Application of Advanced Technologies in Seismic Protection of Critical Facilities An MCEER Program

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ABSTRACT

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) has established a coordinated system-integrated research effort to discover, nurture, develop, promote, help implement, and in some instances pilot test, innovative measures and advanced and emerging technologies to reduce losses in future earthquakes in a cost-effective manner. The focus of this research is on critical facilities, such as hospitals, and lifelines. A broad range of technologies are being investigated through this research initiative, and this paper provides a brief overview of some of the technologies currently considered.

KEYWORDS: Advanced technologies, seismic protection, critical facilities, retrofit, loss assessment, emergency preparedness, emergency response, structural engineering, lifeline engineering, geotechnical engineering.

1. INTRODUCTION

Earthquake losses in recent years have exceeded $30 billion in direct costs in California alone and are expected to rise at an escalating rate in future years unless major loss reduction programs are undertaken. Past experience makes it clear that the immediate threat to society lies in existing, seismically vulnerable infrastructure and critical facilities, and that current response and recovery programs are often overwhelmed by unprecedented demands. But rehabilitation and effective response remain elusive goals because both are impeded by a lack of detailed knowledge about seismic hazards, an incomplete understanding of the complex behavior of structures and lifelines during extreme events, and societal impediments to launching a comprehensive loss reduction program. Furthermore, the high costs of conventional rehabilitation schemes are a serious disincentive, except perhaps to households, governmental entities, and organizations in the most active seismic zones.

Reducing the cost of rehabilitation, improving its reliability and removing barriers to implementation will substantially reduce future earthquake losses. Recent developments in advanced technologies offer great promise in this regard while at the same time offering a higher level of performance than is possible with conventional techniques. Furthermore, powerful new methodologies for quantifying expected losses make it possible to better characterize risks and to analyze the costs and benefits of alternative loss-reduction strategies, opening the door to meaningful incentives and the adoption of new advances in risk management. These same tools can be applied to strategic disaster planning and early damage assessment and thus improve the effectiveness of emergency response and crisis management.

Within this perspective, the Multidisciplinary Center for Earthquake Engineering Research (MCEER) has established a coordinated system-integrated research effort to answer the above needs. The mission of the Center is to discover,

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nurture, develop, promote, help implement, and in some instances pilot test, innovative measures and advanced and emerging technologies to reduce losses in future earthquakes in a cost-effective manner.

Advanced technology research at MCEER includes innovative applications of:

- engineered systems and materials,
- scientific methodologies, and,
- concepts and analytical approaches

that have not traditionally been used in earthquake engineering and loss reduction problems, with an emphasis on applications which require a multidisciplinary effort.

This mission of the Center is predicated on the premise that the future of earthquake engineering lies in advanced and emerging technologies and associated innovative measures. These include, but are not limited to:

- site remediation technologies,
- structural control and simulation,
- high performance materials,
- condition assessment technologies, including technologies for estimating both potential and actual earthquake losses
- decision support systems.

However, the Center also recognizes that societal barriers to loss reduction and adoption of new technologies are real and substantive, and that they must be overcome before progress can be made. Thus, a significant effort is undertaken to address these impediments and discover rational workable incentives that accelerate the adoption of loss reduction programs and realize the potential that these exciting new technologies have to offer.

2. VISION AND RESEARCH PROGRAM

The ultimate vision of the Center is to help establish earthquake resilient communities. The Center progresses toward that goal through an interdisciplinary and coordinated research program, emphasizing fundamental and applied research combined with sustained and systematic education, outreach, and implementation efforts. In this paper, only research activities are summarized.

The goals of the Center's activities in research are pursued through the following four major research thrusts:

2.1 Advancement of loss estimation methodologies for the quantification of building and lifeline performances in future earthquakes.

The first of these research thrusts is to develop the next generation of loss estimation methodologies, and to use them to quantify the threat to the built environment. These more efficient methodologies are key to the other two research thrusts involving the rehabilitation of critical facilities and response planning, crisis management and recovery. The development of real time remote sensing to rapidly assess earthquake damage, the study of socio-economic barriers against the mitigation of loss reduction measures, and the development of incentives for the implementation of new knowledge in loss reduction also support the objectives of this program.

