# SEISMIC BRIDGE RESEARCH IN TRANSPORTATION NETWORKS PROGRAM OF MID-AMERICA EARTHQUAKE CENTER


Timothy D. Stark[1]

Daniel P. Abrams[2]

and

Neil M. Hawkins[1]



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1 Professor of Civil Engrg., University of Illinois, 205 N. Mathews Ave., Urbana, IL, 61801, (217) 333-7394, (217) 333-9464 FAX, e-mail: t-stark1@uiuc.edu

2 Hanson Engineers Professor of Civil Engineering, Center Director, Mid-America Earthquake Center, University of Illinois, 205 N. Mathews Ave., Urbana, IL, 61801, (217) 333-0565, (217) 333-3821 FAX, e-mail: d-abrams@uiuc.edu

# SEISMIC BRIDGE RESEARCH IN TRANSPORTATION NETWORKS PROGRAM OF MID-AMERICA EARTHQUAKE CENTER

Timothy D. Stark, Daniel P. Abrams, and Neil M. Hawkins
Mid-America Earthquake Center and
Professors of Civil & Environmental Engineering
University of Illinois
205 N. Mathews Ave.
Urbana, IL, 61801

**ABSTRACT:**

This paper describes some of the research on the seismic behavior, analysis, and retrofit of bridges that is being conducted under the Transportation Networks Program of the Mid-America Earthquake Center. The seismic bridge research is being conducted to achieve the objectives of this Program, which are to: (a) assess vulnerabilities and estimate potential economic losses in the national transportation network, and (b) identify effective retrofit methods for reducing these potential losses. The bridge related research encompasses a range of topics including analysis techniques for bridge retrofit measures, techniques for retrofitting or modifying existing bridges, foundation improvement techniques, and development of innovative materials for seismic retrofitting. This paper presents a brief description of the seven research projects that are focused on seismic bridge research.

## INTRODUCTION

The Mid-America Earthquake (MAE) Center (http://mae.ce.uiuc.edu) assembles researchers from seven core institutions across six states with complementary talents in seismology, geophysics, geotechnical and structural engineering, social science, economics, risk assessment, and urban planning. The Center's focus is directed at the infrequent, but high consequence, earthquake hazards of the eastern and central United States. All research efforts are coordinated through two parallel programs on *facilities* and *networks* that will evolve over the lifetime of the Center. (Education, implementation, outreach, and collaboration activities are also integrated among the core institutions.)

The mid-America transportation network includes substantial portions of the nation's highway and railway 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). For example, the Memphis airport is ranked first in the world in volume of air freight and the St. Louis airport is ranked seventeenth in the world for passenger volume. Highway and railway traffic across the major rivers is constrained to relatively few long-span crossings; e.g., there are only nine interstate highway crossings of the Mississippi River. The regional and national economic consequences of just a few outages of these crossings would be extreme. Experience suggests that these crossings are vulnerable; structural damage, loss of bearing support, damage to approach spans, and loss of foundation support due to liquefaction and lateral spreading may occur.

The consequences of failure of a transportation system from earthquake shaking could involve: (a) direct loss of life due to collapse or structural failure, (b) indirect loss of life due to an inability to respond to secondary catastrophes, such as fires, and/or provide emergency medical aid, (c) delayed recovery operations, (d) release of hazardous materials and environmental impact, (e) direct loss of property and utility service, (f) economic losses due to interruption of access to a transportation system, and (g) disruption of economic activity across the region and nation. Because of time and funding constraints, the Transportation Networks Program (TNP) is focusing on the disruption of economic activity (item g) since losses to the national network of transportation are expected to be a significant percentage of the total loss expected when the next major earthquake strikes in mid-America. As a result, the primary objectives of the TNP are to: (a) assess vulnerabilities and estimate potential economic losses in the national transportation network, and (b) identify effective retrofit methods for reducing these potential losses.

## PROGRAM DESCRIPTION

The Transportation Networks Program is outlined in the flow chart in Figure 1. Relations between individual research (rectangular shapes) and implementation (octagon shapes) projects are shown to illustrate the integration and reliance of one project on another in the Transportation Networks Program. Projects representing the end products of the program are shown at the top of the flow chart. The phasing or sequencing of the projects is shown on the timeline for the TNP in Table 1. A more detailed flow chart and timeline are presented in the MAE Center website. In addition, a detailed task statement for each of the eighteen research projects shown in Table 1 is given on the MAE Center website.

