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A Summary Report Of The 2nd Workshop On Structural Health Monitoring September 8-10, 1999

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A Summary Report of the 2nd Workshop on Structural Health Monitoring

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This report summarizes results of the panel discussions, organized in three sequential sessions: Space and DoD Applications, Civil Infrastructures Applications, and Where To Go From Here?. Transcripts of Panel Discussions are presented in the report. The Air Force Office of Scientific Research (AFOSR), The Army Research Office (ARO), the Federal Highway Research Administration (FHWA), and the National Science Foundation (NSF) provided funding for the Workshop.

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INTRODUCTION

Major concerns in the operation of in-service structures are the reliability of the structures and the cost associated with maintaining reliability. For structures which require high reliability such as transportation systems and vehicles (spacecraft, aircraft, helicopters, ground vehicles, etc.), civil structures (bridges, highways, power plants, tunnels, etc.), and high-valued manufactured products (satellites, launch systems, semiconductor equipment, etc.), rapid access to the health of the structures is crucial to maintain operational availability and productivity, reduce maintenance cost, and prevent catastrophes.

Traditional structural maintenance procedures are typically derived from maintenance manuals, designed by manufacturers and based primarily on laboratory coupon data and analytical predictions during the design and manufacturing stages. Limited or no in-service data are used in developing the manuals.

Since in-service conditions experienced by structures are typically unknown and may vary from one structure to another, traditional maintenance and inspection requires following a specific time schedule, which can be time-consuming, labor-intensive, and very expensive. Because all structures age, maintenance service frequency increases, and so does associated maintenance cost. However, specific procedures and time intervals derived from the manuals for performing inspections are not revised or changed unless a catastrophe or unexpected failure occurs, between inspection intervals. When this happens, maintenance schedules are most likely intensified, further increasing the maintenance cost.

As a consequence, based on the current schedule-driven maintenance philosophy, the reliability of in-service structures will continue to deteriorate as structures age, regardless of maintenance procedures and frequency of inspection. Increasing maintenance service intervals may ease the decay of reliability, but will also substantially increase the cost of maintenance as the structures age.

Furthermore, because of a lack of information of the actual in-service condition (loads, temperature, stresses, etc.), design data (limit load, design allowables, etc.) and analytical tools (fatigue analysis, damage analysis, finite element simulations, etc.) developed at the design and manufacturing stages are usually excluded from being considered for use to appropriately update maintenance procedures, as structures age. This leads to the result that maintenance procedures are not up-to-date or not appropriate in response to the actual conditions of the structures. The breakdown in communication between the design and analysis and maintenance procedures is primarily due to unknown structural conditions once in service. Figure 1 depicts the traditional design and maintenance philosophy in structural operation.

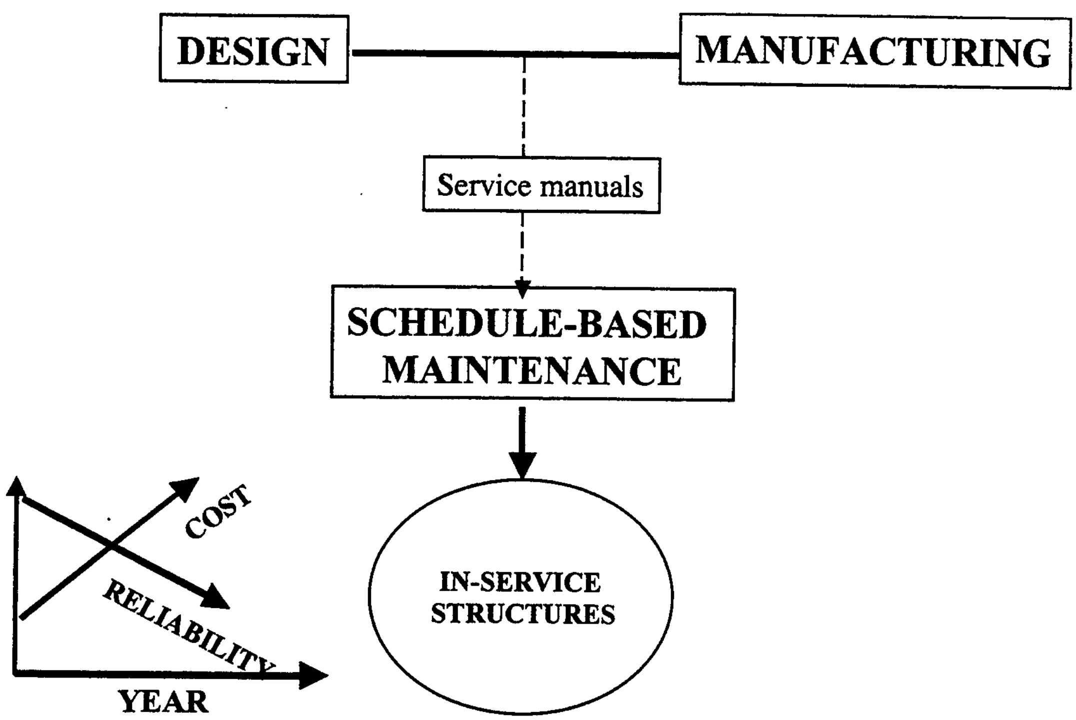

Figure 1. Traditional design and maintenance philosophy in structural operation. Maintenance cost continues to increase, and reliability decreases as structures age.

Structural health monitoring (SHM) offers a promising technology to revolutionize maintenance of structures in the future. With a built-in sensor network on a structure, SHM could provide information regarding the condition and damage state of the structures as they age. Maintenance would be performed based on the actual performance of the structures, not on a specific time frame. Such performance-based maintenance would be able to hold catastrophes to a minimum, while sustaining reliability and reducing maintenance cost.

Furthermore, with information about the actual service condition, SHM technology would enable maintenance procedures and service manuals to be updated appropriately, with assistance from design and analysis tools developed originally for the specific structure. Maintenance procedures and schedules would be up-to-date, and structures would be maintained according to the actual service condition. Figure 2 describes the new philosophy of integration of design and maintenance in structural operation using structural health monitoring technology.

