RESEARCH ON REDUCING ECONOMIC LOSSES FROM INFREQUENT, HIGH-CONSEQUENCE EARTHQUAKES

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Abstract

A number of regions of the world are subject to earthquakes that are infrequent by nature, but may be prone to severe consequences in the unlikely event that such earthquakes should occur. Research aimed at loss reduction for these infrequent seismic events is unique in the sense that physical, technical, social, political and economic situations may differ from situations in more active seismic regions. This paper provides a summary of how research is organized within the Mid-America Earthquake Center to address the infrequent earthquake problems of the central and eastern United States in an effort to help facilitate international collaboration with other earthquake research centers in the world posed with similar problems.

Introduction

For a number of decades, earthquake engineering research concentrated on improving the understanding of how individual structures responded to ground excitation without looking beyond to more global problems of community or national loss reduction. This was because research was funded to individual investigators who produced salient results, but could not afford the luxury, or appreciate the rewards of a true cross-disciplinary endeavor. Now that centers of earthquake engineering research are in existence, research thrust areas can now be inclusive of system-wide, cross-disciplinary problems related to loss reduction across a community or an entire nation. With the center approach to research where engineering talent is combined with talents in economics, social science, urban planning and seismology, the effectiveness of various mitigation measures can be judged with a much wider perspective than in the past.

The inventories of constructed facilities and complex networks of engineered systems across an entire country as large as the United States are remarkably vast. Earthquake engineering research can help to reduce losses to these facilities and networks, but will take considerable time to be truly comprehensive at the present rate that research is done. Priorities must be set for research to meet the most immediate needs. However, with a view towards community-wide or nation-wide systems, limited research resources can be optimally allocated to yield maximum loss reductions across these regional and global systems. This paper provides an overview of the research of the Mid-America Earthquake (MAE) Center that focuses on loss reduction for a specific region of the United States prone to infrequent but high-consequence earthquakes.

As noted in Fig. 1, engineering research projects of the MAE Center are aligned about two parallel tracks related to loss-reduction of: (a) communities and (b) national networks. In addition, a third track is devoted to hazard evaluation which is needed to better define source, path and site effects for the uncertain earthquake motions of the central and eastern United States, and thus help to reduce the uncertainties regarding the magnitude and reoccurrence rates of future seismic hazards in Mid-America. This paper focuses on the first two engineering research programs.

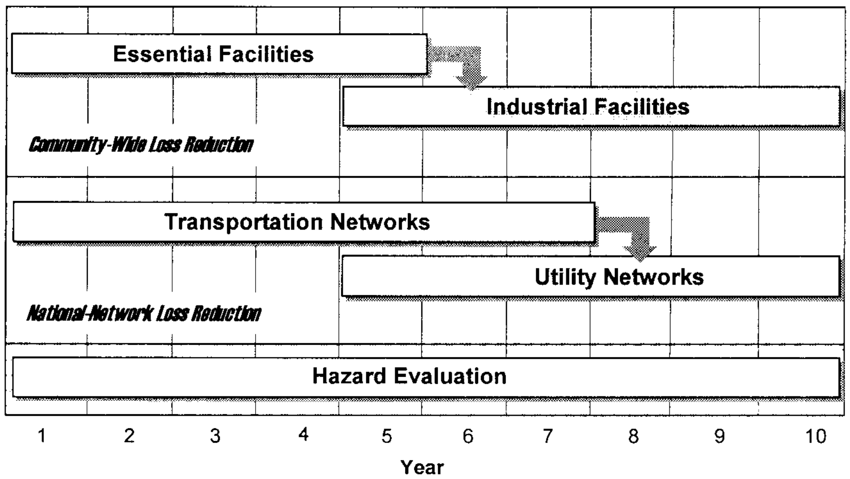

Figure 1. MAE Center Research Programs

The program on community loss reduction is concentrating in the first five years on public health and safety issues. Earthquake risk assessments are being studied for those buildings that must remain functional following an earthquake: firehouses, hospitals, schools and emergency shelters. Reducing earthquake losses across a community as a result of the damage to these essential facilities is a key objective of this program. Cost-effective retrofit strategies for building structures are studied in terms of their effectiveness in reducing both direct and indirect losses across a community. A subsequent program on industrial facilities will continue the theme of community-loss reduction by focusing on continued operation of structures that are vital to the economy of a local region.