Based on a variety of input, including significant end user input, highway and waterway systems were given a higher priority than railway and airway systems in the TNP. Since these modes interconnect, the total national shipping system depends on all four modal networks. The program will address all of them, but the depth of coverage will be greater for highway and waterway modal networks than for railways and airways.

## BRIDGE RELATED SEISMIC RESEARCH PROJECTS

The following bridge related research projects are underway or planned for the TNP. It can be seen from Table 1 that there are seven projects (ST-3, ST-12, ST-13, ST-14, ST-16, ST-17, and GT-5) in the Program that are focused on the seismic performance of bridges. These projects are briefly described below.

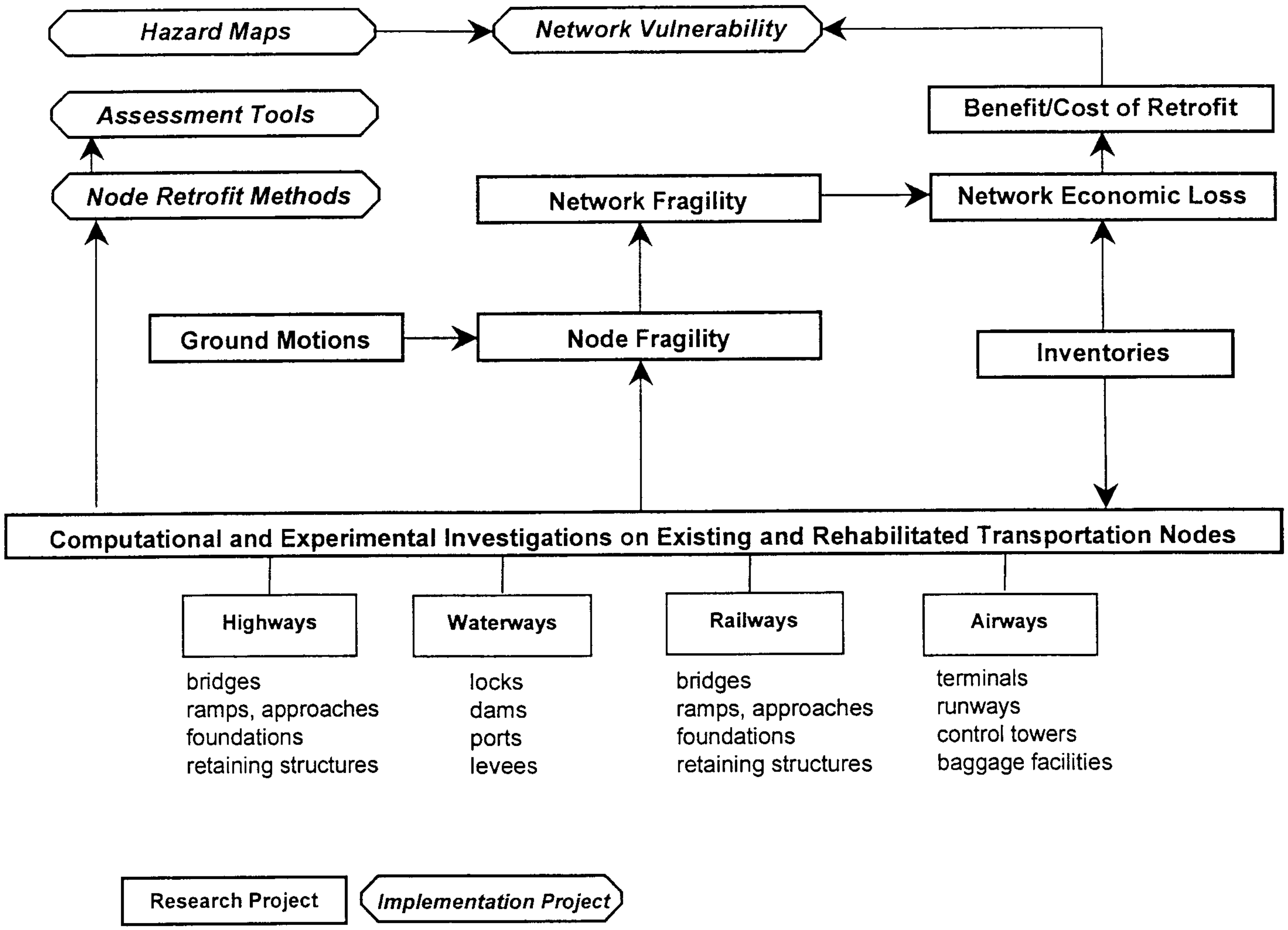


Figure 1. Coordination of Tasks for Transportation Networks Program

**Table 1. Sequence of and Investigators for Research Projects in Transportation Networks Program**

| Project Number and Title | Year 1 | | | | Year 2 | | | | Year 3 | | | | Year 4 | | | | Year 5 | | | | Investigator(s) | *Institution |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | | |
| RC-3: Coordination of Transportation Networks Program | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | Stark | UIUC |
| SE-3: Inventories of Transportation Networks | | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | | French, Lipinski, Aschheim | GT, UM, UIUC |
| SE-4: Regional Economic Flows for Transportation Networks | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | Kim, Hewings, Boyce | UIUC, UIC |
| SE-10: Network Economic Loss | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | Sussman | MIT |
| SE-11: Benefit/Cost of Retrofit | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | Hawkins, Hewings | UIUC, UIC |
| SE-12: Network Vulnerability | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | Sussman | MIT |
| RR-4: Fragility of Transportation Nodes | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | Hwang | UM |
| RR-5: Fragility of Transportation Networks | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | Veneziano | MIT |
| ST-2: Evaluation/Retrofit of Trans. Structures | | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | | Leon | GT |
| ST-3: Analysis of Bridge Retrofit Measures | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | Ghaboussi, Foutch | UIUC |
| ST-12: Response Modification of Bridges | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | Leon, Desroches, Dyke | GT, WU |
| ST-13: Rehabilitation of Bridge Columns | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | Hawkins | UIUC |