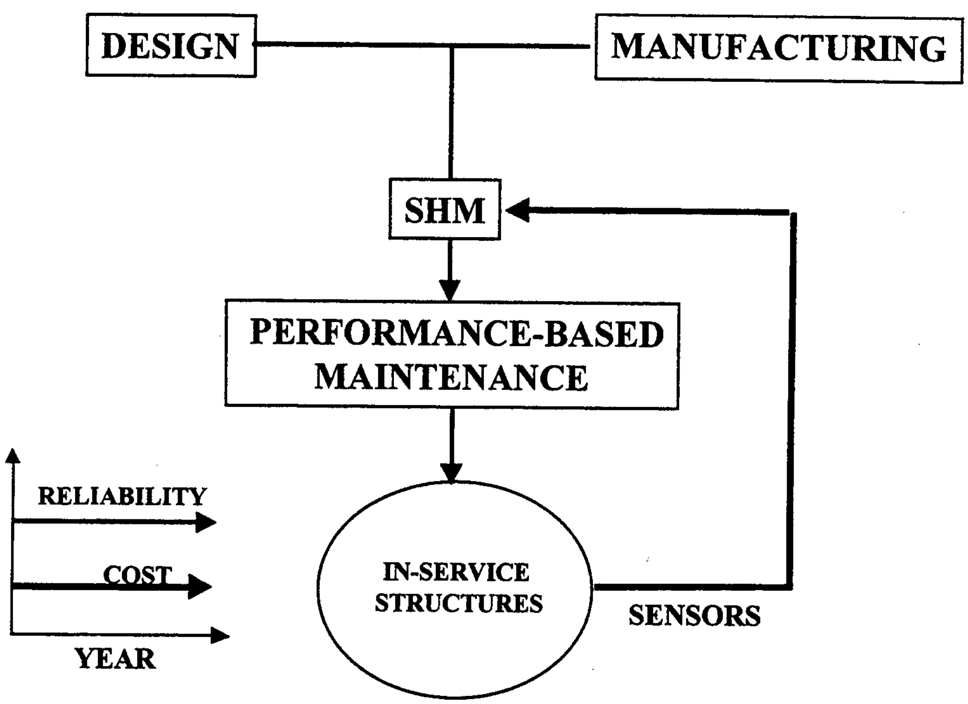

Figure 2. New philosophy of design and maintenance in structural operation. Maintenance cost and reliability are constant.

Since the SHM technology relies on the changes in sensor measurements at two different times to diagnose the condition of the structures, the technology is applicable to both existing and new structures. However, in order to utilize the technology in practical applications, there are many challenging technical and implementation issues that need to be resolved. The 1999 panel sessions provide in-depth discussions of the most important issues concerning the current status and future prospects of structural health monitoring.

Transcripts of Panel Discussions
prepared by Fu-Kuo Chang, Stanford University
and Emin Aktan, Drexel University

This report contains the transcripts of the panel discussion sessions, **Space and DoD Applications**, **Civil Infrastructures Applications**, and **Where to Go From Here?**, of the 2nd International Workshop on Structural Health Monitoring held at Stanford University, September 8-10, 1999. In the first session, the technical issues and concerns of structural health monitoring for space transportation and military systems were the major focus of discussion. The second session discussed the need for codes and standards for structural health monitoring for civil infrastructures as well as the technical and practical challenges for implementation of the techniques in civil structures. In the last session, suggestions and comments on the future directions and activities of this research were raised and discussed.

Session I: Space/DoD Applications

Moderator:
Dr. Thomas Hahn, Professor of Mechanical Engineering, UCLA
Panelists:
Mr. Jeffrey Schoess, Principal Research Scientist at Honeywell Technology Center, Minneapolis, Minnesota
Dr. David Hyland, Chairman of Aerospace Engineering, University of Michigan
Dr. Christian Boller, Chief Engineer at DaimlerChrysler Aerospace, Germany
Mr. Charles Simonds, Assoc. Director of IT at NASA Ames
Dr. Rao Varanasi, Unit Chief of Structural Engineering at Boeing Company

Hahn – We are very fortunate to have 5 distinguished panelists here. First, the panelists will say a few words.

Hyland – My interest dates back to a previous life at Harris Corp. At Harris, we worked on advanced programs in large deployable structures of RF systems. There are near term uses in structural health monitoring in those types of systems. For example, monitoring of in-mission geometry through strain sensors on large graphite/epoxy structures helps to understand the importance of effects that degrade surface accuracy. There are factors which degrade geometric precision of a structure and surface accuracy and RF performance. Monitoring helps show what is important – radiation, thermal deformations – and improves manufacturing processes without relying on in-orbit adjustments.

Another application of monitoring is to gain information on the deployment process. Large space structures have to be deployable. They are folded up and stowed in a launch configuration and then deployed. Monitoring would help recovery from failures. The Galileo high gain antenna anomaly would have been easier to diagnose.

The third area where monitoring would be useful is in advanced space science missions and would help in the advancement of autonomous operations technology for systems with no direct connection to the structure. The Origins enterprise, with its sequence of missions, and other multi-spacecraft systems in remote locations, demand self-monitoring of all functions.

Boller - We are in the middle of a process here. If you look into history, there are two characteristic years, 1954 and 1988. 1954 was the birth of loads monitoring. Many of these applications are now understood. In 1954, we had fracture mechanics and damage tolerance design just emerging. It all received attention with the Comet accident. In 1988, there was the multi-site damaged related Aloha Airlines accident. The value of an aircraft structure is low nowadays – maybe 15% of the total aircraft cost. Maintenance cost is much more significant. We have not used defense articles as they were designed. In 1988-1989, East West conflicts changed, so the use of military aircraft structures changed. Today avionics and electronics software is available to people in an age of plug-and-play. So we have to become flexible regarding usage of the aircraft structures. Aircraft are expensive, critical structures which require loads monitoring regarding their usage. Where are the applications of structural health monitoring in aircraft or engineering structures in general? These are specifically driven by the value of the structure, the maintenance costs of the structures, and damage criticality. These are the sectors where technology has to put the focus on. The next step is: How do we realize this at low cost?

Simonds – NASA is attempting to establish a new discipline – intelligent vehicle health management, which launches and operates in space. It is autonomous and can reconfigure itself, in real time, to sustain the mission objective. Not only is there structural health management, but also more computer-based maintenance than autonomous control. We have experts in propulsion and avionics who are building flight experiments to put on the pathfinder programs. These experiments work in space, flight and launch.

Varanasi –The evolution of aircraft structural safety goes back to the COMET service failures, when we began to analyze structures under operational loads, to define fatigue life to crack initiation. After some accidents in 1978, aircraft structural design philosophy was changed to require the structure to be damage tolerant. This is where a structure has adequate residual strength, even with cracks, and there is a reliable means to inspect, in order to avoid catastrophic failure. The aircraft structure must have residual strength with cracks present, at limit load. Limit load is the largest load an aircraft will see in its operational life time. If an aircraft has limit load residual strength capacity, with cracks present, you are safe. This damage tolerance philosophy has been in place since 1978. In 1988, with the Aloha incident, was the start of another phenomenon known as widespread fatigue damage, or multi-site, multi-element damage. We want to quantify this phenomenon and guard against it. Multi-site damage (MSD) is the simultaneous manifestation of small cracks, where the crack size is so small, it is hard to inspect. Together the cracks have the potential for reducing the residual strength of a structure. Multi-site damage could lead to widespread fatigue damage, which is hard to characterize and guard against. Aircraft doesn't lend itself to online, onboard monitoring until reliability is extremely high. Aircraft maintenance is geared towards programmed checks; A,B, and C checks. In addition, there may be some fatigue critical locations where supplemental structural inspections are necessary following a fatigue threshold. Maintenance is damage tolerance based. The only application of conventional fatigue in aircraft structure is in, for example, landing gear, which cannot have a damage tolerance based certification program because in these structures, the crack size is uninspectably small because of the high strength of materials. These structural elements are exempted from damage tolerance design philosophy and certified instead, on the basis of Safe Life design philosophy.

