Structural Engineering and Structural Response Modification Research: The Center Approach

by

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ABSTRACT

This paper briefly describes the structural engineering research activities at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) from a systems performance perspective. MCEER is established by the National Science Foundation to carry out systems integrated research in earthquake engineering that could not easily be accomplished by using the individual investigator's approach.

By using the "center's approach" the structural engineering studies are components contributing to the required performance level of a system. Under this system context, structural engineering projects including examples related to seismic response modification technologies are outlined.

KEYWORDS: structural engineering research; center approach

1.0 INTRODUCTION – MCEER RESEARCH PROGRAMS

MCEER's research objectives are twofold: to increase earthquake resilience by developing seismic evaluation and rehabilitation strategies for the critical facilities (hospitals) and systems (electrical and water lifelines) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake.[1]

The significance of these research objectives is supported by a recent NSF-funded research project conducted.[2] In 1999, a survey was conducted with a random sample of residents in Alameda County, California, where many of the impacts of the Loma Prieta Earthquake were experienced. Respondents were given a list of 20 types of structures (e.g., public schools, office buildings, apartment buildings, etc.) and systems (highways, water systems, communication systems, etc.), and were asked to identify the five most important structures or systems that **must** remain functional and operational during and following an earthquake. The three most frequently given responses were: water pipelines and facilities (mentioned by 76% of the respondents); hospitals (76%); and electrical power lines and facilities (73%). The next most frequently given response was the importance of functionality for public safety buildings (48%). These four types of structures and systems — identified by the Alameda County residents as the most critical systems that should remain functional — completely overlap with three coordinated program areas MCEER has identified as thrust areas for intensive research, by using the "center approach."

MCEER research thrust areas can be summarized in Figure 1.

2.0 SEISMIC EVALUATION AND RETRO-FIT OF HOSPITALS

The objective of this MCEER research thrust is to identify, explore and develop advanced technologies for the rehabilitation of hospitals to meet or exceed the high level of performance

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expected of these facilities. The initial expense of these technologies may be high, but increased implementation based on sustained research efforts is expected to reduce future costs to the point where overall costs will be less than for conventional retrofitting.

To properly account for the differences in type of construction as well as in the seismic environment and awareness of the eastern and western United States, close links have been established with both the New York State Department of Health (NYSDOH) and the California Office of State Health Planning & Development (OSHPD). California has already enacted legislation that makes it mandatory for health care facilities to evaluate the seismic adequacy of their buildings by January 2001, and upgrade these facilities to ensure life safety by 2008, and full operationality following earthquakes by 2030. Advanced technologies are already being considered as potentially the only way to achieve these stringent seismic rehabilitation projects. The established cooperation between the California OSHPD and MCEER is thus ideal to achieve the aforementioned synergy goals. Furthermore, participation of key members of the NYSDOH offers similar advantages, albeit with the recognition that seismic risk mitigation in these other states of lower seismic awareness, in the absence of legislative pressures, will require additional effort to justify the need to allocate resources for seismic retrofit of hospitals in a community.

The MCEER hospital research program may be classified into the following tasks.

2.1 Technology Portfolio: Structural

The technology portfolio contains a balanced mix of low-risk, moderate risk and high-risk technologies. Low-risk technologies are defined as those being near implementation and having a high probability of acceptance. Moderate risk pertains to those technologies with a mid-term range for implementation and that have a moderate to high probability of acceptance. High-risk technologies are those defined as having long-term implementation potential and a moderate probability of being accepted.

This task is currently invested in the following technologies: Passive control technology – dampers and base isolation systems (low risk); metallic passive energy dissipation approaches (low risk); passive energy dissipation using new composite materials (medium risk); and hybrid systems (high risk). This task focuses mainly on the concept of passive energy dissipation (which is the most promising at this time), these technologies can be divided in two distinct approaches: Use of specific manufacturer-produced devices, and use of infill materials. In each case, technologies at the various risk levels are being considered.

While some technologies exist to address the problems at hand, best solutions may actually be discovered amongst the new materials and enabling technologies that are constantly emerging. Hence, MCEER regularly conducts workshops to investigate how new and emerging material and enabling technologies could be used in a seismic rehabilitation perspective. This assures the dynamic nature of the task on Structural Technology Portfolio.

2.2 Technology Portfolio: Nonstructural Evaluation and Retrofit

The seismic performance of nonstructural components is a most important issue in hospitals. MCEER's research on the seismic performance and rehabilitation of nonstructural components focuses on ensuring that the hospital's critical equipment remains functional as a result of excessive structural response.

