretension cables).

4.2 Decision Making Process Issues

The general discussion on decision making brought up the following questions:

- What value is added by a structural health monitoring system, if owners still have to pay inspectors to go out and inspect in addition to sitting behind a computer system and evaluating data?
- Why should owners instrument for preventative maintenance of a bridge?

- What stress is currently being seen on a global scale? This is a concern and can it be addressed?

- Alkali-silica reaction in concrete is still a problem. Need embedded sensors to detect if there are problems before they surface. Do they exist?

The following summarizes the general views presented in discussions with respect to the decision making process:

- A monitoring system should provide quantitative data to support bridge operation ratings.

- The decision process should utilize monitoring sensors to verify theoretical calculations. Current theoretical methods do not match the "real world" findings of sensors i.e., the measurements had shown that the structure was significantly stronger than theoretical methods predicted. These may be attributed in some cases to theoretical analysis not evaluating some structural components such as railings and walkways.

4.3 Damage Identification Issues

Some of the direct quotes by the attendees about damage identification issues are presented below.

- Most of the states have identified fracture critical locations and have know-how of identified problems. Only a small fraction of bridges need attention.

- Researchers do things that will never be used.

- Technology transfer from aero-industry might not be directly useful for bridgework.

4.3.1 General Observations

The following general observations were made by the moderators during the discussions:

- Two types of damage sources:

  - Slow continuous
  - Impact

- Methods of damage identification:

  - Visual
  - Sounding
  - NDT

- General purposes of bridge inspection:

  - Deterioration
  - Structural integrity

- Bridge inspection interval:

  - Bridge inspections are mandated to be conducted at least once in two years. Is it required to conduct every two years? Can we increase the interval?

4.3.2 Specific Questions and Concerns about Damage and Damage Identification

Various discussions on damage identification issues are grouped and summarized below.

- **Damage identification in research**

  - Theories on damage detection: too much theory, little practical use.
  - Practitioners are skeptic about research.
  - Damage detection is usually associated with global modes and global damage. The global damage may be detectable using existing theories.
  - Corrosion: Different scale of damage. It is not an unsolvable problem.

- **What is the damage and what to do about it?**

  - Damage is something that disrupts traffic by the reducing load capacity.
  - Cracks: repaired immediately.
  - Weld cracks: program to replace.
  - Crack detection: visual inspection.
  - What to monitor for: fatigue life.

- **How do you prioritize monitoring?**

  - Daily traffic
  - Value of the structure
  - Age of structure
  - Operationally dysfunctional structure

- **How would you validate the new technology?**

  - Pick few bridges and prove
  - Will depend on design loads
  - Installation effectiveness
  - Maintenance
  - Problem being monitored

- **Would you use funds for automatic damage detection or manual damage detection?**

  - Manual detection preferred by owners.
  - Local damage detection is the way of the future.
  - Several data issues should be considered in selecting an appropriate method.
  - Owners may not have use for all the data.
  - Measured data may not give much information about local damage.
  - State-of-the-art is not suitable for damage detection.
  - Seeing real-time data may be good in limited sense, not for local damages.
  - Most valuable data is load testing.
  - From owners' point of view, damage detection means load testing.
  - Knowing about reserve capacity is good.

- **How do you link load rating to the condition of the bridge? What is the factor of safety?**

  - Factor of safety (FOS) may be subjective, and depends on redundancies.
  - FOS depends on the degree of uncertainty. Lesser FOS means more realistic knowledge of the bridge.
  - Trend of saving weight (sacrificing redundancies) should reverse.
  - Less redundant bridges are less costly.

- **Cost versus reserve capacity issues**

  - Unanticipated events
  - Account for our ability to not handle uncertainties.

- **Reliability of analytical techniques if results are counter-intuitive**

  - Fair amount of confidence in deflections, moments; less in strains and none in failure modes.
  - Monitoring is useful to calibrate analysis.
  - Monitoring doesn't realistically model material properties.

- **How do you model welding?**
  - Stresses in welds are near or beyond elastic limit.
  - How does welding affect the model?
  - Do we know enough about structures locally? One of the functions of measurements is to verify how well the model works.

- **General Modeling Issues:**

  Analyst should have a good understanding of the issues and expected outcomes. The following are some of the parameters, which should be studied thoroughly before damage identification issues can be considered.

  - Geometry
  - Physical behavior
  - Material
  - Connection properties
  - Know the goal:
    - Fatigue?
    - Bending?
    - Shear?
    - Welds?
    - Bolts?

4.4 Health of Machines versus Bridges

Health monitoring of bridges was compared to health monitoring of machines, where monitoring issues were well studied and are successfully adopted. The following comments were made in discussion of this issue.

- Major concepts in health monitoring of infrastructure are based on health monitoring of machines. Currently, the health monitoring field is research driven. Owners must find their needs and tools that can make their jobs easier.

- Stresses in machines are generated from rotations, fluid flows, etc., and could be duplicated to a great extent. Stresses in bridges result from corrosion, cracking, aging, etc. which cannot be duplicated.

- Gap between research and application.

- Solving incorrect problem.

- Lack of communication.

- Lack of trust.

4.5 Summary of Sessions by Individual Attendees

Specific notes made by individual participants are listed in this section.

- **Participant 1**

  - Problem of gap between research and application.
  - Health monitoring part has real problems.

- Can we salvage something out of it?
- Use health monitoring tools to help owners.
- Find problems from owners and feed them to researchers

- **Participant 2**

  - When do we say the problem is solved?
  - Reproducible results are very important.
  - How do we make decision about models and problems?
  - Most of the time, research is not a part of the structure.
  - Secondary effects need to be discussed.

- **Participant 3**

  - Better communication is needed between researchers and owners.
  - Need to relate damage identification to a bridge's ability to carry traffic.
  - Data we are collecting should really be suitable to detect damage.
  - Global assessment not suitable.

- **Participant 4**

  - Need proper tools for damage identification at local level.
  - Need for technology convergence: Currently, we apparently have technology divergence.
  - Communication between researchers and owners is needed.

- **Participant 5**

  - Analysis and damage ID should be correlated.
  - One has to know what he is doing.

5 Session 6

Four different groups were formed, by carefully mixing and matching the participants, to further discuss engineering structural health concepts. Again, each group consisted of members representing all four communities, and was asked to build upon the discussions they had in the previous sessions. A moderator and a note taker were designated by each group and this section presents their summary of the sessions.

5.1 Sample of Quotes from Attendees

Specific quotes made by individual participants are listed in this section.

- General experience is the key to successful monitoring project.

- In-house expertise is a key factor to successful project. An educated owner is important.

- We (owners) prefer passive instrumentation vs. active instrumentation: passive is read manually by inspectors, active is read automatically by ADAS (automatic data acquisition systems).

- Owner is the key for responsibility. Peer Review is important. Owner should set the project scope, etc., from the beginning and consider the end from the start. Engineering judgment should not be forgotten.

- Knowledge of fatigue history of a structure would be useful.

- Owners would prefer not to monitor, but there are some cases where they have no choice (if the structure is deteriorated and the retrofitting can not be done right away).

- High factor of safety (5-10) for bridges is good because of reduced maintenance. Some say that an ideal bridge is a bridge with a high factor of safety so that you do not have to monitor it.[1]

One of the owners, in the group discussing the instrumentation issues made the following insightful personal observation:

> "A brief discussion occurred regarding the data recorded during the visual inspections. I had asked if there was a national database of all the bridge structures and there is apparently not one. If there were a database where bridge inspection information was collected, it would seem it could be utilized

[1] The comment was quoted by an owner, and one other participant (owner) agrees with this comment.

> to enhance monitoring methods. Although every bridge is unique, bridges could potentially be categorized by structure type, and each type has yearly reports to update owners of common problems diagnosed on bridges throughout the nation. This could be utilized to focus instrumentation and monitoring dollars to reduce costs as well as providing concerns/information to both large and small-scale bridge owners."

5.2 Instrumentation/Measurement Issues

This section summarizes the discussion on instrumentation/measurement issues.

- We can measure anything; the technology is here. But we still need human eyes and will rely on them in the foreseeable future.
- We need to determine where the damage is locally.
- We need to flush out what we really want to measure; we need to solve the right problems.
- There is a gap between owners and researchers; owners may need to be convinced what the research will get them.
- We need a good, reliable method to measure corrosion and to detect problems early. Specifically in the area of pre-stressed concrete, and more specifically, post-tensioning. Current state-of-the-art allows this, but as far as we know, only if there is access to the ends of the strands.
- Fatigue is not a problem so long as the bridge was designed properly. But indeed, fatigue may be of some interest for diagnosing specific structures.
- The area and uncertainties of FRP (fiber reinforced polymers) are wide open for inspection needs in terms of monitoring these new materials.
- Need a non-invasive method of detecting voids in grout and corrosion in pre-stressed concrete.
- Methods of detecting scouring and movement: drop rods and "talking rocks" (heavily instrumented items placed around pilings).
- Most bridges that fail, do so due to flooding or scouring.
- Fiber reinforced polymers (FRP) have been having delaminating problems; these can be monitored in some cases by thermal imaging.
- Signs on bridges are another item, which should be instrumented. NY has had several sign structure failures due to truck windblasts and other elements.

