MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
A National Center of Excellence in Advanced Technology Applications

MCEER Workshop on Advanced Materials, Non-Destructive Evaluation, and Condition Assessment for Critical Facilities

held at the
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Preface

This document reports on the results of the *MCEER Workshop on Advanced Materials, Nondestructive Evaluation and Condition Assessment for Critical Facilities*. This workshop, sponsored by MCEER and NSF, discussed the advanced technologies and materials that have the potential to impact the monitoring and evaluation of failure in civil infrastructures. In particular, the workshop was designed to identify the issues, theories and experimental results that define advanced materials and technologies, and to discuss some of the novel and potentially interesting approaches for the future. The format of the workshop was to bring a number of experts with overview knowledge of similar programs outside the civil infrastructure community together with a group of experts in earthquake engineering to formulate new trends in research focused on monitoring and condition assessment. The goal was to try and leverage results from the DoD, DoE and NASA communities into use in the rehabilitation and evaluation of civil infrastructure problems stemming from earthquakes in an attempt to minimize the post-event operation of communities. The results of this workshop are reported here.

Introduction

This document reports the results of an MCEER-sponsored workshop held in Buffalo, New York, on August 26 and 27, 1998, to formulate the way forward using advanced technologies to monitor, evaluate, and control failures in critical facilities following an earthquake. To facilitate this, 30 researchers from a variety of disciplines were brought together to discuss the issues and suggest advanced technologies that would be suitable for adaptation to critical facilities. Participation was by invitation only; list of the participants appears in the Appendix.

The principal issues in global vibration-based damage detection have been well summarized in the literature [Ansari, Doebling, Masri]. What remains is to put an earthquake engineering focus on it and to incorporate the use of advanced materials with the particular concerns of critical facilities. The intention of this workshop was to take a step in that direction by bringing together appropriate representatives of two research communities:

- Earthquake engineering, with focus on structural dynamics analysis and experimentation (those having a problem needing a solution), and
- High-performance materials, non-destructive evaluation (NDE) and condition assessment associated with structural health monitoring which has been conducted primarily in the aerospace and defense sectors (those hopefully having solutions and technologies appropriate for the first group).

The format of the workshop was to start with seven overview lectures (copies of lecture transparencies are contained in the Appendix) to set the tone for the discussion groups that followed. The first lecture (G.C. Lee) was intended to give an overview of critical facilities, MCEER and the general class of problems of interest. This was followed by six overview lectures: three on advanced technologies ("Sensors", by R. O. Claus; "Advanced Materials", by R. Crowe; and "Health Monitoring" by S. Masri), and three related federal programs (Army Research Office, by G. Anderson; DARPA, by E. Garcia; and NASA, by A. McGowan). The transparencies from these talks can be found in the Appendix. Following these presentations, the participants broke up into three smaller groups to facilitate brainstorming regarding the use of advanced technologies in the monitoring and assessment of critical facilities.

The three groups were "Advanced Materials", "Nondestructive Evaluation" and "Condition Assessment." The groups were led by R. Crowe, W. Spillman and S. Masri, respectively. Each group was asked to brainstorm for ideas and methodologies that would fit into the infrastructure problem. The group members are listed in the Appendix, complete with contact information. Periodically during the following day, the three groups reconvened to discuss progress and share results. This document summarizes the discussions and suggests several promising avenues of research for future efforts.

Summary of Overviews

George Lee introduced MCEER and provided an overview of the problems of interest. In particular, the Center is interested in quantifying building and lifeline performance in future earthquakes by estimating expected losses. They are interested in developing cost-effective, performance-based rehabilitation technologies for critical facilities. They hope to improve response and recovery through planning. Their approach is multidisciplinary and systems-integrated, and includes social science and societal issues. MCEER's organizational structure includes a research committee that formulates research programs and teams. Emphasis is placed on applying advanced and emerging technologies; hence, the focus of this workshop. Dr. Lee offered Table 1 as a definition of Critical Facilities.

Table 1. Critical Facilities and Functions

Critical Facilities

Buildings/Contents (Structures/Non-Structural Components)
- Emergency Command Centers
- Hospital and Health-Care Facilities
- Fire Stations/Extinguishing Facilities
- Manufacturing Facilities
- Etc.

