2008-2009 Annual Report

Infrastructure Technology Institute
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Dear Friends:

Infrastructure is the connective tissue of our economy and society. The extent and capacity of US transportation infrastructure are characteristics we take for granted until something goes wrong. The collapse of the I-35W bridge in Minneapolis was a wake up call about the importance, and risks, of that infrastructure. Such large failures are quite rare, but smaller, disruptive failures are more commonplace. Like most major infrastructure failures, the loss of I-35W can be attributed to multiple factors, but the consequences of such losses, immediate and long term, remind us of the need to assure the integrity of critical transportation infrastructure.

Northwestern's Infrastructure Technology Institute is about ensuring our nation's surface transportation infrastructure against failures large and small. A primary focus of the work of ITI is structural health monitoring (SHM) – developing and deploying technologies and methods to assess the condition of key transportation components, and to convert condition and performance data into information that is useful to support decision making.

In an era of much competition for scarce resources, it is imperative that we make wise decisions about infrastructure management, and good information can contribute to better decisions.

ITI SHM research and development efforts gather data at different points in the life of a structure – from construction through long-term utilization and life extension. Using periodic static measurements or real-time dynamic measurements, our engineers deploy powerful tools to capture, transmit, store and display infrastructure data, often in challenging environments and over great distances. The data are typically presented via a secure web site to provide timely support for evaluation and decision-making.

ITI researchers are also engaged in the development of advanced structural modeling methods and the creation of new, designer materials that solve old transportation infrastructure problems and meet new needs.

The work of ITI is done in conjunction with external partners, usually owners and operators of major infrastructure facilities and systems who bring us problems and a willingness to share in the pursuit of solutions.

This Annual Report provides an overview of activities and achievements of ITI during the year 2008-2009, the second year of our support under SAFETEA-LU. It reflects the work of a community of researchers – faculty, students and staff, and their deployment partners across the U.S.

Sincerely,

Joseph L. Schofer
Director of the Infrastructure Technology Institute
Associate Dean for Strategy and Communications
Robert R. McCormick School of Engineering and Applied Science
The theme of the Infrastructure Technology Institute is to develop strategies and tools to protect and improve the condition, capacity, and performance of the nation’s highway, railroad, and mass transit infrastructure systems.

The Michigan Street lift bridge in downtown Sturgeon Bay, Wisconsin was remotely monitored by ITI for nearly ten years as part of life-extension efforts. It is now undergoing a long-awaited retrofit.

Center of Excellence
The physical infrastructure of surface transportation (highways, bridges, pavements, signs and signals, intermodal facilities, etc.), comprises the most obvious and essential component of the nation’s transportation system. Transportation infrastructure is ubiquitous and extensive, supporting the ability to go anywhere and ship anything. Our transportation system and its infrastructure support our economy, the welfare of our society, and the security of our nation.

Because of the rarity of major failures, it is easy to take this transportation system for granted. Surface transportation infrastructure requires careful monitoring, planning, and management; continuing reinvestment to maintain condition and assure performance, safety, and security; capacity expansion, the addition of new connections and services; and the adoption of new technologies to improve efficiency and sustainability. All of these requirements necessitate deployment of resources that is fact-driven, based on objective measures of physical condition, performance, and current and expected needs.

Northwestern University’s Infrastructure Technology Institute (ITI) is committed to ensuring our nation’s surface transportation infrastructure against failure by developing and deploying techniques and technologies to assess infrastructure condition and to improve that condition with new materials and processes. A primary focus of the work of ITI is structural health monitoring (SHM): developing and deploying technologies and methods to assess the condition of key transportation components and to convert this condition and performance data into information that is useful in decision making.

ITI SHM research and development efforts gather data during different periods in the life of a structure – from construction through long-term utilization and life extension. Using static or real-time measurements, our engineers deploy powerful tools to capture, transmit, store, and display infrastructure data, often in challenging environments and over great distances.

ITI researchers are also engaged in the development of advanced structural modeling methods and the creation of new, designer materials that solve old transportation infrastructure problems and meet new needs. Much of the work of ITI is done in conjunction with external partners, usually owners and operators of major infrastructure facilities and systems, who bring us problems and a willingness to collaborate in the pursuit of solutions.

Founded in 1992 under the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), ITI is a National University Transportation Center presently funded under the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy For Users (SAFETEA-LU). This report describes the activities and achievements of the ITI team for the period between September 1, 2008 and August 31, 2009, its second year of funding under SAFETEA-LU. It goes beyond our technology advances to describe our educational achievements and support of policy analysis and the infrastructure policy debate.
ITI is an interdepartmental center within Northwestern’s McCormick School of Engineering and Applied Science. ITI is directed by Dr. Joseph L. Schofer, Professor of Civil and Environmental Engineering and Associate Dean of the McCormick School. The Institute employs four principal administrative staff members to perform day-to-day operations, and a five-person research team with experience in non-destructive evaluation and remote monitoring of transportation infrastructure.

The Research Engineering Group (REG) supports faculty, research staff, and graduate students engaged in Institute-supported research projects. REG professionals possess exceptional skills and experience in development and field deployment of advanced instrumentation techniques for monitoring civil infrastructure facilities. Their experience is applied to the three-fold mission of the ITI REG:

1. Conduct the REG’s own research on development and deployment of innovative instrumentation and monitoring techniques to solve real and current infrastructure problems, in partnership with infrastructure owners and operators across the nation

2. Support ITI-funded researchers and their students with instrumentation, communications, and deployment expertise, ensuring that state-of-the-art monitoring and communication technologies are available for and deployed in ITI research applications

3. Support other ITI technical program functions as necessary, including teaching, conference communications, and outreach

Left: ITI Director Joseph Schofer teaching a class
Right: Chief Research Engineer Daniel Marron and Professor David Corr put on their harnesses to go in a lift bucket in Hurley, Wisconsin
ITI selects projects for funding based on an annual proposal solicitation and review cycle. Requests for continuing funding must be accompanied by progress or final reports as well as a list of publications produced with previous ITI support. Proposals are reviewed by our Research Advisory Committee which meets annually to review, discuss, and recommend proposals for the upcoming funding period. The Director weighs the recommendations of the advisory committee against the Institute’s strategic plan and available funding. As part of this review, the Director verifies the matching arrangements for each proposed project to ensure that match requirements will be met for the Institute’s overall program. For field applications, the match usually comes from in-kind services provided by the deployment partner or client. For projects that do not have a collaborating partner that can provide substantial matching funds, other arrangements are made, including the use of internal expenditures by Northwestern University for activities that have a direct programmatic connection to the project and/or the ITI mission.

To track short-term research progress, identify opportunities for cross-linking of ITI projects, and support broader interaction between faculty, staff, and students, ITI hosts a monthly research meeting attended by all funded principal investigators, their students, other Northwestern University researchers and research administrators, and representatives of related centers (the Transportation Center, the Center for Quality Engineering and Failure Prevention, the Center for the Commercialization of Innovative Transportation Technology, and others).

At these meetings, members of the research teams present technical updates on work in progress and selected principal investigators give in-depth reports. This provides an important opportunity for synergistic interaction, generating new ideas about methods and projects, and providing a rich, interdisciplinary learning environment for students.
Success in Education
ITI’s educational objective is to enhance the understanding of civil infrastructure systems, particularly those critical to surface transportation, and to prepare undergraduate and graduate students for productive careers in infrastructure and transportation.
EXCEL PROGRAM

Part of ITI’s education agenda for Year 2 of SAFETEA-LU was support of the EXCEL program of Northwestern’s McCormick School of Engineering and Applied Science. The program provides an intense five-week summer academic session for incoming engineering students who demonstrate leadership skills and interest in diversity issues. Students start their college careers with all-day classes in math, chemistry, engineering analysis (linear algebra and computer programming), leadership, and design problems for real-world clients.