2.2 Development of cost-effective, performance-based, rehabilitation technologies for critical facilities.

The second thrust is to identify, explore and develop advanced technologies for the rehabilitation of selected critical buildings and lifelines to meet or exceed the high level of performance expected of these facilities that, by definition, must remain operational following a major earthquake. 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. As in other Center programs, engineering and social science researchers involved in this program work together to identify impediments to rehabilitation and incentives for the adoption of new technologies.

2.3 Improvement of response and recovery through strategic planning and crisis management.

The third thrust focuses on two areas where emergency response and crisis management can be made more effective with the use of advanced technologies. These areas are pre-event strategic planning for immediate response and recovery using loss estimation methodologies, and crisis management involving response coordination, early damage assessment, and search and rescue with an emphasis on the use of advanced technologies.

2.4 User Networks in Facilities and Computation.

The fourth thrust requires MCEER investigators working on projects requiring networking to develop two User Networks, one for experimental facilities and computing environments and the other for computational and analytical resources. The ultimate objective is to make the networks accessible to individual researchers and practitioners sponsored by MCEER or by other research centers. The Facilities Network in Earthquake Engineering (FNEE) focuses on both computational and experimental facilities. It is to be established by linking and coordinating existing resources at member institutions and facilitating access by remote users. The Computational Network in Earthquake Engineering (CNEE) focuses on assembling a full range of analytical resources for the analysis, design, evaluation and testing of structural and lifeline systems including both existing and new software. Addition of this Network provides all MCEER's researchers with up to four levels of sophistication, ranging from basic back of the envelope estimates of critical structural response to high-end continuum approaches to compute time history response simulations.

Figure 1 attempts to illustrate, in a simplified manner, the close interaction that exists between these areas of research. It also shows that all activities lead to a comprehensive education mandate, that is particularly important in those regions of the United States when seismic awareness is generally low.

In the remainder of this paper, some of the advanced technologies that are considered within the MCEER/NSF research program are briefly described, to provide an overview of the type of technology applications being considered. Note that this research is conducted by 28 researchers in 13 affiliated institutions across the United States.

3. ADVANCED TECHNOLOGIES.

3.1 Performance Assessment of the Built Environment

The poor performance of the built environment during recent moderate-to-large earthquakes has been the principal cause for death and injuries and escalating social and economic losses. Thus, it is essential to develop reliable methodologies to assess the seismic performance of the built environment in terms of expected societal and economic loss resulting from a damaging earthquake. Estimated expected loss then becomes an important quantitative measure of the seismic performance of the built environment, providing the analytical basis for cost-effectiveness evaluation for the selection of optimal rehabilitation measures for the existing inventory. The loss estimation methodologies in this context requires information about three major ingredients: hazards, inventory and fragility. This Program generates and integrates the information on these ingredients in order to develop such methodologies by carrying out the following tasks.

Seismic Hazard and Ground Motion: Analytical models for ground shaking to be used for ENA (Eastern North America) earthquake events based on both engineering and seismological approaches are being developed and calibrated with recorded earthquakes in ENA. Current work includes development of response spectral amplitude and study of its sensitivity to magnitude and epicentral distance, and development of scattering function and models for near source ground motions. This is complemented by centrifuge model tests of liquefaction and lateral spreading to investigate the nature of ground motion due to liquefaction. Seismological studies are also conducted in support of other tasks within MCEER's coordinated research effort, to assist investigators working on generating fragility information, particularly in terms of developing inelastic response spectra considering explicitly the soil behavior in the ground motion time histories and in introducing soil-structure interaction effects into fragility curve construction.