Lifeline Systems
- Water and Wastewater
- Information and Communication
- Energy Generation/Distribution (electricity, oil, gas)
- Transportation (evacuation routes, bridges, airports, etc.)
- Etc.

Critical Functions (importance of above)
- Emergency Medical Services
- Emergency Management
- Rapid Damage Assessment
- Fire Extinguishing
- Financial

Rick Claus reviewed the objectives and requirements for sensor systems and discussed the importance of making reliable measurement of engineering parameters of interest. He underscored the importance of resolution and dynamic range, speed of response and the need for self-calibration. Other issues of importance are the avoidance of cross sensitivities and the ability for multiplexing and remote access, especially through the Internet. He reminded us of issues of cost, and pointed the way to using wireless interrogated sensor arrays and RF networks.

Bob Crowe provided an overview of advanced materials as they pertain to evaluation of a structure's health. He proposed the concept of first determining the structure's health, and then adapting the structure if it is damaged. He pointed out that piezoceramic materials have a large experience base, but are expensive, very rigid, brittle, and dense. On the other hand piezo-polymer materials are very temperature-sensitive. Fiber optic repair is difficult, and processing and I/O integration is difficult. Polymeric synthetic muscles are being developed and may show some promise here. Relaxor crystals give a couple of percent strain and are available now, but may not be well known in the civil engineering community.

Magnetically activated shape memory actuators provide higher bandwidth but still need development. Researchers have produced 0.17% strain in the largest material by looking at a combination of SMA and magnetostrictive materials. The metrics currently used for advanced materials are blocking stress as a function of strain, and power density. Other issues are pacing issues, the ability, or lack thereof, to measure and evaluate the state of material, and structural damage and scientific laws or rules to scale up actuation materials and devices. Low-cost fabrication of materials and devices still remains an important issue in all applications, including those considered here.

Sami Masri reviewed the field of structural health monitoring (SHM), which is a very interdisciplinary topic in itself. There are many technical challenges and questions to be considered. In particular, there are such a wide variety of structural materials used and many variables to be considered:

What is the nature of the damage mechanism of interest?
What is the level of the damage and deterioration of concern?
What type of sensors should we use?
What is the nature of the instrumentation network?
Is the SHM system affected by ambient dynamic environment?
What is the degree of measurement of noise pollution?
What is the needed spatial resolution of the sensors?
What is the configuration and topology of the test structure?

Other issues include the available computing technology, the complexity of the detection schemes, and data analysis and assessment. There is a difference between short-term, after-event monitoring and long-term monitoring, particularly related to issues of data acquisition, integration and fusion (data mining).

It was noted that an interesting problem occurred after the Northridge earthquake because the most significant damage was cracking in the steel joints and this was hard to inspect because joints are hidden behind walls and building infrastructure. What methods can be used in the structural steel subassembly to provide information about the health of the joint? There is an ongoing effort in using neural networks to sort this out. A basic question here is: "Can we predict the failure based on previous measurements and perhaps a learning environment, based on previous failures? Can we build many cheap structures and perform this test?"

Gary Anderson reviewed the Structures and Dynamics program at the Army Research Office. His program focuses on: air vehicle dynamics, weapon system and land vehicle dynamics, weapon system precision pointing, and structural damping. Customers for his research program are the Army Research Lab, the Vehicles Technical Center, the Weapons and Materials Directorate, the Sensors and Electron Devices Directorate, the Aviation and Missile command, the Tank-Auto Armament Command and the Soldier Systems Command.

While driven by non-civil structures' applications, his program has several strategic research objectives involving smart structures. A number of these areas may have an important effect on the focus of this workshop. These are: fabrication processes for micrometer- to millimeter-scale actuators and sensors; power delivery systems; and smart electromagnetic antenna structures (F18 has 66 antennas in 37 locations – goal is to drop to 9 locations by considering thin wide band conformal surfaces and actuators). The possibilities of changing antenna shape to steer beam, changing beam shape and making antenna multi-use (both structural and antenna functional) may have use in telemetry systems for health monitoring. In addition, ARO has a small program in the mechanics of inflatable structures which may be of use to the loss mitigation applications of civil infrastructure (i.e., air bags to protect critical functions).