To wrap up the 2009 academic term, the EXCEL students took a architectural boat tour of the Chicago River, the location of some of the world’s most complex urban infrastructure. The tour guide explained the significance of engineering feats such as the reversal of the Chicago River, the Chicago-style trunnion bascule bridge, the elevated section of Wacker Drive, and the downtown skyscrapers built on air rights over active railroad tracks. The architecture tour was followed by a visit to Infrastructure Engineering, Incorporated. Northwestern and EXCEL alumnus Michael Sutton, P.E., president of Infrastructure Engineering, described his company and career path to students, after which they met with staff engineers of the organization.
In March 2009, members of Northwestern’s student chapter of the American Society of Civil Engineers (ASCE) took an alternative spring break trip to San Francisco to tour the region’s unique transportation infrastructure. The trip, jointly sponsored by ITI, the Illinois Section of ASCE, and the students themselves, built upon the successful San Francisco tour undertaken by Northwestern students in 2007. Eleven undergraduate engineering students and three ITI staff members spent four days exploring bridges, public rail transit, public ferry transit, sustainable building design, seismic research, and urban planning.

The trip included a tour of seismic retrofits to the San Francisco-Oakland Bay Bridge, including the replacement of the entire eastern span, a portion of which collapsed during the 1989 Loma Prieta earthquake. Hosted by members of the construction and design teams, students learned about the structural design characteristics and construction process of the span, as well as the environmental and social impacts of this massive transportation infrastructure project. Students also visited the seismic research facility at the University of California-Berkeley, where they witnessed a demonstration of the laboratory’s five-story tall earthquake simulator.

The tour included Caltrain engineering facilities and a train trip to San Jose, accompanied by a group of local public officials, architects, and transportation experts. The discussion en route covered both transportation infrastructure and service design. In San Jose, the students met with Rod Diridon, former Santa Clara County Supervisor and champion of California’s new high-speed rail initiatives. The students toured the San Jose-Diridon passenger station and the new state-of-the-art locomotive maintenance facility.

The group also visited the new California Academy of Sciences building, a LEED (Leadership in Energy & Environmental Design) platinum-certified structure with a green roof, solar panels, and extensive use of recycled materials to minimize its CO₂ footprint.
In the Classroom

CAD CLASSES

During SAFETEA-LU Year 2, ITI continued to invest in the professional components of engineering education to prepare students for careers in transportation and other civil engineering fields. A key element of this program is the computer-aided drafting (CAD) course based on AutoCAD software. Utilizing the newly established CAD laboratory, which is furnished with 21 workstations donated by General Motors, and Autodesk design software furnished by ITI, Research Engineer Daniel Hogan and Adjunct Professor Wayne Bielski once again offered a two-quarter course sequence in engineering graphics and computer aided design to 20 undergraduate engineering students. Responding to student feedback after last year’s course, a new feature of this year’s course was more in-depth education in the fundamentals of engineering graphics.

ACOUSTIC EMISSION TRAINING

In September of 2008, the ITI Research Engineering Group hosted a short course in acoustic emission (AE) technology to provide the most current training to experienced users and to introduce the technology and practice to engineers with interest but no previous experience.

AE is a naturally occurring phenomenon whereby a material under stress produces sounds. These sounds, though usually imperceptible to a human ear, can be monitored with the use of special equipment. The location and intensity of these sounds can be used to measure degradation in a material. This technology, though under continuing development, has already proven useful across many engineering disciplines. AE can be used to measure the performance of medical implants, the integrity of pressure vessels, the condition of steel bridges, the condition of wind turbines, and the strength of new materials.

Professor Richard Nordstrom of Portland State University, an expert in AE technology and practice, conducted lectures and tutorials on basic AE principles, then provided hands-on demonstrations and lessons using the equipment in the ITI laboratory. Students were encouraged to ask questions about their specific applications of AE technology.

The two-day short course was attended by members of the ITI team, graduate and undergraduate students in civil engineering and materials science, and members of private engineering firms. The course was well-received and will likely be offered again.

STUDENTS CONTRIBUTE TO STRUCTURAL HEALTH MONITORING PROJECT AND LEARN ABOUT INSTRUMENTATION

Undergraduate students from the structural steel design course in Northwestern’s Department of Civil and Environmental Engineering joined the ITI team for a structural health monitoring (SHM) project. The students repurposed a small steel bridge built several years ago for a student design competition as a mockup for a bridge in Hurley, Wisconsin, where ITI and the Wisconsin Department of Transportation installed a SHM system later in the year.

The ITI engineering staff worked closely with the students, teaching them hands-on instrumentation techniques including strain gage installation and data acquisition methods. Using their knowledge of steel design, the students installed strain gages at fourteen critical high-stress areas of the mockup bridge. The mockup provided a platform for a realistic test of all sensors and electronics prior to deployment in the field. This helped ensure a smooth installation during the time allotted, which was strictly limited by the availability of access equipment. Future SHM efforts will also benefit from the availability of a corps of willing students with instrumentation experience.

Once the instrumented mock-up bridge is no longer needed for the SHM project, it will be deployed at various Northwestern events to showcase ITI’s SHM abilities and to spur interest in civil engineering careers among undergraduates and pre-college students.
Civil Engineering senior Alexander Stack learns to install strain gages on a mockup of a steel bridge that was later instrumented by ITI engineers.
UNDERGRADUATE STUDENT CONTRIBUTES TO ITI RESEARCH

During his sophomore year, Jeff Meissner, a Civil Engineering senior from Rochester, Michigan, started working on ITI-sponsored research with Prof. Charles Dowding. Jeff met Dowding through Northwestern’s Engineering Design and Communication program in which freshmen work on real design projects to give them an early experience with engineering.

Jeff’s initial efforts with ITI research included assembling Prof. Dowding’s blast vibration literature into a searchable electronic library. After gaining familiarity with the literature, Jeff began to take an active role in analysis of data from ITI’s monitoring sites. He analyzed vibration and settlement data from a structure near a limestone quarry in North Carolina and co-authored a paper describing the results for presentation to the annual meeting of the International Society of Explosives Engineers in February 2009. Jeff also presented a poster on his work at the Northwestern Undergraduate Research Symposium in May 2009.

Currently, Jeff is analyzing the response of a structure in south Florida to wind gusts, thunder, and ground vibration from blasting. During the summer of 2009, he worked full-time for ITI, continuing to study the dynamic response of structures to events such as blasting, heavy construction activity, wind gusts, and thunder. During the summer Jeff also participated in ITI field deployments, both directly related to Jeff’s research as well as to other ITI projects involving instrumentation of civil infrastructure.

Jeff reports that research and coursework complement each other well, saying, “It’s fun to take concepts learned in the classroom and apply them to new and different situations.”

In addition to his coursework and research, Jeff is involved with the Northwestern student chapter of the American Society of Civil Engineers and is president of Northwestern’s club baseball team. Following graduation, he plans to pursue graduate study in structural engineering.

ITI regularly employs undergraduate engineers in its research projects to enhance their education and to draw more young professionals into infrastructure engineering.

