Emerging Technologies for Risk Reduction II: Structural Control and Health Monitoring

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1 INTRODUCTION

This paper summarizes the second panel discussion on emerging technologies for risk reduction. The focus of this panel was the use of structural control, damage detection, and health monitoring techniques in civil engineering for risk reduction. Each panelist was invited to share some thoughts on the topic before the discussion was opened to questions from the audience. The questions focused on issues related to economic and social perspectives, structural control and its relevance to performance based design, and achievements to date in these areas. The panel discussion is summarized herein.

2 PANELIST PRESENTATIONS

Professor Beck

Dr. Beck focused his comments on the decision process one might go through for implementation of these technologies, specifically for seismic hazards. In particular, to make the decision to implement this technology, a decision maker would require information to weigh the costs and benefits of the proposed approach. Decisions are typically made, not by looking for the best technical solution, but by finding a strategy that, while meeting required (possibly minimal) standards, produces the best return for the cost of implementation. This requirement implies that we need to study our proposed solutions within an economic framework.

One question we, as researchers, should be asking ourselves is: “How can I compare these approaches in such a way that I can make a decision as to what device(s), if any, to install?” Of course, in such a decision we must make appropriate comparisons under equivalent conditions. The total cost of the systems is equal to the installation cost, plus the present value of the lifetime operating costs of the system. The benefits are more difficult to quantify, especially in monetary terms, and are highly uncertain because there is a large amount of uncertainty involved in estimating the risks from the natural hazard. Benefits would include elements such as the reduced earthquake losses over the life of the structure, due to the cost to repair/rebuild, and the cost associated with the loss of use (and loss of future business/opportunities). Note that for some owners/users the cost associated with the loss
of use will dominate, while for others the cost of reconstruction/repair of the facilities will govern the decision process.

A suitable strategy would be to consider total life-cycle costs (LCC). The system should be installed if we can show that the proposed strategy results in a situation in which the LCC with the device are less than the LCC without the device. For risk-neutral decision makers (where very little of total equity is in this structure) we may consider the expected value of LCC ($E(LCC)$), through seismic hazard and fragility analyses. For risk-averse decision makers, the process is much more complex, and little research has been done in this area.

**Professor Bergman**

Dr. Bergman is a strong proponent of this technology. He believes that, if a good technological solution is available, it will eventually get implemented, though the process may be slow and initially only occur at a few locations. However, once the technology does become implemented, it will spread throughout the rest of the industry. Although the near-term application of structural control is less certain, the development and implementation of structural health monitoring systems will probably develop and spread rapidly within civil engineering. With the development of inexpensive, wireless sensors, the cost of such systems is decreasing. As the cost decreases over time (partially as new construction costs increase and monitoring costs decrease), the rate of acceptance and use in the US will increase. In the future buildings will become increasingly smarter. They will have built-in monitoring systems that can tell the owner or user that maintenance is required, how immediate the need for the maintenance is, and where in the structure the problem is located.

**Professors de Flaviis and Jofre**

Drs. de Flaviis and Jofre are in the Department of Electrical Engineering and their research efforts have focused on telecommunications. Recent accomplishments in information technology have driven the costs of sensor technology down, making it more feasible to implement sensors in civil structures. They discussed two current research efforts to develop technology for sensing in civil engineering environments, including:

(a) Microwave Imaging Systems – utilization of microwaves to “see” objects, both in open space as well as hidden within a structure. Microwaves can easily penetrate nonmetallic structures, especially when low frequency waves are used. The resolution of the information obtained is related to the wavelength utilized. With modern sensors, we can obtain resolutions to within 10 cm and higher resolutions up to 1 cm are feasible.

(b) C-Band Miniature Dime Antenna Sensors – miniature, inexpensive sensors that are also capable of supplying their own power by converting RF (radio frequency) power to DC power. The information gathered can be transmitted to a central location for recording via radio transmission without any wires. As these sensors are very small (smaller than a dime), they can readily be placed on structural elements.

