

**NORTHWESTERN UNIVERSITY  
INFRASTRUCTURE  
TECHNOLOGY INSTITUTE**

*2010 - 2011  
Annual Report*

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Research Engineers Mat Kotowsky and Brian Quezada explain sensor readings on a model steel bridge to students from Waukegan (Illinois) Middle School as they load the bridge by walking across it.

**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.**

ITI research engineer David Kosnik prepares a steel column for sensor installation.



**CENTER OF EXCELLENCE**

The physical infrastructure of surface transportation (highways, bridges, pavements, signs and signals, intermodal facilities, etc.), is 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 a 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 challenging engineering situations 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, 2010 and August 31, 2011, its fourth 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.

# Center Staff



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 administrative staff members to perform day-to-day operations, and a five-member Research Engineering Group with experience in non-destructive evaluation and remote monitoring of transportation infrastructure.

The Research Engineering Group (REG) supports faculty, staff, and students engaged in Institute-supported research projects. REG members 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

## Principal Administrative Staff

**Joseph L. Schofer**  
Director

**Elizabeth M. Brasher**  
Assistant Director

**Melissa Mattenson**  
Manager of Publications &  
Communications

**John Pickett**  
Business Manager

**Stacy Hester**  
Accounting Assistant

## ITI Research Engineering Group

**Daniel Marron**  
Chief Research Engineer

**David Corr**  
Clinical Associate Professor of  
Structural Engineering

**David Kosnik**  
Research Engineer

**Mathew Kotowsky**  
Research Engineer

**Brian Quezada**  
Research Engineer

# Building the Research Program & Community

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.

## Executive Board

In addition to the Director, the governance structure of ITI includes an Executive Board composed of senior Northwestern faculty and administrators. This group provides occasional strategic advice to the Director. Members during Year 4 of SAFETEA-LU were:

Professor Richard Lueptow, Chair  
Senior Associate Dean, McCormick School of Engineering and Applied Science and Professor of Mechanical Engineering

Professor Raymond Krizek  
Director, Master of Project Management Program, and Pepper Professor Civil and Environmental Engineering

Professor Surendra Shah  
Director, Center for Advanced Cement-Based Materials and Walter P. Murphy Professor of Civil and Environmental Engineering

## Research Advisory Committee

A Research Advisory Committee made up of senior engineers and researchers not otherwise affiliated with Northwestern University, provides advice to the Director on the selection of research projects. Members of this panel during Year 4 of SAFETEA-LU were:

Dr. Kurt Bauer  
Executive Director Emeritus, Southeastern Wisconsin Regional Planning Commission

Ms. Sheila R. Duwadi  
Bridge Safety, Reliability, and Security Team Leader, Federal Highway Administration

Mr. Bernard J. Ford  
Executive Vice President, McDonough Engineering

Dr. Edwin C. Rossow  
Emeritus Professor of Civil and Environmental Engineering, Northwestern University

Student members of the NU ASCE steel bridge team pose with their bridge.



# 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.

## Student of the Year: Ken Fuller



(From left to right) ITI Student of the Year J. Ken Fuller, ITI Research Engineer David Kosnik, and ITI Director Joseph Schofer.

ITI named J. Ken Fuller, a senior in Civil & Environmental Engineering at Northwestern's McCormick School of Engineering and Applied Science, as its student of the year for 2010.

Over the past two years, Fuller worked closely with the ITI Research Engineering Group on several of their most important projects, including actively participating in the installation of a remote monitoring system in Hurley, Wisconsin. Fuller followed the field work by engaging in an independent study project with ITI researcher Professor David Corr to investigate the effects of truck loads on the structure, specifically investigating the correlation between input measures, such as vehicle speed, axle configuration, gross weight, and axle weight) and

outcome measures, such as the observed strains, accelerations, and deflections of the bridge and its components.

This past January, Ken travelled to Washington, DC to accept this award and a \$1000 scholarship at the 14th Annual Council of University Transportation Centers Awards Banquet as part of the 90th Annual meeting of the Transportation Research Board.

Ken graduated from Northwestern in June 2011 and has now begun in infrastructure management career as an engineer with the Canadian National Railroad.

# ITI Assists ASCE Student Chapter in Steel Bridge Competition



Members of the NU-ASCE student steel bridge team pose with their bridge at the ASCE Great Lakes Student Conference.

Northwestern University's student chapter of the American Society of Civil Engineers (NU-ASCE) revived its Student Steel Bridge Competition team during this past school year when its membership decided to compete in the ASCE Great Lakes Student Conference for the first time since 2003.

The team of six students raised over \$8,000 in corporate donations to fund a fabrication of the 21-foot long bridge. Starting in the fall of 2010, the students spent long hours designing, machining, welding, testing, and practicing assembly of the bridge, preparing it and themselves for competition that happened on April 2, 2011. At the competition, the bridge was tested against strength and serviceability limits - how much weight it could support, and whether it could support weight without deflecting too much. Although the bridge was disqualified from final competition due to a technicality, the student team was pleased with the bridge's performance under load.

ITI Clinical Professor David Corr, who advised the students during the bridge construction, said, "While most teams at these competitions have built up years of experience, the NU team began the process with no members who had previously taken part in the competition. The most competitive teams have a lot of institutional knowledge that is handed down," Corr said. "All of ours is gone because it has been a number of years since we competed."

The team's final act was to sacrifice the product of their efforts to make next year's bridge better: on May 16, 2011, they loaded the bridge to failure in public view as part of a campus-wide Engineering Week event. With assistance from ITI engineers, the NU-ASCE students instrumented the bridge with strain and deflection sensors and collected live data throughout the load test. Students will use the collected data to verify their models and improve next year's design.

# NU-ASCE and ITI Give Middle School Students a Taste of Engineering



Civil Engineering juniors Kendra Pickard and Hannah Iezzoni discuss their experiences in engineering with visiting middle school students.

On May 3, 2011, Northwestern's student chapter of the American Society of Civil Engineers (NU-ASCE) and ITI hosted a visiting group of 90 middle school students from Waukegan, Illinois, to give them a glimpse of the lives of engineering students in college. The NU-ASCE/ITI demonstration was part of a larger, day-long event coordinated by Promote 360, a student organization that aims to enhance social, academic, and professional well-being of minority and under-represented students.

The goal of the day was to immerse students in a broad survey of activities that would educate them about campus life and inspire them to pursue higher education. After introductions and ice-breaking activities, the students ate lunch in a dining hall and toured the campus. In the afternoon, the students attended performances and presentations from various Northwestern student groups, including NU-ASCE/ITI.

The NU-ASCE speakers, Civil Engineering juniors Hannah Iezzoni and Kendra Pickard, focused their presentation on a general introduction to engineering, showing the students what engineers do and the many ways engineers benefit society. The speakers touched upon many of the different engineering majors available at Northwestern as well as the

extracurricular activities in which they both take part, including joining a team that designs and builds real bridges from scratch.

The second portion of the presentation was a live demonstration of the steel bridge that NU-ASCE members had just constructed for the annual ASCE-sponsored Student Steel Bridge Competition, held the previous month in Milwaukee, Wisconsin. With instruction and assistance from the ITI research engineering staff, NU-ASCE members installed several strain sensors on portions of the bridge, allowing the young students to see on the projector screen how the bridge "felt" the weight of the ASCE members as they showed that the bridge could easily support several adults standing on it at once.

At the end of the presentation, the visiting students were invited to walk across the bridge on a special wooden deck constructed for the demonstration. As NU-ASCE members guided the students over the bridge, the audience watched in amazement as the sensor readings showed their footsteps as they walked across the wood and steel structure. As the students finished their walk, they were treated to a close-up view of the strain sensors, smaller than the size of a postage stamp, which made possible the exciting demonstration that they'd just seen.

# 2011 Summer High School Infrastructure Camp



ITI Summer Infrastructure Camp students and staff pose in front of a runway closure marker as they tour the Chicago O'Hare Airport Modernization Project.

