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STRUCTURAL CONTROL RESEARCH ISSUES ARISING OUT OF THE NORTHRIDGE AND KOBE EARTHQUAKES

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ABSTRACT

This paper presents an overview of some important research issues related to the general field of structural control which arose as a result of the 1994 Northridge and 1995 Kobe earthquakes.The broad field of structural control is a part of earthquake engineering and deals with a wide spectrum of topics including adaptive structures, intelligent/smart materials and systems, health monitoring and damage detection, actuators, sensors, and hybrid vibration control of civil infrastructure components under the action of earthquakes, wind and man-made loads. A subset of problems related to near-field ground motion, cracked steel joints, damage detection/condition assessment, base-isolation approaches, performance of critical lifeline systems (including bridges, power systems and hospitals), active control approaches, and strengthening and retrofit of vulnerable structures are considered. For each of these topics, the relevant research issues and technical challenges underscored by the recent earthquakes are discussed. Some promising approaches to alleviate these problems are presented in the context of the broad field of structural control of dispersed civil infrastructure systems. A brief resume of high-priority research topics is presented and is used to illustrate the need for and to motivate sustained international collaboration in the field of structural control research and applications.

KEYWORDS

Northridge Earthquake, Kobe Earthquake, Structural Control, Cracked Joints, Monitoring, Condition Assessment, Base-Isolation, Active Control, Sensors, Actuators, International Collaboration

1. INTRODUCTION

Background:

In many countries the infrastructure of cities is inadequate, obsolete, inefficient, and potentially hazardous during earthquakes; and this requires special study and planning for future improvements. The subject of structural control offers opportunities to design new structures and to retrofit existing structures by the application of counter-forces, smart materials, frictional devices, etc., instead of just increasing the strength of the structure at greater cost. A variety of applications already have been installed in building structures to control wind induced motions that are objectionable to the occupants; and many applications of passive control, such as base isolation, have been installed to reduce structural accelerations produced by strong earthquake ground shaking. There is a consensus that structural control has the potential for improving the performance of structures, new or existing, if appropriate research and experimentation are undertaken.

It should be noted that "structural control" is not the same as "control theory" which has been developed in electrical engineering and applied mechanics, or the methods for control of space structures. The essence of "structural control" is the satisfactory management of the performance of relatively massive structures by physical means which require the application of large forces but do not require a high degree of accuracy. Control theory and control of space structures have developed knowledge which, to some degree, provides information of value to "structural control" but does not solve the problems of structural control.

Since the convening of the Ninth World Conference on Earthquake Engineering (9WCEE) held in Tokyo/Kyoto in 1988, there has been a growing world-wide interest in the subject of "smart" civil structures that are capable of adapting their characteristics in order to minimize their response under arbitrary dynamic environments. Several national and bilateral workshops have been convened in the recent past to deal with various aspects of intelligent structures and materials. Among such workshops that were specifically concerned with civil structures are:

1. Taiwan: "International Workshop on Intelligent Structures," (Chong et al., 1990).
2. USA: "U.S. National Workshop on Structural Control Research," (Housner and Masri, 1990).
3. Italy: "International Workshop on Intelligent Systems," (Wen, 1991).
4. Hong Kong: "International Workshop on Technology for Infrastructure Development," (Chen and Beck, 1991)
5. Japan: "National Symposium/Workshop on Structural Response Control," (Kobori, 1992).
6. UK: "First European Conference on Smart Structures and Materials," (Culshaw et al., 1992).
7. Italy: "U.S.-Italy -Japan Workshop on Structural Control and Intelligent Systems," (Housner et al., 1992).
8. USA: "International Workshop on Structural Control," (Housner and Masri, 1993).
9. USA "First World Conference on Structural Control," (Housner et al., 1994)

In addition, several countries have established, or are in the process of establishing, formal organizations to coordinate their respective national activities in the field of structural control. These activities are a clear indication of the breadth of interest in this promising and challenging field.

Recent Earthquakes in Northridge and Kobe

The earthquakes of 17 January 1994 in Northridge and of 17 January 1995 in Kobe, being moderately large earthquakes occurring in modern urban regions, provided earthquake engineers with valuable information about the performance of civil infrastructure systems subjected to near-source ground motion. While the performance of most systems during these earthquakes was quite predictable and duplicated previous experience, there was some unanticipated structural behavior as well as some encouraging structural performance of systems incorporating modern protective systems. This paper is focused on some of the significant engineering features of the earthquakes that have important implications for the broad field of Structural Control. Specifically, the following topics will be discussed:

- Cracked Steel Joints (need for monitoring and condition assessment; research on joints; NDE; radar)
- Base-Isolated Structures (pitfalls of improper isolation system properties; active isolation; near-source earthquake motion)
- Critical Lifeline Systems, including bridges, electric power systems, and hospitals (smart materials; specialized strain, acceleration and position sensors; health monitoring)
- Active Control (need for algorithms and devices for dealing with strong earthquakes)

2. DAMAGE TO STEEL JOINTS

Problem Definition:

Most of the $30 billion damage incurred during the 1994 Northridge earthquake was to be expected, given the intensity of ground shaking that the San Fernando Valley experienced. However, a totally unexpected type of damage was sustained by modern, welded steel-frame buildings. More than 100 of these structures, ranging from 2-stories to 22-stories in the region of strong shaking, sustained a variety of types of crack at the joints.

Most of the cracks were in the weld metal that attached the lower flange of the I-beam to the column flange; however, in some cases cracks developed in the column flange and, in some cases, the cracks progressed completely through the column thus cutting it into two pieces. The tallest buildings in the San Fernando Valley that sustained cracking were 18-stories high and 22-stories high. In these taller structures, the cracking at the joints occurred mainly in the upper half of the building with little damage to the lowest stories. Similar cracks developed in braced-frames, and through the 4" thick base plates under a 6-story high set of single-bay braced frames. All the cracking was clearly associated with welding, but the extent of crack propagation through the original steel of beam and column flanges was an unusual feature.