| ST-14: Railroad Bridge Assessment Methods | | | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | Foutch, Hjelmstad | UIUC |
| GT-5: Foundation Improvement for Bridge Columns | | | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | Briaud, Hueste, Long | TAMU, UIUC |
| GT-6: Seismic Performance of Lock Structures | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | Truman, Gould | WU |
| GT-7: Seismic Performance of Waterfront Structures | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | Mesri, Stark, Hall, Ebeling | UIUC, USACE |
| ST-15: Vulnerability of Airport Facilities | | | ■ | ■ | ■ | | | | | | | | | | | | | | | | Gould, Truman | WU |
| ST-16: Innovative Materials for Seismic Retrofit | | | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | Zureich, Buyukozturk | GT, MIT |
| ST-17: I-40 Memphis Bridge Instrumentation | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | Pezeshk, Johnston | UM |

*** Research Institutions:**
UIUC - University of Illinois at Urbana-Champaign
UIC - University of Illinois at Chicago
GT – Georgia Tech
UM – University of Memphis
MIT – Massachusetts Institute of Technology
WU - Washington University
TAMU - Texas A & M University
USACE – U.S. Army Corps of Engineers

## ST-3: Analysis of Bridge Retrofit Measures

The analysis of bridge retrofit measures project has reviewed the methods for seismic analysis and evaluation of retrofit measures for major river-crossing bridges in mid-America. Based on this review it was determined that the research should focus on (1) methods of analysis of soil-structure interaction, (2) methods of analysis for pile-soil-structure interaction, and (3) modeling and analysis of multiple support excitation. After consultations with the Illinois Department of Transportation (IDOT), the I-57 Bridge in Cairo, Illinois was selected for modeling and seismic analysis. This bridge, which crosses the Mississippi River at Cairo, is located in a seismically active zone and is scheduled for seismic retrofit. The main channel crossing is a truss-arch bridge with a central span of 821 ft and two side spans of 518 ft each. The whole bridge, including the multi span approaches of 1547 ft on the Illinois side and 456 ft on the Kentucky side were modeled. The three dimensional model was first analyzed with fixed foundations subjected to synthetic earthquake records. The results of these analyses revealed the vulnerabilities of the truss arch structure near the supports, and the large torsional motion of the two 300 ft spans on the Illinois side approaches.