ITI's 2011 Summer Infrastructure Camp, a 5-day program hosted at Northwestern University's Evanston Campus, welcomed rising junior and senior high school students into the world of engineering.

Students split their time between a brief lecture and discussion in the morning and then a field excursion in the afternoon. The morning programs included material on public transportation, freight infrastructure, airports, bridges, and monitoring the health of various structures. Field trips throughout the week included a trip to the Belt Railway Company of Chicago's classification yard, a tour of the O'Hare Airport Modernization Project, and a riverboat tour of downtown Chicago architecture.

ITI continued its summer camp collaboration with the Northwestern University Partnership for International Research and Education: Intelligent Structural Health Management (PIRE-ISHM) program. The PIRE-ISHM

program is funded in part by the National Science Foundation and is engaged in cutting edge research in the field of Structural Health Monitoring. Both ITI and PIRE-ISHM Researchers and staff provided some of the lectures during the camp and were available to discuss topics of interest with students.

The goal of the Camp was to give students the opportunity to learn more about infrastructure and the engineering disciplines that support it from leading experts while providing a real-world experience through field trips to active field deployment sites and industrial and commercial facilities. Overall, the camp was a great success -- students enjoyed the planned activities, and a post-camp evaluation showed a favorite of the group was the O'Hare Airport tour.

ITI plans to continue the summer camp during the summer of 2012.

US Rep. Daniel Lipinski speaks at the 2010 William O. Lipinski Symposium on Transportation Policy, sponsored by ITI.



# SUCCESS IN TECHNOLOGY TRANSFER

**ITI continued to work closely with its deployment partners during the past year, including:**

- **University of Kentucky Research Foundation**
- **Kentucky Transportation Cabinet**
- **Illinois Department of Transportation**
- **Chicago Transit Authority**
- **New York City Metropolitan Transportation Authority**
- **Wisconsin Department of Transportation**
- **Ohio Department of Transportation**
- **California Department of Transportation**
- **Geotechnical Consultants, Inc., Westerville, Ohio**
- **Jones Mining Company, Naples, Florida**
- **GeoSonics Inc., Warrendale, Pennsylvania**
- **Vulcan Materials Company, Sycamore, Illinois**
- **STS AECOM, Vernon Hills, Illinois**
- **AASHTO TSP2 Program hosted at Michigan State University**
- **GeoTDR**

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

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 bridges.

# The 4th Annual William O. Lipinski Symposium on Transportation Policy



Left: Former US Rep. William O. Lipinski opens the 2010 Lipinski Symposium.

The 2010 William O. Lipinski Symposium, held this past November at Northwestern University, focused on the challenges and opportunities facing public transit in Chicago, in the Midwest, and nationwide. Attendees participated in a full day of presentations, panel discussions and question and answer sessions with national and international transportation leaders and experts.

Former US Representative William O. Lipinski began the session with opening remarks with a strong statement underscoring the financial need: "If we don't get an infusion of money on the state and federal level, mass transit is going to crumble. Not only in northeastern Illinois, but throughout this nation." His assertion was echoed by many presenters in the morning session.

ITI Director Joseph Schofer summarized the confronting transit in the Chicago region, as well: "Mass transit in this region carries approximately 9% of all trips. Key parts of the transit system are 100 years old and need an enormous amounts of maintenance and in some cases total reconstruction. Costs are increasing and revenues are stagnant. Integrated

thinking is a big part of the solution to ensure seamless travel for trip makers. Importantly, the future lies in innovation and change. We need to look for new ideas for better service coverage, cost control, revenue enhancement, integrated traveler experience, as well as modernizing design and maintenance."

US Reps. Peter DeFazio (D-OR) and Daniel Lipinski (D-IL) discussed the national perspectives on the challenges facing public transit. Both discussed the need for communicating to government leaders and the public the idea that putting money into transportation is an investment, making the country more energy efficient, producing a higher quality of life, stimulating community growth and raising tax-revenue. "If we want to tread water, we'll need an 18% increase in funds," Rep. DeFazio said. "If we want to improve our systems, we'll need a 65% increase, but ultimately if we want to put everything in a state of good repair, we'll need to double the transportation investment – \$30 billion per year."

Leadership of Chicago area transportation agencies discussed critical transit issues at the regional level. Speakers were Richard Rodriguez, President



Illinois Deputy Republican Leader Timothy Schmitz speaks during the afternoon panel.

of the Chicago Transit Authority; William Tupper, Acting Director of Metra; Thomas J. Ross, Executive Director of Pace; and Kristi LaFleur, Executive Director of the Illinois State Toll Highway Authority. The concern of each was the combination of rising costs and static revenues. The leaders of each agency offered ideas for improvements and new projects they would start with new money, but funding remained the main barrier to progress. Mr. Ross argued that, “We need to begin treating public transit as a public service, not a for-profit product.” Ms. LaFleur urged the other panel participants that all agencies in the region must “think regionally,” and that no forward progress can really be made if they “continue to work in silos.”

Professor Hani Mahmassani, Director of Northwestern’s Transportation Center, discussed new technologies and concepts available to enhance the travel experience of transit users, including sensor technologies that track vehicle location, systems to deliver real time information to users, and strategies to integrate highway and transit services to provide seamless travel. He urged participants that “the idea is to think mobility, not just transit.”

Dr. Robert Peskin of AECOM discussed the difficulties of continued reliance on sales tax to fund transit and suggested possible solutions, including cost management measures such as productivity

improvements, competitive contracting, basing decisions on life-cycle costs, and even considering public-private partnerships.

This year’s David F. Schulz award was presented during lunch to Samuel Skinner, who served as Secretary of Transportation and later White House Chief of Staff to President George H.W. Bush, as well as chairman of the Regional Transportation Authority for northeastern Illinois. Mr. Skinner echoed all presenters saying, “the presentations from this morning are right on. It’s clear that there are needs and the funding mechanisms in place currently are not working.” He also pointed out that there are some good signs: “We have a president who is extremely committed to infrastructure. While we may argue about his priorities versus ours, he has decided this is important – and it is.” Skinner went on to say that now that we have “licked our wounds and celebrated our victories,” we must get back to work and recognize Illinois’ severe problems with infrastructure. In the afternoon session, Glen Weisbrod, president of Economic Development Research Group, Inc. spoke about the changing economy and how the issue of public transit is much broader and more complex than many people realize, with implications for how (and how much) we invest. “Transportation spending – and particularly public transportation spending – allows a particularly high portion of funds to stay in the regional economy. The operators and



Presentation of the David F. Schulz Award to Samuel Skinner at the Lipinski Symposium. Left to right: US Rep. Daniel Lipinski, ITI Director Joseph Schofer, JoAnn Schulz (widow of David F. Schulz), Samuel Skinner, former Northwestern University President Henry Bienen, former US Rep. William O. Lipinski.

maintenance workers are local, vehicle manufacturing is not all regional but does take place in America. But of course we don't justify our public transportation spending now because it is creating jobs, we do it because in the long-term it increases the productivity and competitiveness of our economy, nationally and internationally."

Gerhard Menckoff of the Institute for Transport Policy and Development discussed the promise and productivity of Bus Rapid Transit (BRT), presenting examples from Europe and South America. BRT differs significantly from traditional bus service, including off-board fare collection, level boarding of the bus through many doors, and segregated busways. "Nearly every major city in Latin America has implemented a BRT system, and many countries in Europe and Asia are following. There are some cases, such as in India, where the implementation of the system is extremely poor, which then gives all BRT a bad reputation. The truth is that it is not because of the concept, it is because of the execution."

Phillipe Payen, Chief Prospective Officer of Veolia Transport, discussed the importance of innovative technologies for public transit, as well as the

importance of the idea of "mobility management" rather than the traditional idea of transportation. "Transit is an industry looking for innovations – the target of which is to bring more and more intelligence within transportation to city inhabitants and to every piece of the ecosystem. Digital mobility will allow each city inhabitant to choose and control his mobility needs. The commuter time now is an imposed time, and we have to make it a useful time. It can never be more comfortable than the car, but it can be a lot more useful."