After the cracks were discovered, more than six possible contributing factors were identified by engineers, but no consensus has been achieved. It is clear that extensive "full-scale tests" must be carried out if we are to understand the cracking phenomenon and the appropriate measures to avoid cracking in future buildings. Most of the buildings that suffered cracking during the earthquake had not been identified as having damage till the newspapers reported on the first buildings in which cracks were discovered. The owners of the buildings then decided to chop through the interior wall facing and remove the fireproofing from some of the joints, and it was in this way that most of the cracks in buildings were identified. This raises the question of whether other steel-frame buildings suffered cracking at farther distances from the epicenter of the earthquake, especially, the high-rise buildings in Central Los Angeles. Similar cracking occurred during the Kobe earthquake. As a consequence, all steel-frame buildings in highly seismic regions such as Los Angeles, San Francisco, Tokyo, Beijing, etc., are now suspected of harboring such weaknesses, and is another reason why it is essential to carry out "full-scale" tests.

The fact that modern steel-frame structures have been built in almost all highly seismic countries makes this an international problem which, logically, should be studied through international cooperation. There is a need for collaboration to collect data on tests of welded steel joints that have been carried out in different countries. The data from various countries should be exchanged and analyzed for any trends, etc., from which conclusions can be drawn. This set of data can form the basis for future analytical and experimental research on cracking of welded joints.

Inspection and Monitoring Needs:

One of the major problems highlighted by the 17 January 1994 Northridge earthquake is the inability to accurately and rapidly evaluate the condition of damaged structures immediately after an earthquake. Building inspectors were overwhelmed by the scope of the disaster, and major business disruptions were suffered by many organizations (even when their buildings were not seriously damaged) due to the lack of enough trained personnel to quickly assess the structural condition of their buildings. More worrisome is the fact that there were numerous instances (some are still being discovered!) of structures appearing not to have sustained any damage that were in fact severely damaged, even though no visible signs were obvious at the time to members of the rapid inspection teams; only when suspicious engineers started a careful inspection involving exposure of such joints was the insidious nature of this damage realized! For example, in the four-story Holy Cross Hospital building, 90% of the steel joints were cracked following the earthquake, but this serious damage was not discovered for a period of weeks, during which time the hospital continued to function on a regular basis. In one instance, a 17-story building had a first mode with a 3.4 second natural period which the earthquake changed to 4.9 seconds -- a clear indication of many cracked joints. This is an extreme case in which the stiffness was reduced to 50% of pre-earthquake stiffness.

Obviously the present situation places Los Angeles City officials in a no-win situation: either not mandate detailed structural steel joint inspections and thus possibly endanger public safety, or require inspections of joints that would impose economic hardship on the building owners who already feel overburdened by too many legal requirements which lessen the economic competitiveness of the region.

Due to the significant cost involved in the careful inspection of steel joints to detect the presence of cracks, and since using traditional inspection approaches necessitates gaining visual access to the steel joint region through the removal of interior wall facing and the fireproofing material, it is clearly worthwhile to explore other approaches for the nondestructive evaluation of the condition of the suspect steel joints. Several approaches may provide useful information on the condition of welded steel joints. One of the promising approach relies on the use of state-of-the-art radar technology being used currently for military applications in conjunction with the B-2 bomber to "map" defects in the B-2 stealth bomber.

Radar Imaging Applied to Cracked Steel Joints

Radar imaging, begun in the 1960s, is a mature art. Today military reconnaissance aircraft routinely radar image (map) hostile territory. Satellites routinely radar-image large sectors of the earth's surface for a variety of purposes. Radar imaging technology is called Synthetic Aperture Radar (SAR) and derives its name from how early researchers performed their analyses using antenna theory. The fundamental concepts of radar imaging are simple enough. However, the signal processing for some applications is quite complex; it is this processing that has evolved over the past three decades. Much has been written about radar imaging, but a publication by Hughes (1983) contains a tutorial chapter on SAR that provides a good insight into the technology.

An exploratory study of the potential of the use of radar for nondestructive examination of steel framing in buildings, by employing both radar imaging and bi-static (transmit and receive antennas separated in space) radar techniques to identify cracks in steel beams and broken welds, was performed by a research team composed of investigators from USC and Hughes Aircraft Company. In these preliminary experiments, a steel I-beam (4"x8"x20") was used as a test article in which intentional defects were introduced: relatively small welder's torch-cuts in both the web and the flange. The influence of the orientation of the radar beam illumination and its polarization characteristics on the detectability of the induced cracks was investigated. It was found that depending on the test conditions and orientation of the crack relative to the radar beam, the energy scattered back by a crack may produce a large signal (i.e, the damage is clearly visible on a radar map) or a very small signal (damage not detectable) competing with a strong signal. This is the classic radar problem: extracting small signals in the presence of large "clutter." Success of the proposed approach depends upon developing discriminates that can be detected by sophisticated signal processing. These discriminates are unique to the radar application, and there is a need to develop and evaluate a variety of approaches before this exploratory approach becomes ready for field implementation.

Conceptually, in a field application, a building would be nondestructively examined using a small, lightweight, portable radar.The radar would be mounted on a quickly assembled support frame that provides the necessary angular rotation to make images. A PC would provide real-time signal processing and image processing. The radar would, of necessity, be dual polarized (possibly multi-frequency band) and would have sufficient power to overcome the attenuation of drywall, fireproofing and other common building materials. Architectural drawings of the building would provide the general location of structural support intersections, but the radar would be used to determine the exact location.

Condition Assessment Based on Signal Processing Approaches

Damage detection and structural condition assessment is a challenging problem which is under investigation by numerous research groups using a variety of analytical and experimental techniques. Nondestructive evaluation (NDE) methods for the detection of damage in structural systems have been receiving increasing attention in the recent past (Agbabian and Masri, 1988). Among the promising NDE methods are those based on the analysis of structural dynamic response measurements to identify a suitable mathematical model corresponding to the (changing) state of the physical structure. The use of system identification approaches for NDE problems has expanded in recent years due to (1) development of practical analytical methods on the basis of experimental response measures and (2) advances in data processing and signal analysis capabilities brought on by developments in sensor technology and the continually increasing computational power and economy of microprocessors.

The potential of using system identification approaches for damage detection in structures has been recognized by many researchers. However, the universe of damage detection scenarios likely to be encountered in realistic applications to all candidate physical systems is very broad and encompassing.