2008 STUDENT OF THE YEAR

ITI was pleased to name Ivan Vlahinich, a Ph.D. candidate in the Department of Civil and Environmental Engineering, as its Student of the Year. Ivan’s studies and research focus on the behavior of cement-based and other heterogeneous materials, and he works with ITI researchers Professors Hamlin Jennings and Jeffrey Thomas on the chemical and microstructural properties of cement.

Ivan earned his B.S. in civil engineering at Columbia University, graduating magna cum laude in 2003. During and after his undergraduate studies, he worked as a civil engineer in design and construction in the US and abroad.

ITI selected Ivan because of his important research achievements: He has developed a new mathematical formulation to describe the dimensional changes of a porous body during drying, as the water or other fluid evaporates from the pores. This is important theoretical work in the field of poromechanics and geomechanics with immediate practical implications to shrinkage of concrete. Ivan’s model has been verified using data from both cement paste and porous glass, and he is lead author of a paper describing this work, recently accepted for the Mechanics of Materials journal. Ivan expects to complete his Ph.D. in 2010. His dissertation is titled “Mechanical performance cement-based and other heterogeneous materials: approach based on granular microstructure.”

Top: Civil Engineering senior Jeff Meissner presents his ITI-sponsored research at Northwestern’s Undergraduate Research Symposium.
Bottom: 2008 Student of the Year Ivan Vlahinich
During Year 2 of SAFETEA-LU, ITI’s research agenda presented several opportunities to provide hands-on research experience to undergraduates in Northwestern’s Department of Civil and Environmental Engineering. In late 2008, freshman Olivia Nelson and sophomore Ken Fuller began work with ITI’s Research Engineering Group (REG). These students provided valuable support to ITI’s research efforts, including the preparation of electronics for the deployment of long-term structural health monitoring systems, assisting with field trips to install and service these systems, preparing samples for and conducting laboratory experiments, and supporting ITI’s technology transfer events.

Olivia traveled to Naples, Florida with the REG to perform maintenance and upgrades to a structural health monitoring system that measures the effects of road aggregate mining on nearby structures. Ken took part in the preparation and execution of several laboratory experiments to evaluate a new technique to monitor crack propagation in steel bridge members. Both students worked in ITI’s laboratory in preparation for deployments and traveled to Hurley, Wisconsin for field installations.

Civil Engineering undergraduates Olivia Nelson (left) and Ken Fuller (below) assisted with installation of a SHM system on a bridge in Hurley, Wisconsin.
Success in Technology Transfer
A primary avenue for technology transfer at ITI is our work in partnership with infrastructure agencies and owners to develop and deploy innovative structural health monitoring technologies to help those partners solve real infrastructure performance and condition problems.

Institute researchers work directly with partner agencies which, in turn, provide support and matching resources to the Institute’s activities in three ways:

- Provision of on-site personnel and equipment to support ITI researchers in the installation and demonstration of SHM technologies
- Provision of engineering and other support services that are essential for conducting ITI deployment field work
- Occasional direct contracting with Institute researchers to provide technical assistance for field deployment of advanced technologies

Among the deployment partners with whom we have worked in the past year are:

- Kentucky Transportation Cabinet
- Wisconsin Department of Transportation
- California Department of Transportation
- Illinois Department of Transportation
- Chicago Department of Transportation
- Schnabel Foundation Company, Southborough, Massachusetts
- Jones Mining Company, Naples, Florida
- GeoSonics Inc., Warrendale, Pennsylvania
- Vulcan Materials Company, Franklin, Wisconsin
- Union Tank Car Company, Chicago, Illinois
- Lafarge North America, Herndon, Virginia
- Coachella Valley Water District, Coachella, California
- STS AECOM, Vernon Hills, Illinois

These partnerships are usually initiated by the agencies and facility owners who have learned about our expertise through our web site, conference appearances, or publications. Occasionally we will approach a potential partner when we see a particularly challenging infrastructure monitoring problem, or, in the case of our material development work, where we can bring special expertise to bear on an infrastructure material need.

Our partners not only benefit from the resolution of a problem or need, but in some cases they acquire the knowledge, skills and technologies to conduct their own advanced SHM activities.

ITI has continued to develop and move material technologies into practice through the design of advanced steels for applications to tank cars and bridges.
The ITI-sponsored Midwest Bridge Working Group (MBWG) held two meetings during Year 2 of SAFETEA-LU: one in Louisville, Kentucky in December 2008, and one at the Illinois Department of Transportation (IDOT) District 1 Headquarters in Schaumburg, Illinois, in June of 2009. The two meetings attracted over 220 bridge professionals from state highway agencies, consulting firms, vendor companies, and universities. Several dozen more joined via live Web broadcast of the Louisville meeting. The forums focused on discussion of best practices and technical, political, and financial issues in the field of bridge maintenance and inspection. Each meeting featured a wide variety of talks on new technology and methodology for bridge inspection and maintenance.

One notable presentation in Louisville was an extensive explanation of Missouri’s Follow-Up Action Required procedure by Ken Foster, who recently joined the staff of the Federal Highway Administration after a long career with the Missouri DOT. Mr. Foster explained that the procedure enables inspectors to report bridge problems or deficiencies which require immediate investigation or corrective action. The development of the process in 2003 was prompted by a group of inspectors who found that certain potentially critical bridge problems never seemed to be remedied in spite of inspectors reporting them after every inspection. Under the Follow-Up Action Required procedure, inspectors submit a form documenting an issue of particular concern (including photographs and other documentation) along with a recommended plan of action for review by an engineer. If the issue is deemed a Critical Inspection Finding (CIF) in need of immediate attention, inspectors and engineers then work together to develop a response plan. Because the new procedure ensures timely and thorough response to inspection results, the number of CIFs in the first year of the program dropped from 15 to 2, and there have been no more than four CIFs in each of the subsequent years.
Two ITI researchers gave presentations during the Louisville meeting. Chief Research Engineer Daniel Marron spoke about noise localization on a rolling-bascule lift bridge. Mr. Marron’s talk drew on ITI’s years of experience and pioneering work in the application of acoustic emissions (AE) testing to large civil structures, particularly steel highway bridges. In this case, the ITI team was able to locate the source of loud banging noises that occurred during movement of the bridge. David Corr, Clinical Associate Professor of Civil Engineering and the newest member of the ITI team, discussed lessons learned from the collapse during construction of the Marcy Bridge in upstate New York. Prof. Corr’s presentation concentrated on the application of finite element models to investigate the collapse.

The Schaumburg meeting included two unique field trip opportunities for the attendees. The first tour, hosted by IDOT, was of the District 1 Traffic Control Center. Meeting participants were treated to a close-up look at traffic monitoring systems, incident response technology, and the control system for the reversible express lanes on Chicago’s Kennedy Expressway. Attendees experienced a hands-on tour of the Congress Parkway Bridge, a trunnion bascule lift bridge that carries traffic from Chicago’s Eisenhower Expressway over the South Branch of the Chicago River into downtown Chicago. Meeting participants received a tour of the bridge operator house and mechanical rooms and heard former CDOT employees explain aspects of the system of lift bridges for which Chicago is famous.