The last and most highly anticipated panel of the day featured leadership of the Illinois state legislature, including Illinois Rep. Michael Madigan (D-22nd Dist.), House Deputy Republican Leader Timothy Schmitz (R-49th Dist.), Illinois Senate President John J. Cullerton (D-6th Dist.), and Illinois Senate Republican Leader Christine Radogno (R-41st Dist.) Panelists took questions from participants, and discussed the difficulties in securing revenue for Illinois transit projects. All panelists agreed that this is the greatest challenge with moving the region's transit forward.

# ITI Participates in University Research Technology Transfer Day



RITA Administrator Peter Appel addresses attendees at University Research and Technology Transfer Day in Washington, DC.

In early April, the REG traveled to Washington, D.C. to participate in the University Research Technology Transfer Day at DOT headquarters, presented by the Research and Innovative Technology Administration (RITA). This one-day demonstration/exhibition displayed prominent university transportation products developed through US DOT sponsorship, highlighting the accomplishments and impact of college and university-based research and education programs. This included meaningful technology transfer from the university transportation programs in use at various federal, state and local agencies. The event also included poster sessions, remarks by Deputy Secretary of Transportation John Porcari, and panel discussions about research.

At the event, ITI research engineer David Kosnik presented the REG's work on advanced techniques for retrofit performance and reliability monitoring on the John F. Kennedy Memorial Bridge in Louisville, Kentucky. Since 2007, ITI has used advanced computer-controlled sensing systems for real-time measurement of critical engineering quantities, which has

provided important insight for detection and repair of corrosion-related failures of uplift bearing components, helping keep this bridge of both regional and national importance in good repair and safe for the 120,000 vehicles that cross it daily.

On the evening of September 29, 2008, the automated structural health monitoring system measured a large, sudden shift in strain measurements on an uplift bearing anchor rod, suggesting that the rod had fractured. ITI researchers in the Chicago-area lab reviewed the data and promptly alerted the bridge owner. Upon inspection, the rod was found to be completely severed. Without monitoring, no one could have known about the fracture until the next routine inspection - even then, the fracture would have been nearly invisible, as the paint remained intact.

The goal of this research is to develop structural health monitoring systems that can be deployed readily by state DOTs and other transportation infrastructure owners.

# REG Presents Research Results at Conferences Nationwide

Members of the ITI Research Engineering Group (REG) attended a variety of technical conferences to present the REG's work and exchange ideas with transportation and infrastructure professionals.

In June 2010, research engineers David Kosnik and Mathew Kotowsky attended the International Bridge Conference in Pittsburgh, Pennsylvania. Kosnik presented a paper, "Noise Localization via Acoustic Emission Monitoring on a Rolling Bascule Bridge", (co-authored by the other REG members) on locating the source of unusual "banging" noises on a new movable bridge using acoustic emission (AE) technology. AE data from several test configurations showed that the noises were not coming from the bridge's lift machinery but were instead originating along the bottom flange of the bascule girder where the girder was attached to a track plate. Further testing strongly suggested that the source of the noise was benign, highly-localized stick-slip behavior along the girder-track plate interface as the bridge opened and closed.

In July 2010, research engineer David Kosnik presented at the Review of Progress in Quantitative Non-Destructive Evaluation (QNDE 2010) conference in San Diego, California. QNDE 2010 featured a special track on applications of advanced non-destructive evaluation techniques to civil infrastructure, including bridges, railroad tracks, and pavements. Kosnik presented a paper, "Acoustic Emission Monitoring for Assessment of Steel Bridge Details," which described the ITI REG's experience in applications of acoustic emission monitoring to two large fracture-critical highway bridges: the Bryce Bend Bridge, a 4,050-foot-long steel trapezoidal box girder structure which carries Interstate 80 over the Sacramento River in Sacramento, California, and the

John F. Kennedy Memorial Bridge, a 2500-foot-long steel cantilever truss which carries Interstate 65 over the Ohio River at Louisville, Kentucky.

In October 2010, David Kosnik, in collaboration with David Simon, roadside facilities engineer with the Wisconsin Department of Transportation, gave an invited talk to the Western Association of State Highway and Transportation Officials Committee on Highway Transport (WASHTO-COHT) at their meeting in Reno, Nevada. The presentation, "Doing More with Weigh-In-Motion on a Wisconsin-Michigan Border Bridge", described the combined weigh-in-motion and bridge structural health monitoring system installed by the REG and the Wisconsin Department of Transportation on the US Highway 2 bridge over the Montreal River between Hurley, Wisconsin, and Ironwood, Michigan.

In December 2010, research engineers David Kosnik, Mathew Kotowsky, and Daniel Marron attended the Transportation Research Board's 7th International Bridge Engineering Conference, held in San Antonio, Texas. Kosnik presented a paper, "Continuous Remote Structural Health Monitoring for Life Extension of an Uplift Bearing Assembly on a Large Cantilever Truss Bridge", which was co-authored by the other REG engineers and Theodore Hopwood of the University of Kentucky. The paper described instrumentation and monitoring for an uplift bearing on the I-65 John F. Kennedy Memorial Bridge over the Ohio River at Louisville, Kentucky. The uplift bearing monitoring project, which was distinct from the acoustic emission project presented at QNDE 2010, involves continuous remote strain monitoring of a large bridge component, including remote detection of a failure of one of the sub-components.

# The Midwest Bridge Working Group



Prof. Robert Connor of Purdue University presents at the Winter 2010 meeting of the Midwest Bridge Working Group, held at Indiana DOT headquarters in Indianapolis and sponsored by ITI.

The Midwest Bridge Working Group (MBWG), a technology transfer forum sponsored by ITI and operated by the University of Kentucky, held its winter meeting December 13-14, 2010. The meeting was hosted by the Indiana Department of Transportation at the Indiana Government Center in downtown Indianapolis.

The meeting attracted 118 people: 47 state department of transportation personnel representing 14 states, 13 researchers representing five universities, two Federal Highway Administration representatives, and the balance representing consultants, vendors, and industry. The meeting was divided into a full day of maintenance, inspection, and safety topics of general interest to bridge professionals followed by a half-day session dedicated exclusively to coatings for steel and concrete bridges.

One of the more notable talks was given by Prof. Robert Connor of Purdue University. Prof. Connor presented results from two research projects, the first a fitness-for-purpose investigation of the US-41 bridge over the White River in southern Indiana. The bridge was to be subjected to extremely heavy permit truck loads due to construction of a power plant in the area. Prof. Connor presented his team's analysis of the bridge for various limit states under the expected loads and then compared the predictions to data acquired from sensors on the bridge as

heavy trucks crossed. Prof. Connor's second presentation was a discussion of advanced computer image analysis to identify out-of-plane bending and other performance problems on gusset plates.

Another interesting talk was given by Ted Zoli of HNTB on a rare but serious bridge safety incident: hydrocarbon fuel fires on bridges. Recalling the 2007 gasoline tanker fire and subsequent collapse of the I-580 "MacArthur Maze" connector in Oakland, California, and similar incidents, Zoli discussed the mechanics of hydrocarbon fires as they related to bridges and ways to mitigate the risks and respond to bridge fires.

Recognizing that protective coatings (including, but not limited to, paints) are critical for preservation of bridges, the second day of the meeting was devoted exclusively to coatings. Presentations included improved methods for field measurements of surface profiles, performance evaluation of one-coat paint systems on new steel bridges, weathering performance of various polyurethane coating formulations, new coating systems for bridges, inspectability of certain coating systems, and the results of a 20-year study of bridge repainting system performance.

ITI research engineer David Kosnik lays out strain gauges on a retrofit to the John F. Kennedy Memorial Bridge in Louisville, Kentucky, while the retrofit awaits final assembly in the steel fabrication shop.



# SUCCESS IN RESEARCH

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.