I am interested in all of these areas and will be happy to contribute in any way I can, from the perspective of commercial aircraft structural health assessment.

Schoess – Honeywell is a controls company, with sensing, processing, and output. Usually there is a control function, as in a paper mill application, which produces paper for books, or airplanes with air data systems or flight control management applications. The systems age and breakdown. They require maintenance. How can we provide a means of better maintenance control? How can sensors be tied together for better production architecturally? How can MEMS be used to provide low cost solutions to customers?

For aging structures, there are alternate solutions for sensing, processing and control. A new role starts. Now there is an additional sensing capability, or a health monitoring sensing capability, in addition to control sensing. You will have a smart system, marrying conventional sensor types and smart sensor types and control sensor types, to provide a means of control in the end. A good example is adaptive control for airplanes. Reduce drag by providing reconfigurability, and a better means of performance for that platform. It comes back to the role of sensing, processing, and control.

ISSUES RAISED BY THE AUDIENCE:

1. <u>Hot spot monitoring vs. global monitoring</u>

Participant – I was interested in Roy Ikegami's* comments knowing where a critical area is, so you instrument that area. He had high sensor density. Looking at a global health monitoring system, what about trying to ensure the integrity of the whole structure. The sensor density for a small area is very large. Will sensor density be practical for a global system? How feasible is a global monitoring system for a complex structure? It's ok for bridges and pressure vessels, but aerospace structures are more complex.

Boller – I agree. I think there are two approaches: the design approach and the technology approach. Where are the hot spots? This is just my guess that hot spots occupy about 5% of a typical aircraft structure. Hot spots are mainly in areas of high structural geometry and loads complexity. Although many designers of the now aging

* Roy Ikegami, Manager, Boeing Company, a keynote speaker at the Workshop

aircraft have retired, these hot spots could be found with redone finite element analyses, or better, revisiting the aircraft generally, which can minimize the number of sensors.

Then there is the technology approach. We need to develop new SHM technology and to optimize the number of sensors needed based on the physical parameters used in the technology. Computers can be used to numerically optimize sensor locations. We must reduce the number of sensors because for no sensor can 100% reliability be guaranteed, regarding its response, so the more sensors used, the more the reliability of the structural health monitoring system is reduced.

Hyland – We could get mileage from advanced computational processing of sensor signals. A paper from the workshop showed simple processing algorithms leading to good detection behavior despite low sensor density.

Schoess – No sensor density does it all. If you have a global application, in a loads-monitoring format, and you want more detail. Break it down using acoustics or other means, while addressing costs. A good architectural study, with MEMS, is important. With multifunctional sensing, more is provided. For example, with virtual sensing, where you use what you already have, and other new technologies. I don't agree with the hot spot focus. Additional coverage is needed to anticipate the aging problem, in a cost-effective manner.

2. Can SHM make structures more reliable and have better performance?

Participant – We build structures with large margins for safety. Can health monitoring help make safety margins smaller?

Simonds – Most NASA engineers overengineer for safety. In a space launch environment, where weight is a penalty, if designed lighter, there's a huge tradeoff for space vehicles. One researcher is working to install paint-on sensors to surfaces and use paint for conductivity. Then the sensor number is not critical. This is driving us to micro and nanotechnology in the sensor world. We are focusing on sizing down instrumentation so there is no weight penalty.

Varanasi– Commercial aircraft have been designed for the required margins of safety. We cannot afford to have any extra ounce of weight commensurate with the designed level of safety. Aging aircraft were designed with a fail-safe philosophy, which utilizes multi-load path structure. If there is a loss of one load path, there is still adequate residual strength with the remaining load paths. With fracture mechanics, multi-site damage and multi-element damage, if you want the same margins as before, there will be a weight penalty. One means of attack is to limit the sensors to a manageable number of hot spots in an aircraft structure. Then it is a manageable problem. We have to be careful how we approach it.

Boller – What we are selling you is reliability, a certainty that it won't fail. If reliability goes down, we have to do something. If we can't increase reliability with a monitoring system, and stay at the same level of safety, we cannot deliver the structure to you. So we are improving reliability. An increase in safety means more mass, more systems and thus more cost. So if you derive the function between safety and cost, it becomes a terribly non-linear function.

Varanasi – That is appropriate. We can't afford to compromise safety. There is currently an aging aircraft initiative, which says that continuous structural assessment cannot assure safety. This initiative calls for mandatory structural modification beyond a defined time/flight cycle limit. Pick a time/cycle limit, beyond which you are not happy with procuring a level of safety by continuous structural monitoring. At this limit, there would be mandatory modification to the structure. I second the thought that we can't compromise structural safety.

3. Is there difference in Health Monitoring of Aging Aircraft vs. Spacecraft ?

Participant– Your concept of aging aircraft is different from mine. Take a 737, operating for 30 years, retires after 10,000 cycles. This is different from NASA using a shuttle with 100 cycles on it. What do you do when airframes are comparably aged, but cycle life is different?

Varanasi– For aging aircraft, understand that a 737 design objective was for 20 years of operation, or 75,000 flight cycles – whichever is earlier. This Design Service Objective is an economic concept. However, it does not mean that you do not need any inspection/maintenance prior to the Design Service Objective; you have mandated inspections during service operation, to ensure safety. For the case of low cycle, long calendar time, I can only answer from the commercial aircraft point of view. We have a phenomena called corrosion, which is a major problem. Though there are few flight cycles, with calendar-based degradation mechanisms in place, you may still have a safety problem. I'll let someone else answer with respect to NASA.

Simonds– The question you pose is one reason Jean and I have a job, which is to find the next generation space vehicle. Today, for the shuttle, every time it lands, we either replace or inspect every component on the vehicle. Depending on whether you're using the agency's official model or my model – costs are between $90 million and $500 million per launch, to launch a shuttle. We cannot continue to go to space with those numbers. We have to advance the technology to trust that we can turn a vehicle around based on continual knowledge of the vehicle, without taking it apart, inspecting it, putting it back together, and replacing parts, based on the number of hours of usage, not the number of hours of life left. Based on a time frame, not a launch schedule, our orbiters go back to be totally re-outfitted. It is not an issue of number of cycles, because we effectively rebuild the vehicle every time it hits the ground. We have to have more confidence in the launch vehicles we are putting into orbit.