MBWG has been supported by the Infrastructure Technology Institute since 1996, and continues to be a successful forum for the interchange of information among participating state highway agencies on issues related to bridge inspection and maintenance. ITI works closely with the Kentucky Transportation Center and the University of Kentucky Civil Engineering Department to facilitate Working Group activities.
The Ohio Department of Transportation (ODOT) is deploying a continuous remote monitoring system developed with ITI support to safeguard a section of Interstate 70 in Muskingum County that is threatened by collapse of an abandoned coal mine beneath the highway. This deployment, a cooperative effort between ODOT, ITI, and Geotechnical Consultants, Inc. of Westerville, Ohio, represents the continuation of ITI’s previous work in geotechnical applications of time-domain reflectometry (TDR) technology pioneered by ITI researcher Prof. Charles Dowding, and the successful transfer of TDR monitoring technology from university research to practice.

TDR may be thought of as “cable radar”: a radio-frequency pulse is sent down a coaxial cable and the reflected signals are analyzed. In geotechnical applications, TDR cables are typically grouted into boreholes in soil and rock; the pulse will be partially or completely reflected by localized shearing of the soil or rock, complete severing of the TDR cable, or upon contact with the ground water table. In their book, Geomeasurements by Pulsing TDR and Probes, Prof. Dowding and Dr. Kevin O’Connor cited a coal mining case study in which TDR detected subsurface movement four days before movement was detected at the surface. Thus, TDR data may be used both to provide early warning of sub-surface failures and to evaluate the performance of mitigation efforts.

ITI’s TDR applications to highway subsidence in Ohio began in 1996 when a 10x12-foot section of I-70 near the city of Cambridge in Guernsey County suddenly dropped into a sinkhole formed by the collapse of an abandoned coal mine. After the highway was repaired and the mine was grouted, TDR cables were installed underneath the highway to monitor for any additional sinking of the roadway. ITI provided the TDR data acquisition system and ODOT personnel interrogated the cables manually for several years. In 2001, ITI began autonomous remote monitoring of the site: each night, data were downloaded and posted on a web site – without human intervention – for easy comparison with historical norms. Continuous Internet-enabled remote monitoring continued through May 2009, when the Guernsey County site was determined to be stable and remote monitoring equipment was removed.

The new Muskingum County site will feature an expanded instrumentation suite with five TDR cables installed in horizontal boreholes under the highway. The instruments will be remotely monitored before, during, and after the sealing and grouting of the mine to provide increased confidence in the safety and functionality of the highway.
Technical Presentations

**ASNT Presentations**

Members of the ITI Research Engineering Group (REG) frequently travel to conferences and meetings to present and share results of Institute research. During SAFETEA-LU Year 2, the REG travelled to two significant conferences to share information and seek out new deployment partners.

In September 2008, members of the REG attended the American Society for Nondestructive Testing’s “Structural Materials Technology Conference 2008: NDE/NDT for Highways and Bridges” conference in Oakland, California. The conference explored the role of non-destructive evaluation and testing throughout the life cycle of transportation infrastructure. ITI research engineer David Kosnik presented “Monitoring of In-Situ Strains in Bearing Assembly Anchor Bolts on a Large Through-Truss Bridge,” which summarized testing and structural health monitoring work done by ITI and University of Kentucky researchers on a major Interstate highway bridge.

The paper covered the response of the failure of an uplift bearing anchor bolt on a the John F. Kennedy Memorial Bridge, a large cantilever truss structure which carries Interstate 65 over the Ohio River at Louisville, Kentucky. Analysis of the failed bolt showed that corrosion fatigue was the likely cause; additional inspections revealed significant corrosion damage to the remaining anchor bolts securing the bearing to the pier. The entire bearing assembly was observed to be moving relative to the pier cap as a result of the reduced restraint. The three remaining anchor bolts and the bearing were instrumented to quantify strains and bearing movement under live traffic. Similar measurements were performed on the other three uplift bearings on the truss. When the failed anchor bolt was replaced with a threaded rod, the rod was instrumented and tightened to a specified pre-load to secure the bearing. The axial strain was measured by instrumentation as a securing nut was tightened. Changes in strains on the other bearing anchor bolts were simultaneously measured. Dynamic strains in the retrofitted rod and other bearing anchor bolts were monitored under traffic for 17 hours. Continuous remote monitoring of live strains is being employed to evaluate the long-term performance of the temporary retrofit and aid future decision-making.

When not attending conference sessions, ITI personnel staffed an exhibit booth describing ITI’s work to potential deployment partners and others.

**AEWG Presentations**

In October, 2008, members of the REG attended the 51st meeting of the Acoustic Emission Working Group, held in Memphis, Tennessee. ITI research engineer David Kosnik presented his award-winning extended abstract, “A New Approach to Acoustic Emission Testing of Difficult-to-Reach Steel Bridge Details,” which documented the REG’s experience in acoustic emission (AE) evaluation of a crack in a fracture-critical steel bridge member. Previous AE work on highway bridges has been contingent on favorable field conditions – particularly access, weather, and power. To overcome these limitations, the REG developed a weatherproof enclosure and robust communication and control schemes to allow the collection of many hours of data from a detail that was accessible only by lift bucket during limited lane closure windows. The data showed that the crack was not growing; corroborating results were obtained from other, more traditional non-destructive evaluation techniques. In addition, the AE data indicated an additional defect near the crack. The presence of this defect, which is believed to be a slag inclusion, was confirmed by radiography, further validating the utility of AE testing of steel bridge details.
Commercialization of New Weathering Steel for Bridges

Under the TEA-21 grant, ITI researchers Prof. Morris Fine and Dr. Semyon Vaynman designed a 70 ksi yield strength (ASTM A710 Grade B) steel with good fracture toughness at low temperatures, excellent weldability without pre-heat or post-heat, and corrosion resistance superior to all other weathering steels. The Illinois Department of Transportation (IDOT) used this steel successfully to build a bridge in Lake Villa, Illinois in October 2006. During Year 2 of SAFETEA-LU, this research and technology transfer effort continued to address growing needs of the infrastructure community for economical steels that have outstanding fracture- and corrosion-resistant properties. New variants of A710 Grade B steels are under development and are being commercialized by ITI researchers.

At the request of IDOT, a steel containing lower concentration of copper and nickel than the original A710 Grade B steel was developed, laboratory-produced and tested. The cost of this steel is lower than that of the A710 Grade B steel, and its mechanical and fracture properties significantly exceed bridge steel requirements. IDOT has specified this steel for three bridges to be built in Illinois in FY2010. The first bridge will use wide flange I-beams to reduce the number of welds in the bridge. Commercialization efforts during Year 2 of SAFETEA-LU included a presentation at Steel Dynamics, Inc., in Fort Wayne, Indiana. This company agreed to produce the I-beams for bridge construction. Production of beams for the first bridge is scheduled tentatively for late November or early December 2009.

The Federal Highway Administration has identified a critical need for a “super-weathering” bridge steel that is especially resistant to salt corrosion. The original A710 Grade B steel possesses the best weathering characteristics among current weathering steels. With this as the base, ITI researchers are working to design a “super-weathering” steel by addition of phosphorous and titanium. Phosphorous is the most potent element for improving weathering resistance in steels, but it cannot be added in large enough amounts because the steel becomes too brittle. Fine and Vaynman solved this problem by incorporating titanium into the new steel. Titanium prevents the segregation of phosphorus to grain boundaries, thus suppressing embrittlement. In addition, titanium itself was shown to improve the weatherability of steel. A laboratory heat of this so-called P-Ti-modified steel was produced and preliminary tests show it to be remarkably ductile and fracture-resistant. Assuming this steel’s improved weathering ability is confirmed in testing that is currently underway, the P-Ti-modified steel will indeed have “super weathering” characteristics and will be an excellent material with which to construct bridges exposed to de-icing salt and marine spray.
Close-up of an I-beam made of NUCu steel developed under ITI sponsorship
The Second Annual William O. Lipinski Symposium on Transportation Policy

On November 13th, 2008, policy makers, transportation professionals, faculty, and students assembled at Northwestern for the Second Annual William O. Lipinski Symposium on Transportation Policy.