The second parallel research thrust area is examining seismic vulnerability of national networks. The first phase of this track is devoted to reducing losses across national transportation networks. With the center approach, benefit-cost relations for retrofit of critical transportation components are being studied by combining results from research in seismology, engineering, economics and urban planning. Economic flow models for the national shipping network are used to assess the probable loss in the event an earthquake damages a vital element of the network such as a major river crossing. Network vulnerability models developed with the Transportation Networks Program will be translated to study loss reductions to utility networks in a subsequent program.

This paper describes research projects in the Essential Facilities Program (EFP) and the Transportation Networks Program (TNP) to provide the reader with two examples of how center-type research can be done to focus on system loss reduction. Whereas these two programs are not exhaustive of all possible research programs that can or should be done to reduce earthquake losses in the central and eastern United States, they help suggest the types of cross-disciplinary research that is being done to address the infrequent, but high consequence earthquake problem.

Basic Research Organization

Each of the two engineering research thrust areas is organized using the same project flow model as depicted in Fig. 2. Basic information on how structures respond to excitation at their base, as determined from computational, laboratory and field studies, is used with synthetic ground motions to establish fragility relations for various structural types (buildings, bridges, etc.). Fragility curves expressing probabilities of particular damage levels for given ground motion intensities are estimated for existing structural systems as well as for retrofitted structures. Fragility curves for vital components of networks (bridges, ramps, airports, tracks, etc.) are used to generate fragility curves for national networks. These curves are then extrapolated across communities or networks knowing basic information on inventories to estimate earthquake losses.

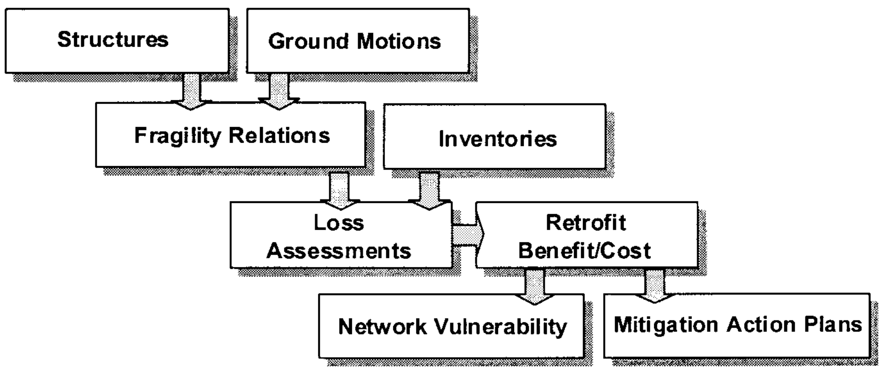

Figure 2. Interdependence of Cross-Disciplinary Research for EFP and TNP

Loss estimates are based on not only repair costs for damaged structures, but also indirect business losses resulting from loss of functionality of facilities or critical network components. By taking differences in loss estimates for existing and retrofitted structures, the relative benefits of retrofit on earthquake loss reduction are estimated. These studies are then used as the basis for establishing mitigation action plans for communities or overall network vulnerability studies.

The integration of talents in engineering, seismology, reliability, urban planning, social science and economics produces deliverables from the research that cannot be obtained through a series of independent and individual research projects. Details of how this organizational model is applied to community-wide and national network loss reduction are discussed in the following two sections.

Essential Facilities Program

The thrust area on community-wide loss reduction is first directed at those building structures that must remain operable immediately following an earthquake to ensure public health and safety. Retrofit of these essential facilities are generally dependent on community-wide concerns for access in response and recovery operations rather than on simply recovering the repair costs for the amount of direct damage.

Essential facilities include important structures to the fabric of a community such as firehouses, police stations, school buildings, hospitals and clinics, yet the structural systems for these building types are usually quite simple with a wall or frame structure of a few stories. However, dynamic response of these simple systems is not clear to practicing structural engineers because many have been designed to resist gravity loadings and not earthquakes. Walls are often not connected to floor or roof diaphragms. Masonry elements typically are not reinforced. Developing effective seismic rehabilitation methods for these essentially unengineered structures poses a good challenge to researchers. Serviceability issues for essential facilities are a relevant issue because their continued operation following an earthquake is mandatory to ensure the safety of a community. Subsequent research thrust areas on industrial buildings will extend this retrofit research to other building types where the interest will again be continued operation of a facility rather than the more simple life-safety criteria of present building codes.