4. What is critically needed for SHM technology beside new sensors?

Participant– Most presentations here suggest minimizing the number of sensors, but there are increasing numbers. I am getting loads of data. There is an effort getting resources for new sensors and equipment. There is no effort for technology to validate data, manage data, and tools for understanding data. Can the panel members comment on anything they know of?

Simonds – I have the job to advance the technology because it is our concept that if there are multiple components of this technology with the instrumentation, we also need to communicate the output of the instrument to the processing unit, then process, and control. At Ames, we are the center for excellence in information technology. We have a job because we established the concept that it is intelligence processing that has to integrate output from the instrument and understand what to do with new knowledge. It is our goal to develop advanced algorithms to be able to take autonomous control of the vehicle. We did an experiment on Deep Space One where "Remote Agent" took over control of a vehicle on two occasions for a period of time, and executed all commands necessary to operate the vehicle.

One paradigm I use to convince people that this is a good way to advance information technology and help the spacecraft and launch vehicle world meet their goals and objectives is: What we are doing is changing the paradigm of the information technology industry. In the 60s, we did data processing, in the 70s and 80s, information processing, and now we are acquiring knowledge from assimilation of information. Our objective is to acquire wisdom from knowledge collected from instruments so we can make valid reasoning.

Hyland – I second those opinions. These are not problems of more or better sensors, but problems in cognition. That is what impressed me on the first occasion of this workshop two years ago. People were proposing to instrument large structures with hundreds and hundreds of sensors, and collecting much data. They don't know what to do with the data or how to infer imminent loss of function from patterns of data. I feel NASA programs are addressing this cognitive problem. Another observation is that it doesn't make sense to monitor without managing. There is a space vehicle at a remote location, and it reports back to earth that it is ailing. If you don't do something, it's no use to monitor.

Schoess – Going back to architecture – If you are dealing with lots of information, only 5-10% of the data acquired is of any use. What you should do quickly is sort out information that will give symptomatic content to make decisions with. Putting sensor data into engineering units, qualify the data locally, event detection, get symptomatic content, and if data doesn't make sense, don't pay any attention to it.

Boller – I appreciate your question because you are putting a finger on the disease we are in. If you see the amount of information we get through Email, publications, and the Web – 5% of the information is useful. We are experimenting at acquiring data easily, but you need the same effort for extracting the true features.

5. Can SHM technology be borrowed from biological sensoring systems such as a human?

Participant – Nobody has looked into human health monitoring. There is a wealth of information and transition paradigms that have developed over many years, and lately accelerated with technology and information technology. I'm worried about my heart and took an EKG. Someone looks at the traces and can tell what I'm doing. Now they are investigating machines with artificial intelligence that will be faster and inexpensive. Another direction is that we have a population of aging aircraft and aging people. There is a lot of emphasis on health monitoring of aging people. Can we transition anything?

Boller – This human material that we have as skin on our body has millions of sensors. This intelligent system seems able to handle structural health monitoring. I don't know how this is managed. Aircraft structures are dead material. The strategies are very opposite.

Hyland – There are many parallels between our problem and human health monitoring, especially in the direction of cognition, or how you process data. I was involved with a heart valve that had difficulties over the last decade. It involves a valve that opens and closes on a simple flexural member. The flexure wears out and the patient's heart stops. There is a lot of study of neural network-based algorithms to take acoustic monitoring data and tell if a member is ok or failing. That kind of problem is similar to the cognitive problem in structural health monitoring. There is room for interplay.

Simonds – Bio-sensors for astronauts to swallow are being developed. These help get information about the person's structure while in a vacuum. Our primary objective is to understand how life performs in that environment. Maybe it is not applicable for the aging process. Another of our efforts is at the Institute for Human Machine Cognition. We have done work in using artificial intelligence techniques to understand the subtleties of what the human body is telling the medical community. There is an additional degree of intelligence in monitoring a variety of instances to come to the right conclusion where humans can't process so many variables. If you look at the ranges of 20 different parameters, you can identify a pending heart attack associated with "blue fingers," prior to its occurrence, but less than 1% of cardiologists in the world could make the diagnosis. We need to have more information processing to help medical professionals understand what the body is telling us. We are a unique animal – information is getting back, but not being processed.

Our research is on future vehicles. We are trying to migrate vehicle health management back into the shuttle as a retrofit, but this is very expensive. The technology needs to be designed up front. For structural applications, we are developing thermal protection systems so that they are more intelligent. Space travel involves extreme temperatures on entry and reentry. Future vehicles will be more composite than metal because of less weight, but more complex. We will integrate instrumentation into the structure. Gene Austin's X33 has fiber optics embedded into a composite structure. The future should be focused on.

Varanasi – We are concentrating on aging aircraft. We have better systems to keep track of second and third generation aircraft, including structural, mechanical, and electrical systems. Aging aircraft are most important.

Boller – We need both, damage monitoring for aging aircraft and loads and usage monitoring for future aircraft A designer can hardly predict nowadays what will happen to a structure. The monitoring systems therefore have to be built in.

Schoess – If we can make use of current data – derive and interpret data so that the gap can be bridged for existing systems to not be too expensive. Place sensors that make sense into the control architecture and have a cost effective and adaptable solution.

Hahn – We have to stop here. Thank you all for your participation.

Session II: Civil Infrastructures Applications

Moderator:
Udo Peil, Technical University of Braunschweig
Panelists:
Dyab Khazem, Parsons Engineering
Richard Livingston, FHWA
Ming Wang, U. of Illinois, Chicago
Akira Mita, Shimizu Corp.
Charles Farrar, Los Alamos National Laboratory

ISSUES RAISED IN THE DISCUSSION

1. Standards and Codes for SHM

Peil – I think we should schedule the discussion in a way that we can see the influence of standards and codes on structural health monitoring. After that we can go over things like the market. First, we will go around and focus on code standards.

Livingston – I should explain that the Federal Highway Administration does not build bridges. We are like a bank – the monies collected from gasoline taxes are collected into a trust fund – we allocate it back out to the states. The states make decisions about what bridges to build and what to put in them. We can not insist that they do things. We have to encourage them. My office is called Research, Development, and Technology. We do basic research and get results transferred to the states so they will actually constitute the market. At the last meeting here two years ago, things looked pretty pessimistic, because there was so little going on and it was hard to convince the states to actually try this. What's happened since then is new legislation was passed. In it there is an incentive program to use innovative techniques to take some construction monies and add to it for composite materials or smart bridges. So now we are starting to get states interested in putting in these systems and I find that there is no really complete commercial system out there that we can recommend to them. Everything is still in a very early stage. My main interest is fiber optics and there is no specification or standard. I think right now the lack of standards is what is holding up knowledge transfer.