The Symposium brings together transportation leaders to discuss innovative approaches for planning, financing, and constructing transportation infrastructure. Using the 100th anniversary of Daniel H. Burnham's 1909 Plan of Chicago as a vantage point, speakers and participants at the Symposium envisioned a future transportation system for the Chicago region to meet the accessibility, capacity, quality, and sustainability needs of our society and economy for the next century. The series of presentations and panel discussions identified current challenges facing transportation systems locally and nationally and explored avenues for change.

After former US Representative William O. Lipinski opened the forum named in his honor, US Representative John L. Mica (R-FL), Ranking Member of the House Committee on Transportation and Infrastructure, discussed the need for a national strategic infrastructure plan. Rep. Mica emphasized the importance of using targeted infrastructure investments to stimulate economic recovery, and he advocated a clear financial plan and the use of objective project selection criteria. Finally, Rep. Mica spoke of the need to make project implementation processes more efficient, citing the rapid replacement of the I-35W bridge in Minneapolis.

The theme address was given by Carl Smith, Franklyn Bliss Snyder Professor of English, History and American Studies at Northwestern University. The author of The Plan of Chicago: Daniel Burnham and the Remaking of the American City (U. of Chicago Press, 2006), Prof. Smith provided an illustrated summary of the 1909 Burnham Plan, discussed conditions of the city and its transportation system at the time of the plan, and described the impacts of Burnham’s work, in terms of both specific implementations and general principles that have affected the city to this day.

Dr. Michael Toman of Johns Hopkins University spoke next, outlining the global energy picture, its relationship to the environment, climate, and national security, and the implications for transportation. Discussing global warming, Dr. Toman pointed out that one-third of US CO2 emissions come from transportation, and that pricing options are likely to show earlier effects than technologies on reducing both energy consumption and greenhouse gas emissions.

Observing that energy simply can not be left out of future transportation planning, Toman noted that the global market is affected by exploding demand for energy from China and India, as witnessed by the 2008 jump in oil prices and the continuing escalation of the costs of construction materials.

Dr. Martin Wachs of the RAND Corporation was the last speaker of the morning session. He discussed critical policy and financial issues facing transportation, key among which were congestion mitigation,
efficiency of overall transport, fiscal sufficiency, and equity. He contrasted the Burnham era, when solutions were found in infrastructure investments, with contemporary approaches that emphasize financial instruments to influence behavior and provide sustainable support. Wachs described the highway transportation finance crunch in terms of increasing needs and costs contrasted with decreased user-tax revenues due to increasing fuel economy and use of biofuels. He stated that use-based financing was the key to transportation infrastructure investment, and he made a strong case for use-based pricing, including time-of-day (congestion) pricing, cordon pricing (as in London and Stockholm), and mileage charges using vehicle tracking technologies. He cited examples of the effectiveness of use-based pricing in reducing congestion and roadway damage and underscored the political challenges of implementing such financing and demand-management schemes.

A panel discussion concluded the morning session, extending the earlier talks and their implications for Chicago. Larry Johnson of Argonne National Laboratory predicted changes in vehicle technologies, saying the hybrids would become standard, taking advantage of advanced batteries and regenerative braking. Professor Joseph Schwieterman of DePaul University discussed key issues for the Chicago region, including assuring the efficiency of freight transportation and reinvigorating public transit.

ITI Director Joseph Schofer made closing remarks, urging that Chicago recapture a leadership role in transportation innovation. He emphasized that challenges ahead revolve around sustainability of key resources – energy, climate, and funding and the road ahead will be paved with a mixture of capital investments and operational improvements built on advanced communications and computing technologies. Schofer closed with a call to increase collaboration among industry, government, and the several universities in the region that have strength in transportation.

At the lunch break, William O. Lipinski presented US Representative James Oberstar (DFL-MN), Chairman of the US House Transportation and Infrastructure Committee, with the inaugural David F. Schulz Award for Outstanding Public Service in Transportation and Infrastructure Policy. Present during the ceremony were Jo Ann and Bobby Schulz, the widow and son of David Schulz, the late founding director of Northwestern’s Infrastructure Technology Institute. In his acceptance speech, Rep. Oberstar called for action to restore the nation’s rapidly deteriorating transportation infrastructure.

At the start of the afternoon session, Frank Kruesi, Director of the City of Chicago’s Washington, D.C. Office of Intergovernmental Relations, emphasized the centrality of Chicago in the nation’s transportation system. He described some of the important transportation initiatives underway in the City and the region, including re-establishing the importance of transit by expanding the Chicago Transit Authority rail lines; the O’Hare Airport Modernization Program; the Midwest High Speed Rail Initiative; and the transportation elements of Chicago’s 2016 Olympic bid. Paraphrasing Daniel Burnham, Kruesi observed that “…it takes money to stir men’s blood.”

The afternoon continued with a panel of members of the House Transportation and Infrastructure Committee: US Reps. Jerry F. Costello (D-IL), John J. Duncan, Jr. (R-TN), Daniel Lipinski (D-IL), and Thomas E. Petri (R-WI). The panel members shared their views of future transportation needs and issues, as well as the expected and essential elements of the forthcoming surface transportation reauthorization act.

From top to bottom:
- Dr. Martin Wachs gives a presentation in the morning session.
Rep. Petri argued that transportation is not high enough on the national agenda. Noting that President Eisenhower believed that the real strength of the country was in productivity, not in arms, Rep. Petri called for a renewed national commitment to bridges and public transit.

Rep. Petri also spoke in support of project CREATE— the Chicago Regional Environmental and Transportation Efficiency Program, a public-private partnership to enhance rail freight efficiency in Chicago, because of the benefits it will produce for the nation. He observed that the US now spends about 2% of GDP on transportation, while China spends 9%.

Rep. Duncan expressed concern over the state of the Highway Trust Fund (HTF), reminding the group that Congress appropriated $8 billion from the general fund in 2008 to keep the HTF solvent. To make the best use of these funds, it will be important to streamline the project implementation process. This will cut costs and speed project delivery.

Rep. Costello joined in support of the need for and value of reinvesting in surface transportation infrastructure as a part of the recovery program. He said that every $1 billion invested in transportation infrastructure generates 34,000 person-years of employment and an overall return of $6 billion. Rep. Costello noted that we cannot promise to do more and to cut taxes at the same time. To get support for additional funds, it is necessary to make clear what benefits will be produced; this should take the form of a national plan for transportation.

Rep. Lipinski underscored the value of megaprojects, large-scale public infrastructure investments of true national significance. Such initiatives require the support of broad coalitions. He predicted that the surface transportation reauthorization bill would begin with a clean slate, offering great opportunities for moving forward. He declared 2009 as the Year for Transportation, noting the need to reauthorize highway, aviation and transit programs. Directing his remarks more specifically to Chicago, Rep. Lipinski noted the need for more federal support to deal with at-grade railroad crossings, since Illinois has the second-largest number of these crossings among the states.