- Fatigue testing generally not necessary on steel bridges, only diagnostic.

- Large bridges should be monitored to establish real world movements.

- Bridges should be designed with instrumentation needs in mind.

- In some cases, damage is not measured directly, but primarily inferred through stiffness and vibration changes. The point was also made that these measurements will not detect corrosion issues or small failures (eg: A few broken wires in a suspension cable).

- Currently, corrosion is measured as a loss in cross-sectional area. These losses prompt repair actions, but corrosion is not measured directly.

- Testing and inspection identifies damage (deficiencies) but some wear is expected – so after identification, analysis is required to determine acceptability.

- Owner desires reliable, accurate, and inexpensive information that has VALUE (which can be used to make a decision, not just data).

5.3 Structural Identification Issues

This section summarizes the discussion on structural identification issues, and is grouped into two categories: understanding structural identification, and additional concepts of structural monitoring.

- **Understanding Structural Identification**

  - Some people understood this as "Health Monitoring of Structures" or "trying to decide what the properties of members are."

  - There is more concern about fixing and maintaining the bridge, rather than structural identification.

  - System identification has found few applications in solving problems in bridges. Most load ratings are governed by local problems.

  - One approach for structural identification may be to instrument a bridge and study its behavior to develop a better model of the bridge, including local effects.

  - The traditional structural identification may be good for hazards where global behavior may be more important.

- **Additional Concepts of Structural Monitoring**

  - Monitoring can be used to develop better bridge evaluation models.

  - Critical problems can be monitored continuously.

  - Need greater continuous diagnostic capability instead of continuous monitoring. An example of this is the use of acoustics to hear sound from suspenders. Greater sound at the beginning of load is due to the movement of rust. We need instruments that tell us that these suspenders are working well.

  - Instrument for the worst case diagnostic. For example, by finding worst case of corrosion in cables, a decision can be easily made about the condition of other cables.

  - Monitor geometric changes and find faults by computer simulation.

5.4 Session Summary (Round Table)

- Calibrated analysis is very important. It can be used for many purposes not just for engineering health.

- Coordination is important.

- Cost-benefit or pay-off potential and experience are the key factors.

- Coordinated partnership is critical.

- Hydrogen embitterment causing corrosion: the mechanism is not well known.

- "What do we want to measure?" should be the "1st base" of Alampalli--Ettouney baseball analogy (see Appendix D).

- The technology is there in general (strain gages, acoustic, NDE, Ground Penetrating Radar, etc.), but first we have to decide what we want to measure.

- New types of sensors such as fibre-optic sensors are becoming popular replacements for electrical strain gages and LVDTs.

- Corrosion monitoring: there is a technology gap.

- Post-tensioning: there are very few post-tensioned bridges in the U.S., but there will be more (only 2 in NY State). In Europe, they have a problem with the corrosion of post-tensioned members.

- Accelerometer: Used for modal analysis. But the information derived is limited. For example, they can not do damage identification.

- Ambient Vibration Monitoring (with 50 accelerometers on a large bridge) → leads to several modes.

- Controlled load tests are valuable and should be encouraged.

- First study and identify what we want to measure, then decide on the monitoring program.

- FHWA draft of recommendations on bridge instrumentation will be available soon.

- How can we monitor alkali-silica reactions? Are there sensors? What remedial actions (painting the concrete) are available if the alkali-silica reaction is active?

- There is an ASCE Task Committee on Structural Health Monitoring (for buildings in general, but also bridges).

- We can weld a "Fatigue Fuse" on a steel member, but corrosion can not be assessed at the same time.

- FHWA or AASHTO should issue guidelines on how to monitor bridges.

- NY State inspects all bridges once every two years (35-40 million $ / per year inspection cost for 17,500 bridges).

- X-Ray diffraction: good to know the residual stresses in steel (It is the only method according to some). However, results are somewhat difficult to interpret).

- In a particular suspension bridge, 2 strands out of 37 are broken. How can we measure stresses in the remaining 35? X-Ray diffraction has been suggested, but has been rejected by the consultant.

- Clinometers (electro-level type or servo-accelerometer type) are very useful instruments to assess the progression of leaning towers or piers.

6 Session 7

The four groups from the previous session were combined to form two groups. Care was taken to make sure all four communities were represented in both groups. The participants were asked to build upon the discussions they had in the previous sessions. This section summarizes the discussions of the first group.

6.1 Quotes from Participants

Specific quotes made by individual participants are listed in this section.

- Ten years from now, we will be making decisions based on quantitative information.

- The objective of the agency governs the decision making process. QA development and using correlations of different tests/methods is important; and should be used in the decision-making process.

6.2 Decision Making Process: Limitations and Characteristics

The current decision making process and the link between structural monitoring and the decision making process were discussed. The following summarizes this discussion.

- Current decision making process has fundamental deficiencies

  - It does not address causative conditions.
  - It is not quantitative. Becomes quantitative only when costs become higher, mostly qualitative.
  - Should audit causative work.

- Issues governing the alternatives to the current decision-making process:

  - Functions govern the micro issues.
  - Organizational aspects.
  - Rural vs. urban locations.

- Monitoring and decision making process

  - Monitoring will help to make critical decisions, but will not change the decision making process.
  - Use monitoring when unexpected events happen. These data can be used to take care of structures with similar features.
  - Social issues prevail and socio-technical issues are important.

- Monitoring can help answer these all-important questions: 1. which repair methods are useful, 2. what are their life spans? and 3. what are the financial and social costs?
- More integration between decision making and monitoring is required.

- Methodology can / must be standardized.
- Regulatory agency's responsibility is to standardize the methodology.

6.3 Structural Identification Issues

The group felt that before getting started, the subject needs to be defined. Structural Identification was defined as "Global Behavioral Modeling." For example, modeling an entire bridge (instrumented to the hilt if necessary) to determine if the structure is behaving as it should.

The group, at first, discussed structural identification in general followed by the current structural identification practices and needs.

- **General Comments**

  - State-of-the-art to do this modeling is really not there yet – at least on most bridges – with a good enough sense of reliability.

  - We are not going to replace bridge inspectors and hands-on bridge inspection, even in the long term future.

  - While the modeling would be difficult, some modeling should be done on a specific bridge, or groups of bridges, for learning purposes. The data would be good for figuring out how to better analyze structures, developing better models, and recalibrating or developing elaborate models.

  - There is a need to develop better tools to evaluate bridges using diagnostic testing methods.

  - Research is very advanced, but not sufficiently focused at solving the right problem in many instances.

  - Regarding the importance of Structural Identification for:
    - Fatigue life: not needed (bridge biennial inspections are sufficient for this).
    - Load Rating: yes, for specific bridges, but with caution, as this may not be as precise as one would think.
    - Hazards: yes, but only for earthquakes, wind loads, and floods.

- **Current Practice and Needs**

  - Current mathematical models are used more for design than for diagnostics

- All currently feel that, experienced human inspectors will not be replaced, but they could be enhanced if the right tools are used to let them "see" the unseen problems.

- Need specific diagnostic method to see into bridge decks, large cable bundles (over 36"), and pre-stressed concrete beams.

- Owners' trust of global monitoring/modeling is currently thin.

- Overall monitoring system is not practical with current technology and methods.

6.4 Summary (Roundtable)

The participants in the groups summarized their opinions and they are given below.

- The owner controls the decision-making process. Asset management should be explored and should feed quantitative information to decision makers.

- Health monitoring does not change the decision-making process, but will help make better decisions.

- Reliability and confidence (of all parties) of the system is important.

- Attention should be paid to integration of all aspects of structural health.

- Health monitoring is useful for future decisions; and may be useful in other areas as well.

- Regulatory agency is responsible for standardization.

- Regulating agencies should come up with recommendations to all four[2] groups that compose the structural health community.

- Regulatory agencies are responsible for filling the gap between research and practice.

- End goal: Expertise should be well documented and should go into a "cookbook". We are not there yet, bur we should work towards that goal.

- Certification programs, for all four groups that compose the structural health community, are important.

[2] Owners, researchers/academicians, practitioners and manufacturers

7 Session 8

The four groups from previous session were combined to form two groups. Care was given to make sure all four communities were represented. Participants were asked to build upon the discussions they had in the previous sessions.