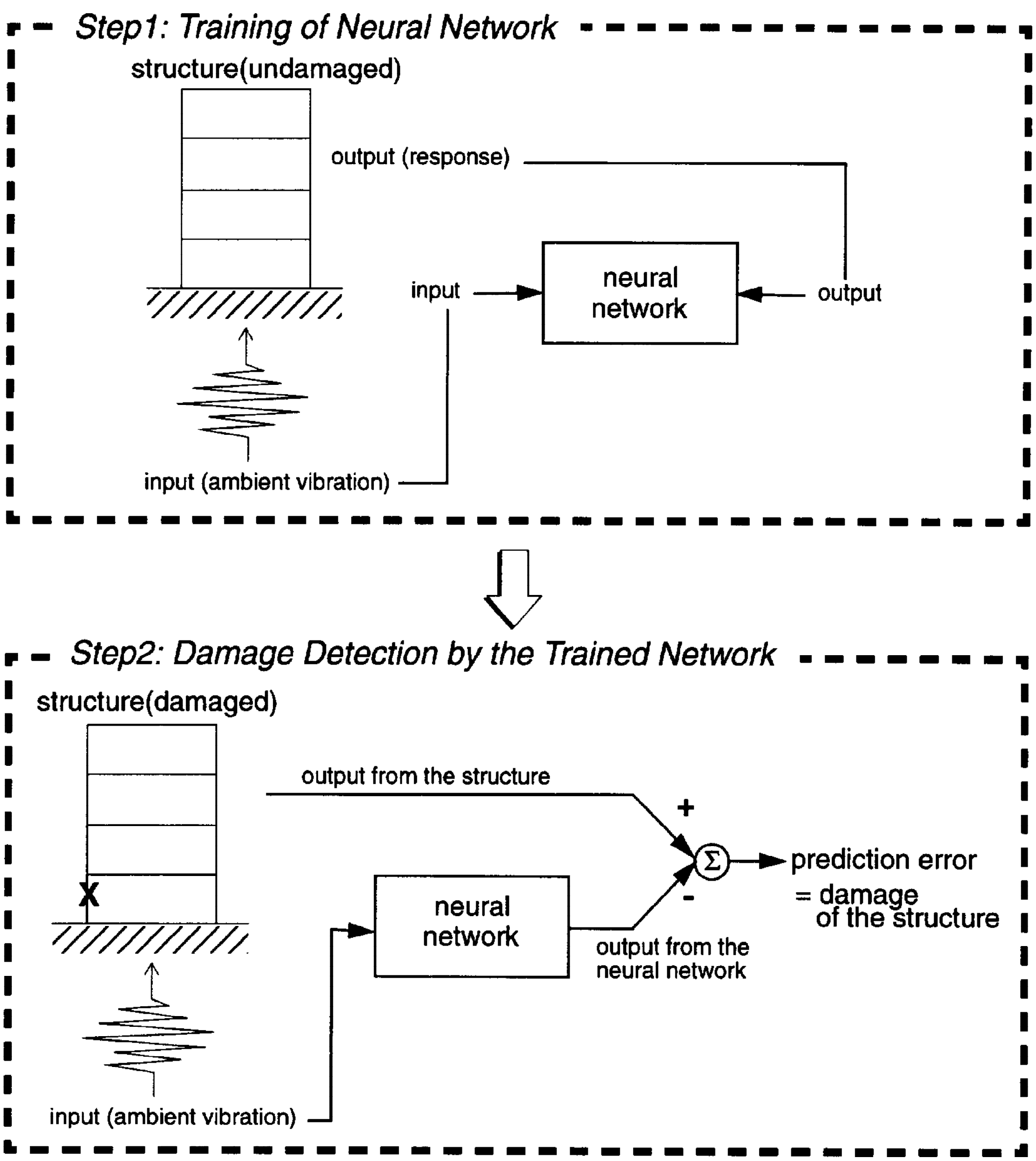

Fig. 1 Schematic diagram of damage detection using neural networks.

Among the numerous considerations which influence the choice and effectiveness of a suitable method are:

- the variety of materials of construction,
- the level of damage and deterioration of concern,
- the type of sensors used,
- the nature of the instrumentation network,
- the extent of available knowledge concerning the ambient dynamic environment,
- the degree of measurement noise pollution,
- the spatial resolution of the sensors,
- the configuration and topology of the test structure,
- the sophistication of available computing resources,
- the complexity of the detection scheme,
- the degree of a priori information about the condition of the structure,
- the selected threshold level for detecting perturbations in the system condition,
- the depth of knowledge concerning the failure modes of the structure, etc.

Consequently, there is a need for a "toolkit" of methods to deal with the variety of approaches required to cope with all the potential application situations. The above listed issues have motivated many researchers to study a wide spectrum of topics related to the signature analysis of the system response. A collection of papers focusing exclusively on the many issues and difficulties involved in the development and implementation of damage detection strategies in structural systems are available in the Proceedings of two recent workshops: (1) *Structural Safety Evaluation Based on System Identification Approaches*, (Natke and Yao, 1988) and (2) *Safety Evaluation Based on Identification Approaches Related to Time Variant and Nonlinear Structures*, Natke et al. (1993).

Role of Neural Networks in the Damage Detection of Structures

While there are many approaches that have been investigated or are still being developed for signature-based NDE of structures, health monitoring approaches that do not require detailed knowledge of the vulnerable parts of the structure, or of the failure modes of the structure, have a significant advantage in that they have the potential to cope with unforeseen failure patterns. Furthermore, health monitoring techniques that rely on nonparametric system identification approaches, in which a priori information about the nature of the model is not needed, have a significant advantage when dealing with real-world situations where the selection of a suitable class of parametric models to be used for identification purposes is quite often a daunting task.

Among the structure-unknown identification approaches that have been receiving growing attention recently are neural networks. A study by Masri et al. (1993) has demonstrated that neural networks are a powerful tool for the identification of systems typically encountered in the structural dynamics field. In conventional identification approaches employed in structural engineering, modal information or information about the mathematical model of the structure is needed to accomplish the identification and subsequent "damage" detection. Assumptions regarding the linearity or nonlinearity of the underlying physical process (structural behavior) will have drastic effects on the model selection and the accompanying identification scheme. On the other hand, not only do neural networks not require information concerning the phenomenological nature of the system being investigated, but they also have fault tolerance, which makes them a robust means for representing model-unknown systems encountered in the real world.