Goals of Essential Facilities Program

The primary goals of the Essential Facilities Program are: (a) to identify needs and priorities for seismic retrofit based on functional criticality, anticipated ground motions, and expected structural performance; (b) to develop, validate, and standardize economical retrofit methods; and (c) to implement those retrofit methods by encouraging planners and public officials to adopt them. These goals are consistent with the overall strategic plan of the Center, and are being met in part through development of enhanced building retrofit guidelines and tools for condition assessment. These guidelines and tools are expressed in terms of parameters that are consistent with those being used with recent national documents such as the NEHRP *Guidelines for Seismic Rehabilitation of Buildings* (FEMA 273).

An inventory of facilities in Mid-America revealed that approximately 25% of essential facilities are constructed of unreinforced masonry (URM) or light steel frames with masonry veneer. Because this form of construction has been observed to be highly vulnerable to past earthquakes, much of the structural engineering research of the EFP is being directed at assessment procedures to depict response and performance of URM components and building systems, as well as performance of retrofitted structures. A typical masonry bearing wall building used as a firehouse is shown in Fig. 3. These systems are low-rise structures with a fair amount of wall area relative to floor area, but the walls are constructed of unreinforced clay-unit masonry and have numerous window or door penetrations. Floor and roof diaphragms constructed usually of timber span long distances between shear walls and perform as flexible elements relative to the stiffer shear walls. Because of their flexibility, diaphragms tend to amplify wall accelerations and drive transverse walls with large displacements normal to the plane of a wall. Foundations are often made with archaic methods and soil flexibility may be a concern since the shear walls are so stiff. Knowledge of the dynamic response of such systems is needed to represent damage states on fragility curves and subsequently to refine loss assessments.

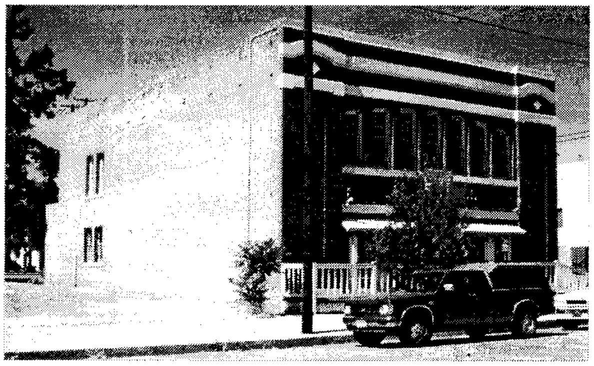

Figure 3. Typical URM Bearing Wall Building

Strategic Research Plan, Milestones, and Deliverables

The EFP research projects have been identified as needed to break the barriers and indeed reduce earthquake losses across communities. The communities themselves are the loss reduction systems for the EF program, and serve as test beds for the final products of the program: mitigation action plans. Barriers to reaching the goal of improved safety include: lack of understanding of community decision making and acceptable risk; inadequate information on benefit-cost of retrofit; and incomplete data on loss assessments associated with a future earthquake.

The mitigation action plans will, upon implementation, help to reduce losses in essential facilities resulting in increased public safety. Research projects have delivered an improved understanding of the benefit/cost of selected retrofit strategies based on increased understanding of structure fragility. Investigations of structural behavior and performance have yielded fundamental information in the form of basic force-deflection data for use in nonlinear dynamic analyses of building systems. Probabilistic ground motions were synthesized for input to these analyses. Fragility relations were then combined with inventory data to produce loss assessments. Benefit-cost studies are now examining the differences in loss with and without retrofit strategies developed as products of the enabling technologies level research activity.

A full-scale unreinforced brick test structure will be subjected to a series of static load and displacement reversals to serve as a test bed for confirmation of computational modeling procedures and development of fragility curves. The test structure will be retrofitted following testing to examine possible enhancements in lateral strength, stiffness and inelastic deformation capacity.

The ultimate deliverable of the research program will be mitigation action plans based on case-study communities of Sikeston, Missouri and Carbondale, Illinois.

Research Advances and Deliverables

The ultimate end users of deliverables for the EFP are practicing engineers who rely on new engineering technologies and updated codes and guidelines, building owners who must endorse seismic retrofit, and communities interested in becoming disaster resistant. Individual project web pages linking all EFP projects (see http://mae.ce.uiuc.edu) provide the latest research results on a particular project. Project accomplishments include the following.

- An inventory of essential facilities produced the first quantitative description of the age, type and composition of such buildings in Mid-America.