# CTA Puts its Viaducts to the Test

## Principal Investigators: Daniel Marron & David Corr

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By Jon Hilkevitch

A deteriorated CTA [Chicago Transit Authority] bridge on the Red Line has an important story to tell about the health of the rail system's viaducts. Each day, thousands of CTA elevated trains operate across 564 bridges, many nearing 100 years old.

The crumbling bridges, some inspected monthly and others every two years, pose a potential danger to CTA passengers as well as to motorists and pedestrians who pass under the viaducts. But the CTA, saddled with a backlog totaling \$7 billion in unfunded capital-improvement needs, can't afford to replace bridges. The antiquated bridges have exceeded their useful life, experts say. They remain open due, in part, to luck.

The bridges were built to carry steam locomotives, which generate approximately four times the load of a moving CTA rail car, said CTA chief engineer James Harper. "We are kind of benefiting from that a century later," Harper said. "One hundred years is beyond anyone's expectation for a bridge structure." The bridge at Devon Avenue and Sheridan Road on the Red Line is one of the most deteriorated crossings in the CTA system. Its arch design columns have lost significant amounts of concrete, exposing — and in some spots shedding — the reinforced steel below, CTA engineers observed. Braces providing additional shoring were installed near the bridge piers late last year to help the structure support the weight of trains and to withstand a possible hit by errant vehicles on the street.

But CTA officials had little idea how much strain, if any, the braces were taking off the bridge.

Then CTA president Richard Rodriguez picked up a newsletter published by the Infrastructure Technology Institute at Northwestern University. The newsletter carried a story about Northwestern researchers monitoring concrete highway bridges in Wisconsin using an automated system that collects and analyzes data.

Rodriguez then surprised Northwestern officials with a phone call. "It was unusual for someone to respond to the newsletter," said Joseph Schofer, associate

dean of Northwestern's Robert R. McCormick School of Engineering and Applied Science. "But Rodriguez was particularly concerned about the reinforced concrete structures on the Red Line and he said, 'Come on down and meet with us.' "

In July, the Northwestern team embedded sensors in the Devon-Sheridan bridge to measure how much the structure bends when trains pass over. That information is automatically stored, analyzed and transmitted to a Web site that Northwestern and CTA officials monitor.

The data collected from the gauges will tell more of a story over time, but officials have learned the yellow steel supports that were added are not doing a lot of work — a good sign that means the original structure is tolerating the strain of train traffic.

But given the CTA's budget constraints, the "temporary shoring" at Devon-Sheridan and other locations likely will be in place for many years, officials said. Replacement dates for the bridges remain indefinite, officials said.

The Infrastructure Technology Institute's around-the-clock monitoring of the Devon-Sheridan bridge will provide an early warning to changes that could compromise the bridge's integrity, Harper said. The monitoring will also provide good clues about the condition of other similarly constructed bridges and any retrofits installed there as shoring.

"Given that we don't have a lot of money to install sensors everywhere, the Devon project is a great predictive tool that helps us predict how much life we have left on our bridges," Harper said.

CTA officials hope over time to expand the monitoring to at least some other bridges and to add Web cameras to create a visual record, including the common problem of trucks hitting viaduct support columns and taking out pieces of concrete, or getting wedged under the crossing, which has a clearance of only 12 feet 10 inches.

"The broader purpose for the monitors is not to tell that a failure is imminent, but to focus on parts of the structure that are most vulnerable in order to identify developing problems," said David Kosnik, a researcher at the institute, which has installed monitoring devices at more than 80 locations in the U.S.

Widespread use of monitoring equipment will



ITI Research Engineer David Kosnik (left) and Prof. David Corr (right) install strain gages on steel columns at the Devon-Sheridan overpass.

depend in part on keeping the cost low, said Daniel Marron, chief research engineer at the institute. “We try to use off-the-shelf components,” said Marron, who estimated the Devon-Sheridan cost about \$35,000. The researchers learned that a tall truck recently struck the Devon-Sheridan bridge. The truck damaged instrument wires, knocking out one of the sensors. Harper said CTA officials plan to install cameras at the bridge to chronicle such mishaps.

The next step would be to deploy sensors and cameras at other viaducts across the system. After Devon-Sheridan, the next bridge in rough shape is at Hollywood, Harper said.

“At this and other locations, we can help a public agency that has serious budget constraints to safely extend the service life of its infrastructure,” Schofer said.

# ITI Develops Novel Sensor Application for Highway Bridge



The John F. Kennedy Memorial Bridge carries Interstate 65 over the Ohio River at Louisville, Kentucky.

## Principal Investigator: Daniel Marron

In the right circumstances, structural health monitoring of large bridges can be a useful management tool, with the potential to improve safety, extend the useful life of a bridge, and reduce the costs of maintaining the bridge over its decades. Unfortunately, standard sensing technology is not always well-suited for the unique and often unpredictable monitoring challenges found on many bridges.

Encountering such a situation while designing a structural health monitoring system for the John F. Kennedy Memorial Bridge in Louisville, Kentucky, the ITI Research Engineering Group (REG) adapted standard sensing technology to develop a new sensor capable of measuring the performance of threaded rod assemblies commonly used in bridge retrofits.

Due to its unique asymmetrical cantilever design, the two ends of the JFK Bridge are held down by large bearing assemblies anchored into concrete piers. This type of design, unusual for large through-truss bridges, required an equally unusual repair when inspectors discovered that one of the bearings was suffering from corrosion damage caused by runoff of deicing chemicals and precipitation. To ensure the downward restraint of the end of the JFK Bridge, the Kentucky Transportation Cabinet designed and installed a retrofit that effectively clamped the end of the bridge more securely to the concrete pier below. The clamping strength of the retrofit is derived from sixteen threaded anchor rods epoxied into holes drilled into the top of the concrete pier, then bolting the bridge bearing to those rods. The nuts on the rods then prevent the bearing from pulling away from the top of the concrete pier.



The ITI-developed clamped strain sensor for threaded rods deployed on the Kennedy Bridge bearing retrofit.

While designing a system to monitor the performance of this retrofit, the REG soon realized that it would be quite useful to know exactly how much these threaded rods were “pulling” down on the bridge. If this pulling lessens over time, it can be inferred that the threaded rods are being wrenched out of their anchor holes and must be repaired. To use standard sensing technology to measure tension in these rods, a portion of each rod would have to be flattened to attach the sensor, damaging the rod and compromising the repair. The REG had to invent a new sensor to measure the tension on these rods without damaging the rods themselves.

The solution took the form of an external clamping mechanism composed of standard strain gages, several large nuts and small screws, and a simple bar of steel. First, the two nuts are split in half so that they can be re-assembled around the threaded rod with six small screws. Then, a steel bar is welded between the two nuts. Finally, strain gages are affixed to the bar. When the bracket is placed on a threaded rod, the strain in the bar is approximately equal to the strain in the rod, allowing calculation of the tensile forces in the rod.

The REG installed four of these sensors on the JFK Bridge in February, after the rods were placed in the concrete pier but before the clamping force was applied. The sensors reported the tension developed in the rods as the retrofit was tightened down and continue to provide insight as to the continued performance of the retrofit. The REG is in the process of analyzing the data from the bridge and performing additional controlled laboratory testing to further calibrate the sensors. Once this testing is complete, the new sensors may be used to evaluate the performance of the many other retrofits that employ threaded rods to develop tensile forces.

# Rational and Safe Design of Concrete Transportation for Multi-Decade Sustainability

## Principal Investigator: Zdenek Bazant

Prof. Bazant and his team recently published the results of analysis of excessive deflection of the Koror-Babeldaob Bridge, a very long span pre-stressed concrete box girder bridge in Palau which collapsed in 1996. This latest analysis has shown that the excessive deflections were the consequence of erroneous multi-decade creep prediction models in the standard design recommendation of ACI and AASHTO, and in Europe by CEB-fib, raising an important question: if these recommendations were wrong, would many other bridges suffer the same fate?