Wang – I wish that code development related to the monitoring issue should have been standardized at this moment. I don't think we have a panel for that – hopefully in the future we will have a panel for it. So far, most of the problems I have faced are related to existing structures. Those structures – a tremendous number of them – are in danger or at risk, and under harsh circumstances, especially due to temperature and environmental effects. So this is a real problem. I don't think there is a code for that.

In these large structures, it is hard to relate local damage to global response. You have to optimize the number of sensors for local and global monitoring – from my point of view, not 1000 sensors, not even 100, but as few as possible. A lot of people discuss with me, how much a system would cost– but always they want to limit their sites or money they can spend. So the local damage and global response is the issue we need to find out. But I hope the focus will be on the global issue – if you can use the global response of the structure to provide some details about the localized damage. Most of the time that could be enough for the engineer to make the decision.

The other thing is the frequency issue. There is no way to use the frequency to define damage in a global sense. However, if you have a whole year of measurements due to temperature and environmental effects – you could probably use a probabilistic approach to correct your frequency. With that I hope we could develop an approach using frequency as a warning system because a small frequency change is an indication of structural distress. However, it is nearly impossible to define the location of damage using just frequency data. Some of the locations have severe damage but there is no frequency effect. There could be so much distress – even collapses – but the frequency change doesn't show up or appears very small. Those are the kinds of issues that we need to address. On the contrary, if there is a small frequency change after the correction of the temperature effect, it can give a warning– an engineer can go back to the bridge and perform some assessment. Also, to know where the damage is located? We could use the damage index and other methods. If they can be used efficiently for critical structures, you will be able to find damage location. So far, we still have the challenge – how much damage – and how can you relate that damage back to your finite element program – how do you put that data back into your model or math model or future prediction?

Another issue is cable force – cable force is very important on many large bridges. Wireless communication is another issue. You would like to have wireless sensors. Wouldn't it be nice if the data can be stored in a small box and wirelessly transferred to the engineer while passing by the bridge. I hope that in the near future this is the direction we will go. But not 1000s or 100s of sensors. They must be installed only at critical points. You need to utilize your engineering experience to make the decision on where or what kind of sensors to use. Don't install them everywhere and then try to determine what you want.

Mita – I think I am the only person from Japan and I would like to talk about civil structures. The Japanese Building Standards Act was changed last year. The design will be changed to performance-based design from specification-based design. That means we will be able to introduce new material and new structural systems. But the problem is how can we guarantee the reliability of the system? We are changing the certification system associated with that Building Standards Act. We are thinking of setting up a committee, from private corporations or government agencies, to issue certificates for particular buildings to have enough security and safety. That is going to be our philosophy. We want everyone to enjoy the new design practice. We are now looking at a possibility of using insurance as an incentive to introduce a new product. If you use a new system, for example, structural health monitoring, you can cut insurance costs.

Farrar – Regarding codes issue– to my knowledge, in the United States, there is nothing in any codes that requires any kind of testing of a civil engineering structure, to verify that there is any correlation between the analysis that went into the structure and its actual performance. I think I am speculating but I am going to go out on a limb and say that design codes currently in effect are all developed based on component level testing as opposed to system level testing. That is the way we approach civil engineering structures, at least in the United States. Currently, the issue goes beyond having anything in codes for health monitoring. We just don't do testing of civil engineering structural systems, in general. But, at Los Alamos, we put up satellites for non-proliferation studies. One of those satellites costs about $20 million to build, instrument, and launch into orbit. We also did a test on the I-40 bridge. The replacement cost of the bridge is also about $20 million. I would bet the new design of the I-40 bridge was done by hand, probably with no computer modeling. Once the new bridge was put into place, there were no measurements made to see if the measured response correlated with the response predicted by the analytical model. We wouldn't dream of launching a satellite without a lot of modeling, correlation with testing, and assuring that there is agreement between the experimental and analytical results, even though the satellites have virtually no economic impact if they don't go into orbit. In fact, 25% never make it into orbit because there is a systems failure during launch.

Khazem – Regarding the application of structural health monitoring and its relation to codes. In the United States, we began to adopt the load resist effect of design for bridges. As you mentioned, Charles, it is based on component-level testing, not system-level testing. On the Williamsburg bridge project, we instrumented a full-scale piece of the deck and we tested it in the lab at Lehigh University. We used the same instrumentation in the field, once it was constructed. We discovered the codes are not conservative enough to predict live loads on the bridge. We had to alter our safety factors, make modifications to fatigue endurance in welded structures. That adds another dimension to the significance of in-place instrumentation and structural health monitoring of structures.

Peil – I feel this is a good point. This is a good approach – to reduce safety factors a little bit if the structure is monitored. Very simple. Or another situation you discussed, Charles. Normally no testing is done on structures. We all believe in models. I feel the only real working models are not static or dynamic models, which predict a lot of failures. I think we have some good ideas to earn some money.

Participant– Here is a comment on Charles' supposition regarding codes. In fact, I am pleased to tell you that there is one code in the United States that allows for recognition of monitoring as an alternative to conventional destructive or other engineering investigation. It was just published by the ACI. The code allows the use of continuous acoustic monitoring to detect failure of unbonded post tension strands in concrete structures. It took years to obtain. The major obstacle was not that the technology wouldn't work. It does. Or, not enough experience to generate real savings. The real problem is conventional engineering practice is not used to perfect information. We are not talking about probabilistic or reducing chances of collapse. We are talking about elimination! Until the engineers doing the maintenance and repairs change their perception, no codes will be implemented.

Livingston – It would be helpful to understand how, for the highway system, new standards are implemented and developed. For the federal highway system, standards are set by the AASHTO. These are administrators, not scientists. They ask the ASTN to develop standards and allow them to be used. How does ASTN operate? They are a voluntary organization. There is a committee for monitoring bridges, but they are inactive. There is no financial incentive. ASTN committees are driven by the industry, or people who see the need to have standards, to market their technology. Until recently, no companies out there are doing that.

Participant (Canada) – We have had a design code for the past 20 years which permits evaluation of load-carrying capacities of bridges by testing. The drawback is the proof test that is required to be put on the bridge is equivalent to the nominal failure load. I must inform you that in the last 25 years at least 250 bridges have been tested and have withstood maximum proof loads, despite the fact that they failed evaluation by analysis.

2. How can structural health monitoring be applied in practice?

Peil – What should we do to enforce the use of structural health monitoring in practice? A good approach was to reduce safety factors. What else? Otherwise, this is just an academic discussion.

Wang – Sometimes when people ask you about monitoring for damage assessment, it is too late, sometimes the bridge is already near to collapse. Then officials are notified, and the newspapers gave a report. That is the most effective way. This happened in Korea and Japan. After an earthquake you will have incentive to monitor and to make adjustments. From the engineering community, we have to think more practically. You have to talk to engineers in a way that they will accept it. You don't want to instrument too much, maybe about 10 instruments in the beginning. Hopefully that will provide the maximum potential information to the engineers.