7.1 Sensors: Types and Availability

All the comments during the discussions on sensors and associated technologies are given in this section.

- Some of the available sensors/methods: Strain gage, LVDT, vibration monitoring (natural frequency and modes, stiffness of structure), acoustic monitoring, radiography (large and generally impractical), magnetic flux leakage.

- Sensor technology not available for the following:

  - Acoustic emission for crack growth.
  - Corrosion process (oxide on cables tend to detach and emit, however it is not yet fully available).
  - Evolution of hydrogen: emits a weak signal, also not yet available (even less available than oxide). The present systems are still prototypes and they concentrate on oxide, crack and flaw detection in cables.

- Vibration monitoring is useful, but in practice the small ruptures of wire, steel member, etc. do not have a large effect on the stiffness of the structure. Therefore, the vibration monitoring does not really help to identify defects or damages.

- Distributed sensing: According to one manufacturer, it is possible to put an optical fiber in a bundle of 30 wires each 5.2 mm in diameter and to make a distributed measurement of strain and temperature along the full length of the optical fiber. This technique is not yet commercial but there are some field trials on-going. The difficulty is inserting the optical fiber in the wire bundle. Also, it is not currently possible to differentiate between strain due to temperature dilation and mechanical strain. The cables are prefabricated in factory or sometimes pulled in place.

- The deterioration rate of stay cables and suspension cables would be useful to measure.

- Wireless sensors: Are wireless sensors the key to the future? Many people agree that they are. There will be much more wireless monitoring once prices become lower.

- One company is trying to put together an acoustic emission based product that can detect corrosion, if the corrosion process is active.

- Corrosion detection in reinforced concrete: electro-chemical based systems are the only ones currently available (electrode and measuring currents).

- One of the participants from the consultant group noted that the difference between diagnostic tools (to establish baselines) and instrumentation should be made; and more focus is needed on reinforced concrete.

- Acoustic emission: detect crack growth and possibly corrosion; detect/monitor hydrogen activity although the signal is difficult to discriminate between natural and unnatural noises.

- Magnetic flux leakage: crack and flaw detection.

- Vibration monitoring: indicate deterioration of structure, crack formation or weld cracking.

- X-Ray diffraction: partially successful for cable stress analysis.

7.2 Sensors: Issues

- Noise in measurements: Software integrated with data acquisition to throw out sensor noise.

- "Smart" sensors

  - Sensors can be programmed to do the processing: Difficult from researcher's point of view. The burden should be placed on sensor people.
  - Extremely important to know what problem we are trying to solve.
  - These devices are rather easy to use.
  - Sophisticated systems can be used in adverse environment.

- Wireless Technology issues: Interference and noise may be an issue. At the same time, they may have less noise than conventional sensors.

- Sensor Life

  - Sensors that can outlast the bridge life may be needed.
  - Sensor industry suffers if sensors don't last long since owners will not instrument.
  - Manufacturers can provide guarantee at additional costs.

7.3 Decision Making Needs

- Primary concern of owners is how long until repair/replacement is needed.

- Decision Making: who decides what and where to measure? Needs to be close interaction between owners' technical point of contact and the manufacturer to identify problems and determine best method to meet needs.

- Owner-Practicing Engineer - Researcher partnership will give true benefit of a bridge monitoring system.

- Use existing system data to determine what is wrong. If this method fails, use higher level assessment or monitor more frequently.

- Life cycle costs associated with structural health monitoring are needed.

7.4 General Technical Observations

- Coordination/interaction among all applicable parties is needed for real successes.

- You don't know what you don't know. Owners may be working on their own in determining what to do. More communication is needed to ensure the best results and understanding.

- Owners are reactive to situations.

- There is a lot of available technology (you can measure anything you want!).

- We don't really know the best method to handle all of the data that's collected. Models may not represent local effects (need to solve the right problem(s)).

- There's an apparent disconnect between the research and manufacturing communities and what the owners need.

- It is vital to connect all parties to ensure the best results.

- Minimize the need for monitoring; keep things simple [KTS].

- Sensors could play a key role in determining preventive maintenance.

- We need better/smarter tools for inspectors (eg. thickness meters; see inaccessible areas). Is there an indirect measurement method that will lead us to the right ultimate answer (for example, in determining stiffness and strain)?

- We need a good movement from qualitative to quantitative. For example, is it more informative for us to know "What's the stress/strain in a beam?" as compared to "Is the bridge safe?"

- Monitoring would be good for verifying design specifications.

- Are we gathering too much data that is simply/only good to know, but does not give us important information that we really need to know or want to know?

- The most important objective is diagnostic monitoring. Global modeling is insufficient in determining local effects, which is the real need.

- We need a good and reliable corrosion sensor.

- We don't want to compromise the factor of safety.

- Regarding "Load Rating," the present culture is such that the owner really doesn't want to tweak the numbers for all bridges, just certain case-by-case bridges. Funding reductions would most probably result because of the link between load ratings, structural condition of bridges, and funding apportionment.

- The time dimension is important. That is, while a bridge may be safe today, how about next year, or in the long term?

- Instrumentation is probably, or would be, cutting into the Factor of Safety. However, if we have better information, we can be more confident as to what the FOS really is. However, a reasonable acceptable-type reduction in the FOS would not result in any appreciable savings in dollars – realistically speaking.

- If a bridge can safely carry the loads we would like it to, we are comfortable. Otherwise, we have a problem.

- A beta factor of 3.5 is an <u>average</u>.

- Should we replace bridges when their Factor of Safety is reduced to an unacceptable number? Bridges, however, will fail locally first.

- Instrumentation has its place, as compared to a visual inspection.

- Local instrumentation, as a tool, can augment the visual inspection.

- We need smart instrumentation for critical elements and areas.

- There is something to be gained through global monitoring, if only to help identify areas of the bridge that need a closer look.

7.5 Sample of Specific Opinions/Quotes of Participants

- If irrefutable evidence exists that the structure is doing fine, it is OK. If not, the whole perspective changes and consultants want to be conservative. Prudence is important in this case. Liability is also important as consultant has more of this.

- There is a difference between consultant designs and owner designs.

- Owners should make final decisions.

- Peer review is needed for certain projects.

- Situations when peer reviews result in conflicting opinions must be addressed. What will be done in the case of conflicting reviews?

- Collaboration is important: One group alone cannot do the job.

7.6 General Needs

- Meet again in one year.

- There should be another meeting organized in western US next year.

- There is a need for a book on Guidelines on Health Monitoring (ASCE, FHWA, etc.).

- It is suggested that a list of reference books or papers on bridge health monitoring be prepared and sent to all attendees. As an example, there is a guide for instrumentation for bridge pier scour available from FHWA.

- "Smart" sensors were discussed. They are market driven as to what is available or manufactured.

- It is difficult to keep experienced, embedded programmers at a company for any length of time.

7.7 Partnership with University Professors and Owners

- Technology transfer

- Collaborative partnership for sensor development

- Combined partnership with university professors and owners

  - Professors' expertise in solving application problems.
  - University professors interact with manufacturers more frequently.
  - Combined discussions of professors and manufacturers about the needs of infrastructure owners.

- Government and SBIR proposals for sensor development

8 Closing Session

The workshop ended with a closing session, where all the participants were grouped together to summarize the workshop experience through closing/parting remarks. First, owners were asked to summarize their experience, since the workshop was meant to benefit the infrastructure maintained by the owners. Then, all the participants were asked to give their closing comments. This section summarizes this session.

8.1 Final General Remarks by Owners Group Representatives

- **Participant 1**
  - The cost-benefit ratio is the most important issue to the owner.
  - There is a need for National Guidelines for Bridge Testing and Health Monitoring.
  - Partnership between the owners, researchers, consultant, and FHWA is very valuable in advancing health monitoring for bridges.
  - There was mention that monitoring of critical bridge elements is more feasible than of the entire structure.
  - Intermittent recording of responses is preferable to continuous recording.
  - Generation of a finite element model which correlates well with the existing structure is very important. Also, the parameters used in the FE model must be adjusted at times to account for changes in physical properties and dimensions including deterioration.
  - Managing and interpreting the large amounts of data generated is another important task which must be done better.
- **Participant 2**
  - The current market for non-destructive techniques is extremely dynamic and it is not likely that a list of recommended methods will become available to bridge owners soon.
  - Owners, consultants and manufacturers must all work at identifying appropriate monitoring.
  - Low bidder selection is particularly inappropriate for this type of work.
  - Peer review is particularly appropriate.

- Safety factors have been lowered, not necessarily by LRFD. Design codes should not assume perfect maintenance. Owners should recall that codes are not intended for special structures.