**Mr. Lund**

Mr. Lund is a consultant specializing in the seismic restoration and mitigation of pipelines. He focused on an overview of the existing technology available in this area. Pipelines in urban environments must provide large quantity and high quality water to the locations its services, and thus their reliability is a high priority. One may need to rehabilitate an existing pipeline for the following reasons: i) deterioration of the pipes; ii) known or suspected seismic damage; and iii) mitigation of future seismic hazard. Several technologies are available for mitigating seismic hazard in pipes. These technologies also serve to improve the quality and quantity of water provided. Mr. Lund discussed the details of one approach in his area of expertise, the use of cement mortar linings, which is one of the method of trenchless technology (no new trenches are dug). This involves cleaning the pipe with a “squeegy”, with a hydraulic press to move the device. A camera is utilized to inspect the process. A hose with special head is then used to spray the mortar and carries a trowel to smooth the sprayed material with a hydraulic press. This strategy minimizes disruption of use and environmental impact,
as well as not requiring any additional space for installation (utilizes same space as existing system). It has a low construction time and cost, as well as requiring minimal waste disposal.

**Professor S. Masri**

Dr. Masri focused on the role of the field of structural control in reducing seismic risk. He discussed the following four distinct areas that require further development:

(a) **Materials.** Researchers have been investigating the development of high-performance, advanced, smart materials. An example includes the endeavors to develop fiber-reinforced materials, in which the embedded fibers serve as sensors. Another example is recent developments in self-healing materials. Very recently, researchers at the University of Illinois have published work on self-healing plastics that, when damaged, release a substance that repairs the damage. Possibly, similar materials may be adapted or developed for civil applications.

(b) **Sensors.** New developments in sensors include MEMS-based devices. These inexpensive systems would utilize thousands of sensors on a structure. Currently, MEMS do not meet the requirements for civil engineering systems because they are limited in resolution and frequency range (MEMS systems are appropriate for high frequency systems). Another possible opportunity is to investigate fiber-based sensors that are, by nature, distributed. Again, these sensors are not suitable for dynamic applications at this time.

(c) **Devices (including passive, active and semi-active).** Research efforts should focus on the development of devices suitable for full-scale implementation, and yet have minimal power requirements. Indications are that full-scale implementation of these systems for severe seismic hazards (as opposed to current systems which are intended for mild hazards and increasing comfort levels) would be quite challenging due to the high-force, high-power requirements. Research efforts should focus on the development of semi-active actuators.

(d) **Non-destructive evaluation/structural health monitoring.** This arena is a relatively new one for civil engineers. Several research needs exist, including the collection of large quantities of high-quality data, and the sophisticated processing of these amounts of data.

**Professor Reinhorn**

Nature is filled with examples of control – it is a broader field than we sometimes think. Thus the potential exists to try to use the approaches that have been developed for active control systems in all of engineering. The process of control includes: obtaining data, determine whether or not data gathered meets our criteria, and then use that information to modify the behavior of the structure as a whole. Additionally, new developments in Performance-Based Design in earthquake engineering are at the root of the control process (or share the same principles). The question we should be asking is “how can we use control theory to impact the performance of the entire structure?” For example, can we utilize the theory behind active systems to design or develop new semi-active systems? Can we utilize this same approach in the design of passive systems?

**Professor Yang**

The reduction of risk in civil engineering is associated with the reduction in response of structures. Specifically, the development of strategies for risk reduction associated with near-field effects is needed. Urban areas have been in the near-field zones of several recent earthquakes (Northridge, California, Kobe, Japan, and Chi-Chi, Taiwan). Near-field motions are characterized by a large velocity pulse, distinguishing them from far-field ground motions. One approach that has potential to mitigate the risk in these situations is the development of appropriate protective systems (semi-active, passive structural control systems). In particular, a hybrid system combining the demonstrated performance of base-isolation with the attractive characteristics of a semi-active damping device, seems to have a great deal of potential for such scenarios.
3 SUMMARY OF PANEL DISCUSSION

The panel discussed several issues relevant to structural control and health monitoring with the audience. The discussion started by summarizing some of the prior accomplishments in these areas. Then, the discussion focused on the potential influence that these technologies may have in regard to performance-based design and reduction of losses in near-field earthquakes. Finally, several needs were identified for further research in these areas. The following paragraphs describe the main points of the discussions.

3.1 Previous Accomplishments in Structural Control and Health Monitoring

In several countries in Asia, structural control systems (including active, passive, and semi-active) have been widely adopted and have attracted a great deal of attention. In fact, after the successes of these systems in the Kobe earthquake, approximately 20 base-isolated buildings are being constructed in Japan each month. Also, over 25 buildings in Japan incorporate active or semi-active control systems. However, practitioners in the US have been slow to implement this technology. Although passive control (in particular, base-isolation) has gained acceptance for seismic-resistant design, active and semi-active systems have not been adopted. Even semi-active systems, which are essentially passive devices that can be controlled, have only been implemented on one full-scale structure in the US. The need to convey the attractive characteristics of semi-active systems (which might be better termed controllable passive or smart dampers) to the practicing engineer, particularly its higher reliability than active systems while maintaining an adaptability not found in fully passive systems, is critical to the implementation of these systems.