They ask, "How is my structure now? Is it still healthy or not? What do you suggest?" Decide what method to use to answer these simple questions in an effective way with a most economic consideration. That is the big problem I face. And the best way to get people's attention for monitoring, assessment, and structural health is after a major disaster.

Farrar – We do have monitoring in California with strong motion instrumentation. How was this mandated? If buildings cost more than a certain amount, instrumentation is required. This has been legislated. So until other types of monitoring are legislated, for instance as in Asian countries, this technology will not go anywhere. It costs extra money to put monitoring systems in place, which will cause most people to avoid it, if it is not mandated.

Peil – It takes 10-20 years to change philosophies. First universities have to put ideas into the brains of the students. Testing is an excellent method to assure safety of a structure. It must start here. And it takes 20 years.

Wang – Engineers in many organizations accept it. They are willing to pay. What is the most effective way? Let's say you want to do a load test. Can you close the bridge for 1 day? No way! How effectively can we provide the bridge owner a cost effective and convenient method. Do the test, without interrupting traffic Get him maximum information in a short period of time. We have to do this in our communities in order to persuade the structure owner to buy the service of health monitoring.

Mita – We took a short cut to give incentive to owners to make it shorter – within 3-5 years. The shortcut is to convince owners they can reduce life cycle costs by introducing a health monitoring system. It is more expensive initially – but by using the system to maintain the structure, costs can be reduced. Interruption is minimized, which is important to banking and insurance people. With a computer – important in a banking network – it is necessary to ensure no interruption at all. For important structures which are located in earthquake-active zones, for instance, the owner can be convinced to implement a sophisticated monitoring system. This is the first step in implementing the real system.

Say, we have a building bond. If you want to sell the building to thousands of investors, it is divided into very small shares. To do this, you need to ensure the performance of the building. After a major earthquake, you need to pay engineers to inspect the building to assess the integrity of the building. If there is a health monitoring system, it can tell the investors the building is safe to a certain reliability level. Then you can put up more value on the building. That is another way to convince the owner.

Livingston – In the United States, things don't happen because people decide to do something. It is because courts demand it. We have the construction companies guarantee the bridges' performance. Now there is more interest in health monitoring because bridges are certified for a certain level of traffic. If something is wrong, it is not the construction companies' fault.

Khazem – Another way would be to – in collaboration with the FHA – do a demo on a bridge. This would give the owner a flavor of the new technology so they can trust it. I see that pure technology is represented here. On the George Washington bridge, a demo was done for acoustic condition to detect broken wires. A field demo gives owners confidence that the technology works.

Then as consultants we recommend, in the long run, do planned replacement of certain members, using health monitoring with sensors. This identifies which members are ready to be replaced and when. There are only limited funds from tolls. There can be planned replacements and money is saved without capital investment up front.

Participant – Dr. Mita, I feel the real parameter is life cycle costs. Is this parameter for large structures such as bridges, dams, or tunnels, communicated too much dependent upon politicians? In Germany and central Europe, there are many old buildings and railroad bridges. There are discussions about removal. The public says no because of architectural value. If there would be something that tells you about the real remaining value, using low-cost health monitoring, then it might be easy to break through the actual opinion of politicians.

Peil – It costs 25 thousand billion dollars, with an optimistic life cycle of 100 years, year by year, for renovation and retrofitting. In Germany, there is an increase in cost for retrofitting, then a decrease in cost, because there is no more money. That means the exponent of the exponential function is larger. Costs can be reduced by monitoring. Prolong the life of the structure with monitoring.

Farrar – Should monitoring be in the construction or the maintenance budget? In the Tsing Ma Bridge presentation we heard today, the instrumentation was put in place up front. The instrumentation cost was high, but relative to the overall cost of the bridge, it was low. But the maintenance budget does not typically have the flexibility to adopt new technology. It is better to get the monitoring system in place as part of the construction budget, because of the improved cost/benefit ratio. However, as Ming Wang says, people are asking for monitoring in a retroactive mode; after something has gone wrong, or after construction has been completed.

Participant – In Hong Kong, during construction of large bridges, the government has money to invest. After completion of the bridge, the government says OK to health monitoring, as long as there is maintenance money available. The design life is 120 years. There are no new projects for health monitoring. We have to apply for money to do research and development. Before the economic breakdown of Hong Kong, the industry was blooming. The government had money. We would ask for an investment. After the breakdown, the government wanted to create more jobs. No money was given out for research and development. We only had to wash and clean the bridges.

Participant – Most bridges in the northeastern United States are 100 years old. It is impossible to replace them all. Instead, in Connecticut, the DoD is developing monitoring for fatigue, using a centralized data bank. This is in the last five years. The states are working on monitoring.

Livingston – Connecticut is doing monitoring, but the scope of the systems is not nearly what we have been talking about here for structural health monitoring. In some states, there is no interest.

Wang – We can get money easier with structures other than bridges. I made an inquiry about how to find out the health of a nuclear power plant, or in Hong Kong, a building that has lasted 50 years. Will it last another 50 years? There are 1000 owners in it, and each is paid $1 million dollars. To ensure the safety, owners and authorities request health monitoring. We should make people aware of these situations. We are getting old and buildings too. Someday there could be a collapse. We have to make authorities of housing and other important structures like nuclear power plants aware of the importance of health monitoring.

Participant– There are differences in rationalizing structural health monitoring systems for bridges versus buildings. Bridge owners remain the same throughout the bridge life. In the United States, buildings are bought and sold continually. The life cycle cost for a building has no merit at all. Life cycle cost is not based on an individual or a group.

Another point is that if a building is inspected, it is difficult to get a letter to the owner saying the building has imperfections or inadequacies. Or, perhaps there is a structural health monitoring system with inadequate reliability and every week the owner is told there are serious problems. More research is needed because there are very serious legal issues.

Wang – That is right. How are we going to persuade the owners. We need a better approach. It is not good enough now. We have to do more research to have a better approach. For instance, a bridge owner asked me to perform monitoring or damage assessment on a bridge, but the owner told me not to share the results of information elsewhere!

Mita – The situation in Japan is different from the United States. In Japan, building demolition is very expensive, especially in Tokyo. So if you want to sustain a building, structural health monitoring is a tool to assure long life. Also, there should be component monitoring. We could see the component performance, and then we can tell whether the component is healthy or needs to be replaced.

Peil – There are similar situations in Europe. Not only old buildings, like the leaning tower of Pisa, but other standing buildings. If they were demolished and there was an attempt to rebuild them, it would not be allowed.

Participant – On very complicated bridges, there are ledges below which are used for inspection. On prestressed concrete bridges, people go into special rooms inside the bridge pillars to inspect and make adjustments. Humans are doing this. How can we automate this? That is one potential area. Another potential problem with bridges is that you never know how much traffic is going over a bridge, so design a structural health monitoring system such that it also contains loads monitoring.