- What is conservative? Is conservatism “across the board” always the correct (or even the safest) choice?

- The role of the expert system vs. the expert: the expert must be enhanced not replaced. The FHWA report suggests unreliable or incompetent inspectors. Most of them were not licensed. NYS inspections appear to be among the most detailed. Results are still subjective, but can be treated to reveal information.

- “Objective” measurements vs. subjective condition ratings: both are prone to three types of inaccuracies - vagueness, ignorance and randomness.

- **Participant 3**

  - Open mind.

  - Coordination & integration with existing ideas.

  - Peer review is valuable.

  - Health monitoring is another tool available to owners – use it only when needed.

  - Think and justify in terms of cost-benefit.

8.2 Individual Remarks From All Participants

The participants made these remarks on the last session of the conference. They are presented in the chronological order they were made and some may be redundant, but are presented in this way to describe what points received more emphasis.

- Educational Experience – new definition learned for structural identification. More should be studied about structural models.

- Repeat the experience in one year.

- Obtain inspiration from ASCE Task Committee for Instrumentation for Dams.

- Include list of references about health monitoring for bridges.

- Networking with professionals of the field to make proper decisions with more knowledge of existing technologies: “know whom to call.”

- Good to know what owners need and their constraints – Work together.

- Evolve from qualitative decisions to quantitative decisions.

- Good to know the technology available for bridge monitoring (sensors).

- Work needed on regulatory issues – a community effort.

- Lack of detachment – good to see all groups together.

- Standards for monitoring and sensor technology will help the decision making process.

- Collaboration of all groups benefits the whole community.

- Monitoring has to fit to actual needs – develop proper tools to enhance visual inspection.

- Website for exchange of information.

- We were not aware of all the existing methods, sensors and monitoring techniques.

- The owners' skepticism has to be answered by proving that methods work.

- Challenging problems ahead – good to know what owners expect.

- Lots of tools are available but there is a great need for analysis of results.

- Some prejudices were dispelled – some solutions show promise.

- Skepticism about Health Monitoring – How could owners relate to it? Good ideas to work on in the future and for use at work.

- Are these techniques cost effective?

- The challenge ahead: to use these tools to make our job of maintenance easier.

- New feeling of cooperation with infrastructure owners – discussion is on the table and it may lead to the end of many miscommunications.

- Lots of tools in development, but also some exist that may be used readily.

- Need specific tools to increase the solutions – work together to advance the technology of structures.

- Preconceived notions were dispelled.

- Sensors are geared towards local damage.

- Consensus that tendency towards lighter structures should stop.

- Little is still known about Health Monitoring Systems.

- Bridge Management Systems: involvement of human inspectors versus sensor measurements.

- Coordination, open-mindedness and peer-review for research projects are important.

- Sensing technology can be an extra tool, although more cost-benefit analyses have to be done.

- Organize this same workshop in another regional location (West Coast?).

- Develop codes that practicing engineers can apply (at federal level), although they should be implemented locally at first.

- Qualitative vs. quantitative information (why not both?).

- Experience shows that condition of bridges does change between biannual inspections – Health Monitoring System may tell us what changed and where repairs are needed.

- Careful implementation of software for bridge maintenance – danger of blindly believing the computer results.

- Do not replace maintenance systems but enhance the existing ones.

- Structural Health Monitoring is beneficial to maintenance if we know what to monitor.

9 Summary and Recommendations

The *Engineering Structural Health* workshop brought representatives from infrastructure owners and government officials, practicing engineers, academia, and sensor/equipment manufacturers together to discuss the current state of structural health engineering. The goals of the workshop were to increase communication between the groups involved in this field as well as review necessary aspects of successful bridge infrastructure condition assessment.

The workshop showed the value and importance of direct communication between various structural health communities. The major outcome of the workshop was increased understanding of the owners' needs to improve condition assessment (health) of bridges. It also increased the awareness of problems that need addressing to advance the structural health engineering field.

The main observations and recommendations, both general and specific, are summarized in this section.

9.1 General Observations and Recommendations

1. General consensus of the infrastructure owners is that the field of engineering structural health is still in its infancy. Currently, short-term monitoring predominates the long-term monitoring in importance. It is recommended to dedicate some resources, if possible, to long term monitoring projects addressing issues that may become problems for bridge owners in the future.

2. Cost-benefit ratio is the most important issue to bridge owners. When planning a structural health project, all principal participants should pay special attention to the cost-benefit issue. Tools and methodologies that can help in accurately predicting the cost-benefit of structural health projects are needed.

3. Monitoring critical bridge elements is currently more feasible than maintaining the entire structure, therefore more research and development should concentrate on critical bridge elements. At the same time, the effect of changes at the element level on global behavior of the structure should be considered.

4. National guidelines for bridge testing, structural health monitoring and decision-making methods are needed.

5. Peer Review is a valuable tool and should be used often in all stages of a structural health project.

6. Low bid selection is not appropriate for this type of work. The successful bid should be chosen based on the quality of the proposal and not on cost alone.

7. Certification(s) for those who work in this field (e.g., inspectors, those who place and read sensors, etc.) might be needed.

9.2 Specific Observations and Recommendations

1. The owners need to be as specific as possible in identifying the problem and the desired results of the project. The entire community feels that the failure/success of the project is the sole responsibility of the owners.

2. There are several instrumentation systems and data collection methods commercially available but there is a great need for accurate data analysis. In most situations, the current systems on the market do not meet the owners' expectations.

3. Encourage communication between different parties associated with the project. The owners should insist on some kind of communication between sensor makers and consultants.

4. Check existing literature (and websites) for exchange of information.

5. Continuous recordings should be utilized only when its cost-benefit is assured. In general, intermittent recording of responses is preferable to continuous recording.

6. Reliance on analysis of existing structures can be a major cost-saver. However, validation of analytical models should be performed and reviewed carefully.

7. Monitoring has to fit the actual needs. One has to ensure that the final results of the project will resolve the current problem, or mitigate future ones.

8. Rely on both qualitative and quantitative information. Ensure that both types of information lead to consistent conclusions. Explain any inconsistency in results before making decisions. There is a need to evolve from qualitative decisions to quantitative decisions.

9. If the project is going to generate large amounts of data (such as in a continuous recording situation), it is imperative to a) justify the need for such a large amount of data, and b) establish a plan for storage, reduction, and maintenance of the data.

10. Health monitoring systems might be beneficial in investigating conditions between biennial inspections of bridges. In the case of visual inspection, ensure that the inspector has proper tools. Careful implementation of the bridge maintenance software is required to ensure that the solutions presented are reasonable.

11. The current trend towards lighter structures is not always beneficial. In the current multihazards environments, light weight might not be cost effective in the long run.

Appendix A – List of Attendees

List of Attendees

1. Anil K. Agrawal, Ph. D., P.E.
   Department of Civil Engineering
   The City College of New York
   New York, NY 10031

2. Emin Aktan, Ph. D. P.E.
   Director
   Drexel Intelligent Infrastructure and Transportation Safety Institute
   Drexel University
   3201 Arch Street, Suite 240
   Philadelphia, PA 19104

3. Sreenivas Alampalli, Ph. D., P.E., M.B.A.
   Acting Director
   New York State Department of Transportation
   1220 Washington Avenue
   Albany, NY 12232-0869

4. Raimondo Betti, Ph. D., P.E.
   Professor
   Department of Civil Engineering and Engineering Mechanics
   Columbia University
   New York City, NY 10027

5. Maciej Bieniek, Ph. D., P.E.
   Consultant
   121 Cross Street
   Demarest, NJ 07627

6. Daniel Byer, P.E.
   New York Division Bridge Engineer
   Federal Highway Administration
   Leo W. O'Brien Federal Building, Room 719
   Clinton Ave. and North Pearl Street
   Albany, NY 12207

7. Sante Camo, P.E.
   Senior Associate
   Weidlinger Associate, Inc.
   375 Hudson Street
   New York, NY 10014

8. Pierre Choquet, Ph.D., P.E.
First Vice-President
Roctest Limited
Geotechnical and Structural Instrumentation
665 Pine Avenue
Saint-Lambert, Quebec J4P 2P4
Canada

9. Michael J. Docherty,
Manager, Engineering Systems
NACE Corrosion Technologist
National Defense Center for Environmental Excellence (NDCEE)
100 CTC Drive
Johnstown, PA 17904

10. Joseph Englot, P.E.
Chief Structural Engineer
Port Authority of NY & NJ
2 Gateway Center, 16th Floor
Newark, N.J. 07102

11. Mohammed Ettouney, Ph. D., P.E.
Principal
Weidlinger Associate, Inc.
375 Hudson Street
New York, NY 10014

12. Guillermo Franco
Student
Department of Civil Engineering and Engineering Mechanics
Columbia University
New York City, NY 10027