Advanced Technologies for Loss Estimation; Development of Damage Functions using Remote Sensing and Real-time Decision Support Systems: This research involves the review of advanced and emerging technologies with the objective of improving existing loss estimation methodologies. Technologies that are being investigated include: real-time earthquake monitoring systems, early warning systems, GPS technology, interferometric synthetic aperture radar (IFSAR) technology, optical satellite imaging, laser technology (Lidar) and aerial photography. Current work focuses on the development of building inventories for loss estimation using IFSAR and laser (LIDAR) technologies. Pilot studies and calibration are conducted using areas in the Los Angeles basin for the purpose of inventory development. This data permitted to develop "building height signatures" for these pilot areas. Building height signatures are cumulative plots of total building footprint area as a function of building height. These are created for standard grid cell sizes measuring a half a mile by half mile. The results show that depending upon the type of development (residential, commercial, industrial), building or construction density (square footage of ground floors), and distribution of building heights, a building height signature will have varying slopes and intercepts. In addition, for cells that contain a higher percentage of high-rise buildings, the curves will extend out to higher building heights. A comparison of building height signatures developed from the various methods (including the aggregation of data from the county assessor's files) will help to answer the question "can remote sensing methods be used to quantify the number and types of buildings in an urban environment, thereby enhancing or replacing conventional methods of building inventory development that are often costly and sometimes inaccurate. It is expected that the most suitable technologies identified by this research will be mature enough to be utilized in the inventory development and damage assessment studies conducted by other MCEER investigators.

Loss Estimation Methodologies: This research focuses on reliability analysis of a spatially extended system (LA County expressway network). Preliminary assessments are made on the basis of empirically developed fragility curves of bridges. To date, some examples have been used to demonstrate loss reduction using structures based-isolated and not base-isolated. Current work is focusing on the direct cost of damage sustained by individual bridges, buildings and lifeline systems. Selected existing loss estimation methodologies are being reviewed, and a benchmark dataset on losses in recent disasters is being developed. Research is also underway on methodological refinements to analyze the loss reduction potential of advanced technologies and strategies for pre-event rehabilitation and post-event response. In parallel, indirect loss estimates methods rely on the computable General Equilibrium analysis, and considers how influencing various economic factors that appear in the analysis can further reduce economic losses. These various approaches must then be integrated to develop a loss estimation methodologies, involving both direct and indirect, implementable for demonstration projects.

Inventory for LADWP Water Delivery System: Data collection and inventory identification must be accomplished in a digital format that permits consideration of advanced technologies for loss estimates. Hence, to date, the entire 100 km of trunk lines and 11,000 km of distribution pipelines were digitized and incorporated in a GIS model together with topographical, surficial soil and Northridge strong motion and ground water data. On-going work includes information gathering and incorporation into GIS system of the information needed to assess the interactive features of seismic performance of LADWP's water and electric power system. The result will be used for evaluation of loss reduction by system rehabilitation by advanced technologies in the LADWP demonstration project.

Seismic Reliability Analysis and Retrofit Method for LADWP's Power System: Seismic data collected on the LADWP's power system permitted to improve an original systems analysis computer code (from the power engineering point of view). Work is underway to use a newly acquired flow analysis computer code from EPRI together with the improved systems analysis method, and Monte Carlo simulation assessments of the degradation of system performance under different levels of earthquake intensity, to examine the enhancement of system performance due to rehabilitation of key system components by means of advanced technologies.

Inventory Development for NY Hospitals: Following a workshop held in New York City to define the post-disaster needs of hospital owners/administrators, critical subsystem components, and desired seismic performance criteria, hospitals inventory data is being collected. This work is to support the demonstration project within MCEER's research plan. Further work is also underway to development a consistent hospital performance criteria by involving engineering practitioners and hospital administrators. Analytical models for seismic performance of hospital systems (e.g., fire protection system) is also being developed along with a computer code to identify critical components in these systems.

Development of Fragility Information: Studies here investigate the consequence of various levels of analytical sophistication on the reliability of fragility curves. Work is also underway to develop robust fragility curves for structures, nonstructural components and equipment, to be used by other MCEER researchers. The levels of analysis considered are consistent with (1) design compatible method, (2) response spectrum-based method, (3) analytical method utilizing such computer codes as ABAQUS and DIANA and (4) analytical method with the aid of high-performance computational platform. The results derived from these methods will be compared with one another and calibrated with empirically as well as experimentally obtained fragility curves. These methods will be integrated to form a coherent numerical and analytical procedure for fragility curve development that can be used for demonstration projects. In this context, the resulting coherent procedure will also be used to develop the fragility curves for rehabilitated structures, components and equipment.