Livingston – Human inspection is one reason we are doing research. It is not only subjective, but dangerous. Each bridge is supposed to be inspected every two years, but this doesn't really happen. We are now using loads monitoring in a system in New Mexico, and collecting load data. The first installation is always the problem.

Participant – We have experience with owner reaction to structural health monitoring. The owners were relieved that the building were safe. We monitored millions of square feet of buildings. The buildings are shown to be in better shape and deteriorate less rapidly than with conventional investigation. If the owners have a monitoring system, when the buildings are sold, there won't be delays or costs as there are conventionally. Dr. Livingston, have you had experience with monitoring a bridge or other structure where monitoring reduced risk and owner discomfort?

Livingston – With many bridges in a poor condition, the owners have to decide whether to demolish or limit the load. They have to be conservative with no information available. There have been situations with tradeoffs, and then they are willing to monitor more intensively. If there are more inspections, and they are reassured that there won't be a collapse, then the load remains the same.

Khazem – On the Williamsburg bridge, in 1987, we found over 200 broken wires in the main cable. The mayor closed the bridge, although it is a vital link over the East river. So the cable was monitored 24 hours a day. An in-depth inspection was done on the cable, with sensor assistance. Given stress ranges within acceptable limits, we found that the bridge could tolerate reduced traffic. There was no shutdown, just reduced traffic lanes. Traffic continued, but rehabilitation took months.

Participant– Can't an owner be convinced to use structural health monitoring if superloads are going over a bridge?

Wang – Usually the load is small compared to the bridge's load-bearing capacity. But temperature influence is 10-20 times more than a regular load. The load is usually minimal, unless the bridge is in an urban area where there are always traffic jams.

Peil– That is for the bridge structure. What about the bridge deck? That is affected by load traffic.

Wang – Decks are maintained continually.

Participant– I have worked for the last 25 years in aerospace. When designing a structural health monitoring system, don't allow human factors to influence the outcome of the message. The design might be OK, but a worker might make an error, and there is no record. Avoid human factors in design.

4. Peil- What are the most important problems that we face?

Farrar – I am thinking of the welded connections in steel moment resisting frames. The system should be installed proactively, before fire retardants and architectural cladding are put in place. In this manner the system could be cost effective. But, to install such a system after the fact is very expensive. It is very expensive to retrofit.

Mita – It is most important to implement monitoring into new structures. Afterwards, use monitoring to sustain building life. We want to open the market, with government's help.

Wang – The design of monitoring systems should be by civil engineers, with input from electrical engineers. A question I have is - how can we measure corrosion inside concrete without opening the concrete? We have a long way to go with corrosion.

Livingston – Corrosion in steel and concrete, which is hard to detect, is important. Very few bridges are out of service from fatigue.

Khazem – I second that opinion. Next in importance is loads monitoring. Thirdly, we have to measure existing loads, using vibration techniques and other techniques. Measure not only applied loads, but also existing loads.

Peil – I think we have had a very interesting discussion. Thank you, panelists and all of you.

Session III: Where to Go From Here?

Moderator:
Dr. Panagiotis Blanas (Army Research Laboratory)
Panelists:
Dr. Richard Livingston (FHWA)
Dr. Christian Boller (DaimlerChrysler Aerospace)
Dr. David Hyland (U. of Michigan)
Dr. Charles Farrar (Los Alamos Laboratory)

Blanas – Welcome to the final panel discussion, which is appropriately named, "Where to go from here"? First of all, let me introduce myself. In the last 3 days, we have had many good presentations. We have set the state of this health monitoring business. The question comes to mind, "Where do we go from here"? What do we need to see in two years? Which technical areas can be applied to real applications, and which technical areas need more basic research? Have we missed anything? Having said that, can the panelists give a statement and then we will open the discussion.

Livingston – For the last 3 days, I have noticed the number of studies on the durability of fiber optic sensors – at least 4 – and the conclusion is that they are more durable and reliable than ordinary strain gauges. We should get the sensors out there and see what information we can gain.

There is a range of opinion on the usefulness of strain sensors versus modeling for structural health management. One person says 0 sensors. Then, there is the middle ground, or a combination of modeling and physical data. Another group says emphasize strain sensors as much as possible. We should develop more confidence in modeling and the best tradeoff between the number of sensors and modeling.

I have tracked the number of sensors being used in structural health management. Civil engineering has hundreds. Finally, to get these used in the field, the customer has to feel comfortable. We need standards and codes.

Boller – Communication is important. For instance, take this workshop. We have had presentations, panelists, seen hardware, and had long breaks. For the future, number one is keeping this workshop alive. Secondly, I noticed the number of presentations from academia, government labs, and industry. Academia has the most papers, academia has 66, government labs have 22, and industry has 16. There are 6 joint papers between academia and industry. We have to improve the industry part. We had a project in Germany called Monitor, presented by Peter Foote*[1] earlier. There was a big wing component model there.

I remembered in the nuclear power sector there was a power plant for conducting research projects run by the Germany Ministry of Science and Technology. They funded

[1] Peter Foote, British Aerospace Corp., a keynote speaker at the Workshop

the projects, and we did a lot of testing for the projects. What would push this structural health monitoring research ahead is to take aging structures (like bridges or factories) and open the academic field for applying techniques and then comparing and discussing. Then have a workshop where the academic side says what they think. This would improve technology transfer between academia and industry.

Hyland – I have asked people where we should go. Here are four issues for your attention.

1) Where is the benefit?
In the civil structures area, do an assessment of costs versus benefits of structural health monitoring. Maybe, a side-by-side comparison – take systems without structural health monitoring and compare them with systems with health monitoring. Imagine an alternative future; trying to assess where the real benefits are. Use the data to determine what technological advances would be beneficial. There are applications for civil structures, aircraft, and space systems. You would want to monitor helicopter rotor blades, but in the civil area, we are not clear what the benefits are.

2) Health Management
You have to include remedial action resulting from health monitoring. There is always remedial action, rescue, or an alarm that follows. Monitoring is pointless unless there is management.

3) What is the optimal number of sensors needed?
This viewgraph illustrates a problem with schemes involving many sensors and actuators embedded in a sensor system. This may introduce more issues with the reliability of the sensor system than you solve. It is difficult to monitor and test numerous devices. It is unlikely you will be able to replace failed units. A control or monitoring system has to work around device faults. The processing we use has to be localized and decentralized to let us do something with large numbers of sensors.

4) Sensors don't help if we can't use the data.
Sensors are taking data but how do we interpret patterns of sensory response? What patterns of sensory data change? Estimates of structural characteristics will change over time. It is not clear what changes can be attributed to structural degradation. This point was made in the conference two years ago. Superficial damage does not mean loss or impaired function. You need an intelligent monitoring system to interpret what it is seeing. The last time the question was what indicates structural health? This question is not addressed yet.