Research must thus seek to determine the conditions that lead to those undesirable levels of performance. The path towards resolution of this complex problem has many barriers. First, the key input parameters that impact seismic performance are not well known for the various types of failure and nonstructural systems considered, whether these are peak or relative floor accelerations, velocities, displacements, energies, or others. This requires fundamental research work on calibration and sensitivity of fragility curves, as well as experimental testing to establish performance of various systems considering examples of equipment rocking, equipment sliding, light and heavy piping systems, large tanks and reservoirs, and other special critical components such as elevators. Second, the most promising advanced technologies to effectively retrofit these systems must be identified and their effectiveness must be analytically and experimentally established. Third, the complex interaction between structural and nonstructural retrofit must be understood and optimized. Indeed, some structural retrofits may abate or eliminate the need for many nonstructural retrofits, and whether one should focus on expensive technologies to control the structural behavior or invest to comprehensively retrofit the nonstructural equipment is an unanswered question. This is particularly important given that the available resources and incentives for seismic retrofit vary greatly across the various seismic regions of the country, and that the acceptable levels of seismic performance differ accordingly. The best strategies for trade-offs in seismic and non-seismic retrofit are likewise tied to these constraints. This also requires the establishment of complex linkages between fragility analyses for both structural and nonstructural components, and depends greatly on the reliability of these analyses.

2.3 Fragility Analyses Development

Full operationality of a hospital following a major earthquake is a stringent performance requirement that requires consideration of non-conventional analysis tools. Furthermore, the engineer must be able to formulate his/her recommendations on structural and nonstructural performance in a format manageable by the key decision-makers. Experience indicates that a probabilistic approach is best suited for this purpose, and fragility curves can provide the framework necessary to cast the problem in the desired format. This analysis platform also makes it possible to integrate seismological uncertainty, and can provide engineering data in a format compatible for cost-benefit analyses. Some key challenges in this research tasks are: First, fragility intrinsically depends on the available of practical and accurate analytical tools. Research is needed to establish whether and how the gains in computational complexity can enhance the reliability of fragility curves. Second, the representation of fragility curves as a function of peak ground acceleration is inadequate, and alternative measures of the ground motion intensity that better capture behavior in a representative way must be investigated. To find an accurate and simple definition of fragility curves, basic research involving sample properties of stochastic processes must be conducted, followed by development of the identified ground motion intensity measures into simple measures for practical implementation. Third, the gradients of various seismic performance indicators calculated relative to the uncertain system and input parameters, also know as sensitivity factors, can be used to identify the critical components of a system, that is, the components that affect the most the overall seismic performance of the system. The identification of critical components is most useful to, for example, develop rational rehabilitation strategies for existing structures. However, current computer codes provide no information on sensitivity factors.

2.4 Facilitating Technologies: Structural Evaluation and Retrofit

Facilitating technologies within the context of MCEER Hospital Program are the principles and approaches that must be developed to implement the advanced technologies in building retrofit by the architectural and engineering professional community. It is the heart of system integrated approach concerning the performance of a system (structure with added device and material components), so that cost-effective strategies can be realized by the designers for a given structure and prescribed earthquake risk. The spectrum of research includes some very fundamental dynamic responses of structures that may only be studied by multiple DOF models including nonlinear effects on one hand, and some very practical issues such as the formulation of simple design guidelines and procedures on the other. In between, a major challenge is the development of user-friendly computer programs that are the tools for the engineers to realize the conclusion of a cost-effective retrofit strategy.

Hospitals found in the eastern United States generally have a steel structural frame system, the older ones having frames assemble using flexible semi-rigid connections, the newer ones having more conventional steel frames with rigid connections. Many, when located in dense urban centers, are mid-rise buildings, with 20 story buildings being common in dense urban centers. As a result, these buildings generally have a longer period which attract lower seismic forces, but typically undergo large drifts during earthquakes, and may therefore suffer from both structural and nonstructural damage, and in some instances risk collapse from global instability. This later damage state is particularly difficult to quantify and may require special consideration. The low-rise hospital buildings typically found across the country also rely on flexible frames to resist earthquakes, the greater architectural flexibility afforded by frames having a considerable appeal. In fact, in many instances, masonry partitions infills originally erected within the steel frames of older hospitals have been generally removed over time as most hospitals reorganized their space usage and underwent various remodeling. Advanced technologies to seismically retrofit this type of hospital having flexible structural systems are thus required and is first investigated. Both hysteretic energy dissipating sacrificial elements and passive and semi-active damping technologies are pursued toward that goal. While dampers are becoming more appealing in the western United States, their cost may be a barrier to implementation in zones of low to moderate seismicity. Special hysteretic structural components may be more acceptable, but research is required to determine which approaches can lead to satisfactory seismic performance. Hence, both strategies must be pursued: (a) damping technologies as well as ways to leverage the performance of dampers (such as scissor-jack dampers) must be investigated, and (b) advanced composite and/or cementitious materials must be considered as potential techniques to favorably modify building response. Techniques to control excessive drifts and potential instability effects without reducing the period (such as to prevent large floor acceleration) are desirable.