In an interchange among panelist about successes with large projects in Europe, Rep. Lipinski observed that Europeans have higher expectations for service quality and greater willingness to pay for it. Rep. Petri said that in the US, infrastructure investment is a hard sell, but Americans expect projects to be done well.

The afternoon ended with a panel discussion by state and local leaders. John McCarron, former editorial writer for the Chicago Tribune and adjunct lecturer in Northwestern’s Medill School of Journalism, suggested the need for more communication with journalists to explain the need for and value of infrastructure to the public: citizens and decision makers need to know why transportation projects are so costly, and what value they produce.

State Representative Elaine Nekritz, chair of the Illinois House Railroad Subcommittee, observed that we have neither a state nor a national plan for transportation. She contrasted that with public-private collaborations elsewhere that seem to produce results. She argued for making freight transportation a key issue because of its importance for economic competitiveness, and she supported expansion of transportation infrastructure to increase capacity.

Milton R. Sees, Illinois Secretary of Transportation, stated that while infrastructure costs money, it generates benefits that produce more money for the economy. Without additional funds, there are severe limits on what the state can do today to improve the condition of transportation infrastructure. Under the current budget situation in Illinois, bridge maintenance is necessarily the main priority.

The legacy of Daniel Burnham and his Plan of Chicago was the underlying theme for this Second Annual Lipinski Symposium. Like Burnham, participants agreed on the critical importance of efficient transportation infrastructure and service to ensure the success of our economy and society. There was broad support for plans – grand plans – for transportation at the regional, state, and national levels. Those plans must be based on a system-wide perspective that balances needs, values and impacts. To justify the costs and secure funds to meet them, it will be essential to help decision makers and their constituents understand the links among transportation, economic competitiveness, and social success.
Frank Kruesi of the City of Chicago's Intergovernmental Relations Office in Washington, D.C., presents at the Lipinski Symposium.

Responding to Chicago's Transportation Challenges: Planning Big, Making Magic

Frank Kruesi
City of Chicago
Success in Research

Electronic components of the structural health monitoring system installed on the USH-2 Montreal River bridge in Hurley, Wisconsin.
The Institute’s research program focuses on ensuring the viability of transportation infrastructure systems through the development and application of innovative measurement, monitoring, and communications technologies to gather critical data on the structural health of infrastructure systems. ITI has also invested in the development of new and improved infrastructure materials.

Institute researchers have deployed advanced continuous remote structural health monitoring (SHM) technologies on transportation infrastructure facilities around the nation. In collaboration with deployment partners, we have used elements of the nation’s infrastructure as our field laboratory to develop, deploy, and test advanced SHM technologies. In the process we have helped agencies to identify and understand significant problems with their transportation infrastructure. These partnerships have provided unique and challenging settings for research and invaluable learning opportunities for our students.

Research work during Year 2 of SAFETEA-LU included:

- Development and deployment of tools and methods for structural health monitoring (SHM) of transportation infrastructure, including applications to fracture-critical bridges
- Development of tools and methods for monitoring the impact of transportation construction and resource extraction activities on nearby facilities, including autonomous measurement of site deformation and construction vibrations
- Development of advanced wireless data acquisition systems that can monitor the growth of cracks in steel bridges
- Development of innovative materials for transportation infrastructure, including continued evolution of weldable, high strength weathering steels for bridges and new concrete mixtures optimized for slip-form paving
- Analysis of critical infrastructure failures as the basis for developing safer codes and standards for design of concrete structures
ITI's Research Engineering Group (REG) has partnered with the Kentucky Transportation Cabinet (KYTC) and the University of Kentucky (UK) since 2007 to address questions about the end bearing anchor bolts on the John F. Kennedy Memorial Bridge, a large through-truss structure which carries Interstate 65 over the Ohio River between Louisville, Kentucky, and Jeffersonville, Indiana. The bridge has two large bearings at each end which, due to the design of the continuous span, must resist substantial uplift forces. In a 2006 inspection, one of the four anchor bolts restraining one of these uplift bearings was found to have fractured, while measurable section loss was noted on the other three.

The results of a 2007 short-term strain gage study by ITI engineers contributed to a retrofit design by KYTC in which the remainder of the fractured bolt embedded in the concrete pier was drilled and tapped to receive a replacement anchor bolt. Four large “keepers” anchored directly into the concrete pier would provide additional redundancy. ITI was asked to monitor the performance of the replacement bolt and the entire bearing assembly during and after retrofit. ITI engineers installed a variety of instruments on the assembly, including strain gages to measure axial, torsional, and bending strains on the replacement bolt and displacement and acceleration transducers to monitor the overall movement of the bearing assembly. Load cells were also installed on the keeper anchors to indicate if the keepers became loaded due to movement of the bearing assembly.

SAFETEA-LU Year 2 work began in late 2008 when ITI engineers installed a continuous remote monitoring system on the troubled bearing. This system logs and transmits readings from strain gages on the anchor bolts, load cells on the keepers, and displacement sensors on the bearing assembly itself, along with ambient temperature and humidity, back to ITI via a cellular data connection. This information is automatically processed and posted daily on the secure project web site.
Within two months of installation, the continuous remote monitoring system recorded an event involving significant redistribution of loads on the bearing assembly, including the unloading of the replacement anchor bolt, indicating possible failure of the new bolt. Authorities were made aware of this anomaly promptly. ITI and KYTC engineers confirmed fracture of the new anchor bolt during a subsequent site visit. During that visit, ITI also installed two Internet-accessible cameras to provide visual confirmation of any future indications.

Through the use of continuous remote structural health monitoring, ITI was able to detect very quickly the fracture of a structural member in a bridge over 300 miles away without the benefit of an on-site inspection. When the next retrofit of the bearing is performed, KYTC will continue to use this successful monitoring technique. Demonstration of the benefits of monitoring technology to retrofit design and performance validation continues to be a major thrust of the ITI REG’s ongoing research.
Novel Structural Health Monitoring System on a Wisconsin-Michigan Border Bridge

**Principal Investigator:**
**Daniel Marron**

The ITI Research Engineering Group (REG) has partnered with the Wisconsin Department of Transportation (WisDOT) and International Road Dynamics, Inc., to develop and deploy an innovative structural health monitoring system on the US Highway 2 bridges over the Montreal River between Hurley, Wisconsin, and Ironwood, Michigan.

Concerns over possible damage to the bridges by overweight trucks led WisDOT to specify a weigh-in-motion (WIM) system to measure the weight and speed of passing trucks for the dual purposes of traffic enforcement and collecting data on the truck loads to support engineering evaluation of the bridge. Building on its years of experience in instrumentation of highway bridges, ITI deployed sensors to measure strain and acceleration on critical details of the bridge carrying the westbound lanes. The combined weigh-in-motion and bridge monitoring systems are expected to be fully operational by late 2009. The novel real-time combination of WIM and structural health monitoring data makes the Hurley project the first of its kind in the nation.

According to Prof. Joseph Schofer, director of ITI, the USH-2 bridge project represents a logical evolution of ITI research. “This is a great opportunity to integrate sensor-based structural health monitoring (SHM) – one of ITI’s core research areas – with an intelligent transportation system (ITS), in this case a weigh-in-motion device. By building this connection between ITS and SHM, we can help assure the safety and serviceability of the nation’s transportation infrastructure.”