Calibration of Fragility Information: This task relies on results from experimental studies to provide calibration of fragility analyses, more specifically shaking table tests at the University of Nevada Reno, and SUNY Buffalo, on pipeline joints and structural frames respectively

Much future work is foreseen on loss estimation methodologies, on identifying what constitute acceptable losses in various contexts, and integrating this multidisciplinary research through a demonstration project using the LADWP's power system, NYC's hospitals, LADWP's water system and Memphis lifeline systems.

3.2 Development of cost-effective, performance-based, rehabilitation technologies for critical facilities

The objective of this research trust is to identify, explore and develop advanced technologies for the rehabilitation of selected critical buildings and lifelines to meet or exceed the high level of performance 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. As part of this research program, engineering and social science researchers work together to identify impediments to rehabilitation and incentives for the adoption of new technologies.

Engineering research focuses on advanced technologies that can be effectively used for seismic retrofit in geotechnical, structural, and lifeline engineering. A schematic of these three separate major sub-objectives is presented in Figure 2.

The geotechnical engineering studies focus on site and foundation remediation technologies to mitigate soil liquefaction. Analytical and experimental centrifuge research investigates how shallow soil around pile caps can be either replaced by frangible materials, or stabilized by the injection of reactive materials. In the short term, this research investigates the adequacy of various materials for those tasks, including expanded polystyrene, light weight fills, crushable materials, as well as various chemical and bacteriological reactives toward the states objectives, and analytical models are developed in support of future experimental work.

The lifeline engineering studies investigate how advanced materials can be used to retrofit the capacity of welded slip joints on critical water trunk lines, and how critical substation power system components can be retrofitted to remain functional immediately following major earthquakes. Demonstration projects with the Los Angeles Water and Power division are imbedded within these two tasks. To date, development of analytical models and testing of non-reinforced specimens has been accomplished, with testing of retrofitted specimens to follow shortly.

The structural engineering part of this program is two-fold. A first task investigates how emerging advanced materials can be used in new seismic retrofit concepts, while a second tasks focuses on new approaches to provide seismic retrofit to critical buildings, i.e. facilities that require to be fully operational following earthquakes. Both tasks focus on hospital buildings at this time, although concepts that can find broad acceptance for other types of critical facilities are also investigated as appropriate. Currently, scissors-jack energy dissipation assembly and various types of advanced engineered composite frame infills are considered for structural retrofits. Non-structural retrofit schemes being considered include tether systems and isolating equipment supports, and reliability analyses are to be conducted and integrated with fragility analyses. Demonstration projects secure participation by the potential beneficiary of this research, and provide the test-beds where all related efforts converge, and where the true multidisciplinary aspects of this research emerges. In the medium term, selected hospitals will provide actual critical facilities against which adequacy, economy, and acceptability of the proposed concepts will be gauged. Such demonstration projects will further tighten the interactions between researchers working in the areas of advanced materials, advanced retrofit strategies, cost-benefit studies, and social sciences.

3.3 Intelligent Response and Optimal Recovery

Pre-earthquake mitigation strategies seek to reduce earthquake losses by implementing measures that prevent or reduce losses. Mitigation strategies include land-use regulations, seismic construction and retrofit codes, and improved engineering practices. Effective mitigation will result in the avoidance of many losses that could result from future earthquakes. However, since current knowledge about earthquakes and their effects on the built environment is incomplete, since major impediments exist that block the adoption of potentially effective mitigation strategies, and since comprehensive loss-avoidance is not economically feasible, earthquakes continue to produce damage and disruption on a very large scale. Additionally, although mitigation measures do provide considerable protection, one of the key features of earthquake disasters (in contrast with "routine" emergencies) is that they produce unanticipated impacts that overwhelm the coping capacities of affected social units. For these reasons, there is a continuing need for robust disaster response and recovery strategies.