- Three-dimensional computational models have been developed for estimating dynamic response of bearing wall buildings with flexible diaphragms (see Fig. 4).

- Seismic performance of existing, and retrofitted, floor diaphragms and unreinforced brick walls and piers (see Fig. 5) has been studied with a series of experimental studies to define stiffness, strength and inelastic deformation capacities.

- Shaking-table tests of unreinforced masonry bearing walls supporting heavy gravity loads and subjected to large out-of-plane diaphragm motions have provided benchmark data for development of computational models for estimating dynamic stability.

- Passive modification systems have been explored for retrofitting URM bearing wall buildings. Simplified analytical modeling approaches and an energy-based methodology for designing passive response modification systems in low-rise URM structures have been developed.

- Statistical methods for generating fragility curves that account for structural variability across a region.
- An ATC-21 survey of major structures in two case-study communities is now complete, and key vulnerabilities are being identified in each community.

The survey will lead to evaluation of how damages and casualties are distributed by structure type, functions, occupancies, and location for various scenario earthquakes. Benefit/ cost studies for both the two communities and for the entire region will follow as a prelude to identification of acceptable risk and retrofit options for these two communities.

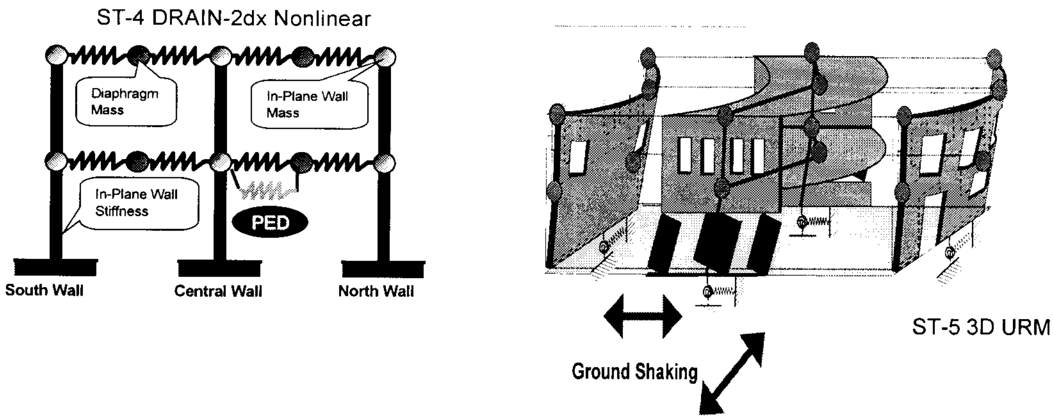

Figure 4. Lumped-Mass Dynamic Analysis Model

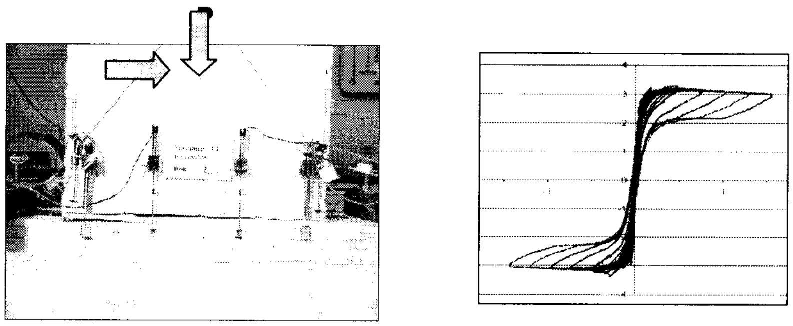

Figure 5. Testing of URM Piers and Sample Force-Deflection Curve

Future Plans for Essential Facilities Program

Loss assessments are currently being made in the two case study communities based on improved understanding of the fragility of low rise URM buildings in Mid-America. Fragility estimates will be refined as results become available from the full-scale laboratory testing of the two-story structure. Project PI's have already begun to make preliminary determinations of retrofit benefit/cost for selected essential facilities in Sikeston, Missouri and Carbondale, Illinois. Work has begun with key city managers to determine appropriate mitigation actions. These activities will contribute to reaching one of the key objectives of the entire Essential Facilities thrust area: to implement cost effective retrofit methods by encouraging planners and public officials to adopt them.