This has indeed turned out to be the case. Success in forming an international RILEM Committee TC-MDC (Multi-Decade Creep, chaired by Bazant) helped a painstaking search for bridge deflection data in company reports, society publications and diverse journals. This search, still continuing, has already revealed 64 large-span bridges of the same type that deflected excessively and had to be closed or retrofitted. It is now estimated that world-wide there exist hundreds of similar cases of excessive deflections, the causes of which were not connected before. In all these cases, wrong codes or recommendations for creep were shown to be the cause. A short paper reporting these startling results has just been accepted in ACI Concrete International and a detailed one in ACI Structural Journal.

Since the vast majority of laboratory creep data around the world deal with creep durations under six years, the only way to verify and calibrate a theoretical model for multi-decade creep is by inverse analysis of multi-decade deflections of structures. Only excessive deflections of creep-sensitive large-span bridges dominated by self-weight can be used for such inverse analysis, and the collected data are of just such a kind. However, such data are often sealed due to litigation; thus, full data for inverse finite element analysis could so far be obtained for only 6 among the 64 bridges. However, an alternative statistical approach has been devised to use relative rather than total deflections, which in combination with the database should allow validation and calibration of a realistic creep model for new standard recommendations.

The prospect of widespread changes to concrete creep recommendations in design codes - which seemed out of sight just a few years ago - is now on the horizon. Following the achievement of the release of data from the Palau disaster and creation of a world-wide collection of excessive bridge deflection data, it may soon be possible for long-span concrete bridges to be commonly designed for multi-decade safety and sustainability to the benefit of the traveling public.

## Excessive Deflections of 55 Prestressed Concrete Segmental Bridge Spans



Wake-up call: Excessive deflections of prestressed segmentally built box bridge spans collected from various reports and publications. They show that the standard recommendations used in the design of these bridges were incorrect, and especially that the assumption of compliance curves that terminate at a finite bound (or horizontal asymptote) was erroneous (in the original publications the data were presented either in tables or linear scale graphs from which the lack of asymptote is not apparent) These data will represent a valuable source for updating the standard recommendations.

# New Materials for Bridge Construction: Superweathering Steel and Lower-Cost High-Performance Steel

**Principal Investigators:**  
Semyon Vaynman, Morris E. Fine,  
Y-W. Chung

## Development of Lower-Cost High-Performance Steels

In the last few years, the focus of US transportation agencies has shifted toward the use of new high-performance steels for bridges that are less expensive than previous high-performance steels. In coordination with the Illinois Department of Transportation, we have designed a 60-ksi-yield steel with mechanical and fracture properties that significantly exceed bridge construction specifications and cost less per pound than A709HPS or A710 Grade B steels. To further reduce the cost of bridge construction by eliminating welding, the steel was produced in the form of wide-flange I-beams at Steel Dynamics, Ft. Wayne, IN. The 165-ft-long bridge carrying Dixie Highway over Butterfield Creek near Flossmoor, IL was finished in November, 2010.

## Role of Nanosized Copper Precipitates

Recently, we developed a theory of steel strengthening and toughening using nanosized copper precipitates. Nucor Steel Company of Decatur, Alabama, used our concept to improve the mechanical properties of coiled steels by small additions of copper and nickel. This addition lead to about 15% increase in yield and ultimate tensile strengths, from 71 to 82 ksi and from 85 to 97 ksi respectively. The absorbed fracture energy of the steel was very high, more than 150 ft-lbs at -20°F in subsized Charpy specimens. Addition of copper and nickel also significantly improved the corrosion resistance of steel; the ASTM G101 corrosion index for the new Northwestern-modified Nucor steel increase from about 4.2 to 6.2. This value indicates that the steel under standard weathering conditions will suffer only 70% of the corrosion loss of ASTM A588 W steels commonly used for bridge construction and A606 steel used for signs, sign structures, light poles and other highway structures.



ITI-developed A710 Grade B steel bridge components awaiting installation

## Development of Superweathering Steels

The annual direct cost of corrosion in infrastructure is estimated at \$25 billion. In addition, the corrosion of bridges could result in very early failure. The goal of the Federal Highway Administration is to develop a “superweathering” bridge steel to mitigate the problem especially in saline environments. We developed a superweathering steel by modification of the A710 Grade B steel previously developed at Northwestern University and used in construction of a bridge in Illinois. Small amounts of inexpensive elements, phosphorous and titanium were added to the steel. The steel is strong, tough and easy to weld. 2000-hour-long accelerated weathering tests performed at Kentucky Transportation Center in accordance with ASTM standards demonstrated significant superiority of this newly developed steel over other steels tested. The corrosion loss in this steel was 72% less than in non-weathering A572 steel used in older bridges, 60% less than in weathering A588-50W steel that is used in currently built bridges and 44% less than in our original A710 Grade B steel, which is the best weathering steel on market today. The further development and commercialization work is still in progress.

# Inexpensive Wireless Structural Health Monitoring System for Tracking Expansion and Contraction of Cracks

## Principal Investigator: Charles H. Dowding

The wireless autonomous crack monitoring (ACM) system has been operating in and around a farmhouse adjacent to an active limestone mine for almost two years. A mesh network of four of these nodes, each operating on three solar-rechargeable AA batteries, measures the width of various cracks in the structure. Results are transmitted to a base station on-site then sent via the Internet to Northwestern where they are graphically displayed on the Web.

These wireless, autonomously operable remote systems that cost as little as \$500 for the remote nodes and \$1500 for base stations, representing a significant savings over their wired counterparts. Because of the dramatic savings in cost and installation labor, systems like this are likely to become commonplace in structural health monitoring within the decade. Systems like this can be employed to monitor other structural phenomena, such as cracking in steel bridges, and may prove to have applications across the transportation industry.

In this deployment, opening and closing of cracks is tracked with a string potentiometer displacement sensor because it requires little power to operate. Crack opening is an index of the potential for extension of a crack. Increasing crack width is analogous to splitting wood with a wedge. Just as a wedge is driven into a log to "widen" a crack to extend the crack and eventually split the wood, widening of a crack beyond its maximum will lead to crack extension.

## Field Qualification of a Micro-Inch Structural Health Monitoring System on Adobe House during Road Construction

A micro-inch resolution ACM system developed by ITI is now undergoing field qualification

during road construction conducted by the New Mexico Department of Transportation (NMDOT) in Albuquerque, New Mexico. The photo shows instruments in place on an adobe structure adjacent to major reconstruction of a one-way couple. While this crack monitoring system has been employed on other structures, it has never been deployed on adobe construction. Use of this system by NMDOT should speed the adoption of this technology as a primary regulatory instrument. This configuration allows comparison of dynamic and long term crack response for data-driven control of ground vibration associated with construction of transportation facilities.

## Improved Data Acquisition and Management For Sinkhole Monitoring

ITI personnel are working with the Ohio Department of Transportation (ODOT) to improve the display of time-domain reflectometry (TDR) based cable response signatures for the monitoring of critical structures. ODOT has hired private consultant GeoTDR contractor to install TDR cables beneath Interstate 70 in Muskingum County, Ohio., and sought ITI's expertise in Web-based data visualization to make the data more useful to its engineering staff.

This installation represents the marriage of two new technologies: horizontal boring and TDR cable surveillance. By grouting TDR cables into nearly horizontal holes, large length of highway can be monitored with a single instrument. GeoTDR provides the structural health monitoring surveillance and interpretation for Ohio DOT. ITI provides additional display technology and modifies the display in response to ODOT evaluation. This in-field operator interaction should provide another step toward increasing use of TDR to monitor large segments of the infrastructure network. and I changed the headline to be "Novel Instrumentation Technology has Broad Impact on Structural Health Monitoring"

# Intelligent Structural Health Management of Civil Infrastructure



## Principal Investigator: Sridhar Krishnaswamy

The ITI sponsored project on Intelligent Structural Health Management of Civil Infrastructure is in conjunction with a five-year NSF-funded program on Partnerships for International Research and Education: US-Asia Network of Centers for ISHM of Safety-Critical Structures. The PIRE-ISHM program is led by Northwestern University and partners with universities and industry from China, India, and the US. The aim of the program is to develop 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.