2.5 Geotechnical Technology Portfolio: Evaluation and Retrofit of Liquefiable Soils

A significant problem arises from the fact that many hospitals have been constructed on soils that are likely to liquefy during an earthquake. While it is relatively easy to consolidate such liquefiable soils in the freefield, there currently exists no simple retrofit procedure that permits geotechnical remediation at minimal or no disturbance to the occupants. The problem is further compounded by shortcomings of the existing analytical models when attempting to model the behavior of pile-foundations on liquefiable soils. The geotechnical research within the hospital project aims at the experimental investigation of advanced technologies to fill these gaps in knowledge and to concentrate on the development of analytical tools necessary to permit their reliable consideration in seismic rehabilitation work.

2.6 Decision Models: Social and Economical Incentives and Impediments

The best seismic retrofit technologies are useless unless they are eventually implemented. While some hospital owners/administrations in the jurisdictions exposed to the most severe seismic risks are ready to undertake retrofit and embrace these new advanced technologies, others require that important nontechnical questions be answered first. Budgetary constraints and limited resource allocations tend to negatively impact seismic retrofit efforts, particularly in those regions where seismic awareness is lowest in spite of large seismic risks. Thus, to ensure extensive and effective implementation, social studies are required to clearly identify the nature of barriers against implementation, to determine what implementation incentives are possible and necessary, and to quantify the tangible social benefits resulting from various policy scenarios. This requires research to collect representative information directly from hospital owners/ administrators and the public, to establish the current perceptions and expectations, and to determine how various measures can positively modify these positions. Given that seismic retrofit requires an outlay of capital, it is difficult for decision makers to justify such expenditures without a clear vision of ensuing benefits. To overcome this problem that often leads to entrenched status-quo positions, reliable cost-benefit analyses, specifically tailored to recognize the unique characteristics of hospitals, must be developed. Such decision tools then make it possible to investigate the relative benefits of various seismic retrofitting approaches, and determine the best approach to follow.

3.0 MODELING OF A HOSPITAL

As pointed out earlier, MCEER hospital projects thus are divided into two separate aspects in their initial phase. For the more general situation (represented by California hospitals), major efforts are devoted to engineering activities to establish fragility information for the physical components and systems and identify critical problem areas in structures, nonstructural components, equipment, etc. that require seismic retrofit. For the special situation (represented by NY hospitals) we concentrate on establishing a decision-making method which can provide information on the impact to the community if medical service function is lost after an earthquake due to different levels of damage scenarios to the various required service functions of the hospital. Once a decision is made to seismic retrofit, the process will be merged with that for the California hospitals. At that point, we consider impact to the community when there are multiple hospitals, followed by benefit-cost analyses for different possible retrofit options.

The above can be simply illustrated by the diagram of Figure 2 that shows the current MCEER hospital tasks.

To illustrate the "center approach" in earthquake engineering research, the hospital performance analysis and evaluation component of Figure 2 is examined. To describe the medical service function of a hospital, we have advanced the concept of a "patient flow" model[3] such as the one shown in Figure 3.

If the hospital service function is considered as a process, the key element in this patient-flow model is the center block that describes the process of how patients receive their medical services. The services are supported by both human resource and material resource. Since the structural engineering concern is to evaluate the benefits of structural/nonstructural retrofit, the emphasis is given to the material resources, which typically include power system, water system, information system, medical system, transportation system, HVAC and others. Depending on the designated function of hospitals (trauma center, general hospitals, special medical care, etc.), the center will involve different service units.

4.0 STRUCTURAL RESPONSE MODIFICATION RESEARCH

In the patient flow model of Figure 3, we can separately consider the important physical systems that are necessary for delivering medical services. A simplified hospital physical systems model is given in Figure 4.

Although the physical systems model in Figure 4 is intended to show the complex relationships among various structural and nonstructural/ utility/equipment systems as they affect the medical service function and capacity, it also serves to provide a systems perspective of the structural engineering research components of MCEER'S hospital project.