3.2 Perception of the Research Efforts

Few practicing engineers have had exposure to the latest research on structural control systems. Once introduced to the concept of smart damping technologies and structural health monitoring, they typically are intrigued about their potential. However, before this technology will be adopted in practice, we must address questions of cost, reliability, and performance of such systems. The advantages of structural control and health monitoring must be clearly identified, and put into terms that are meaningful to the engineers and owners.

Initially, the likely users of this technology will primarily include government and corporate entities that must offer functional and continued-operation of their products and services immediately after an earthquake. For instance, state and federal government agencies, utility/communications companies, hospitals, and emergency services must not only survive, but must offer assistance to others, and supply needed services. The loss of a key bridge will not only impede rescue attempts, but would have a huge economic impact on the entire region.

Aside from implementation of these systems in such critical facilities, widespread adoption of this technology requires that the technology be shown to be cost-effective. If we can translate the advantages of these systems into an economic framework, they will be more meaningful to the end-users. Passive control (in particular base-isolation) has demonstrated itself to be cost-effective. With further research, as the cost of the required sensors and control devices drops, the capital and maintenance costs of structural control and monitoring systems will decrease rapidly. Additionally, recent advances in wireless technology will simplify the installation, maintenance, and replacement of such systems, making these systems much more attractive for civil engineering structures (including retrofit/rehabilitation applications). However, more interaction is required between the civil engineering researchers and the electrical engineers developing new sensors to ensure that the sensors under development are appropriate for measuring the dynamic responses of civil structures.

Certain corporations have recognized the importance of performance-based design, realizing that even a temporary loss of function could result in huge losses of their market share when their customers turn to alternate sources of their product. Thus several corporations have designed key facilities to
standards above those required by codes. This risk-averse nature of certain corporations is also expected to be a driving factor for acceptance of this technology.

3.3 Future Directions and Identified Needs

3.3.1 Demonstrating Benefits and Costs of Control

Currently the research community is promoting structural control and monitoring systems based on their ability to reduce responses and the knowledge that is gained by employing these systems. However, it is difficult to translate to the owner the concept of “reducing loss.” It is more appropriate to discuss this technology in terms of “reducing cost,” which is something that is very real and tangible to them. Therefore, to “sell” these systems to engineers and owners, their advantages must be put in terms that they are more familiar with, in an economic framework. But how do we know when we have reduced the costs of such technologies to an acceptable level?

We need to begin investigating the cost-benefit relationships for this technology. Methods are needed for comparing the life-cycle costs of a number of very different structural design approaches, including traditional methods and intelligent systems. The challenges here lie in the fact that there is a great deal of uncertainty in the types of loading a structure will be subjected to during its lifetime. Additionally, it is not clear how one assigns a value to knowledge or to the reduction of risk. In the cost-benefit relationship, it is important to recall that the implementation of structural control and monitoring systems offers owners/users a greater chance to remain operational after severe dynamic loading (reduced risk of catastrophic loss), which is relevant to retaining income immediately after the event, as well as market share. Rented facilities with high seismic design standards will be able to charge higher rents. Simple repairs can be made quickly in monitored structures before the damage becomes more extensive, potentially increasing the lifetime of the structure. Further, once the advantages of intelligent structures are widely established, the capital costs involved are expected to be offset by insurance discounts. All of these issues must be considered in such an economic analysis.

Panel members strongly believed that structural health monitoring systems are likely to be widely implemented first. Monitoring systems are used continuously, and every structure experiences some degradation in its lifetime. Thus, significantly less uncertainty exists that the system will be beneficial to the owner.

3.3.2 Sensor Technology and Data Acquisition/Processing

Both of structural control and monitoring require the use of a large number of reliable and inexpensive sensors. Recent developments in sensor technologies may offer alternatives that will significantly decrease the costs associated with such systems. Especially in the area of structural health monitoring, wireless sensors could lead to widespread acceptance of this technology. Several needs were identified relevant to sensors and data processing in such applications. These are described herein.

In monitoring (or controlling) a long-span bridge, hundreds of sensors may be employed. At this time the cost of using wireless technology is prohibitive. Thus, a tremendous amount of time is required to install the cables for recording the data and powering the sensors. These sensors and cables are also vulnerable to weather conditions, sources of electronic noise, and loading of the structure. Thus, the implementation of appropriate wireless technology would greatly simplify the installation of such systems.