Since the main span piers are founded on caisson foundations and the approach piers are founded on pile foundations, analysis techniques are being developed to model the entire structure and soil-structure interaction effects. This research is being assisted by the investigators of GT-5: Foundation Improvement for Bridge Columns, which is providing different methods for including the foundation-ground interaction. The resulting computer software will be made available to the engineering community. In the process of analyzing the major river-crossing bridges as well as shorter span bridges, fragility relationships will be developed for use in the subsequent network vulnerability analysis in the TNP.

## ST-12: Response Modification of Bridges

This project is exploring economical and innovative methods for modifying the seismic response of typical highway bridges in mid-America. The response modification techniques to be studied range from simple and economical to highly innovative applications of new materials. An example of the former is the replacement of existing, tall rocker bearings with elastomeric pads. An example of the latter is the replacement of heavy concrete parts of the superstructure with fiber reinforced composite elements to substantially diminish the mass of the structure. The first objective of the project was to identify the typical support and superstructure types for critical bridges in mid-America. The bridge inventory information revealed that the three "typical" bridge types are (1) Multiple-Span Simple Supported (MSSS), (2) Single Span, and (3) Continuous. A two-dimensional nonlinear model of a MSSS bridge has been developed to assess the performance under various synthetic earthquakes. This model was used to determine the response modification due to replacing steel bearings with elastomeric bearings and adding cable restrainers at the decks and abutments. The results of the analytical model will be verified using laboratory tests. Through both experimental and analytical studies, appropriate techniques for both evaluation and upgrading of existing bridges are being developed. Finally, fragility relationships for typical MSSS bridges in mid-America with and without retrofit will be developed for use in subsequent vulnerability analyses.

## ST-13: Rehabilitation of Bridge Columns

The rehabilitation of bridge columns project has developed procedures for the design, specification, and job site quality control of prestressing strand and advanced composite wraps for the seismic retrofit of bridge columns. IDOT is using this technology to cost-effectively address the seismic hazard existing in its large inventory of reinforced concrete bridge columns. The hazard is caused by an inadequate length lap splice at the connection between the column and the crash wall or foundation that supports it. Further, most columns in Illinois are located on soft soils so that any measure taken to correct this hazard must also not significantly stiffen the column. Otherwise, the strengthening method may overstress the soil and also require retrofit of the foundation. The procedures developed using this research satisfy all of these requirements.

In addition, this project has developed a data base of existing information on column wraps and analysis of that data was used to investigate the applicability of splices retrofitted with prestressing strand wraps, performed in accordance with the guidelines contained in FHWA Report RD-94-052 " Seismic Retrofitting Manual for Highway Bridges," to Illinois conditions. This analysis showed that splices retrofitted with advanced composites required a wrap thickness that is significantly less than that required by the FHWA guidelines. An analytical model that can replicate that effect was developed and use of the model is required for all column retrofit designs in Illinois.

## ST-14: Railroad Bridge Assessment Methods

The railroad bridges crossing major rivers in mid-America such as the Mississippi, Ohio and Missouri Rivers were all built in the late 1800s. These are usually steel truss bridges supported on stone piers. The superstructures are usually not at great risk from seismic loads, but the bearings and substructures are vulnerable. In addition, the unreinforced stone piers supporting the superstructure are highly vulnerable. These were built from slabs of granite and are usually supported on caissons. With support from the Burlington Northern/Santa Fe Railroad, a comprehensive three-dimensional finite element model of a typical major river crossing was developed using the computer program SAP 2000. The model is being enhanced to include a nonlinear analysis that incorporates the response of the stone piers and caissons.

A finite element analysis of only the stone piers is currently under way to investigate the vulnerability of the piers. Due to the age of the piers, it is being assumed that the mortar will not be effective and sliding of the stone slabs relative to each other will be resisted only by friction and interface interlock. Under low axial force and large overturning moment the slabs can separate forming crack-like openings between slabs or between the slabs and foundation. This can lead to overturning-collapse or crushing at the toe of the opening. Finally, failure of the caissons or supporting soil, which is usually very soft, is also being considered.