13. Hamid Ghasemi, Ph. D. P.E.
Research Structural Engineer
Federal Highway Administration
Office of Infrastructures R&D
6300 George Town Pike
McLean, Virginia 22101

14. Wanlong He, Ph.D.
Student
Department of Civil Engineering
The City College of New York
New York, NY 10031

15. Dryver R. Houston, Ph. D., P.E.
    Professor
    Department of Mechanical Engineering
    University of Vermont
    Burlington, VT 05405

16. John Huston
    Concurrent Technologies Corporation
    Staff Engineer
    100 CTC Drive
    Johnstown, PA 17904

17. Khaled Mahmoud, Ph.D., P.E.
    Director of Long Span Bridges
    Hardesty & Hanover, LLP
    1501 Broadway
    New York, NY 10036

18. Ken Maser, Ph. D., P.E.
    President
    Infrasense, Inc.
    14 Kensington Rd
    Arlington, MA 02174-8016

19. Dennis Mertz, Ph.D., P.E.
    Professor
    Structural Engineering Department
    360-D Dupont Hall
    University of Delaware
    Newark, DE 19716

20. Ron Miller, Ph.D.
    Executive Director
    Physical Acoustics Corporation
    195 Clarksville Road
    Princeton Junction, NJ 08550

21. Thomas J. Moon, P.E.
    Director
    Bridge Program and Evaluation Services Bureau
    NYS-DOT
    Bldg. 5, MC 0600
    1220 Washington Avenue
    Albany, NY 12232-0600

22. Hani H. Nassif, Ph. D., P.E.
    Professor
    Department of Civil and Environmental Engineering
    Rutgers University
    98 Brett Road
    Piscataway, NJ 08854

23. Alex Rong, Ph. D., P.E.
    Senior Engineer
    Delaware River Port Authority (DRPA)
    2 Riverside Drive, One Port Center
    Camden, NJ 08101

24. Peter R. Stapf, P.E.
    Director of Structures
    New York State Thruway Authority
    200 Southern Blvd
    Albany, NY 12209

25. Matt Wheatley
    Regional Manager - North America
    Pure Technologies US Inc
    10015 Old Columbia Road, Suite B-215
    Columbia, MD 21046

26. Bojidar Yanev, Ph. D. P.E.
    Director
    New York City Department of Transportation
    Bridge Inspection / Research and Development
    2 Rector Street
    New York, NY 10006

Appendix B – Workshop Agenda

Detailed Agenda

Day	Time	Location	Program	Session
May 16, 2002	1:00 -1 :55	Main room	Opening Remarks: Dr. Ettouney Welcoming Remarks: Dr. Alampalli, NYSDOT Welcoming Notes: Dr. Daddazio, Weidlinger Self-Introductions: All participants Keynote Presentation: Dr. Alampalli, NYSDOT Overview of Workshop: Dr. Ettouney, Weidlinger	Opening Session 1
	2:00-2:45	Conference Rooms	Meetings of Four Uniform Groups	2a, 2b, 2c, 2d
	2:45-3:15	Conference Rooms	Meetings of Four Mixed Groups: A, B, C, D	3a, 3b, 3c, 3d
	3:15-3:30	Main Room	Coffee Break	
	3:30-4:00	Main Room	Presentation: Dr. Aktan	4
	4:00-5:30	Conference Rooms	Meetings of Four Mixed Groups: A, B, C, D	5a, 5b, 5c, 5d
May 17, 2002	8:00-8:30	Main Room	Breakfast	
	8:30-10:15	Conference Rooms	Meetings of Four Mixed Groups: A1, B1, C1, D1	6a, 6b, 6c, 6d
	10:15-10:30	Main Room	Coffee Break	
	10:30-12:00	Conference Rooms	Meetings of Four Mixed Groups: A1, B1, C1, D1	7a, 7b, 7c, 7d
	12:00-1:00	Main Room	Lunch	
	1:00-2:15	Conference Rooms	Meetings of Two Mixed Groups: E and F	8a, 8b
	2:15-3:15	Conference Rooms	Meetings of Two Mixed Groups: E1 and F1	9a, 9b
	3:15-3:30	Main Room	Coffee Break	
	3:30-4:00	Main Room	Summary and Resolutions of Breakaway Sessions	10
	4:00-5:00	Main Room	Round Table Discussion	
	5:00	Main Room	Closing Remarks: Dr. Alampalli, NYSDOT Closing Remarks: Dr. Ettouney, Weidlinger Adjourn. Wine, cheese, and Refreshments	

Appendix C – Keynote Presentation: Dr. Sreenivas Alampalli

Engineering Structural Health

Dr. Sreenivas Alampalli
Acting Director, R&D Bureau
New York State DOT
Albany, NY 12232-0869

Dr. Mohammed M. Ettouney
Principal
Weidlinger Associates
New York, NY 10014-0356

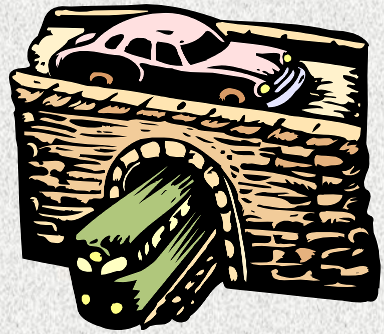
Engineering Structural Health Meeting
New York, NY
May 16, 2002

Main Points

- **Four phases of "Engineering of Structural Health"**
  - Measurements
  - Structural Modeling / Identification
  - Damage Detection
  - Decision-Making Process
- **Integral approach to all aspects of the field is absolutely necessary**
- **Decision making process is extremely important**
  - Without clear and predetermined decision making procedures, the entire process is incomplete and should not start.

The Problem

- For a given operating structural environment:
  - Start with what decision is required?
  - Can the damage/deterioration be detected when needed?
  - When detected, can the type, magnitude and extent of deterioration be estimated?
  - After detection, what is the decision-making process for the response?



Baseball Analogy

Damage/Deterioration Detection:
- Location
- Type
- Extent

Second Base

Structural Identification:
- Mathematical modeling
  - Fine tuning based on measurements
- Modal testing?
- How accurate are FE models?

Third Base

Aspects of Engineering Structural Health

First Base

Decision Making:
- What to do?
- Rehabilitation techniques
- Cost analysis

Home Plate

Measurements:
- Number and type of sensors
- Location of sensors

Measurements, Structural ID and damage/deterioration detection are collectively known as the "Structural Health Monitoring" problem

Decision Making Process (Bringing it Home)

- **The final aspect of Engineering of Structural Health Field is Decision Making**
  - Least studied
  - Probably most important
- **For a given well identified deteriorated/damaged structure, define the course of action**
  - Demolish the structure?
  - Complete retrofit?
  - Partial retrofit?
  - Do nothing?
- **Costs**
  - Environmental
  - Social
  - Economical
  - Other

Issues

- **Four different groups involved**
  - Infrastructure owners
  - Practicing Engineers
  - Research community
  - Manufacturers
- **Problems**
  - Enormous money spent on instrumentation, analysis, and testing
  - No decision making, i.e. not using the results
- **Coordination between four groups is very important for returning home**
  - State-of-the-art
  - Not understanding the final issue

Workshop Purpose

- All the above issues led to this meeting
- Understand other groups and their concerns
- Improve coordination
- Develop a strategy/advice on what to do?

Some points to remember

- All of you know some people in other groups
- Focus on general issue not on specific project
- Relate to your experience and views
- Open communication (Specific people or organization names will not be stated in the summary report)
- Focus on all concerns – yours as well as other groups

Conclusion

Any questions?

Appendix D – Engineering of Structural Health Paper #1

Ettouney, M.M. and Alampalli, S. "Engineering Structural Health," ASCE Structures Congress and Exposition 2000, Philadelphia, PA, May 2000 (printed with permission from American Society of Civil Engineers).

Engineering Structural Health

Mohammed M. Ettouney, Ph.D., P.E.
Principal, Weidlinger Associates, Inc.
375 Hudson Street
New York, NY 10014-3656

Sreenivas Alampalli, Ph.D., P.E.
Head, Structures Research
New York State DOT
Albany, NY 12232-0869

Abstract

Monitoring structures such as bridges, dams, and buildings has received significant attention in the last decade. Several owners and researchers are actively pursuing development of monitoring systems, with reliable sensor technologies and remote monitoring systems for decision making. Most of the system identification process thus far is concentrated in three phases, namely data acquisition, structural identification, and damage detection, and lacks decision-making phase. This paper presents a comprehensive view on the engineering of structural health process integrating the decision making process.