The emphasis for the next year will be to optimize the implementation potential of research results from prior research as the EFP draws to a close. Projects on performance of rehabilitated floor diaphragms, masonry walls and non-structural components will formulate updates to present engineering guidelines and will enlarge the knowledge base on how these systems behave. Model-based simulation of seismic response will help extend the experimental test results to the base of fragility information needed to refine loss assessments. The large-scale laboratory test of a two-story masonry building will provide a proof-of-concept test bed for simulation models. Projects on benefit-cost relations for retrofit and acceptable risk will provide the needed information for development of mitigation action plans. A new project on light-frame construction will produce information on fragility of residential construction subjected to light, moderate and strong earthquakes.

Transportation Networks Program

The Transportation Networks Program was intentionally conceived with a high leverage potential by including the four basic types of transportation networks inherent in Mid-America: highways, railways, waterways and airways. The nodes and links of transportation networks represent the coarsest mesh of networks and are thus the easiest to identify and model. A subsequent networks program is envisioned on utility systems that will benefit from the network vulnerability models developed in the first phase on transportation.

Goals of Transportation Networks Program

The Mid-America transportation network includes substantial portions of the nation's highway and railroad systems, major waterways and shipping facilities on the Mississippi, Missouri, and Ohio Rivers, and airports that serve as hubs for the nation's airline (St. Louis) and air freight operations (Memphis). The Memphis airport is ranked number one in the world in the volume of airfreight and the St. Louis airport is ranked number seventeen in the world for passenger volume. Thus, extensive damage to any of these networks has severe national economic and security ramifications, and would seriously impact emergency response and recovery operations. These networks are part of the national transportation system whose performance will be enhanced through the fundamental and applied research of this thrust area.

The primary goals of the Transportation Networks Program (TNP) are to: (1) assess vulnerabilities and estimate potential economic losses across the national transportation system resulting from an earthquake in Mid-America, and (2) identify effective full and partial retrofit methods for reducing these potential losses.

Strategic Research Plan, Milestones, and Deliverables

The TNP addresses loss reductions across the national transportation system. Needed knowledge for these systems, or otherwise stated as barriers, include:

- inventories of the network
- a determination of economic flows across the network
- economic loss assessments resulting from perturbations to the network
- a determination of the relative costs and benefits of retrofit to selected components of the network
- an overall assessment of system vulnerability

System-level test beds for the TNP include the four transportation networks with emphasis on highways in the economic flow model. An extensive inventory of transportation networks has been completed (see Fig. 6).

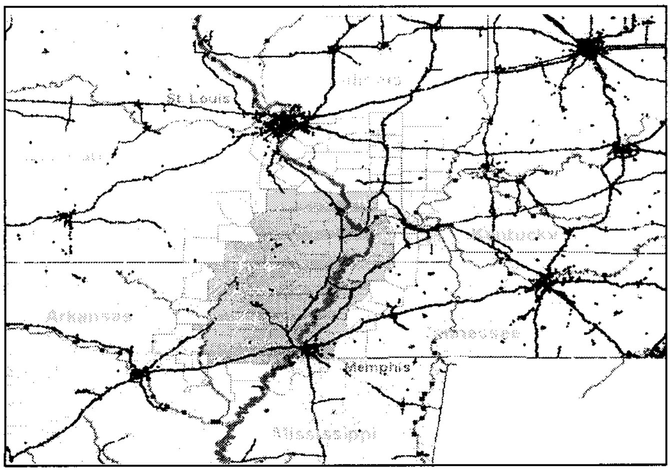

Figure 6. Inventories of Transportation Networks overlayed on Seismic Intensity Maps

Technologies needed to enable loss reductions across national networks are implicit with mitigation measures for critical components of the transportation system. Needed research to enable new technologies include the following.

- a better understanding of seismic response for existing and retrofitted bridge structures
- an evaluation of the cost and practicality of partial and full retrofit techniques
- development of improved fragility relations for transportation structures and systems

Research has relied on real-life applications to serve as proof-of-concept test beds of construction applicability. Bridge columns in the approach complex to the Poplar Street Bridge that crosses the Mississippi River are being retrofitted with procedures developed through research of the TNP (see Fig. 7). Steel and carbon based fiber-reinforced composites are being used to strengthen the concrete pier caps. Experiments were done to determine the fiber, resin, and void volume fractions of three different lay-up configurations. This information was used to develop new technologies for retrofit of bridge columns by wrapping

Figure 7. Retrofit of Bridge Columns with Composite Wraps

the columns with composites. A project on innovative materials developed information on properties, specifications and installations of fiber-reinforced polymers for this application. Because of the harsh winter climate, the investigation had to consider the effectiveness of column wraps to resist freeze-thaw and corrosion. Another project, co-funded by the Illinois Department of Transportation, is developing fragility relations for retrofitted and non-retrofitted bridge columns to provide data for subsequent loss assessment estimates.