## ST-16: Innovative Materials for Seismic Retrofit

Fiber-reinforced polymeric (FRP) composites are being investigated as a means for retrofit of existing bridge structures. The project is considering the use of new materials including FRP composites for seismic retrofit of bridges because of the increasing requirements for lightweight, high stiffness and/or strength, and non-corroding materials. The main objective of this project is to model the behavior of concrete members retrofitted using FRP composites under the coupled effects of cyclic loading and environmental conditions. Such a model is necessary for evaluation of the safety and reliability of retrofitted systems, which have been in service for a certain duration of time, in the case of an earthquake. A fracture-based analysis is being used to model the behavior of concrete beams and columns retrofitted with FRP composites due to the limitations of the classical ultimate strength approach.

At present a literature survey of fundamental properties of FRP composite systems used for structural rehabilitation activities and some initial laboratory tests on beams strengthened with FRP composites have been completed. The composite system includes fibers embedded in a polymer matrix and an adhesive resin used for bonding. The properties compiled include density, tensile strength, elastic modulus, Poisson's ratio, coefficient of thermal expansion, failure strain, fracture toughness, impact resistance, fatigue resistance, and durability under several environmental conditions. Laboratory testing aimed at quantifying the effect of moisture absorption on the tensile behavior of wet lay-up carbon fiber reinforced composites typically used in the strengthening of concrete columns is being pursued.

The results from this project will be used to develop important information on the properties, behavior, specifications, and installation of fiber-reinforced plastics for use in the project on rehabilitation of bridge columns (ST-13). In particular, the use of carbon based fiber-reinforced composites to strengthen the concrete pier caps is being investigated.

## ST-17: I-40 Memphis Bridge Instrumentation

The I-40 Hernando DeSoto Mississippi River Bridge in Memphis, Tennessee is scheduled to be retrofitted. The objective of the retrofit is to keep the I-40 bridge fully operational following a strong earthquake (2500 year return period). The I-40 Bridge will be retrofitted with Friction Pendulum™ Isolation Bearings to ensure the integrity of the main span superstructure. The first phase of the retrofit is scheduled to begin in late summer of 1999. During this retrofit construction phase it is proposed to install an integrated system of seismic strong-motion instruments in and around the vicinity of the bridge. If sufficient funding is obtained, the strong-motion instrumentation will consist of approximately 65 data channels at 25 different locations on the bridge and one in the free-field in the vicinity of the bridge. This will provide needed data to better understand the ground motion and response of the retrofitted bridge in a strong earthquake. The acquisition of this structural response data will also be used to confirm methodologies for the analysis and design of earthquake-resistant structural systems in other TNP projects.

**GT-5: Foundation Improvement for Bridge Columns**

The foundation improvement project has identified that the predominant foundation improvement techniques for the seismic retrofit of bridge foundations are piles, post-grouted anchors, and drilled shafts. The research team is working with the IDOT and the Missouri Department of Transportation to develop an analytical model to confirm the performance of the retrofitted foundations using finite element analyses via the computer program ABAQUS. Load test data for pile types suited to bridge foundation retrofit have been used to verify the analytical model. Analysis has been performed for a 3 x 10-pile group, with and without a micro-pile retrofit, to assess the relative static and dynamic stiffness values.

The final goal is to optimize the depth and location of additional piles, anchors, and shafts for the retrofit of a bridge foundation. The results of this study are being used by ST-14: Railroad Bridge Assessment Methods because preliminary results indicate that some of the stone pier foundations will have to be retrofitted. GT-5 is also providing analytical methods and results to ST-3: Analysis of Bridge Retrofit Measures because previously ST-3 was only considering the response of the bridge structure and simply modeling the foundation as a linear-elastic material. The ABAQUS analysis approach is being used to provide a more realistic analysis in ST-3 by modeling the foundation soil as a nonlinear-stress dependent material.

**SUMMARY**

The Transportation Networks Program of the Mid-America Earthquake Center has developed an integrated, multi-disciplinary approach to assess the vulnerabilities, and estimate potential economic losses, in the national transportation network due to an earthquake in the eastern and central United States. To accomplish this integrated and multi-disciplinary research, investigators from seven core institutions with expertise in seismology, geophysics, geotechnical and structural engineering, social science, economics, risk assessment, and urban planning have been assembled. Eighteen projects are underway or planned for the Transportation Networks Program. These projects include seven projects on the seismic behavior, analysis, and retrofit of bridges. This paper presents a brief description of the seven projects focused on bridges, which address a range of topics including analysis techniques for bridge retrofit measures, techniques for retrofitting or modifying existing bridges, foundation improvement techniques, and development of innovative materials for seismic retrofitting.