Ephrahim Garcia summarized some of the current DARPA programs including the SAMPSON (Smart Aircraft and Marine Propulsion System) Program. Here, the object is to develop smart material-based submarine and aircraft propulsion system components (*e.g.,* reduce inlet area as speed increases) to demonstrate how smart structures can expand vehicle operating envelopes and enable new missions. Some results in networks of actuators and sensors embedded in a flexible or elastomeric skin were mentioned. This network of sensors and actuators can also be used for structural health monitoring and may have an impact on the critical facilities projects. Power distribution for military applications (*e.g.,* subs) may be similar scaling-wise to the technology needed for civil structures. In addition, they have programs in smart materials and structures for vortex wake control (they used SMA-driven devices to maximize the naturally occurring instabilities to accelerate the wake breakup). Another aspect of this program is total system design, i.e., all the stuff in the middle, including PWM amplifiers power, etc., and this whole system design aspect may have significance when transitioned to civil structural health monitoring as well.

Other DARPA projects include implementing rotor blade shape control on a full-scale helicopter, UCAV (Unmanned Combat Air Vehicle)—the first models are Dark Star and Predator. We can use the same system of actuators used for structural control and structural health monitoring to assess effectiveness and adapt the aircraft operating limits but still fly the aircraft. DARPA research interest is dual use – use same system of actuators for structural control as are used for structural health monitoring to assess effectiveness and adapt the aircraft operating limits but still fly the aircraft.

Anna McGowan reviewed the NASA Aircraft Morphing Program, which provides another example of a large complex system taking advantage of advanced technologies. In this program, the materials research goal is to increase energy transfer rates. However, long- term performance, reliability, and drift are unknown. One of the technical challenges in implementing advanced technologies is that the scaling results to full-scale are not understood, making scale model experiments of dubious value. Current analytical models are not accurate enough for control law design - all control laws are currently designed using experimental data. Another important problem is that piezoelectric power consumption issues not well understood. Power issues may be pivotal for realistic applications. The Morphing program requires the use of large arrays of actuators and sensors efficiently and effectively, and the technology developed here may impact the monitoring issues for critical civil facilities. They have developed an experimentally- validated model of the piezoelectric power consumption model which may also be of use in the civil infrastructure community.

Summary of Group Reports

Group One, Advanced Materials, focused on the way forward in advanced materials (smart materials) as applied to the monitoring, assessment and control of critical facilities. Brainstorming resulted in discussions of the potential uses of embedded fiber optics in composites, concrete and polymers, as well as the need to measure triaxial stress states. Problems identified consist of information management (*e.g.*, use of local optical phone lines to measure change in state) and scaling issues. Discussion focused on the need to use and develop sensor materials that "sense the right stuff". In line with this, concern was expressed over having well-defined indicators of the state of damage based on such things as residual stress and measurable quantities and a standard to distinguish between acceptable and unacceptable levels of damage.

Group One also discussed combining the concepts of damage assessment with advanced materials to produce self-healing components for critical facilities. Discussion on this topic focused on following biometric examples, epoxy injection and self-assembly results. Examples of ideas here are to use smart materials (*i.e.*, shape memory alloys, electro-rheological fluids, magneto-rheological fluids, etc.) to form self-healing systems, to harvest the mechanical work of the event (accumulate energy devices to close valves water and gas lines) and to reinforce components weakened by the event.

Additional brainstorming sessions suggested combining embedded communications and city-wide networks based on combining fiber optics and satellite-based systems. For self-healing or preventive materials, nano capsules filled with goop were suggested, as well as using flexible load-bearing macro-reinforced metal matrix composites to provide graceful failure. Current rigid pipelines could be replaced with flexible sections of gas pipes.

The use of pressure-sensitive paints was suggested to form sensor grids, and snap-in structures (current Air Force project) could be investigated to allow large structural movements while remaining reversible. It was also suggested that the Corps of Engineers' facilities be used as test beds because the constraints on them are less than on those of civilian structures.