A study by Masri et al (1996) explores a methodology based on using a neural network to detect parameter changes in either linear or nonlinear systems. A schematic diagram of this damage detection methodology using neural networks is depicted in Fig. 1. It is shown that the proposed approach is a robust method for detecting, through the monitoring of the system restoring force, of relatively small changes in the dominant parameters of the underlying physical system.

3. BASE-ISOLATED STRUCTURES

Problem Definition:

The recent Northridge earthquake, which was of magnitude 6.7, was the strongest earthquake to hit the Los Angeles metropolitan area. While there were numerous structures and systems that suffered severe damage and demonstrated the penalty for not devoting sufficient attention to seismic mitigation measures, there were also some examples of success stories that illustrated the benefits and cost effectiveness of appropriate structural control approaches when intelligently applied to actual structures.

The California Office of Statewide Health Planning and Development (OSHPD) reported that 18 Los Angeles area hospitals sustained moderate or major damage. It is estimated that the earthquake damage repair expenses to hospitals could reach $1 billion, out of which about $390 million is in damage to the Los Angeles County - USC Medical Center, a county-run facility administered by the USC Medical School. Two older buildings in this Center sustained severe damage that necessitated their closure the Pediatric pavilion and the Psychiatric hospital. Among the private hospitals that suffered serious damage are: Northridge Hospital Medical Center, Holy Cross Medical Center, Cedars-Sinai Medical Center, St. Johns's Hospital and Health Center, and Santa Monica Hospital Medical Center. Two additional major public hospitals had their operations interrupted during the critical period after the earthquake due to nonstructural damage: Olive View Hospital and Veteran's Administration Hospital.

The new University Hospital building is located at the Medical Campus of the University of Southern California in East Los Angels at 1500 San Pablo Street, about 36 kilometers southeast of the epicenter of the earthquake. This is an eight-story steel braced frame structure which is base-isolated by means of a combination of elastomeric and lead-rubber bearings. A total of 68 lead-rubber bearings are used at the exterior columns and 81 elastomeric bearings are used at the interior columns. Due to site topography and architectural requirements, the plan for this structure is not regular, thus posing some challenging structural dynamics problems. Due to the important nature of the facility the California Office of State Architect was involved in evaluating the design of this hospital. Both, a conventional fixed-base design and a base-isolated design were considered, and it was determined that the latter design is optimal based on overall cost and the estimated level of reduction in damage due to future earthquakes.

During the subject earthquake, 27 records of data were obtained from the extensive instrumentation network. Analysis of the results indicate that the isolators fulfilled their design objective. It is clear from inspection of the recorded response that the base isolators did indeed act as a low pass filter whereby the peak level of acceleration was reduced and the accelerations in the structure clearly indicate the absence of high frequencies (contained in the base input record) from the recorded response within the hospital. The manifestation of this fact is that some hospital personnel who were in the building during the initial earthquake and subsequent aftershocks reported gentle swaying of the building (similar to being on a water bed) which made some people start feeling seasick.

It is worth pointing out that in an adjoining building with a fixed base, the pharmacy suffered significant nonstructural damage, while virtually nothing at all fell in similarly "stacked" storage facilities in the base-isolated hospital.The performance of the USC University Hospital is a very encouraging experience to engineers involved in the field of structural control, since it vindicates their contention that the emerging field of structural control has much to offer as an effective seismic mitigation approach.

Where the contents of structures must be protected against earthquake shaking, as in the case of nuclear power plants, hospitals, emergency communications systems, etc., the Northridge earthquake demonstrated the effectiveness of the base isolation system. This is an encouragement to explore other methods of controlling motions of structures during earthquakes, such as active control of structures. To verify the effectiveness of structural control, it is desirable to first apply such methods to ordinary buildings and thus develop necessary information.

Even though several additional large base-isolated structures in Los Angeles and Kobe performed well during strong shaking (IASC, 1995), there was also a dramatic demonstration of incorrect use of isolators. An individual in Los Angeles who was a strong believer in the structural control capability of base-isolators, equipped his private residence with commercially available isolators. However, since the isolator system dynamic characteristics were not properly selected, the combined building-isolator system caused an amplification instead of reduction in the building's response, and it sustained more damage than neighboring structures on conventional foundations! Obviously, this is not the fault of base-isolation approaches, but rather the failure of proper understanding of all the ground motion and structural dynamic factors which govern the total system.

A comprehensive study by Hall et al (1995b) dealing with near-source ground motion and its effects on flexible buildings has pointed out several worrisome factors that hitherto have not received adequate attention. Specifically, this paper points out that ground shaking associated with large earthquakes close to cities will subject buildings in the near-source region to large ground displacement pulses which are not represented in current design codes. Using simulation studies and projected earthquake ground motion levels, the study indicates that flexible frames and base-isolated structures might experience strong nonlinear behavior leading to failure.

Potential Solution:

The interaction between the long-period ground motion and the gap left around base-isolated structures requires careful attention in order to avoid serious damage. A promising approach in the structural control field that can alleviate this problem and even enhance the performance of the isolation devices is to use the concept of "active isolation" whereby the isolator and the damping characteristics are automatically adapted to match the earthquake ground motions without encountering the dead-space nonlinearity problem. A passive version of this approach involves using hydraulic dampers with nonlinear force characteristics to limit the sway space under strong ground motion. This concept is currently being implemented in a new hospital complex under construction for San Bernardino County in the city of Colton, California. Future versions of such dampers may have adaptive capabilities which will be controlled through the use of controllable orifices or by using "smart materials" such as elctroreheological or magnetoreheological fluids (Masri et al, 1994b).

4. LIFELINE SYSTEMS

Bridges:

Many bridges were damaged and seven bridges collapsed in the Northridge earthquake. Detailed evaluations of California bridge performance under the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake are documented in *"Competing Against Time: Governor's Board of Inquiry Report on Loma Prieta Earthquake"* (Housner, 1990), and *"The Continuing Challenge: Report of the Seismic Advisory Board to the California Department of Transportation,"* (Housner, 1994).