Response activities encompass actions taken during and immediately after disaster impact that are designed to protect life and property and control secondary earthquake impacts (e.g., earthquake-induced fires and hazardous materials spills). Response activities must address the need to deal with both agent-generated demands (i.e., problems created by the disaster agent itself, such as injuries and physical damage) and response-generated challenges (i.e., the need for rapid situation assessment and for information on which to base decisions). Examples of response activities include rapid damage detection, search and rescue, emergency medical care, emergency restoration of essential services, firefighting, emergency communications, and crisis decision making. The federal government, all states, and virtually all communities in the US have plans for responding to major disasters, including earthquakes, although both the quality of these planning efforts and the demonstrated capacity to respond to major disasters varies considerably nationwide.

Recovery activities consist of actions taken to return to (or, ideally, exceed) pre-earthquake levels of activity and productivity. These actions include restoring, repairing, and reconstructing lifelines and buildings, undertaking measures to overcome earthquake-induced economic downturns, and providing financial assistance to compensate for losses. The recovery period is also typically the time in which decisions are made about adopting new mitigation measures, with the long-term objective of increasing the earthquake resistance of the built environment. If undertaken properly, recovery strategies can contain indirect and induced earthquake losses, shorten the recovery period for affected social units, and avoid future losses through improvements in mitigation.

In the US, recognition has grown that it is highly desirable to plan for recovery before an earthquake occurs, and some communities (e.g., the City of Los Angeles) have begun to move in this direction. However, at present, earthquake response planning is much more extensive and more thoroughly institutionalized than recovery planning.

In that perspective, MCEER's Response and Recovery Research Program aims to conduct research on new technologies and technology applications that offer the promise of improving earthquake response and recovery decision making. To accomplish this goal, MCEER investigators will focus on two areas in which recent technological developments appear to have considerable potential for application in response and recovery contexts: remote-sensing, which can be used for rapid post-earthquake damage assessment; and advanced information (IT) and data-management technologies and decision-support systems (DSS).

These technologies are, of course, not truly "new." Remote-sensing technologies, for example, are widely used in defense applications. What MCEER's research seeks to determine are the feasibility and effectiveness of applying these technologies in new ways to address earthquake response- and recovery-related problems. MCEER's research plan is designed to address questions like these: Can remote-sensing technologies produce the kinds of data and information that would enable disaster responders to detect areas of major damage in a more timely and effective manner than they can using currently-available techniques? Is it feasible to use remote-sensing technologies in real-time or near-real time to improve response decision making? Do the agencies and organizations that are charged with responding to earthquakes have the capacity to use new information technologies to manage earthquake disasters, and if not, what would they need in order to be able to do so? How can knowledge about the design and use of decision support systems be used to help agencies improve the quality of their response and recovery decisions? What data needs and user needs are associated with the development of such systems? In what ways can information technologies enhance the ability of governmental units, agencies, and organizations to implement response and recovery plans?

This research is being carried out by investigators with backgrounds in engineering, sociology, public administration, and decision analysis. The studies that are currently being undertaken focus on enhancing post-earthquake response decision making through the use of new technologies.

As part of current research, field work is being conducted in six communities (New York, Memphis, Los Angeles, and one smaller communities in each of those three states) to collect baseline information on information and data management technologies that are currently being used by disaster response agencies and to assess the capacity of these agencies to use more advanced IT and DSS.

Within another project, research is conducted to develop earthquake response decision support systems that take advantage of new advances in computer software and decision analysis and that are tailored to users' needs. This research places a particular emphasis on the uncertainties inherent in crisis decision making and on the value of real-time information in the post-impact crisis response period.

Finally, a last project investigates the feasibility of using synthetic aperture radar (SAR) remote-sensing technologies to rapidly detect earthquake damage by comparing pre- and post-earthquake images of elements in the built environment. If this method proves capable of providing valid damage information, the next step will be to explore the extent to which such information can be used in real-time earthquake response decision making.