Group Two, Nondestructive Evaluation, focused on the need to determine what to measure on large structures in a seismic event. Lack of quantification of "what to measure" frustrates attempts to choose appropriate NDE techniques. One promising idea is to alleviate the problem of inspection by humans walking around the structures after the event to perform visual inspections, by automating this function by incorporating the use of the inexpensive imaging system being developed by JPL. Small camera-like materials could be used combined with a communication system (Iridium system?) to examine critical components, allowing emergency officials to make more immediate post-event inspections. Sensing of maximum allowable acceleration could be used to trigger imaging. Then, the interpretation of the images could occur at a central location for rapid assessment to determine where to focus disaster response resources. In this way, one could focus on looking at critical functions in hospitals based on FEMA handbook standards which make a crisp recommendation. Use of an autonomous agent attached to a critical facility which could carry out detailed damage assessment (*e.g.,* crawling robots are available commercially) was also discussed.

The discussion recognized that there is not a good connection between NDE and structural properties. This requires basic research, education and experience to address. Much more information is needed in order to do the remote and automated structural testing that would replace current visual inspections. Better connection between NDE and test data is also needed in this regard. Another significant factor is that global methods are not as sensitive as local or visual methods. The question was raised that global methods may not be physically capable of detection of local conditions, again suggesting some sort of hierarchical approach.

Group Three, Condition Assessment, focused on a hierarchical approach that would first involve a global city inspection to determine if a given structure had obviously failed or not. Then, further inspection could be directed to determine the extent of the damage and its effect on the performance of the structure.

Research tasks involve defining measures and determine criteria for reaching conclusions. The first task is to solve the forward problem – to assess the condition of critical load-bearing elements in terms of strain, relative deflection, dynamic properties, and wave propagation speed. The next task is to identify sensitive indicators of failure and damage modes (*i.e.*, to solve the inverse problem). This requires knowing sensor requirements. Here, desirable properties are that the system be discrete, use wireless transmission and/or be independently wired, with on-board digitizing and storage capabilities which could be networked.

Discussion after this presentation revealed the importance of using statistical-based methods rather then deterministic-based methods. In addition, the concept of trying to use existing wires to provide diagnostics (where are the breaks?) was suggested. There is a real need to define condition assessment, to define what needs to be measured, and to define a probabilistic-based performance measure. Sensor technology is clearly moving toward the point where thousands of sensors can be distributed over a single instrumentation network; however, it is still unclear how to best take advantage of this massive sensitization. For example, there are 600 sensors on the new bridge in Hong Kong, but we really do not know what to do with all the data. Perhaps we should first use a quantitative approach.

It was pointed out that sensors all have some limitations (range, drift, non-linearity), and that we need direct measurements of displacement (*e.g.,* measure drift in a building). In general the group felt that we cannot yet conduct a condition assessment with a high degree of confidence. To improve our confidence, we need benchmark structures. Both Taiwan and Japan have brand-new earthquake testing facilities and perhaps offer an opportunity for collaboration on bench-marking algorithms, devices and techniques.

Summary of Discussions

Although three distinct discussion groups were constituted, a number of topics found common ground in more than one group. Some of these appear in the description that follows. Also included are suggestions for the way forward as generally accepted by the group. The general agreement was that the following needs to be established. What is the problem we are trying to solve? This question was asked in a variety of ways repeatedly throughout the workshop, perhaps because there are many problems, at many levels. Even the definition of the problem(s) to enable rational discussion requires significant effort. With this in mind, the following represents the summary and recommendations of the group.

A consensus was reached that the group needs some firm definitions. Simply stated, damage may be defined as change introduced into a system which adversely affects the current or future performance of that system. Implications of and assumptions underlying this definition are that we need some performance measure(s) and/or performance indicator(s), and that some kind of comparison is necessary between two different states of the system: the damaged state and the prior-to-damaged state.

One can think of three principal categories of damage detection methods: (1) ordinary visual observation by a presumably trained human eye; (2) localized experimental methods (typical NDE methods), most of which rely on the very restrictive assumptions that: (a) the vicinity of the damage is already known; and (b) the damaged vicinity is readily accessible; and (3) global experimental methods that typically abstract dynamic properties of the entire structure (*e.g.*, frequencies, mode shapes and their derivatives, and modal damping) from vibration data and are plagued by relative insensitivity to minor localized damage in the context of realistically sparse sensor arrays.