For example, most structural response modification technologies are pursued for foundations and structural systems, and many nonstructural component areas. One of the most challenging research areas is the trade-offs between response reduction of structural systems and retrofit of nonstructural components.

In order to carry out such an optimizations study, one must have the information on the response modification technologies and their design methods and the fragility information for all the involved physical components as outlined in Figure 4. Thus, significant amount of structural engineering research activities, both analytical and experimental, are required. This will require multidisciplinary team efforts contributing to the common objective of hospital service functions. It can best be accomplished by using a tightly coordinated "center approach."

Although the structural engineering and structural control components may be themselves fundamental or applied engineering research activities in nature, it is the proper integration and coordination of these efforts together with social science components that can provide cost-effective and useful results for earthquake vulnerable communities.

5.0 SUMMARY

MCEER research programs are conceived and designed from the users' viewpoint of reducing the vulnerability of earthquake risks in urban centers. This user's demand translates into performance requirements for the various critical facilities that should remain functional during and immediately after expected destructive earthquakes such as emergency medical services. The decision to retrofit and the various cost-effective retrofit approaches, particularly using new and emerging technologies, require a systems integrated approach that can be pursued by using the "center's approach" more effectively than the "individual investigators' approach." In this paper, this center's approach is briefly presented by describing MCEER's structural engineering research and structural response modification technologies as components of the hospital project.

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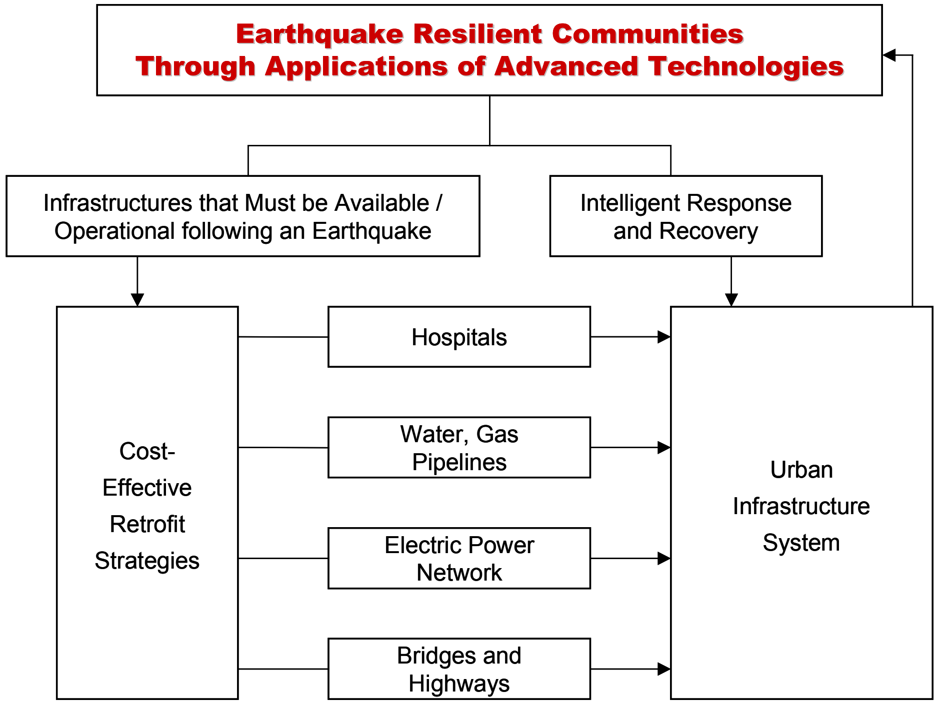

Figure 1. MCEER Research Thrust Areas and Earthquake Resilient Communities.