Introduction

Both existing and new civil engineering structures and constructed facilities throughout the world are subjected to continuous deterioration due to several reasons such as corrosion resulting from exposure to different environmental conditions. Day-to-day service loads can initiate fatigue problems over time. Moreover, infrequent actions such as earthquake, fire and improper use or maintenance result in acceleration of the structure deterioration. This deterioration causes significant degradation of a structure's mechanical properties and its ability to perform intended functions without failure. Due to the immense importance and cost of infrastructures, the subject of structural health and performance during the life span of the structure has emerged lately as a major issue for the engineering community.

Health monitoring of structures is perhaps the most serious attempt to address this problem. In a general sense, it involves three distinct phases: the measurement of performance phase, the structural identification phase, and the damage detection phase. Considerable research and several methods in the literature address each of these three phases and detailed coverage of each of these topics is beyond the scope of this paper and is not the intent of this paper.

Unfortunately, health monitoring of structures in the present form lacks a major component, namely the decision making phase. Assume that a certain damage profile has been detected during a health-monitoring project for a specific structure. With the damage profile information, the decision-maker is faced with the question of what to do next. Thus, important factors and necessary tools that could help that decision-maker should be readily available so that the proper decision can be made.

In this paper, we propose adding the decision-making process to the three health monitoring phases to form an integrated Engineering of Structural Health (ESH) field.

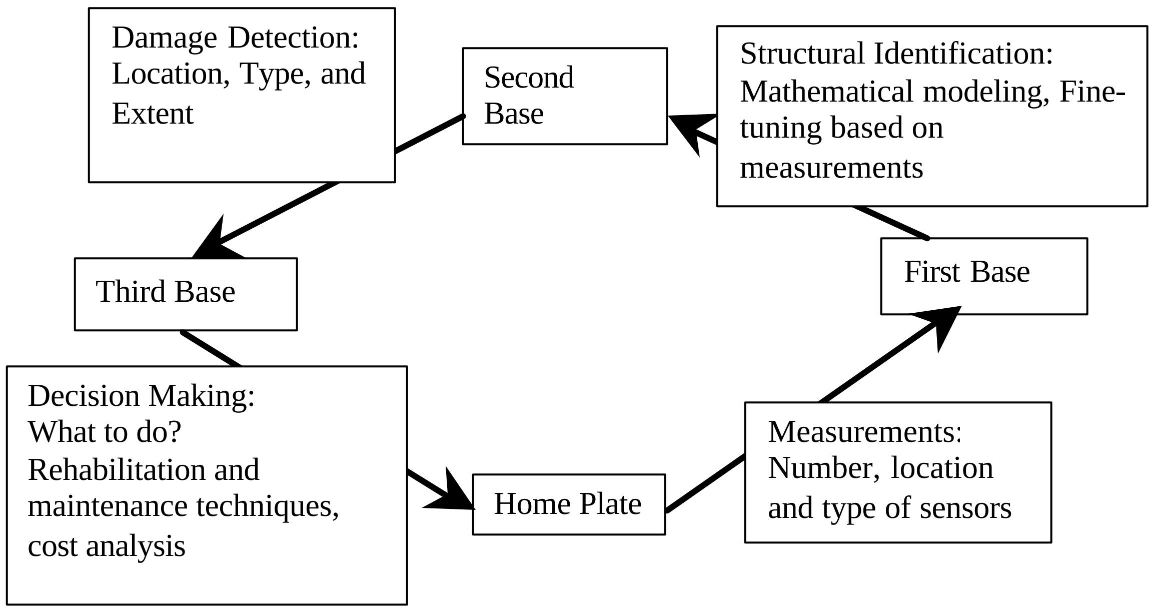


Figure 1 – Schematic of Engineering of Structural Health (ESH) process

This field will then be composed of four phases: measurements, identification, damage detection, and decision-making. Figure 1 shows a schematic representation of this process. Moreover, an integrated approach is proposed to the ESH phases, meaning that all four phases of the ESH process should be considered simultaneously. We will show that failing to do so may yield inefficient or even erroneous results in many situations.

Measurement Phase

General

The first phase in ESH is the measurement phase and forms the basis for the entire ESH process. Measuring structural behavior for ESH will have two main goals. First, it is desirable to numerically identify the structural system, and estimate the state of structural damage, if any. Often this requires structural measurements. The most obvious is selecting structural parameters, which represent important structural response measures of interest. Measuring structural displacements, velocities or accelerations often may be a good choice in many cases. Other conditions might necessitate measuring structural deformation, e.g., strains. Indirect measurements might be employed. An example of this is measuring the acoustics of cable snapping in suspension bridges, and then finding the location of the breaks in the cables by tracing the time of arrival of acoustic waves. In all situations, complete knowledge of the structural system is mandatory to collect successful and efficient measurements. This include all the structural functions, intended use, design loading, required service life span, and economics of maintenance.

All of the above factors will affect the measurement phase in ESH. In any experiment, number of sensors, n_c, is directly related to the economics of maintaining the structure as well as the structural function and the intended use. In addition, number of sensors and their locations are directly related to the type of structure, loading levels, and environment conditions. Any structural measurement scheme not accounting for these interrelationships can lead to inefficient/insufficient data, or possibly measurement information that is not suited for the intended ESH use. A brief discussion of these interrelationships is presented in next sections.

Number of sensors and cost

In any ESH measurements, the minimum number of sensors, n_o, that is needed to insure the required quality of measurement information, q_o are related by the *number* curve as shown in figure 2. In addition, the cost of obtaining q_o is C_o. They are related by the *cost* curve in the same figure. Thus, for a required information quality, q_o, both cost and number of sensors are uniquely correlated. If the actual number of sensors in an experiment, n_c, falls below n_o then the measurement information can be rendered insufficient. In addition, an upper bound sensor cost ceiling, $C_c = C_o$, also exists. It is determined by economic factors that relate to the structure's intended use and importance. Both C_o and n_o requirements need to be consistent for optimum ESH process. If this proves to be infeasible, either the cost ceiling need to be raised, or the technical scope of the measurements has to be reduced. Figure 2 illustrates this process.

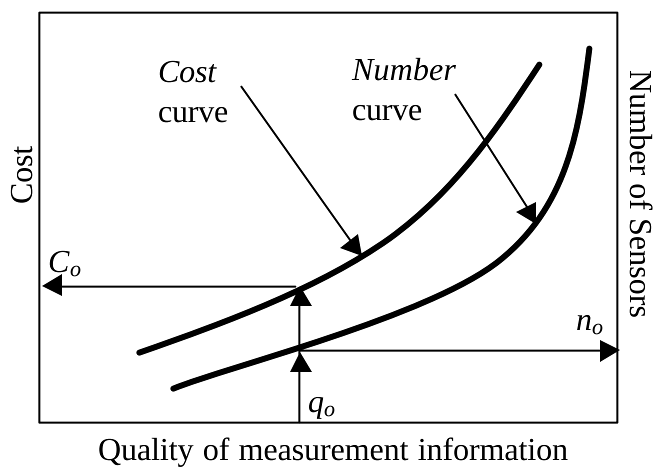


Figure 2 - Cost, Number of sensors and quality of information relationships

Sensor locations and number

Another important step in the ESH measurements is the Optimum Sensor Location Problem (OSLP). See Cobb (1996) for comprehensive review of this important issue. It can be stated as follows: For any given structural measurement problem, find n_o locations of n_c sensors such that the information gathered is optimum. Several methods are available for the solution of the OSLP. However, it was argued (Ettouney 1999) that any

OSLP solution has to account for the usage and the environment of the structure in an integral fashion. Failing to do this may result in sensor locations that do not yield optimum information. The same authors proposed goal-programming techniques to solve the general OSLP. Consider the bridge shown in Figure 3 as an example. By applying the OSL technique of Ettouney (1999) for damages that may occur due to dead load alone