Mr. Terry Bergan, president and CEO of IRD, said, “We are also very excited about working with the Infrastructure Technology Institute at Northwestern University on the USH-2 project. This ITI system will complement our Virtual Weigh Station truck monitoring activities at the USH-2 site by directly measuring the response of critical areas of a bridge structure to truck traffic particularly overweight trucks and permit loads.”

Top: Research Engineer David Kosnik installs a strain gage on a high-stress area of the USH-2 bridge. Bottom: Chief Research Engineer Daniel Marron wires support electronics in preparation for the Hurley installation.
Top: Electronic hardware inside the instrument cabinet for the Hurley structural health monitoring system.

Right: ITI Research Engineer David Kosnik and undergraduate student Ken Fuller test the ultrasonic river stage sensor under the bridge.

Bottom: Undergraduate students Jeff Meissner and Olivia Nelson begin digging a trench for instrument cables.
In September 2008, the ITI Research Engineering Group (REG) partnered with a consulting engineering firm to identify the source of “banging” noises generated during opening and closing of a large rolling-bascule lift bridge over a busy waterway. Reflection and re-radiation of noises along the steel structure made it impossible to determine the source of the noise by ear. The REG drew upon its experience with acoustic emission (AE) monitoring of large civil structures to locate the noise source using arrays of piezoelectric AE transducers coupled directly to various steel structural elements.

The REG monitored a total of ten lift cycles over two days, using four different array geometries to test various hypotheses. The initial test sequence was designed to rule out the lift machinery as the source of the noise. In this case, analysis readily showed that the noise originated from somewhere in the heel area of the bascule girder, far from the machinery itself. Additional testing ruled out the track plate on which the moving bridge leaf rolls as the bridge opens as well as bolted connections on the bottom of the bascule girder as noise sources. Finally, source location analysis suggested that the noise were generated along the interface between the bascule girder and the curved track forging which engages the bottom track as the bridge opens.

The ability to locate the source of the noise through AE – particularly the elimination of the lift machinery as the noise source - provided the consulting engineers with a quantitative basis for decisions regarding operation of the noisy bridge. WisDOT was able to keep the bridge in operation, avoiding disruptions to the flow of both highway and marine traffic.
Tracking the Effects of High-Rise Construction on Chicago Infrastructure

**Principal Investigator:** Richard Finno

The proximity of important infrastructure to excavation support systems imposes strict movement limits associated with the construction of deep basements. While top-down construction techniques generally are thought to provide a stiff support system, and hence small excavation-induced ground movements, as a result of using the permanent floor slabs as lateral support, recent field experience has indicated that lateral movements associated with these types of support systems are similar to more conventional bottom-up excavations that employ temporary lateral support in the form of cross-lot bracing or tieback ground anchors. One source of movement that is not considered when making design predictions is shrinkage of the concrete in the floor slabs that act as temporary and permanent support. These slabs are structurally tied into the perimeter walls, and as they shrink during curing, they may “pull” the wall towards the building and thus cause ground deformations adjacent to the excavation that otherwise would not occur. While this mechanism has been suggested a number of times, it has never been shown by performance data, and thus remains a matter of conjecture.

ITI researcher Professor Richard Finno and his team set out to collect field performance data from the One Museum Park West development in Chicago that would define the relation between shrinkage of the concrete floor slabs used as temporary and permanent lateral support and ground deformations adjacent to the excavation. This project is a cooperative effort between Northwestern and STS AECOM, the geotechnical engineers on the project.

In the first year of the project, ITI research engineers installed a real time monitoring system to evaluate the stresses in the four levels of floor slabs. The gages are tied to the top and bottom rebar in pairs and the wires are brought to several data acquisition and control system boxes on each basement level. From there, a radio link is established to allow remote acquisition of the signals in real time. Using the data collected at the site, Finno’s team is developing a methodology that can be used to predict these effects. The data collected by the real time monitoring system is supplemented by results of conventional optical surveys and inclinometers. As the system continues to collect performance data, the team is conducting analyses of ground deformations as a result of all construction activities, with emphasis on effects of shrinkage of concrete floor slabs.

Successful completion of this research will improve the state-of-the-art and practice of predicting and controlling ground movements associated with supported excavations and tunneling operations. Analyses of the results of the observations will help develop design procedures to minimize the effects of the consequent deformations of adjacent structures and utilities, particularly related to the relation between concrete slab shrinkage and ground movements.
Crack Free Concrete Made With Nanofiber Reinforcement

**Principal Investigator:**
**Surendra Shah**

Recent advancements in cement-based materials have focused on development of high-performance cement composites, which possess high compressive strengths. However, such composites exhibit extremely brittle failure and low tensile capacity and are sensitive to early age microcracking. Typically, millimeter- or micrometer-scale fiber reinforcement is added to the mix to reduce cracking; unfortunately, however, this reinforcement is insufficient to address nano-scale flaws in the cement matrix.

During Year 2 of SAFETEA-LU, ITI researcher Professor Surendra Shah and his team began investigation into carbon nanofibers to reinforce concrete at the cement matrix level which would create a new generation of crack-free material. Research focused on addressing two major drawbacks associated with the incorporation of nanofibers in any type of material: poor dispersion of fibers in the material and cost of the fibers themselves.

For best crack-prevention performance, nanofibers must be uniformly dispersed throughout the cement matrix. However, dispersion is typically inhibited by the fibers’ tendency to stick together due to Van der Waals forces. Ineffective dispersion means that more nanofibers must be included in the mix, increasing cost. Shah’s team has overcome these barriers by adding a surfactant and applying ultrasonic energy to the mix, effectively dispersing nanofibers throughout the cement matrix. As a direct result of improved dispersion, the fracture properties of the cement matrices were substantially improved: electron microscopy and nanoindentation tests have shown that matrix cracks are effectively controlled at the nano-scale and that nanofibers strongly modify the structure matrix itself. Equally importantly, the effectiveness of dispersion means that these results can be obtained with very low amounts of nanofibers, making the material more affordable.

This work has great promise to produce a cost-effective material with greatly increased durability due to reduced early-age microcracking. These improvements may help extend the life of civil structures.
Design and Verification of Blast Densification for Highway Embankments on Liquefiable Sands

Highway embankments built on sand in seismically-active regions may be vulnerable to failure due to liquefaction.

ITI researcher Professor Richard Finno and his team have set out to address this question by developing (i) a quantitative design procedure for blast densification of liquefiable granular soils, and (ii) means of reliable in situ verification of the ground improvement.

Using critical state soil mechanics, Finno's team has developed concepts to quantify the amount of densification associated with a blast, given the initial state of the loose sand in the ground. Through laboratory experiments, soil parameters needed to define the blast response and post-blast recompression have been developed. Other results have shown that shear wave velocity increases as a result of recompression; measuring this value in situ may provide useful field verification of blast-induced densification. This verification is critical, because blasting must continue until the formerly loose sand is densified sufficiently such that it will dilate under imposed shear stresses if liquefaction is to be prevented.