When one needs to know more than just the threshold exceedance, there are two diametrically opposed philosophical methods for interpreting either raw or more typically abstracted experimental data: (1) model-based methods, *i.e.*, in terms of an *a priori* analytical (typically finite element) model used for simulation purposes; and (2) model-free, *e.g.*, in terms of a "black-box" such as a neural network. Basically the effects of damage on a structure can be divided into two groups: linear, where the structure remains linear elastic after damage; and nonlinear.

Probably the most significant unanswered questions are those pertaining to damage severity. How to answer a question often depends on who is asking and why. There are a number of possible variants of the innocent-looking question "how bad is the damage?," *e.g.*, prediction of remaining life or how much time do we have left? To do what? (e.g., to evacuate people or get the damaged structure repaired?). Next is the issue of performance assessment of individual damaged member(s) and how does this relate to a stiffness or strength decrease. How does this relate to the performance assessment of the entire structure ("How serious is the impact of the localized member damage on the global safety of the structure?")

The problems of health monitoring and condition assessment are so daunting that some rather draconian scope restrictions must be imposed on any discussion in order for any plan for progress even to be formulated. Fortunately, the scope of MCEER's focus provides some such restrictions. By focusing primarily on rapid damage assessment following a strong event rather than long-term degradation, the following provides some measure of proposed restriction of scope. Concerns about detectability of subtle changes due to noise level are lessened, since the damage of interest will typically be severe. Quake-damaged structures will typically undergo significant, although localized yielding.

Some unique complications and restrictions are imposed by focusing on critical facilities in compliance with the MCEER research objectives. Damage in many cases will be in multiple locations, each of which could have varying severity, all of which would be of interest. Significant nonlinear structural behavior (strength-degrading or stiffness-degrading or some combination of both) is expected and may well be quite acceptable during the event. Structural collapse risk aside, non-structural aspects are not only of considerably more importance for critical building (hospital) facilities than they are for many other types of structures, but the details of critical components and functions inside a hospital are even more illusive than the structural aspects. This gap should be intentionally addressed in any follow-up work or definition of needed results.

Condition assessment following the extreme event caused by strong ground motion excitation is presumed to rely primarily on quantitative measures and means (*e.g.*, some system identification technique) in order to produce a primarily qualitative indication of performance level (*e.g.*, is the building safe for occupancy?). This view of condition assessment presumes that some measure of screening has already taken place, by which the following has already occurred: a city-wide global inspection, presumably visual via air, that has identified clearly-failed facilities, and a local inspection that has performed some sort of triage in order to identify a not-clearly-failed facility that merits more in-depth assessment in order to determine its condition.

Currently, a considerable amount of useful information is obtained from low-tech visual inspections. A recent FEMA document presents guidelines for condition assessment based essentially on visual inspection. The question, then, must be asked: what further significant benefits may come from more high-tech approaches? In response, it has been noted that the fractures in the beam-to-column connections of steel moment-resisting frame buildings caused by the Northridge and Kobe earthquakes were, in the vast majority of cases, not detectable from any visual indicators. This experience, then, does warrant a more technical approach.

Visual inspection can be thought of in terms of conventional post-earthquake reconnaissance teams in a virtual sense: remote human, and/or artificial use or some form of computational image processing. In either case, use of fixed and/or movable video cameras enter the picture, along with wide-bandwidth transmission protocols, etc.

In the future, there will be the capability to place large quantities of smarter sensors. Thus, the current tradeoffs between amount of instrumentation and processing overhead will shift significantly. Dual use of both existing and evolving nonstructural service systems in buildings should be considered. For example, why not use existing patient-monitoring video cameras in critical (hospital) facilities? Why not use time-domain reflectometry (TDR) in conventional electrical wiring to determine at least where the wires were broken during the earthquake event?

The framework for understanding research needs is complicated. There is a certain "chicken-and-egg" aspect to two of the sets of interrelated tasks identified as in need of further research. The first task starts with using the kinds of measurands that can be readily acquired and poses the question: what can we infer from these measurands? Most health monitoring and damage detection research has taken this sort of approach.