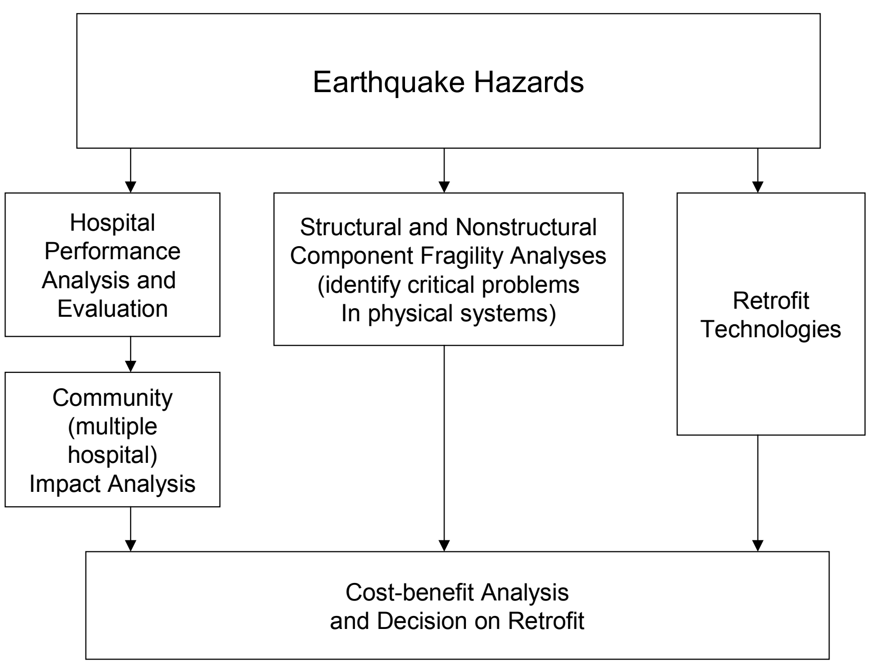

Figure 2. Major Research Components of MCEER Hospital Retrofit Project

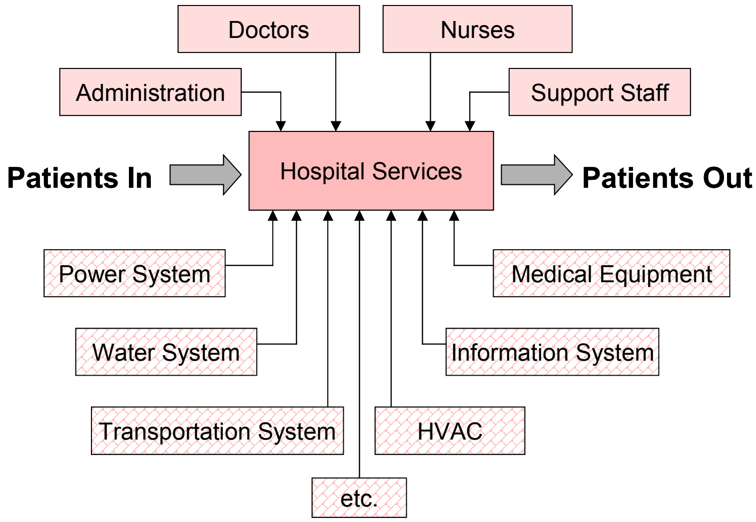

Figure 3. The Patient Flow Model of a Hospital

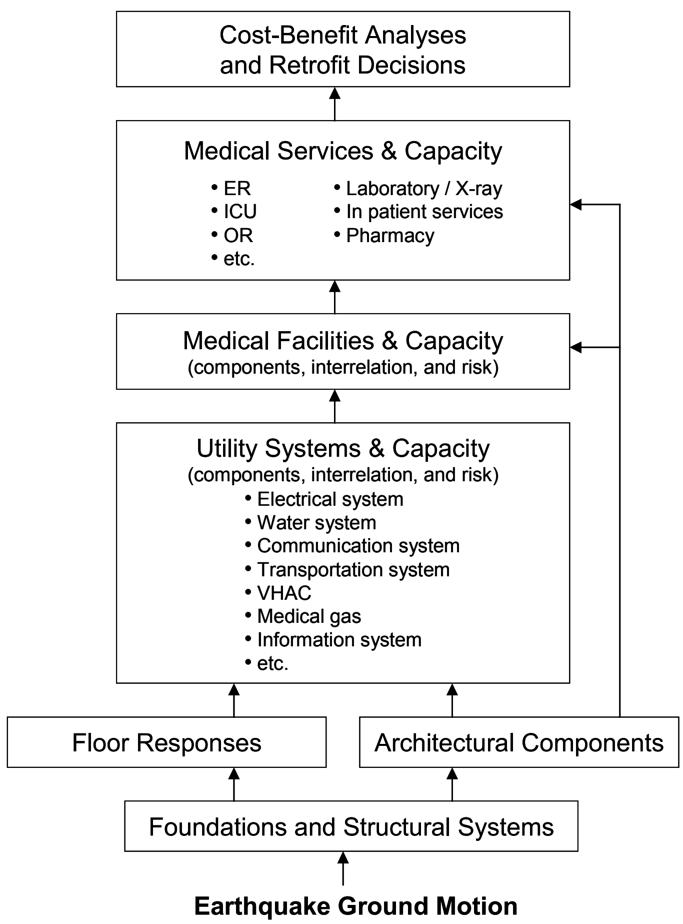

Figure 4. Hospital Physical Systems