4. CONCLUSIONS

This paper has brushed a quick sketch of some of the advanced technologies investigated by the Multidisciplinary Center for Earthquake Engineering Research to reduce losses in future earthquakes in a cost-effective manner. This work is still in the early phases of an ambitious 10-year research agenda that includes fundamental research, technological integration and system development research, and multidisciplinary demonstration projects intended to bring together the various components required to achieve the stated objectives. While much of this research focuses on critical facilities, it is expected that the benefits from this research will prove transferable to other types of engineered work and facilities, thus leveraging the initial benefits.

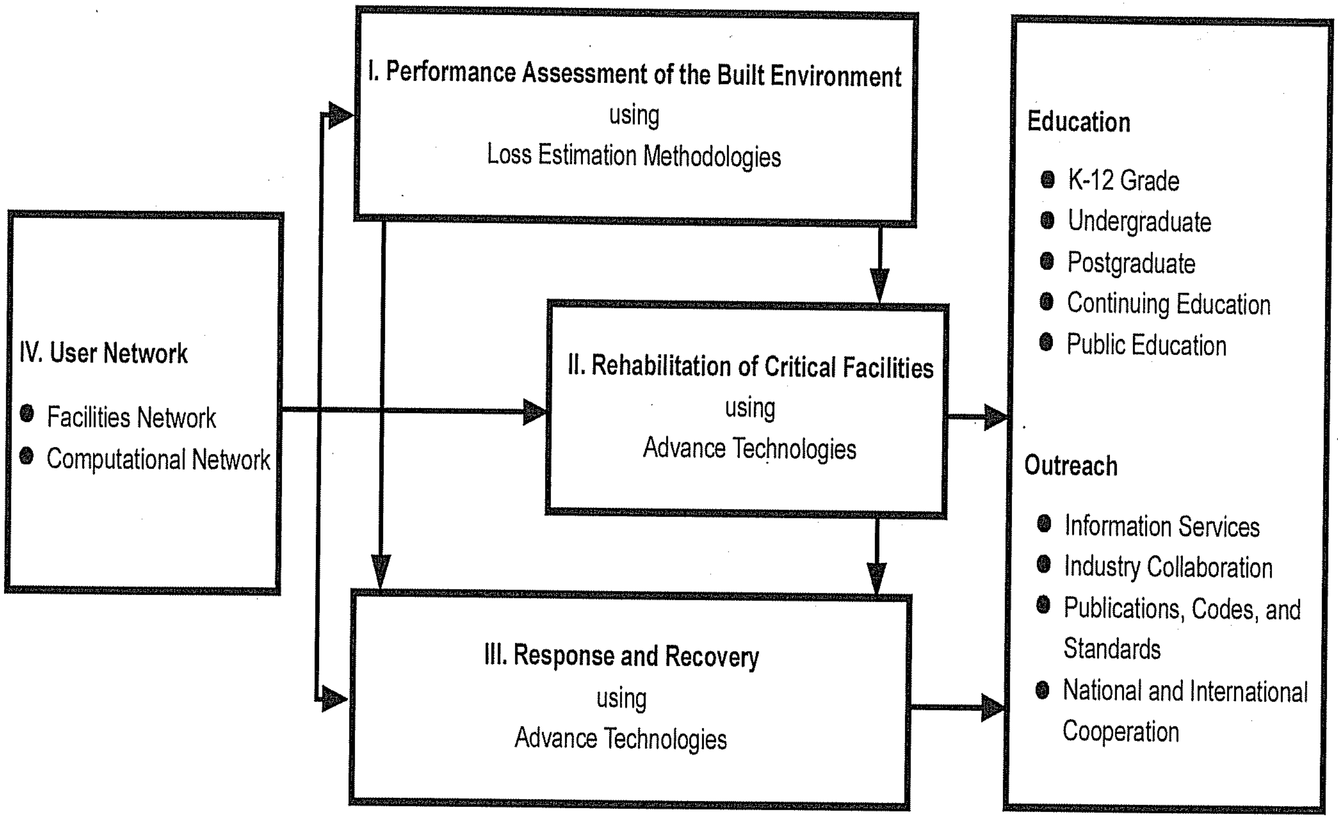

Figure 1. Interaction between various major research trusts

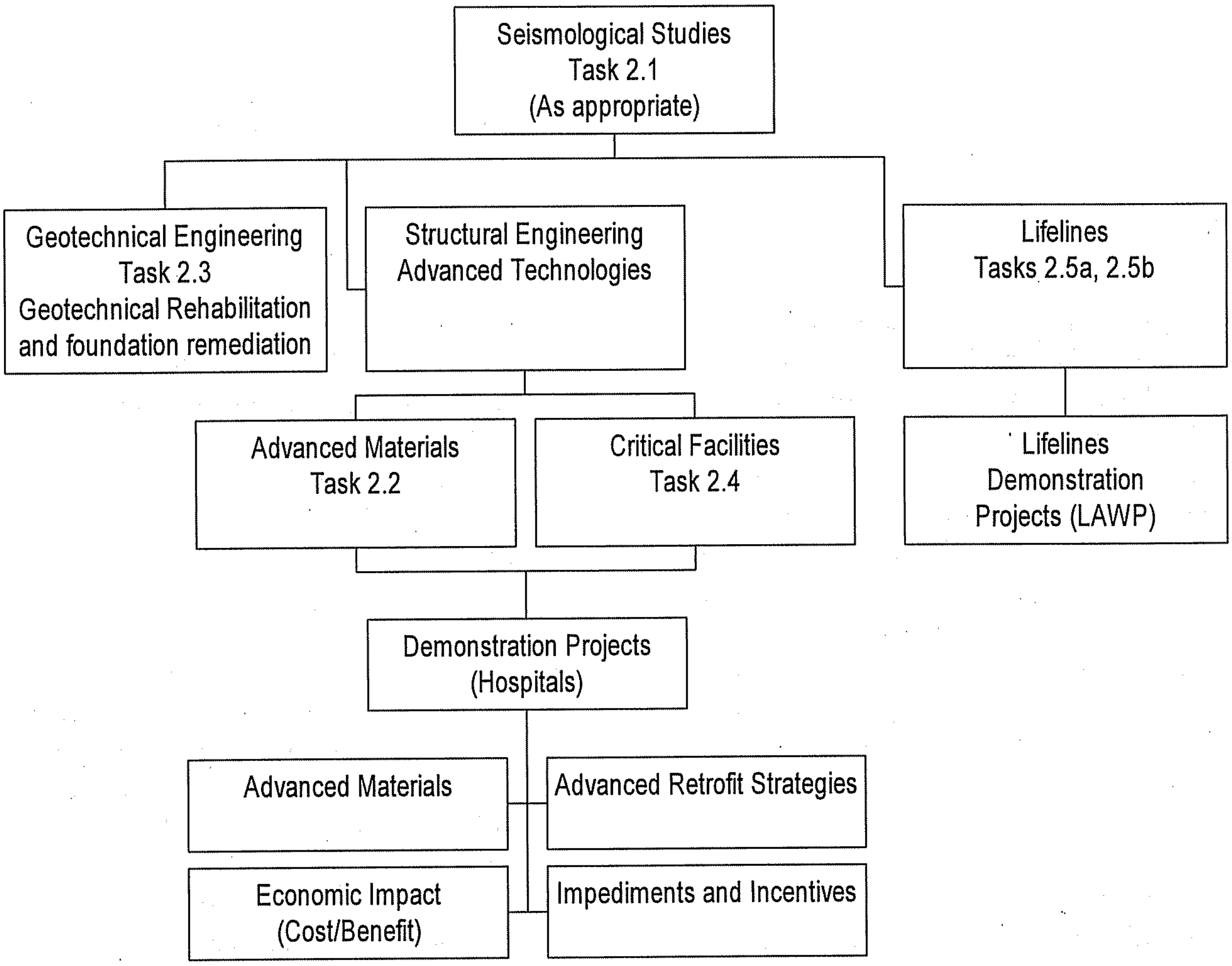

Figure 2. Schematic Structure of Research within Program 2.