As part of the ITI sponsored research in ISHM of civil infrastructure, we have been working on probabilistic damage prognostics due to fatigue and developing advanced fiber optic sensors for structural health monitoring. Selected highlights are described below.

## Thermal Imaging of Composite Wrapped Bridge Columns

Substructure deterioration reduces the service life of highway bridges. A key component of the substructure is the columns. An alternative to replacing

a column that has suffered limited damage is using a composite column wrapping. A composite column wrapping when applied to a reinforced concrete column can increase the flexural ductility of the column in addition to increasing the columns shear strength. This is accomplished by confining the concrete core and longitudinal reinforcement. This confinement will increase the longitudinal bar's resistance to buckling even after a plastic hinge has formed in the wrapped region.

When installed properly, column wrapping can be used to (i) make the structure more resistant to seismic activity; (ii) improve blast resistance; and (iii) reduce the corrosion degradation rate of concrete columns. However, these benefits will not be realized if the wrapping is improperly installed. Also, long term monitoring of these composite wraps is needed since they may be subject to environmental degradation. Thus, a convenient full-field evaluation technique was needed to ensure the utility of column wraps.

A pulsed thermography imaging system was developed to be used as both a long term inspection tool and a quality control check for newly installed wraps. The system uses high intensity xenon bulb flash tubes to momentarily heat the surface of the wrap being inspected. The propagation of the thermal wave in the wrap is then monitored with an infrared



camera. Any subsurface damage will be indicated on the surface as an area of higher temperature relative to the surrounding area or a “hot spot”. Using the sequence of images acquired from the camera it is possible to quantify these “hot spots” and get an indication of the size of the subsurface damage. The system was tested on the approach structure to the I-57 Mississippi River Bridge located in Cairo, Illinois which has been seismically reinforced with composite wrappings.

The system proved capable of detecting and quantifying disbands between the concrete/wrapping interface and between layered wrappings. The previous method to detect disbands was by visual and/or the tap technique; quantifying the disbands with either of these methods was purely subjective. The pulsed thermography system also provided minimal inspection time which is critical for minimizing inspection costs on large structures in addition to providing a digital record of the inspection in the form of a series of images or a movie.

### **Fiber-Optic Humidity Sensors with High Sensitivity and Thermo-Stability**

There is a growing interest in exploring photonic crystal fibers (PCFs) for advanced optical fiber sensing components and devices. In particular, PCFs can be used to detect moisture, chlorides, and chemical byproducts associated with corrosion in civil structures - important information for asset management.

However, the sensitivity, chemical selectivity, response time, and temperature stability of PCFs must be improved before they can be widely used.

To improve performance, we have employed two types of nanostructure film to coat PCF cladding within grating region by an electrostatic self-assembly deposition process. Experimental results have shown a substantial improvement in the ability to detect small changes in relative humidity - important for monitoring corrosion potential in components such as bridge stay cables and post-tensioning tendons. Equally importantly, the new cladding has been shown to make the PCF much less sensitive to temperature changes, making measurements more reliable in outdoor environments. This promises new developments in sensors for SHM of transportation structures.

# Design and Verification of Blast Densification for Highway Embankments on Liquefiable Sands



Prof. Finno's team conducted soil tests following blast densification of liquefiable sands at this site in South Carolina.

## Principal investigator: Richard Finno

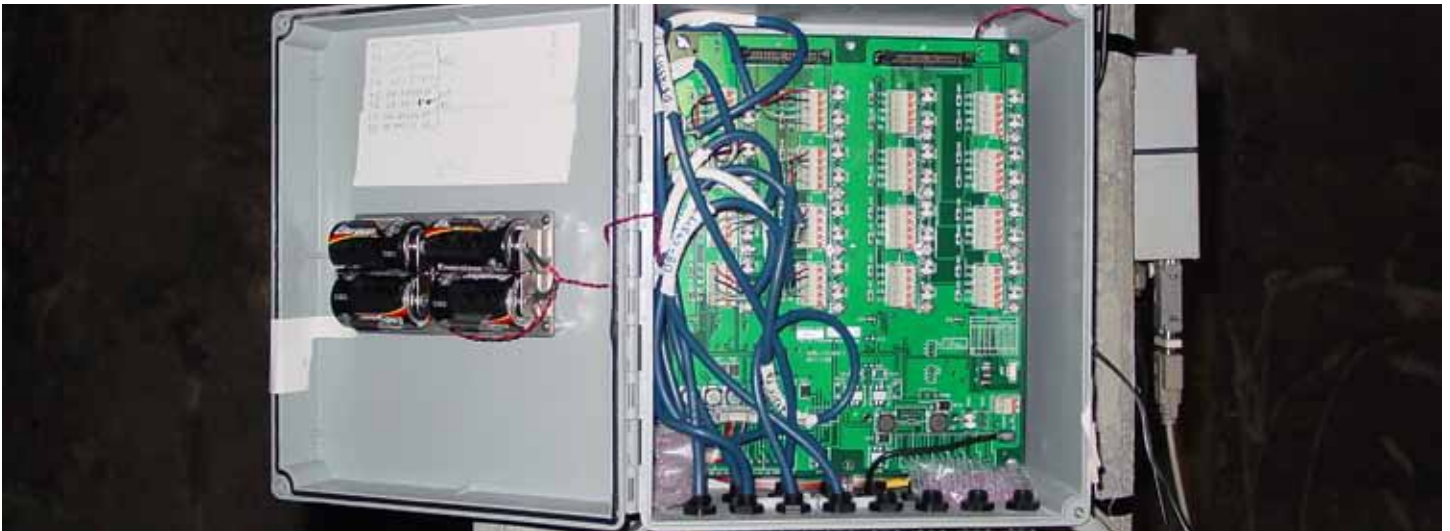
The national transportation network includes many miles of embankments for highways and railroads constructed in seismically active areas of the US. A key design issue for such structures is whether or not liquefaction – the loss of shear strength of sands – will occur during an earthquake. If the soil is susceptible to liquefaction, engineers must improve the ground or risk a flow failure of the embankment. Densification of the loose sands by controlled blasting is an economical approach, especially when large volumes of sands must be improved. However, case studies have shown that while loose sands compress almost immediately after blasting, when common verification tests are conducted, the results provide rather counterintuitive results. If taken soon after the blast, the penetration resistance (a rough field measurement of soil strength) decreases, and at times never increases to levels above the pre-blast level. The lack of increase in penetration resistance suggests that the strength and stiffness of the soil apparently does not improve after blasting. This paradox leads to questions about future performance. Have the loose sands really been improved to the point where liquefaction is not a possibility?

Working with our partners, Geosyntec Consultants, we have developed field data at a blast densification

site near Charleston, South Carolina, that shows that one of the consequences of blasting is the release of gases that remain occluded in the targeted sands. For a period of one month after blasting, we measured quantities of nitrogen and carbon dioxide gases in the sands below the water table. We also measured gases in an area of the site at which blasting occurred four years ago, which supported data collected in Japan wherein gases from sand densification projects (not blasting) persisted as much as 25 years under the water table. We have developed laboratory procedures to inject sand samples with controlled amount of occluded gas. Results of experiments show that the friction angle of the sands with the occluded gas tested at densities representative of post-blasting conditions is about the same as that of the much looser, pre-blast density. This result explains the lack of penetration resistance after blasting observed in a number of studies.

To complete the study, we currently are studying the effects of these gases on the resistance of sands to earthquake-induced cyclic loadings. We also are modifying our previously-developed procedure to quantify the amount of densification associated with a blast event to account for the presence of these gases, given the initial state of the loose sand in the ground. These additions to our understanding of the behavior of sandy soils will help ensure the safety of critical transportation links in active seismic regions.