Geologists in Southern California recently have identified the Elysian Park fault as being similar to the fault that generated the Northridge earthquake but, instead of underlying the San Fernando Valley it underlies Central Los Angeles. It is estimated that a M7.0 earthquake could be generated on this fault and this would subject a large area of Central Los Angeles to ground shaking of intensity equal to or greater than that experienced in the Northridge area. This hazard, together with the known performance of the structures during the Northridge earthquake will provide a considerable stimulus to structure owners to upgrade the seismic resistance and to control the amplitudes of vibration. One of the candidate structures that is currently being analyzed and is in the retrofitting stage is the Vincent Thomas bridge at the Los Angeles Harbor.

The Vincent Thomas bridge is a suspension bridge composed of three 2-hinged decks with massive piers, having a total length of about 2000 feet. It was constructed in 1963 and has been provided with an extensive set of strong motion recorders that have provided valuable information about its dynamic behavior during several earthquakes to which it has been subjected during the intervening years. The bridge has several modes with natural frequencies under 1 Hz; its equivalent ratio of critical damping in the first few modes is about 1%. A variety of structural control approaches and concepts are being considered for the retrofitting of this important bridge. A crucial part of the retrofitting efforts is to install an integrated health monitoring system capable of quickly diagnosing the condition of the bridge under arbitrary dynamic loads caused by natural or man-made loads.

As part of a demonstration study to establish the capability of state-of-the-art instrumentation systems and associated signal analysis techniques to monitor the condition of this bridge, the authors were recently involved in an experimental study to use high-resolution sensors in conjunction with a cellular data communication systems (Housner et al, 1996). Using the remote data communications capability of this temporary system, data were recorded at various times of the day and week. Remote real-time transmission of data was also verified. A sample power spectral density measurement results corresponding to a specific sensor at three different time periods of the day are shown in Fig. 2. The plotted results clearly indicate the extremely low level of "noise" in the acquired ambient measurements due to the 19-bit resolution of the sensor used. The results also indicate the challenge to health monitoring approaches based on vibration signature analysis techniques posed by the sensitivity of the spectral results to temperature variation within

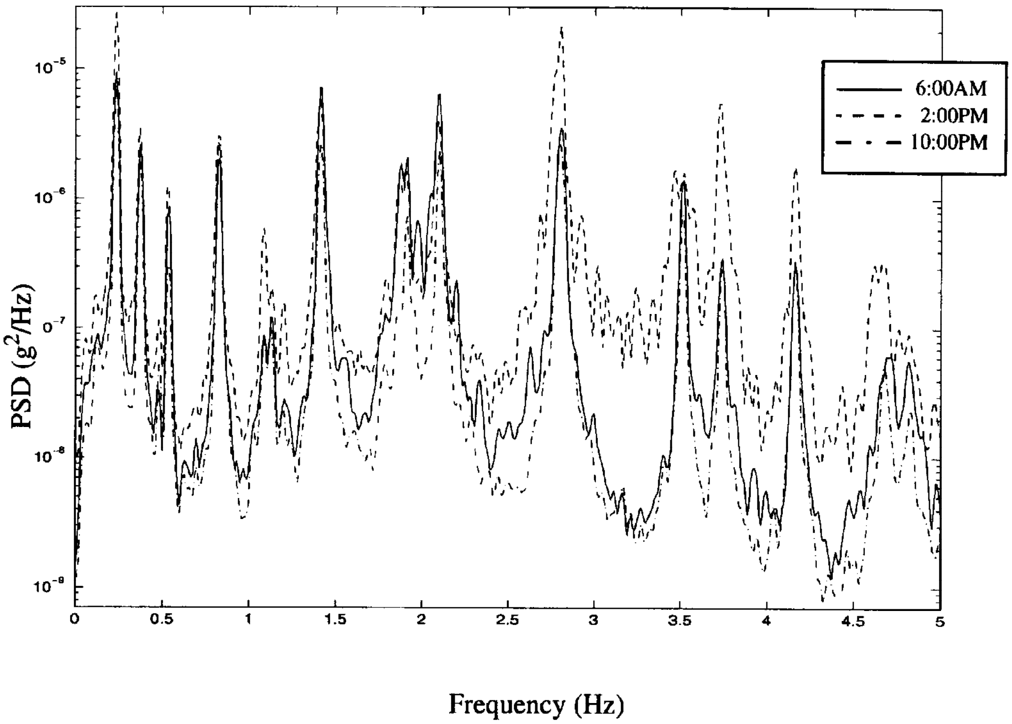

Fig. 2 Sample measurements from the Vincent Thomas Bridge.

the same day. Clearly, the ability to detect relatively small changes due to deterioration or damage in the monitored structures requires a reliable method for factoring out variations induced by cyclical thermal effects.

Electric Power Systems:

Electric power facilities in the Northridge and Kobe regions sustained severe damage, in spite of the fact that prudent seismic mitigation measures were taken. A detailed report on the performance of such systems is available in the work of (Hall, 1995a). Even though the operators of electric power plants are highly motivated to incorporate sophisticated seismic mitigation measures in their system, they have to cope with the lack of suitable sensors for determining the dynamic conditions of their dispersed systems. The instrumentation challenge is posed by the harsh electromagnetic conditions as well as the extreme thermal loads due to high voltages being handled by the system, which renders conventional instrumentation inoperable.

Applications of sensors and sensor systems must take into account the environment in which they will be located. In electric power systems, the environments can differ markedly -- from transmission lines, to substations, to generation stations or nuclear power plants. Some components produce intense electromagnetic fields that can interfere with the functions of the sensors and vice versa. For instance, all high voltage equipment must be designed with enough creepage distance to withstand a potential flashover. This distance is usually provided by a tall porcelain or polymeric bushing. Sensor placement must, therefore, be accomplished without compromising the essential insulation properties of the bushing for a variety of environmental conditions such as contamination, mist, rain, etc. Furthermore, it must be ascertained that these high electromagnetic field (EMF) sources will not interfere with the collection and transmission of signals from the sensors to their monitors. Therefore, research to place these sensors appropriately for various components within an electric power system is an important task. Such a placement strategy can only be confirmed by experiments and measurements done at an actual power station.