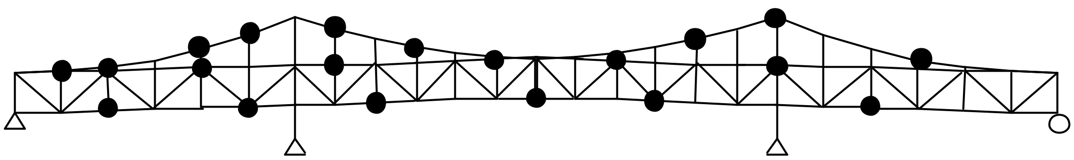


Figure 3a. Optimum Sensor Locations – Dead Load based

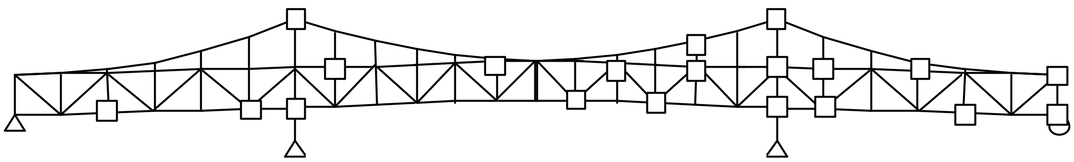


Figure 3b. Optimum Sensor Locations – Earthquake Load based

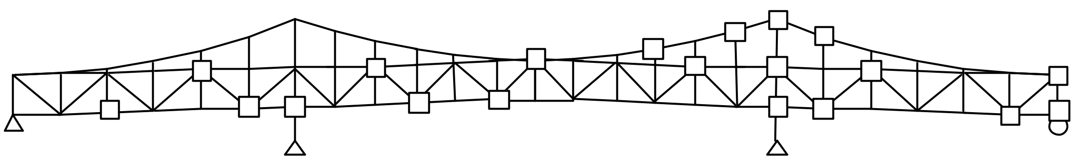


Figure 3c. Optimum Sensor Locations - Combined

Figure 3. Importance of accounting for all loading environments when choosing sensor locations

Symbols:

△ - Fixed support
○ - Roller support
□ - Horizontal motion sensor
● - Vertical motion sensor

and earthquake loads alone will result in OSL shown in Figures 3a and 3b, respectively. However, when accounting for the dependency of the structure on both dead load and earthquake loads in a practical manner, the resulting OSL is shown in figure 3c. It is clear that both loading conditions have to be considered in deciding upon sensor locations, otherwise, erroneous or inefficient sensor locations might result.

Structural Identification Phase

Once data from measurement phase is obtained, transformation of this data to understand the structural properties is necessary. This is widely known as structural identification problem. The structure can be identified by several modes of information. For example, the structure can be identified by the distribution of stiffness throughout the structure, i.e. the stiffness matrix of the structure. Identifying natural frequencies and mode shapes of a structure (modal analysis) is one of the popular structural identification methods. Detailed discussion of structural identification methods is beyond the scope of this work. For more information, the reader is referred to Cobb (1996).

Even with the existence of the large number of studies and methods for structural identification, it is wise to place structural identification in the context of the larger issue of Engineering of Structural Health, ESH. A successful structural identification technique should be capable of addressing the needs of the ESH problem. For example, if the ESH problem on hand is the corrosion of reinforcing steel in a reinforced concrete bridge, the employed structural identification method should be capable of addressing the initiation and propagation of corrosion, and structural deterioration due to corrosion.

This discussion also shows that the choice of a particular method of structural identification method should also depend on the type and degree of damage expected during a structure's life span.

Damage Detection Phase

The third phase in the Engineering of Structural Health is detection of damage that can occur in the structural system. For example, offshore oil platforms need continuous monitoring for structural damage that might occur below the waterline from extreme sea conditions and ship impact. Damage monitoring of bridges is increasingly necessary as the effects of corrosion, ship traffic, earthquakes, and sadly, even terrorist actions continuously threaten the soundness of these vital structures. During the last two decades, research has been focussed on using the vibration characteristics of a structure for structural damage identification (Faarar 1996 and Ettouney 1998). As in the structural identification problem, the structural vibrations can be also used in damage detection methodologies. The vibration characteristics of a structure may be defined by its modal parameters (natural frequencies and mode shapes), that generally depend only on characteristics of the structure and not the excitation and may be determined from taking measurements at one or more locations on the structure. Vibration signatures obtained before and after damages may be utilized to locate the damage and estimate its severity (Alampalli 1998).

A structural member develops strain as it deforms due to an applied load. If the load is excessive, the yield strain (i.e., the strain above which the stress is no longer linearly proportional to the strain) of the member may be exceeded. Therefore, if the change in length of a structural member divided by its initial length is greater than the yield strain, the stiffness of a steel member will be reduced typically by a factor between 10 and 20. For a structural steel member, the yield strain is a function of the type of steel as well as the rate of loading. For typical commercial high-strength low-alloy steel with a static yield stress of 50,000 psi, the static yield strain is typically 0.0017.

The physics behind the detection of damage through measurement of vibration signatures is based on the previously mentioned fact that if the strain in a structural member exceeds the yield strain, the stiffness of the member is reduced. If the stiffness of the member is reduced, then the vibration characteristics of the member (natural frequency, mode shapes and damping) will change as well as those of the complete structure.

Two challenging problems present themselves. First, the number and location of structural monitoring measurements should ideally be kept to a minimum. Second, correlating the results of the measurements to a specific damage mechanism (e.g., hairline cracks, large localized strains, etc.) and damage location is difficult.

Damage detection phase investigates the applicability and accuracy of different damage detection techniques to complex structures. In a study by Ettouney (1998) a typical multi-jointed steel bridge was considered. The damage was simulated analytically in structural models, and the damage detection algorithms were applied to both the damaged and the undamaged structure. The accuracy and efficiency of different damage detection schemes were investigated, including the capability of detecting damage locations as well as the severity and extent of the damage. The capability of the algorithms to predict the location and damage levels was found to depend, among other things, on the number of modes considered. In general, good predictions were observed from all algorithms considered.

Decision Making Phase

Degradation and structural life

After measuring the damage patterns of a structure, the following questions normally arise: For a given damaged pattern in a structural component or a complete structural system, what is the reliability of such a component or a structure? What is the remaining service life before failure?

When an engineering structure is loaded, will respond in a manner which depends on the type and magnitude of the load as well as the strength and stiffness of the structure. Whether the response is considered acceptable depends on the requirements that must be satisfied (Melchers 1987). These requirements might include safety of the structure against collapse, limitation of damage, magnitude of deflection, or any other such criteria. Not meeting these requirements is considered a limiting state violation. Hence, the reliability of a structure is defined as the probability of occurrence of the limit state violation at any stage during its lifetime. This probability can be obtained from measurements of the long-term occurrence of the violations on similar structures, subjective estimation, or by using small-scale prototypes and testing them under different conditions. Alternatively, a measure of the structural degradation with time, such as rate of corrosion, can be used to determine the time at which a structure will cease to function as desired. The level of degradation at that time is referred to as threshold degradation level. Elsayed (1996) classifies degradation models as physics-based and statistics-based models. The physics-based degradation models are those in which the degradation phenomenon is described by a physics-based relationship such as Arrhenius law, the corrosion initiation equation (Enright 1987) or experimentally based results such as crack propagation or crack growth model (Oswald 1983). The statistics-based degradation models are those in which the degradation phenomenon is described by a statistical model such as regression. The description of the advantages and limitations of the two types of models are beyond the scope of this study. An example of the use of a degradation model in ESH follows.

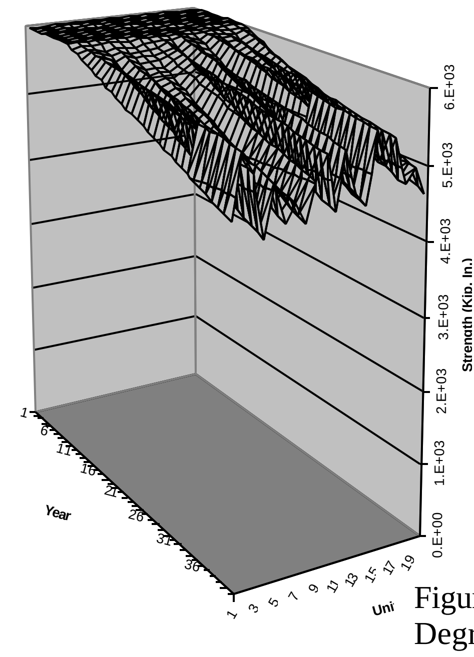


Figure 4. Degradation

Suppose that a degradation/ damaged state database for a structure, such as that shown in Figure 4 can be assembled. The damaged state database of Figure 4 was assembled for a reinforced concrete bridge that is subjected to corrosion. It was obtained using combined analytical, experimental and statistical methods (Ettouney 1999). Using the degradation model that was described by (Eghbali 1997), the reliability of the structure can then be estimated as a function of time,