PRINCIPAL INVESTIGATOR: RICHARD FINNO

The nation’s transportation infrastructure includes many embankments for highways and railroads. In seismically sensitive regions, including areas west of the Rocky Mountains as well as broad areas of the eastern and central US, a key design issue for such structures is whether liquefaction – loss of shear strength of sands – will occur during an earthquake. If the soil is susceptible to liquefaction, engineers must either undertake ground-improvement efforts or risk catastrophic flow failure of the embankment. Densification of the loose sands by controlled blasting is an economical approach to ground improvement, especially when large volumes of sands must be improved. However, it is difficult to assess the effectiveness of blast densification. Case studies have shown that loose sands compress almost immediately after blasting, but follow-up verification tests often show apparent decreases in strength and stiffness. This paradox leads to questions about future performance. Have the loose sands really been improved to the point where liquefaction is not a possibility?
Intelligent Structural Health Management of Civil Infrastructure

PRINCIPAL INVESTIGATOR: SRIDHAR KRISHNASWAMY

In conjunction with the National Science Foundation’s Partnerships for International Research and Education (PIRE) program, ITI has sponsored research on Intelligent Structural Health Management (ISHM) of civil infrastructure with the aim of developing new diagnostic and prognostic methods to ensure structural reliability and to exchange researchers with the other partner organizations to foster a cross-disciplinary research program.

During Year 2 of SAFETEA-LU, ITI-sponsored researchers, in partnership with universities and industry in China, India, Korea, and the United States, made notable progress toward developing thermal and acoustic imaging systems for non-destructive imaging, developing advanced laser ultrasonic methods for the characterization of porosity of cementitious materials, and improving probabilistic prognostics of fatigue crack growth. Highlights from each of these topics are described below.

THERMAL IMAGING OF FIBER-REINFORCED POLYMER WRAPPED COLUMNS

Deterioration of substructure elements, such as columns, reduces the service life of highway bridges. An alternative to replacing a column that has suffered limited damage is using a composite column wrapping. When applied to a reinforced concrete column, a wrapping can increase the flexural ductility of the column in addition to increasing the column’s shear strength. This is accomplished by confining the concrete core and longitudinal reinforcement. This confinement increases the longitudinal bars’ resistance to buckling even after a plastic hinge has formed in the wrapped region. This is an important result in areas of earthquake risk.

However, these benefits will not be realized if the wrapping is damaged or improperly installed. ITI researchers have developed a pulsed thermography technique which makes it possible to monitor both carbon- and glass-fiber wraps for common deterioration modes, including fiber breakage and debonding from the concrete substrate. The same technology can be used as a quality control tool to inspect newly installed wraps. The technique is fast, robust and lends itself well to field application. A typical result of the test is shown above. This tests show the feasibility of using flash thermography to test for delaminations between fiberglass and concrete in wrapped columns.

Left: Image of tested cylinder with black washable paint applied to the outside of the fiberglass
Right: Seismic retrofit of columns on the Interstate 57/Illinois Route 3 bridge in Cairo, Illinois, in the New Madrid fault zone
Bottom: Flash thermography system used for testing a fiberglass-wrapped concrete cylinder
Mechanical integrity and durability of cementitious materials such as concrete are important factors for construction of long-lasting infrastructure. While it is well known that strength and durability depend upon microstructural properties such as porosity and permeability, it is difficult to measure these properties. ITI-sponsored researchers are exploring a laser-based ultrasonic technique with the goal of developing a method for monitoring changes in structural properties of cementitious materials as they age.

This technique involves the measurement of the phase velocity of fast and slow longitudinal waves in water saturated cement paste. The slow wave speed depends on the tortuosity and permeability, while the fast wave speed is controlled by the elastic properties of the porous solid. Experimental results detailing the generation and detection of fast and slow wave waves in freshly prepared and aged water-saturated cement samples with varying water-to-cement ratios were presented at the Review of Progress in Quantitative NDE, Kingston, Rhode Island in July 2009.

Curiously, the slow wave that is present in fresh cement paste specimens is absent in aged specimens, regardless of water-cement ratio. This is thought to be due to a change in the pore connectivity with age since the slow wave speed results from wave propagation through the pore fluid. Likewise, observed phase velocity changes in the fast wave are interpreted as the result of changes in the elastic properties and pore structure of the specimen during drying and re-saturation. These early results suggest that the laser-based ultrasonic method may be a viable approach to monitoring the durability of cementitious materials. The accuracy and reliability of the measurement technique is currently being established.

In a parallel effort, a group of Northwestern University undergraduate students joined post doctoral fellow Bradley Regez on a trip to the Indian Institute of Technology, Madras, in August of 2009 to conduct a series of fatigue crack growth experiments to obtain the Paris Law parameters for the NUCu steel developed by ITI researcher Prof. Morris Fine and coworkers at Northwestern. The aim of this study was to obtain data from several fatigue crack specimens so as to obtain the probability distribution functions for the Paris Law parameters for this unique steel.
Wireless Crack Propagation Measurement

**Principal Investigator:**
Charles Dowding

During Year 2 of SAFETEA-LU, ITI engaged in a project to design and test a proof-of-concept instrumentation system that uses a wireless sensor network to monitor the growth of cracks in bridges. At present, crack growth is recorded qualitatively as part of bridge inspections that occur at least every two years. This wireless system can continuously and automatically measure the elongation of cracks, allowing quantitative measurements of crack growth of a bridge to be recorded over periods of months or years. This system is weather-resistant, battery-powered, and capable of solar recharging such that it can run in the field for up to five years without maintenance. It can be connected to the Internet to allow remote monitoring of real-time data, access to historical data, and timely e-mail alerts of significant crack growth. The system will provide a reliable stream of information to supplement standard bridge inspection practices and further ensure the safety of the traveling public.

ITI engineers adapted a commercially available wireless sensor network system for environmental and agricultural monitoring to operate with a series of crack sensors. Through a series of laboratory tests on small steel coupons, the engineers were able to confirm that this system is capable of tracking the growth of a fatigue crack in a steel member and sending e-mail alerts when a crack grows beyond a certain point. Future work will include deployment of the qualified sensor on an in-service highway or railroad bridge.

Top: Crack propagation gage attached to a steel test coupon mounted in a testing clevis
Bottom: String potentiometer attached to a steel test coupon
Appendix
Funding Sources and Expenditures

Total Funding: $5,716,200

- Federal Grant: 50%
- University: 41%
- Other (Research Partner): 9%

Total Expenditures: $4,516,142

- Research: 48%
- Education: 28%
- Administration: 12%
- Other (Research Partner): 12%
ITI Research Engineer Daniel Hogan passed away on June 19, 2009, following a brief illness. Dan joined ITI early in its history and was deeply involved in many aspects of the Institute’s life and mission.

Dan was a capable engineer and fabricator, designing and building circuitry, enclosures, and fixtures of all kinds for the field instrumentation work of the ITI Research Engineering Group and ITI-supported professors. His work took him to field sites throughout the nation, where his infectious good humor – often in the face of adverse field conditions – made him many friends at Northwestern and among the state highway agencies with whom ITI forged partnerships.

Dan’s most lasting contribution to ITI and Northwestern, though, was his involvement with student groups. He was deeply committed to the success of undergraduate civil engineering students and worked tirelessly to equip them for their careers. Dan organized the computer-aided drafting (CAD) class, which grew into and continues to be a popular two-quarter course sequence. He was the practitioner adviser to the Northwestern student chapter of the American Society of Civil Engineers (ASCE) for many years. He facilitated annual short courses in welding and surveying and organized several ASCE Spring Break field trips to visit the important civil infrastructure of the San Francisco Bay area. It seems somehow fitting that he fell ill very shortly after returning from the 2009 ASCE San Francisco trip for which he had organized an expended schedule including meetings with high-ranking California rail officials.

Dan’s passing is a great loss for ITI, the McCormick School of Engineering and Applied Science, and Northwestern, but most importantly for those who knew him as a friend, co-worker, and mentor.