Sensors can be used, not only to monitor stress and strain, but also, potentially, incipient electrical failure. A knowledge of temperature or electric field strengths will provide useful information in the early detection of power system component failures. Such information may be fed into neural networks or expert systems for decision analysis.

High voltage substation insulators and bushings presently use porcelain. Numerous porcelain insulators and bushings failed during the most recent Northridge earthquake, and more service disruptions can be expected during even moderate tremors. It is practically impossible to embed sensors in porcelain and, therefore, it is necessary to develop or utilize innovative materials that can work with sensors in a high EMF environment.

Potential Solutions: Fiber Optic Strain Sensors

Optical fiber sensors, unlike conventional electrically-based sensors, are fabricated with high-strength silica which will not corrode or be affected by electromagnetic interference (EMI). Their small size and geometric flexibility allows them to be unobtrusively embedded or surface-attached to the host structure. Fiber optic sensors have been used for the quantitative, non-destructive evaluation of advanced materials and structures for over ten years, (Dakin and Culshaw, 1988). For example, in composites, fiber sensors have been demonstrated to be feasible for the measurement of internal material changes during fabrication, the in-service lifetime measurement of strain, temperature, vibration, and other physical perturbations, and the eventual detection of damage or property degradation.Recent advances in fiber optics communication technology and the widespread use of fiber communications have made available a large selection of reliable and inexpensive opto-electronic devices and components for use in sensors and sensor instrumentation support systems. An analytical and experimental study concerning the application of fiberoptic sensors to civil infrastructure systems is reported in the work of Masri et al (1994a).

Optical fiber-based Fabry-Perot sensors reported in the literature have been shown to be highly sensitive to temperature, strain, vibration, acoustic waves, and magnetic fields (Claus, 1992). Fiberoptic sensors are capable of being imbedded or surface mounted on electrical system components to accurately measure absolute displacement and acceleration of critical components. Such sensors can become an integral part of an on-line, real-time data acquisition and signal processing system for continuous health monitoring of electric power systems.

Hospital Facilities:

In the 1994 Northridge earthquake, 68 hospitals in the region had their normal operations disrupted by nonstructural damage. The Northridge earthquake provided further evidence as demonstrated in past events that the functioning of a hospital during the critical hours following an earthquake depends to a large extent on the control of damage to nonstructural components of the building and the equipment. The importance of paying attention to the contents of hospitals was clearly illustrated by the performance of the Olive View hospital during the earthquake. Even though the hospital did not suffer any significant structural damage (having been newly constructed at the site of a similar hospital which collapsed during the 1971 San Fernando earthquake), its nonstructural components were damaged thus effectively shutting down the operations of this emergency hospital at the most critical time!

Obviously, the general field of structural control has a lot to offer hospital lifeline systems from the point of view of monitoring and vibration control of critical nonstructural components, particularly those that require more than simple anchoring to maintain their functionality during and after a strong earthquake. A related item which deserves much attention is the need to develop a *performance-based* code for seismic mitigation of nonstructural components in hospitals and critical care facilities.

In order to evaluate the vulnerability of nonstructural components, to determine their importance in the functioning of a hospital, and to develop suitable standards for hazard mitigation, it is necessary to view the issues from a multi-disciplinary perspective, using modern aerospace "system architecting" approaches. A distinguishing feature of such an approach to the problem, is that all aspects of the functional performance of hospitals during and after earthquakes are addressed in a systematic way to establish quantitative probabilistic measures of the contribution of all pertinent subcomponents of the hospital system (communication, water, power, fuel, equipment, sprinklers, etc.) to the overall performance of the critical facility. When the subcomponent fragility level is established (on the basis of analysis and/or testing), this systematic approach will yield the optimum level of nonstructural systems "hardening" that is needed to achieve a cost-effective level of earthquake resistance for various levels of postulated earthquake intensity levels.

5. ACTIVE STRUCTURAL CONTROL

Background

The NSF-sponsored *U.S. National Workshop on Structural Control Research* (Housner and Masri, 1990) identified the major research needs in the field of structural control and provided a prioritized list of research topics in the various aspects of the field: analytical methods, experimental approaches, building applications and critical function facilities. A follow-up NSF-sponsored Workshop on *Sensors and Signal Processing for Structural Control* (Roberts and Bennett, 1991) concentrated on further refining of the research needs in the areas of sensors, signal processing, and actuators. More recently, the NSF-sponsored *International Workshop on Structural Control* (Housner and Masri, 1993) updated the recommendations concerning high priority research needs. The research needs and impediments to the implementation of this promising technology were further discussed and clarified by two *"Position Papers"* presented at the 1994 *First World Conference on Structural Control*, (1WCSC), (Housner et al, 1994) by Housner et al (1994b) and by Kobori (1994) who identified the research needs for the second generation of active control devices for civil structures. Detailed surveys of research activities and technical issues associated with active vibration control of civil structures are available among the more than 230 papers published in the *Proceedings of 1WCSC.*

Space limitations preclude a listing of the many research issues which still await investigation. However, one of the major themes that kept appearing in the deliberations of the different Working Groups during the Workshops is the need for *actuators* that can cope with the extreme demands of practical applications under *strong* earthquake ground motion. The cited references furnish an overview of the major research issues in the dynamic response control of structural systems. There are major difficulties that need to be resolved before such control strategies become practical for handling strong earthquake shaking.

<u>Structural Control Research Issues Arising From the Recent Northridge and Kobe Earthquakes</u>

Even though there are now more than 20 active or hybrid control devices installed in large civil structures (nearly all of them in Japan), and even though these devices have been performing flawlessly in providing comfort control under wind loading and minor earthquakes (which was their intended purpose), *none* of these devices worked during the Kobe earthquake. The active/hybrid devices which were subjected to the Kobe earthquake were located in Osaka (some distance away from the strong shaking region). The level of shaking in the Kobe earthquake caused their motion to exceed design specifications; consequently, the control devices were shut down in an orderly manner as a precaution to prevent damage to the active control system. Of course, this episode does not detract from the impressive record of performance of the active control systems in mitigating undesirable oscillations due to wind excitations or minor earthquakes; it does however dramatically illustrate that there is a quantum jump needed in the development of actuators and associated control algorithms suitable for dealing with large structures under strong earthquake ground motion.