# Condition Monitoring of Urban Infrastructure: Evaluation of Top-Down Construction Methods



## Principal investigator: Richard Finno

The proximity of important infrastructure to deep excavations in urban environments imposes strict movement limits on excavation support structures. Top-down excavation methods, wherein the permanent floor slabs of the basement levels are used as lateral support for excavation, are generally thought to provide stiff support systems and thus little excavation-induced ground movement. However, recent field experience has indicated that lateral movements associated with top-down construction are in fact similar to conventional bottom-up excavations that employ temporary lateral support in the form of cross-lot bracing or tiedback ground anchors. Investigation of this counterintuitive observation is necessary to allow construction while protecting nearby infrastructure such as pipelines, subway tunnels, and city streets.

One source of movement that is not considered when making design predictions is shrinkage and creep 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. In partnership with AECOM and with help from the ITI Research Engineering Group,

we have collected several years of data with a real time monitoring system to evaluate the stresses in five levels of floor slabs from a top-down construction project in the fast-growing South Loop area of Chicago.. Data collection continues today.

While no lateral wall movements occurred at the site after construction was completed about construction day 500, axial forces in the slabs increase - likely because of consolidation of the clays adjacent to the excavation. To interpret these results more completely, finite element simulations of the excavation process are needed. In addition to representing the construction activities as the site, the stress-strain behavior of the soils has been accurately defined. This aspect of the work was a focus of the doctoral thesis of Dr. Taesik Kim.

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 the interrelation between concrete slab shrinkage, consolidation and ground movements. Furthermore, evaluation of the strain gage data collected in the long term will allow one to develop recommendations for long term lateral loadings on excavation support walls, which currently are empirically-based. These research results will improve our ability to build in dense urban environments without disrupting adjacent infrastructure.

# A Data Processing and Control System to Support Remote Infrastructure Monitoring

## Principal Investigators: Pablo Durango-Cohen and David Corr

Remote structural health monitoring provides new sources of transportation infrastructure performance data, and new statistical methods are needed to maximize the decision-making utility of monitoring data. Using the US Highway 2 bridge in Hurley, Wisconsin, on which the ITI Research Engineering Group and the Wisconsin Department of Transportation have installed structural health monitoring and weigh-in-motion systems, Prof. Durango-Cohen and his student Yikai Chen are developing a data processing framework to extract important information on developing trends from remote monitoring data streams.

The Hurley bridge is subject to heavy loads from daily truck traffic, many of which are believed to be overweight logging trucks travelling from Michigan into Wisconsin. WisDOT is concerned about that the observed traffic will cause premature degradation of the structure due to fatigue and overstress conditions. The data processing framework is being developed to help manage the Hurley bridge and similar structures on truck routes in the region by:

- Processing measurements related to structural health, traffic loads, and environmental conditions in an integrated fashion, thereby yielding comprehensive, facility-level condition assessment and forecasting capabilities;
- Providing real-time, reliable alerts when potential damage or risk of structural change in the facilities is detected; and
- Determining the nature of the detected changes, i.e., inferring underlying structural properties, and identify possible assignable causes.

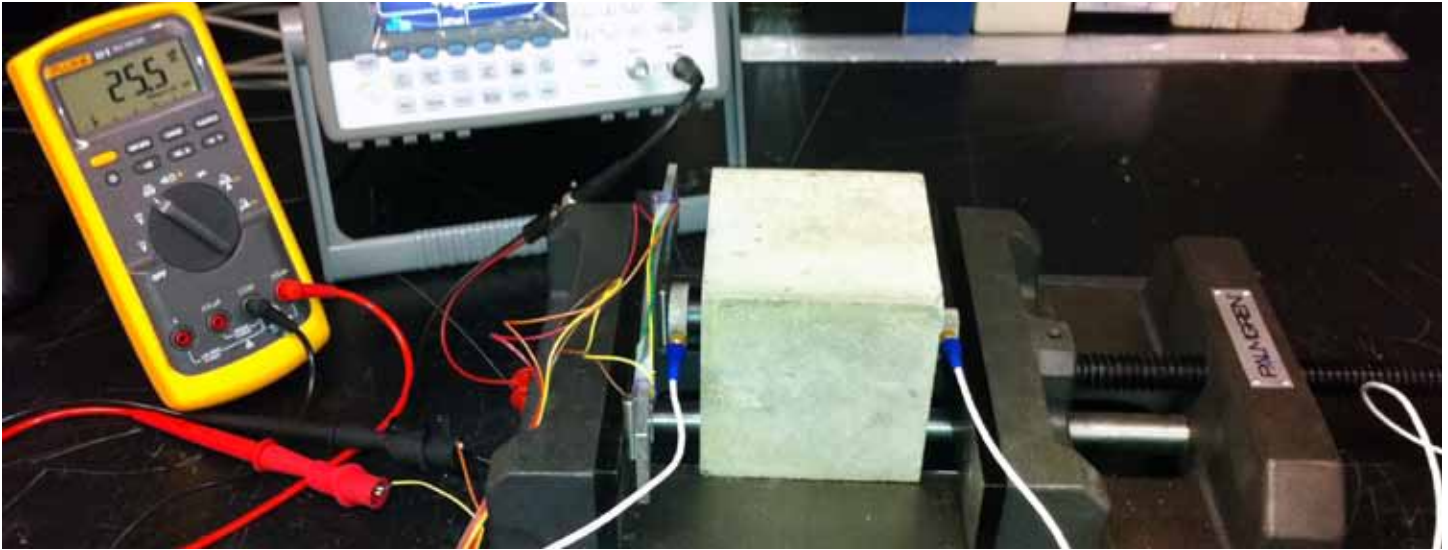
Distress measurements (strains on each girder &

movements of the entire bridge) were collected for 13 months as real-time inputs of the framework. Weather conditions (temperature & humidity) were used to remove seasonal environmental effects through regressions. The process control system has been implemented as a set of individual control charts. The intuition is that monitoring the processed residuals/innovations provides a basis to understand when a process drifts out-of-control. Observations falling outside the control limits provide reasonable evidence that a special-cause change has occurred in the structure.

The data processing system has already yielded a few points of information about the performance of the structure. On October 26, 2010, and January 1, 2011, the control system detected points outside control limits indicating transitory shifts of the bridge on its bearings. These are believed to be caused by overweight trucks. Exponentially Weighted Moving Average control charts have shown a slow, long-term movement of the bridge on its bearings that is distinct from daily or seasonal changes due to temperature. This behavior is consistent with anecdotal evidence from bridge inspections and is now quantifiable for the first time.

While neither of the changes above represent an immediate threat to the safety or serviceability of the bridge, they demonstrate the ability of the data processing and control system to detect out-of-the-ordinary events as well as subtle long-term changes that would otherwise be masked by the effects of temperature changes. Future work will enable similar data processing and control systems to provide alerts of structural performance changes in near-real time.

# Assuring More Durable Concrete



## Principal Investigator: Jianmin Qu

Alkali-silica reaction (ASR) is a deleterious reaction that affects concrete infrastructure in many parts of the country. ASR occurs when alkalis in cement react with the siliceous minerals present in certain aggregates. Knowing the alkali reactivity of aggregates is essential in managing and mitigating ASR induced damage. Since a large quantity of aggregates are used annually, and they come from a wide variety of sources around the world, their alkali reactivity may vary significantly from source to source, sometime even within a single source. To measure the alkali reactivity, many standard test methods have been developed over the years. However, most of the methods in practice today are based on measuring the ASR-induced expansion of concrete samples over time. These methods can only be performed in the laboratory environment, and typically require long testing time, ranging from weeks to years. Therefore there is a critical need for more reliable, low cost and rapid test methods to assess aggregate alkali reactivity.