Industry-wide, the price of sensors is dropping. The possibility of using MEMS sensors is one factor driving this reduction in price. For example, based on recent developments with MEMS sensors, the cost of a gyroscope has been driven from $15,000 to nearly $20. However, at this time, MEMS sensors that are appropriate for civil engineering applications (in terms of accuracy and frequency response) have not yet been developed.

Currently the use of wireless sensors is costly for our experiments and applications. However, with modern capabilities, there are no real technological barriers to the development of wireless sensors.
that are applicable for civil engineering systems. Companies in the electronics industry typically build and sell millions of a single product. At this time, the initial volume of required sensors for civil engineering applications is low, resulting in a high cost per individual sensor. Once the demand for the types of sensors required for civil applications increases, then the cost per sensor will decrease. Also, a mis-match currently exists between the needs of sensors in communications and mechanical/aerospace engineering versus those in civil engineering. To obtain the types of sensors that are needed for our applications, we must collectively determine our requirements and communicate them to the electrical engineering community that is building the sensors. These needs must address the various scenarios in which such sensors may be utilized, and include the sensitivity, resolution, frequency range of the required sensors. Clearly, developments in this field provide an example of a situation in which multi-disciplinary research is essential.

A second area where a need exists is in the acquisition and processing of the data. With reduced sensor costs, the number of sensors that may be used to monitor or control a single structure will increase. With this increase in the number of sensors, there is a tremendous increase in the amount of data that is collected. Once we have the sensors in place, we obtain a great deal of data to transfer, process, apply, and store. In many situations, real-time (or nearly) application of structural health monitoring systems is a necessity. With the advent of inexpensive wireless sensors, the number of sensors, and the amount of data, will increase significantly, resulting in an increase in the time required to transfer and process this data. Initially, monitoring systems will also be used to gain a better understanding of the behavior of the structures themselves, which will require more sensors.

Current research directions should lead to improving how we process this data to obtain useful information. In monitoring, the condition of the structure must always be compared to prior “snap-shots” of the condition of the structure. The goal is to understand how the structure behaves, and to use this new knowledge to identify damage and determine if and when repair is necessary. To do this, we need to transfer the data, which also requires infrastructure, and take that information and transform it into knowledge, so that we know what maintenance and repairs are needed. At this time most monitoring systems are being used to collect data, but the decision-making process (what to do after analyzing the data) requires further research. Appropriate algorithms are needed for these purposes.

3.3.3 Performance-Based Design

Although performance has always been an important issue in the design of civil engineering structures, structural seismic codes have focused on the integrity, reliability and safety of the structure. Certain structures, such as nuclear power plants, have been designed by considering much more than the strength of the structure and its ability to stand up after an earthquake. Serviceability of the structure has also been an important issue for such structures. The term performance-based design has been employed when we are considering the ability of a structure to perform after an event, over and above the need for strength and safety.

Performance-based design may not be necessary in all structures. However, in critical facilities such as hospitals, schools, and police/fire stations, the structure must be designed to function after an event has occurred. Additionally, industrial facilities may have a need for performance-based design. In telecommunications or manufacturing, if the structure remains standing but the equipment is destroyed, the company may be out of business for months, losing productivity and income. The reduction in risk associated with a potentially devastating event may outweigh the additional costs associated with constructing the facilities to a higher standard. Thus, the need for performance-based design is strongly linked to the life-cycle costs of the structure.

Structural control and health monitoring may lead to new directions in the design of structures to achieve performance objectives. Perhaps, in some scenarios, the performance objectives for a given structure may only be achieved with structural control systems. The establishment of criteria for performance-based design of structures involves many issues: public perception, engineering technology, structural reliability, legal/liability issues, etc. It is too simplistic to say that the goals is to design a structure that is always functional. The large amount of uncertainty in the system indicates that a probabilistic approach is required.
4 SUMMARY OF KEY POINTS

This paper summarized several issues that were identified during the panel discussion. The need for inexpensive and reliable wireless sensor technologies that are appropriate for civil structures was discussed. Related to this is the need for improved methods of processing and analyzing the large quantities of data that are obtained in typical applications. As the sensors and analysis methods improve, and the costs for the equipment decreases, the life-cycle costs of these systems will decrease significantly. There is also an interest in developing an economic framework to weigh the costs and benefits of structural control and monitoring systems. This approach is necessary to convey to the decision-makers, including engineers, owners, and risk-managers, the advantages of this technology.