There is currently a poor connection between NDE and structural condition, i.e., what do you measure and how do you infer condition? This question motivates the need for more work in the second task area discussed: what are acceptable damage measures. Here, we should first determine what our performance measures are and only then determine what we should be measuring in order to derive those performance measures. That is, we should identify the indicators we'd like to have and what we could do with them if we had them. Along with this task, we would want to identify the most sensitive indicators of failure/damage modes. This is likely to be a multi-level process.

There is a massive multi-level data fusion problem here, due to the fact that there is no single method and no single problem scenario. While bench-mark scenarios will help, the problem remains very complex. The need for each of the following provides only some of the reasons: both local and global damage detection methods; both model-based and non-model-based computational/identification approaches; both inferring global measures of performance from local measures and desiring to obtain local information (*e.g.*, crack or plastic hinge location) from global indicators.

Sensor and system requirements are critical, but as indicated above, we still do not really know (*i.e.*, haven't figured out yet) what actual measurands we want to be able to record from installed sensors. Even so, the nature of a strong earthquake and past experiences with such events point to the following preliminary list of primary requirements for the sensor and supporting data acquisition and processing system to maximize the probability of the system's functioning both throughout and immediately following the earthquake event:

Discrete (point) sensors that:

- avoid cross-sensitivities, such as EMI, with other systems such as electric power;
- are insensitive to temperature, humidity and other environmental factors while being sensitive (*e.g.*, 19-bit A/D) to their own measurands, especially if intended for dual-use (long-term monitoring as well as extreme events);
- operate independently of each other, since presumably fiber optic cable-based sensors would not survive a major event and since some sensors themselves will end up as casualties;
- are independently powered, *e.g.*, via long-life batteries, since conventional wired electric power would presumably also not survive a major event;
- are economical to manufacture and use;

- are long-life and maintenance-free, since most of these sensors would presumably not be very accessible, and since they must "sleep" for perhaps decades and then function flawlessly when called upon with no advance warning;
- have data transmission/download capability via wireless means, with burst storage to off-site locations and interrogatability by roving equipment, since such wires would presumably also not survive a major event;
- have some on-board storage capability;
- have some on-board digitizing capability;
- are fault-tolerant multiplexed networking infrastructure.

Conclusions and Recommendations

Numerous ideas for the way forward were discussed. Conclusive statements do not necessarily represent 100% endorsement by all participants, but an attempt has been made to present consensus. The following ideas were suggested:

1. Bench-mark tests should be established to both help define tolerances levels for damage and to provide standards for testing sensors, algorithms and techniques, as well as entire systems.
2. Structural Engineering educators should introduce their students to basic NDE techniques in the context of their undergraduate materials and mechanics courses.
3. Structural Engineering researchers and practitioners developing the next generation of codes (*e.g.*, performance-based, dual level earthquakes, etc.) must make appropriate explicit requirements regarding inspectability and must work in teams to ensure that such requirements regarding nonstructural systems are developed along with those dealing with structural performance.
4. Research approaches must account for the wide-ranging uncertainties that pervade this entire area of endeavor, *e.g.*, be statistically-based.
5. In order to best facilitate the use of results and research from non-earthquake-aware researchers who need assistance in selecting and applying their technologies to earthquake preparedness and post-event crisis management, the requirements must be defined. When these researchers in return ask earthquake engineering researchers what information is needed during and after an earthquake in order to conduct a responsible damage inventory and condition assessment, they require a reasonably comprehensive answer, with particular focus on the needs of critical facilities. A suitable representative, yet small, group of earthquake engineering researchers should develop a "white paper" for presentation to the non-earthquake "smart structures" community describing critical facility desiderata during and shortly following a major earthquake event. This list of requirements should be expressed at a level that is more detailed (less fused) than "Is the building safe for occupancy?" Identify what exactly are the performance measures of interest, i.e., what indicators would we like to be able to have, and what could be accomplished if we had such indicators? Essential characteristics of critical lifelines must be identified and distinguished from those of critical buildings such as hospitals. Relevant actual characteristics of "bench-mark" facilities, both lifelines and hospitals, must be identified and the specific information acquired along with the requirements for any comparison studies to be conducted with those bench-mark facilities.
6. In each of the tasks, an attempt to address non-structural concerns associated with critical building (hospital) operation during and shortly following an earthquake should be made.