One of the few railroad bridges crossing the Mississippi River between St. Louis and New Orleans is being used as a second test bed to see how well model-based simulation of earthquake response can apply to an aging structure constructed in the late 1800's. With help from the Burlington Northern-Santa Fe Railroad and a close association with the American Association of Railroads, dynamic response of the bridge is being computed to explore whether traditional structural analysis methods are applicable for modeling older forms of bridge construction. Simulation models are also being evaluated to explore their effectiveness at representing structural response for various retrofit options. Shaking table tests of stone supporting piers will be done to develop analytical models to represent rocking behavior.

For the Transportation Networks Program, research is done to pierce barriers at the fundamental science plane in the areas of:

- economic modeling
- nonlinear behavior and performance of bridge structures
- soil-structure interaction

Deliverables from this research include an economic flow model and analytical models to represent soil-structure interaction and retrofitted bridge foundations.

Research Advances and Deliverables

Research has been coordinated within the TNP to yield specific deliverables and advances in its short life of two years. Information from physical research and model-based simulation yields improved behavioral models and data for structures and foundations subjected to seismic actions. Software, and other simulation tools, is a product of model-based simulation. Newly developed retrofit techniques emerge from testing of physical systems and components. Information and data on the national transportation system (inventories, loss assessments, network vulnerability, etc.) are determined from system-level projects. Deliverables from projects then congeal to form deliverables for the entire program. New technologies for structural and geotechnical engineering practice result from knowledge of new behavior models and new simulation tools. Updates to new code provisions or guidelines will be proposed based on new behavioral models, data, simulation tools or retrofit techniques. New strategies for rehabilitation will result from updated provisions or guidelines, but also from knowledge of new simulation tools, retrofit techniques and system-level information on loss potential across entire networks. The ultimate users of these deliverables include: (a) practicing engineers who rely on new engineering technologies and updated codes and guidelines; (b) stake holders who rely on the national transportation system for their businesses, and (c) governments and industries who own, operate and maintain national transportation systems (public highways as well as private rail and air carriers).

A project on regional economic flows is estimating the economic impact of a catastrophic earthquake in regional and national contexts, emphasizing inter-industry relationships in conjunction with regional commodity flows as well as the assessment of seismic damages on production facilities and the transportation network. Based on the Commodity Flow Survey in 1993, more than 42% of the total commodity flows in the US are related to Mid-America. This project has assembled the interstate commodity flow data for the 36 analysis zones impacted by the New Madrid Seismic Zone. A commodity flow model has been developed to estimate the regional and national economic impact of a catastrophic earthquake in Mid-America.

Another project on foundation improvement for bridge columns has identified that the predominant foundation improvement techniques for the seismic retrofit of bridge foundations are piles and post-grouted anchors. The research team is working with state departments of transportation to address their concerns about the use of these systems and is verifying the performance of the retrofitted foundations using finite element analyses via the computer program ABAQUS.

An example of the team approach to research is illustrated by research projects on network economic loss, network fragility, and network vulnerability. The research team is outlining results needed to estimate network vulnerability and economic impact of altered transportation flows resulting from an earthquake.

Future Plans for Transportation Networks Program

In the next year or two, the TNP will investigate: (a) further refinements to the inventory database, (b) benefit-cost relations for retrofit of transportation structures, (c) overall network vulnerability, (d) vulnerability of air and rail networks, (e) fragility of transportation networks, and (f) response modification of bridges with elastomeric bearings. Projects on rehabilitation of bridge columns and railroad assessment methods will be continued. New projects will be started to investigate partial retrofit of bridges, economic and legal consequences of seismic retrofit and vulnerability of utility networks, e.g., power, pipeline and telecommunication in Mid-America.

Concluding Remarks

This brief paper has provided a summary of two research thrust areas of the Mid-America Earthquake Center to help illustrate the approach taken to investigate the unique physical, technical, economic, political and social problems of infrequent, but high consequence earthquakes. It is hoped that this material may spark the interest of a potential collaborator involved in similar earthquake research. For further information on the research programs of the MAE Center, please visit the Center website at http://mae.ce.uiuc.edu.

Acknowledgements

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