In this project, we are developing a nondestructive testing method to assess the alkali reactivity of aggregates. The method is based on the mixing of nonlinear ultrasonic waves. In the test, a piezoelectric transducer attached to the sample induces two ultrasonic waves of different frequencies into a concrete sample with ASR damage. As the ultrasonic waves propagate through the concrete sample, they interact (mix) among themselves in the presence of the alkali gel, a byproduct of ASR damage. Such

mixing produces a resonant wave that can then be received by another sensor attached to the sample. The magnitude of this resonant wave is called the acoustic nonlinearity parameter. Since the wave mixing is induced by the ASR damage, our hypothesis was that this acoustic nonlinearity parameter is related to ASR damage in the concrete sample.

Preliminary results from the first eight months of our project clearly show that, indeed, the acoustic nonlinearity parameter is very well correlated to the degree of ASR damage in the sample. Furthermore, almost all existing methods require standardized sample size and geometry, because they measure the sample expansion caused by ASR damage. This prevents the field application of these methods to existing concrete structures. In contrast, the acoustic nonlinearity parameter measured in our ultrasonic test characterizes the intrinsic state of ASR damage, independent of the sample size or geometry.

This unique capability enables the application of our ultrasonic method to existing concrete structures. By attaching transmitters and sensors to an existing concrete structure, ultrasonic measurements can be conducted to assess the ASR damage without damaging the structure. Knowledge of the state of ASR damage will then help infrastructure owners evaluate, manage, and repair or rehabilitate structures affected by ASR.

# Stretchable Electronics for Sensing Strain on Curvilinear Shapes



## Principal investigator: Yonggang Huang

Many transportation infrastructure facilities are built of combinations of plates - consider a highway bridge made of steel plate girders. However, many facilities are made of curvilinear shapes - consider pipelines, oil tanks, the curved bascule girders of some movable bridges, among other things. Measuring strain on these non-plate shapes accurately is very challenging with standard experimental stress analysis methods, since it is difficult to bond strain sensors curved surfaces. Using novel stretchable electronics, Prof. Huang and his team are developing a flexible strain sensor that can be applied to curvilinear shapes without loss of fidelity.

The stretchable electronics developed by Prof. Huang and his team can remain functional while flexed tightly or stretched as much as 140% of original length. Thus, they can fully conform to a wide variety of surfaces. Such flexibility enables electronics to conform to any curvilinear shapes such as hemispheres, cones, pyramids, and cylinders.

One promising application of stretchable electronics is to monitor damage accumulation in complex transportation infrastructures and to assess their safety and reliability. As noted above, some critical components of transportation infrastructure have

curvilinear shapes, which made traditional sensors difficult to be mounted on the curvilinear surfaces. Stretchable electronics can be conformally mounted on the surfaces of these complex structures or even inside them, and therefore provide critical information from components for which it would be otherwise difficult or impossible to obtain strain measurements.

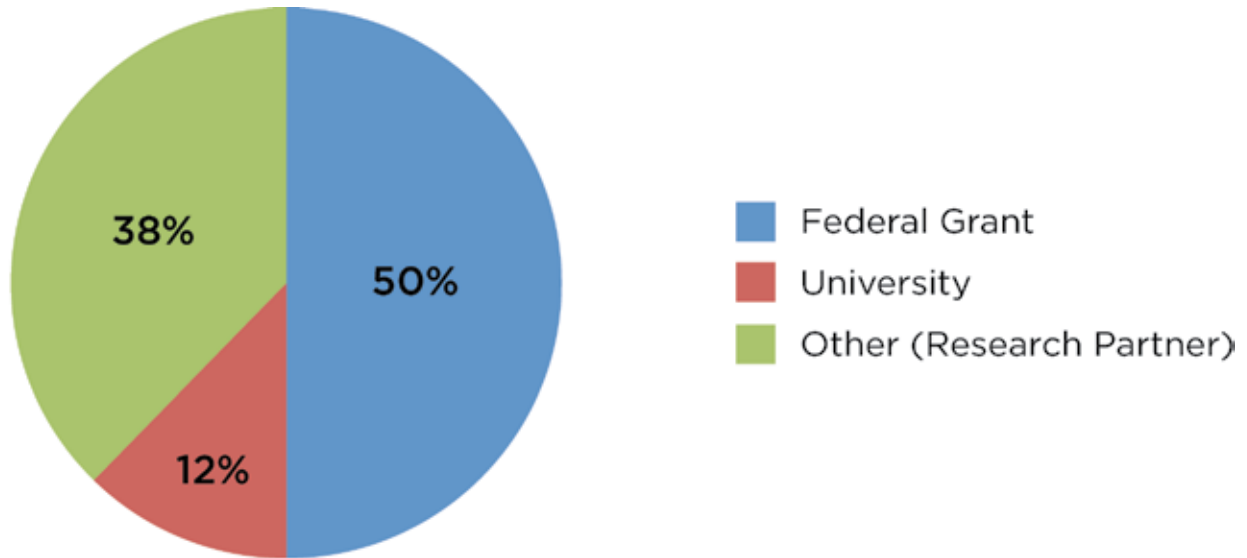
The utility of stretchable strain sensors could be expanded by integration with a flexible silicon solar cell also recently developed by Huang and co-workers. The flexible solar cell has many advantages over typical solar panels: it can be applied to curved surfaces, it is transparent, it operates at high efficiency, and is relatively inexpensive. The flexible solar cell is expected to become a reliable and convenient power source for stretchable strain sensors and associated data acquisition equipment.

Both the stretchable strain sensor and flexible silicon solar cell have attracted considerable attention from scientific and professional organizations and the popular media.

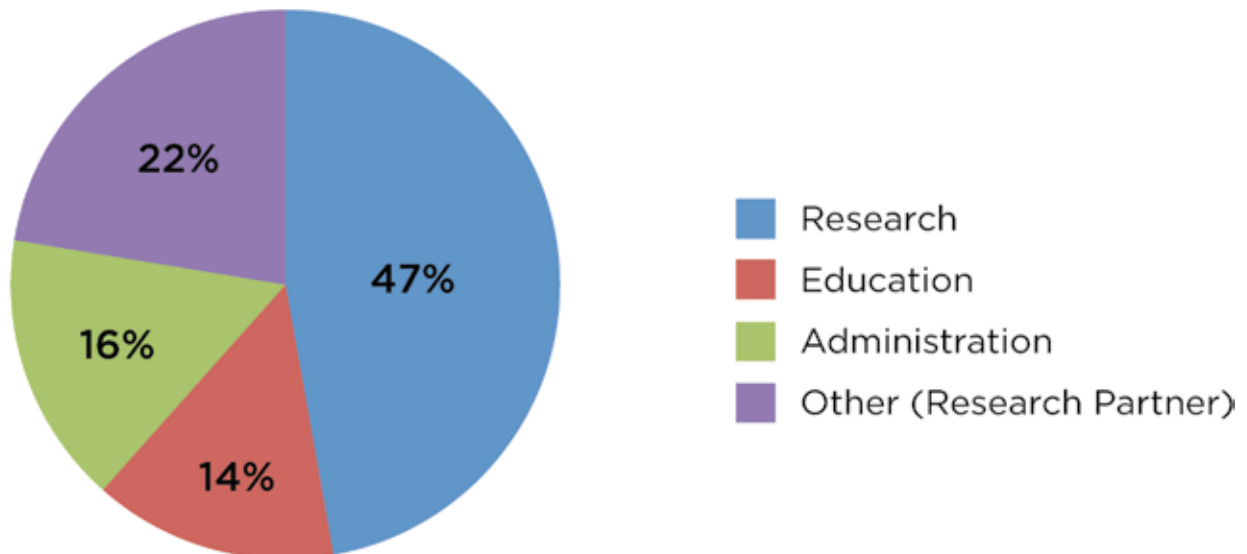


# FUNDING SOURCES AND EXPENDITURES

## Total Funding Sources: \$6,486,800



## Total Expenditures: \$3,608,950



**McCormick**

Northwestern Engineering

NORTHWESTERN  
UNIVERSITY



Infrastructure  
Technology Institute



NORTHWESTERN  
UNIVERSITY