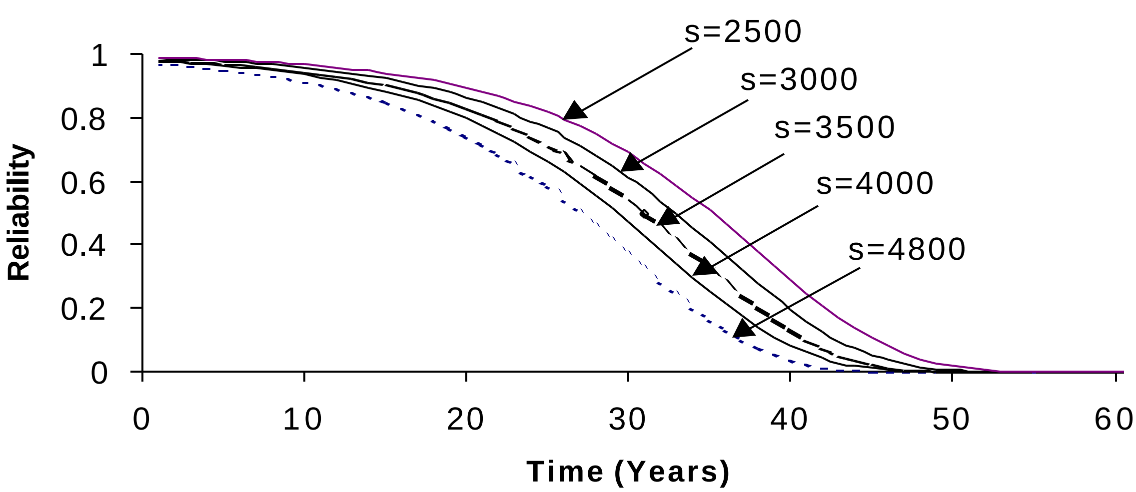


Figure 5. Reliability vs. Time for different strengths (S) of a reinforced concrete beam

as shown in Figure 5. Note that this damage model relies heavily on structural function and usage.

This structural reliability information can then be used to make proper decisions concerning the optimum course of action.

Cost analysis

Perhaps the most important step in ESH is the cost analysis phase. After reviewing reliability and degradation data (similar to those of figures 4 and 5), the question facing the owners of the structure will be; what should be done next? The answer can be obtained by employing a general cost analysis. Some cost analysis tools are available for specific ESH problems, such as corrosion cost analysis. However, cost analysis should include not only monetary costs, but also possible social and economic costs. When cost analysis of an ESH is performed in such generalized manner, it becomes more specific to the structure under study. This shows the importance of integration and inter-dependability of all aspects of ESH.

References

Alampalli, S. (1998), **“**Effects of Testing, Analysis, Damage, and Environment on Modal Parameters. Proc. Modal Analysis & Testing. NATO-Advanced Study Institute, Sesimbra, Portugal, pp. 427-443.

Cobb, R. G. (1996), “Structural damage identification from limited measurement data,” Ph. D. dissertation, School of Engineering, Airforce Institute of Technology, Wright Patterson AFB, OH.

Eghbali, G.H. and Elsayed, E.A., (1997) ,‘Reliability Estimation Based on Degradation Data,” Working Paper No. 97-117, Department of Industrial Engineering, Rutgers Uinversity.

Elsayed, E. A. (1996), Reliability Engineering, Addison-Wesley.

Enright, M. P. and Frangopol, D. M., (1998) “Probabilistic Analysis of Resistance Degradation of Reinforced Concrete Bridge Beams Under Corrosion,” *Engineering Structures*, Vol. 20 No. 11, pp. 960-971.

Ettouney, M. and Elsayed, E. A.(1999), "Reliability Estimation of Degraded Structural Components Subject to Corrosion," Fifth ISSAT International Conference, Las Vegas, Nevada.

Ettouney, Daddazio and Hapij (1999) “Optimal sensor locations for structures with multiple loading conditions” SPIE Smart structures and Materials Conference, San Diego, CA.

Ettouney M., Daddazio, R. and Hapij, A. (1998) “Health Monitoring of Complex Structures” SPIE Smart Structures and Materials Conference, San Diego, CA.

Farrar, C. and Jaurengui, D. (1996) “Damage Detection Algorithsms Applied to Experimental and Numerical Modal Data from the I-40 Bridge,” Los Alamos National Laboratory Report No. LA-13074-MS, Los Alamos, NM.

Melchers, R. E.(1987), *Structural Reliability*, Ellis Horwood Limited.

Oswald, G. F. and Schuëller, G. I. (1983) “On the Reliability of Deteriorating Structures,” in Reliability Theory and Its Application in Structural and Soil Mechanics, Editor: Thoft-Christensen, P., Martinus Nijhoff Publishers, The Hague.

Appendix E – Engineering of Structural Health Paper #2

Ettouney, M.M. and Alampalli, S. "Overview of Structural Health Engineering," ASCE Structures Congress and Exposition 2002, Denver, CO, April 2002 (printed with permission from American Society of Civil Engineers).

Overview of Structural Health Engineering

Mohammed Ettouney, P.E., M.B.A., Ph.D.[1] and Sreenivas Alampalli, P.E., M.B.A. Ph.D. [2]

Monitoring large civil structures such as bridges, dams, and buildings has received significant attention in the last decade. Several owners and researchers are actively pursuing development of long-term monitoring systems, with reliable sensor technologies and remote monitoring systems for system and / or damage identification. This work emphasize that there are several other aspects to structural health in addition to structural monitoring. Considerations of all aspects are necessary before any decision or strategy is made to ensure safe, economic and reliable structural performance.

The safety and adequate performance of any structural or non-structural component can be assured by the well-known capacity / demand equation, as follows:

$$C / D \geq \alpha, \quad (1)$$

Where C and D are measures of the capacity of the system and the demand from the system respectively. The factor α is usually taken as unity. It is referred to as the CD equation.

The process of analysis and design of structures involve the evaluation of the CD equation. In addition, there is an interconnection between the subject of health monitoring and the CD equation. Understanding this interconnection is important for the decision making process in the structural health monitoring subject.

Capacity of a structure, or a smaller component in the structure, can take several forms. These forms of capacity include structural strength, structural strains or structural displacements. One of the most important tasks of any structural design code is describing the process of evaluating the structural capacity. We note that a structural capacity is not a constant entity. It is a time-dependent entity. From the instant the structure is built, the capacity of this structure, and its components, changes. The time-dependent capacity can be either gradual, or abrupt. Generally speaking, structural health monitoring is actually the monitoring of structural capacity.

Monitoring structural capacity is necessary, but not sufficient, step for the overall evaluation of structural capability to perform its intended functions. Evaluating the time dependent demand on a structure, or a structural component, is as important as evaluating the capacity. The demand on any system can change with time. This change can be either gradual or sudden. It can either increase or decrease, depending of the functional changes of the structure.

Based on the above, we observe that health monitoring, as it is practiced now, occupies a small part in the time-dependent structural evaluation process. This process should be dependent on the CD ratio, as shown in equation 1, not the individual values of the capacity and demand. For new structures, it is desired to have $\alpha = 1.0$ for all components of the structure, and for the structure as a whole. Unfortunately, this is not always possible. For practical reasons, the ratio α is generally

[1] Principal, Weidlinger Associates, Inc., New York City, NY [Ettouney@wai.com]
[2] Head, Structural Research, Transportation Research & Development Bureau, Shreveport, NYS-DOT, Albany, NY [salampalli@gw.dot.state.ny.us]

designed to be as close to unity as possible, but not less than unity, such that $\alpha \geq 1.0$. The closer α to unity the more efficient the structure is. In some cases, the design engineer may design a component such that $\alpha < 1.0$. This situation happens when his engineering judgment makes him/her conclude that a CD ratio that is slightly less than unity is still acceptable. There is no quantification of engineering judgment; it is a qualitative measure that is dependent on the situation on hand, and the personal experience of the design engineer. Considering that both capacity and demand are time-dependent, it follows that the CD ratio is also time-dependent. It can increase, or decrease during the life of the structure. The appropriate goal of any structural health monitoring program should be evaluating the time dependent CD. In addition we propose to identify a time-dependent target CD ratio, α. A safe and properly performing structure is operating such that equation 1 is always satisfied. Ideally, designers' goal is to $\alpha = 1$ for new structures. As time progress, α varies in a realistic manner. This variation should reflected engineering judgment, probabilistic considerations, structural service time already spent, and expected / desired life of the structure.

Let us assume that the time dependent CD ratio is known for a given structure, or a structural component. This knowledge can be based partly on a health monitoring system that identifies the state of the structure. Knowing the structural state can be translated into identifying structural capacity. Also, the time dependent demands on the structure are needed for the full knowledge of CD ratio. Let us assume that the target CD ratio, α, is known. Evaluating α can be based on design codes or engineering judgment. Equation 1 can now be executed. Depending on the outcome of equation 1, the decision making process would lead to one of three possibilities a) Do nothing, b) Retrofit the system, or c) Replace the system. Deciding to do nothing is a simple decision. However, the decision of retrofitting, and the levels of retrofit, or replacement can be complex process. Full knowledge of the capacity, demand and target CD, α, are essential for reaching optimum beneficial decisions. Ultimately, cost, social and environmental processes would control such a decision.