Based on the preceding observations concerning the (inadequate) performance of active control devices during the Kobe earthquake, the Japan Society for the Promotion of Science (JSPS) has recently awarded the Japan Panel on Structural Response Control an initial installment of about $800,000 to be spent by March of 1996, to embark on a new research and development initiative focused on the mitigation of the dynamic response of large civil structures under *strong* earthquake loads. The R&D effort is focused on the development of (1) a new generation intelligent aseismic structural control hardware system, (2) aseismic control algorithms, (3) testing of aseismic structural control models, and (4) evaluation of aseismic control performance and development of design criteria. It is obvious from the above discussion that one of the most crucial tasks in the research effort of the Japanese researchers is the development of practical (i.e., energy efficient) actuators suitable for handling the large response of civil structures under strong earthquakes.

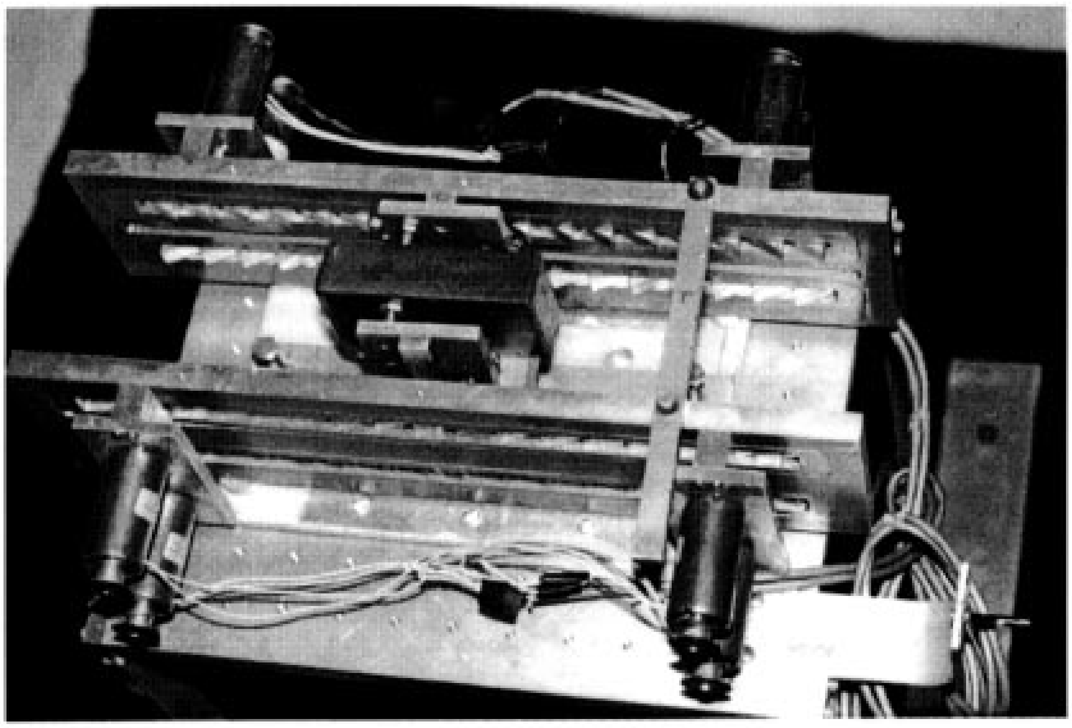

Fig. 3 Mechanical model of semi-active impact damper.

Control Actuators

A review of structural control literature reveals that there are few studies dealing with actuators for structural control. Needless to say, the ultimate success of any structural control scheme, regardless of its potential (hypothetical) effectiveness, depends on the availability of physical actuators to generate the necessary control actions. Since one of the impediments of structural control approaches for full scale structures is the demands on energy and power requirements of the control actuators, the NSF Workshops cited above stressed the need to do more experimental research in novel actuation techniques, particularly those that have the potential of use under strong earthquake loads.

Transduction techniques that have been put forward so far in the structural control community include: active tendons and braces, active mass dampers, active structural appendages, and thrusters. Full scale tests on model buildings have been performed using active braces and active mass dampers. Nevertheless, it is widely recognized in the structural control community that no one class of actuators will be suitable for controlling all types, sizes, and configurations of civil structures under all anticipated types of dynamic environments. Consequently, it is crucial to investigate alternative control actuators and associated motive power to drive particular classes of control procedures.

A promising approach in the development of practical actuators for civil infrastructure applications under strong earthquake shaking is to develop semi-active devices which utilize a relatively small amount of energy to actively control a critical *parameter* of the actuator, rather than directly use a large amount of control energy to counteract the strong disturbance. An example of such an approach is shown in Fig. 3. The illustrated device has a momentum exchange component whose nonlinear parameters are actively controlled to maximize the amount of "chaos" that can be injected into the dynamic response of the primary structure whose motion is to be attenuated (Masri et al, 1989). Another parameter control system in which the stiffness of selected components is actively controlled has been investigated by Kamagata and Kobori (1994).

6. INTERNATIONAL COLLABORATION

The nature of cooperative research that will be of particular importance in the coming years includes: reduction of natural disasters of earthquake, wind, flood, landslide, tsunami, and wildfire. In addition, the retrofitting and upgrading of the civil infrastructure is of great importance in the United States and also in other countries. For example, Japan and China have the same problems of natural disasters and also of building and retrofitting the civil infrastructure, so cooperative research could be of great benefit to all three countries.

Cooperative research could be of several types:

1) different aspects of the same problem could be studied in two or more countries in a coordinated program;
2) a large experimental project could be undertaken in one country and subsidiary projects by researchers from other countries could piggyback on the main project;
3) researchers on related projects in two or more countries could meet annually in a workshop to exchange information and make recommendations for future projects.

In the past, one of the difficulties in establishing a coherent cooperative program has been the identification of the problem and bringing together appropriate researchers to cooperate. For example, the organization of the relevant public and private agencies in the United States, Japan, and China differ so greatly that it is difficult to arrange cooperative projects between appropriate researchers. This is unfortunate because the success of cooperative research depends mainly upon a good match of the interests and plans of the researchers involved.