Recommendations Regarding Future Research

Fortunately, not all meaningful research is dependent on receiving answers to questions regarding the definition of requirements. Clear needs exist for development of certain types of sensing capability (absolute displacement, 3D displacements that are continuous in both space and time, etc.) as well as sensing infrastructure. The following list thus should be augmented with future results that more clearly define the requirements.

1. Data interpretation in terms of comparative assessment of both model-based and non-model-based approaches.
2. Identify (in the context of a large-scale benchmark to be defined) which available indicators are the most sensitive for detecting performance measures considered to be of interest.
3. Review and/or develop methodologies for screening out obviously hopeless and obviously safe structures from the ones requiring more in-depth assessment using promising indicators.
4. Pursue development of damage detection methods that can account for the effects of cyclically nonlinear (hysteric) structural response.
5. Explore/Develop an absolute displacement sensor, primarily for quick indications of interstory drifts.
6. Explore/Develop NDE methods for detecting cracks in steel moment-resisting frame joints without having to strip away architectural facades and fireproofing.
7. Explore/Develop video imaging and other technologies for recording 3D displacements and curvatures in real time and space.
8. Explore/Develop sensing infrastructure to support the laundry list of Sensor and System Requirements presented earlier.
9. Explore/Develop means of harvesting the mechanical work of the earthquake event itself, both for temporary power for sensing systems and for control mitigation devices.
10. Develop large-scale system level benchmarks, perhaps capitalizing on structural systems which are about to be demolished imminently.
11. Team up with existing centers of knowledge such as Iowa State U and Johns Hopkins U (NDE) and U Delaware (Composites).
12. Propose a standardized vocabulary of performance levels and failure measures
13. In conclusion, there is a need to integrate advanced technologies into the assessment, monitoring and control of critical facilities after an earthquake. While many research barriers remain to be solved, the pay-off could be large in terms of decreasing the time to recovery and increasing the number of critical functions remaining after a catastrophic event.

Summary

This workshop identified a number of key areas for future research in advanced technologies as applied to the protection, monitoring and restoring of critical facilities subjected to earthquake loads. Capturing the advanced technology and research developed for other applications (*i.e.*, aerospace, automotive, defense) and reformulating these results to produce results applicable to and useful for the critical facilities problems of importance to earthquake engineers is more difficult than anticipated. To effectively transition and modify technology to a new setting requires a multidisciplinary effort of large proportion and, most importantly, additional research. Problems ranging from terminology and cultural differences to defining specifications and tolerances require members from the civil-earthquake community to work closely with those from the advanced technology areas. Difficult as it may be, the pay-off for such cooperation could be significant, and both groups would benefit their own areas of expertise through the experience, providing safer and more reliable communities.

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Workshop Agenda

Workshop on
Advanced Materials, Non-Destructive Evaluation and Condition Assessment for Critical Facilities

(A forum for mapping the way forward and defining the advanced materials and evaluation techniques showing the most promise for critical facilities.)

Wednesday, 26 August 1998

7:30 Continental Breakfast *
8:00 Welcome (Lee/Inman)
8:15 Critical Facilities Overview (Lee)
9:15 Sensors (Claus)
9:45 Advanced Materials (Crowe)
10:15 Break *
10:30 Health Monitoring (Masri) (Anderson)
11:00 ARO Program
11:30 AFOSR Program (Sanders)
12:00 Lunch

1:00 NASA Program (Horner)
1:30 Aerospace Industry Perspective (White)

2:00 Afternoon Break-Out Sessions

Group I	Group II	Group III
Advanced Materials	NDE	Condition Assessment

3:30 Break
3:45 Reports
4:30 Adjournment
5:00 Motorcoach departure for Niagara Falls
7:00 Dinner-Niagara Falls, Ontario
9:30 Return to University Inn

Thursday, 27 August 1998

7:30 Continental Breakfast
8:00 Group Presentations

10:15 Break
10:30 Summaries

11:30 Adjournment
12:00 Lunch (on own)
12:30 Optional Tour of UB Seismic Simulator Laboratory

Report Writing (Inman, Singh, Chen, Soong, Sack, Lee)

*MCEER Exhibit and Information Service Demonstration will be Offered

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