Finally, the air force guys said you guys don't get the point. They said that this field will take off when we envision revolutionary development of different systems with high impact in how we use health monitoring in buildings, aircraft, and space systems. This morning there was an example of this philosophy. People are pursuing entirely different ways of building aircraft.

Imagine systems which can take care of themselves. They would perform successfully without human intervention, adapt management policies, work around faults and failures, and communicate with humans. These are the four questions which have come out of this workshop and the previous one.

Farrar – I looked at the fundamental challenges to developing the technology further. Some of these overlap with David.

1) Length scale issue

One fundamental technical challenge to health monitoring is the ability to capture response over widely varying length scales. We want to find damage at the earliest possible stage, so the damage is very localized, but we are monitoring big infrastructures, on a large scale. Capturing response over widely varying length scales is what makes turbulence a tough problem for the computational fluid dynamics people. Similarly, we wimp out and use equivalent viscous damping instead of trying to model damping on a phenomenological basis because of difficulties associated with models that must account for widely varying length scales.

2) Time scale issue

The next fundamental issue is the time scale over which damage evolves. Damage can evolve on time scales longer than the career of the maintenance engineer. Sometimes damage evolves very slowly in those structures. We have to account for time scale.

3) Supervised vs. unsupervised learning mode

Another challenge is doing monitoring in a supervised versus unsupervised learning mode. We had a lot of aerospace and civil structure talks presented at this conference, but there were no examples of a damaged structure. It is hard to monitor in an unsupervised learning mode. The most successful application of health monitoring used in practice is that performed by the rotating machinery industry. The rotating machinery application is successful because they perform their monitoring in a supervised learning mode, where they make use of, or learn from data obtained from damaged systems. This monitoring application has been developed to a large extent without codes or standards.

4) What is damage ?

The fourth challenge is to define damage in a system specific manner. Over these 3 days there were a lot of talks about putting sensors on structures and taking data, but up front there was no definition of damage. A technology that has a place here is the use of statistical analysis for data discrimination and decision making. The data should tell us when changes in the monitored data features are significant and indicative of damage and when the changes are not significant. There are existing technologies out there that are directly applicable to the structural health monitoring problem. All structural health monitoring studies should report false positive investigations – measure 2 sets of data from an undamaged structure, extract the damage-sensitive features from each data set, and making sure the structural health monitoring procedure you are employing doesn't tell you that the structure is damaged. We are dealing with measurement data, which has uncertainty. We need to quantify and account for uncertainty. There are statistical tools available that are not being used in the majority of the investigations reported at this conference.

Blanas – Thank you for your comments.

Livingston – We have a facility in Virginia for validating nondestructive testing methods for civil structures. We have 3 bridges nearby where we can do testing.

Participant – We haven't seen any participation from the Navy.

Boller – They are underrepresented. Somehow you should advertise your testing facility. Another important point is signal processing. It is so easy to get data. 50% of these projects should be focusing on signal processing.

Participant – We need cost effective methods for industry. We are usually dealing with maintenance crews who have limited technical knowledge and dealing with them requires simple solutions. What is the next generation of space systems? How do we deal with structural health monitoring for that?

Boller – Regarding future systems; usage monitoring will be useful here. UAV went to this. Damage monitoring is good for retrofitting.

Farrar – It's not possible to detect damage but not define it.

Livingston – I would say impairment of function rather than damage. I support wholly looking closely at health monitoring requirements of future space systems. But these space systems have to have autonomy. So they have to have management systems that share the fundamental problems of structural health monitoring.

Boller – Can we perform monitoring by using already existing sensors in aircraft? We should combine parameters already monitored in flight such as altitude, speed, acceleration, etc., and feed them back into the loads model. Then we can get loads sequences and usage sequences at various locations with virtually any additional sensors.

Hyland – One view chart said, "We want to fly like birds." Birds have many sensors. There's a story that Galileo begged the archbishop to look into the eyepiece of his telescope and see that the moon has mountains. The archbishop said the device is the work of the devil.

Participant – The sensors' part is the easy part. The hard part is getting it installed efficiently without touching paint on the bridge, using union labor to install sensors when not trained, keeping systems up year after year, and data processing. That's what is hard.

Participant – No system has continued to work after a first installation, but that's what it's expected to do.

Farrar – You wouldn't be expected to do that on the development side. On a bridge, we have to inspect every two years. You must convince the highway authorities that you have a system that can reduce the need for, or augment, visual inspections. Initially such a system would be used in parallel with the conventional inspections.

Participant – I didn't mean the system would replace the inspection. The expectation in the community is if a system is installed, it will continue to work.

Livingston – Sometimes data is accumulative. You have to know what acoustic emission events have happened over the life of the structure to determine it's condition. In other cases, you just need to know the current condition compared to the past.

Participant – We have a benign environment here. What about applications in the costs of chemicals?

Boller – We are in an embryonic state now. Later we will tackle the environmental state challenges.

Farrar – The physicists use the fact that their projects are in an embryonic state to justify further expenditures. Many of their projects such as fusion energy are still in an embryonic state. We are using health monitoring all the time. Sometimes it is in the embryonic state, but sometimes it is accepted practice.

Boller – 10 years is not a long time. Loads monitoring started in 1954. It's no longer in the embryonic state. The 'baby' is born now!

Participant – It could be a long time before you see effective health monitoring. The definition of health monitoring is different for different people; delamination of composites, or vibrations, or corrosion of tanks. Military and space systems are easier, but it can be a long time before it's in civil structures. One reason is the standards and codes issue.

Farrar –There are civil engineering health monitoring systems installed on bridges in Taiwan and Thailand. Therefore, I would disagree with your comment about no systems in place, at least in the civil engineering area.

Hyland – In recent decades, 10 years is a typical gestation period for system changes in aerospace. A 10 year old embryo is a still a young fellow.

Farrar – What is an example of a fast-evolving technology?

Participant – It's not that the technology is not mature. We are not reaping the benefits. On the military side, we have data. Systems are there and developing. If you want the fast track career, become a computer game programmer. We have to fully complete the circle to influence what we do and to see positive benefits. We have to use data effectively.

Livingston – 5 years ago, there were no systems available. Now there is one bridge in New Mexico with a system monitoring traffic and studying loads deflection. The lack of supply of systems is the problem.

Blanas – We're running out of time, so can we have a brief comment from everyone.

Livingston – The striking point about structural health monitoring is existing structures are getting older. The challenge is to monitoring aging structures.

Boller – The major point is what is the value of the technology or what is the payoff of health monitoring?

Hyland – The paramount need is to do a careful assessment of the costs and benefits of health monitoring, especially in the civil area, and complete the cycle with reports on cost savings and benefits.

Farrar – There is a lot of existing technology that has not yet been applied to this problem and would help to mature health monitoring.

Blanas – Thank you all for coming.

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