Improvement in cooperative research programs could be achieved by coordination on a planning level in which a Planning Panel is established in each country whose function is to keep informed on the research projects underway and to identify such projects that would benefit from international cooperation. Representatives from each of the panels would constitute an International Oversight Committee that would meet at intervals for the purpose of identifying, initiating, facilitating, and coordinating cooperative research projects. The members of the Oversight Committee would serve for a prescribed term of office, perhaps three years, and an orderly procedure established to retire existing members and bring in new members. In this way there would be continuity in the functioning of the Oversight Committee and, consequently, a continuity in the cooperative research program.

The Oversight Committee would not undertake research projects but would focus on strengthening the cooperative research programs between the countries. The Oversight Committee would act as a standing Advisory Committee whose value would be enhanced by its continuity of service. The name International Initiative for Intelligent Infrastructure Research (I^4R) has been proposed to identify the activity of the Oversight Committee.

In 1994 at the International Conference on Structural Control which was held in Los Angeles, it was agreed that close cooperation between Japan and the United States on earthquake engineering research could potentially be very valuable. The program I^4R was prepared to illustrate how cooperation on research could be implemented. It is true that there have been cooperative projects between the two countries in the past; however, these did not have a continuing oversight and correlation of the research work. This intermittent oversight could be avoided by means of the I^4R type of arrangement. The Japan Committee together with the United States Committee could form the I^4R Coordinating Committee. With its experience, the I^4R Coordinating Committee could make recommendations on research projects that should be undertaken in the future to reduce disasters. In addition, a special joint committee could be formed to provide coordination for a specific project. In future phases, other interested countries could join the Initiative. A sample organization chart of an I^4R initiative for research on steel joint problems is shown in Fig. 4.

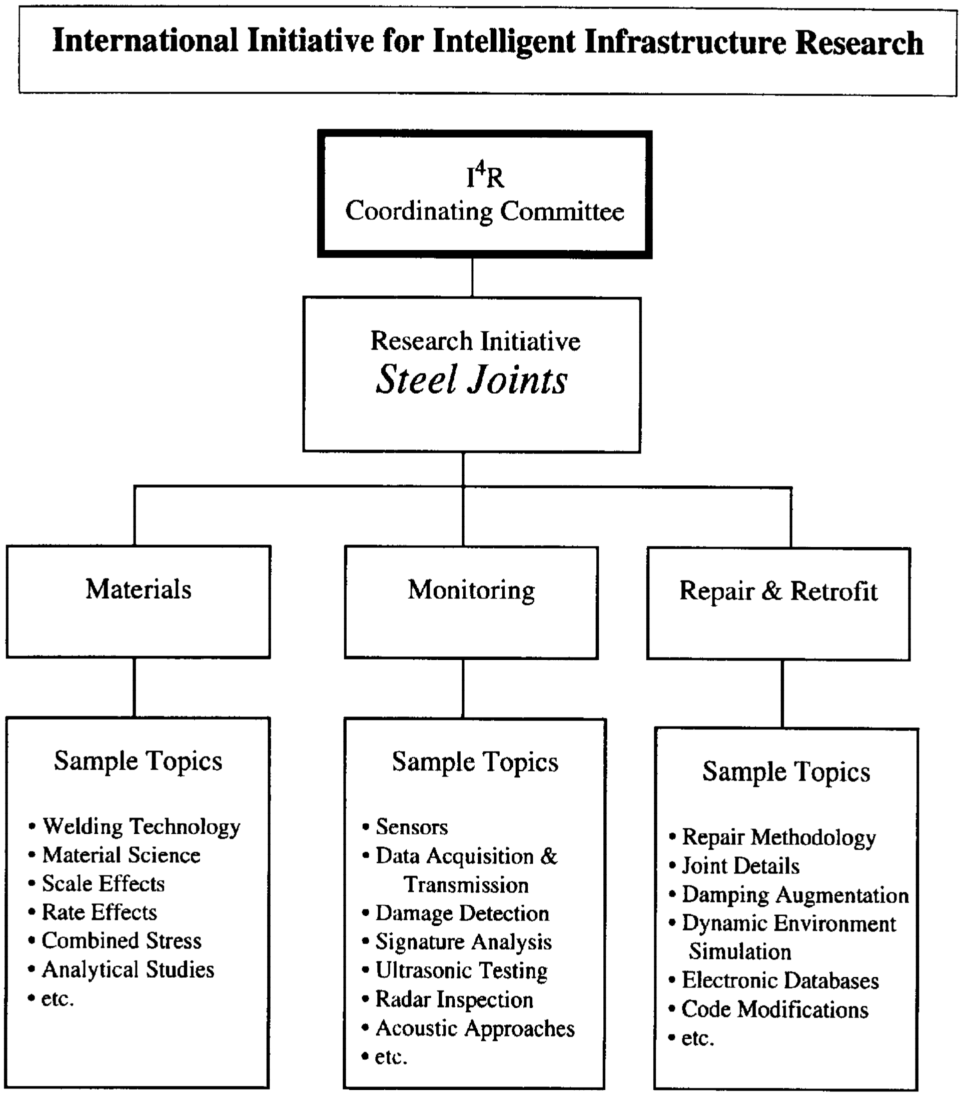

Fig. 4 A sample organization chart of an I^{4}R initiative for research on steel joint problems.

7. SUMMARY and CONCLUSIONS

Based on the preceding discussion, it seems highly desirable to encourage structural engineers and architects to seriously consider exploiting the capabilities of structural control for retrofitting threatened existing structures and also enhancing the performance of prospective new structures that may be subjected to strong earthquake shaking.

Even though a considerable amount of progress has been achieved in the field of seismic response control using various passive and active approaches, there are still many diverse research topics related to the control and monitoring of structural systems that need study and await resolution before the promise of the smart structures and materials technology is fully realized in the context of seismic response control of civil infrastructure systems. Progress in this field will be speeded by multi-national efforts involving world-wide collaborative research projects, exchange of personnel, jointly organized tests, and exchange of data and technical information.

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