INFRA TECH

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The current condition of our surface transportation infrastructure - and particular concerns for the condition and safety of bridges - have sparked much discussion about structural health monitoring (SHM), including issues of methods, new technologies, and deployment strategies. This focus on monitoring and preserving the nation’s bridges comes at a time when the capabilities of both sensor and communication technologies are growing rapidly. New SHM technologies are being developed and tested; predictions suggest that large-scale and widespread use of automated technologies will provide managers and policy makers information that is more timely, more accurate, and less costly.

However, the nature of bridges and their problems and risks suggest that SHM technologies will always need to be deployed in concert with more traditional, hands-on inspection techniques. In the following article, ITI Research Engineer David Kosnik addresses this issue of balance in the bridge monitoring process.
Recent structural failures have highlighted the importance of transportation infrastructure and the consequences of its deterioration. As researchers continue to advance the practice of structural health monitoring (SHM), especially for highway bridges, it is important to understand the role of the spectrum of inspection techniques and to deploy them in a balanced and informed way.

No element of surface transportation infrastructure warrants safety and performance concerns more than highway bridges. Since the beginning of the federal bridge inspection program in 1968, visual inspection has been the primary method for assessing the performance and serviceability of bridges. By federal law, all structures which carry traffic and have a span greater than 20 feet are subject to comprehensive inspection at least every two years. In a routine biennial inspection, trained bridge inspectors check for obvious damage, which may take such varied forms as spalled concrete, corroded steel, and even insect and fungus attack on timber elements; they also examine bearings, deck drains, and expansion joints for proper operation, evaluate the serviceability of bridge substructures, decks, approaches, and appurtenances, and, for waterway crossings, inspect the channel for scour and obstructions to flow.

All of these elements are inspected visually, using basic hand tools where appropriate. The goal of these federally-mandated inspections is to assess and document the condition of essential bridge elements to ensure safety and serviceability and to facilitate the timely programming of maintenance and repairs. This is the essence of structural health monitoring.

Some bridges are also subject to special inspections, in-depth evaluations of the safety and serviceability of particular elements known to have specific problems or present particular risks. For example, special inspections are conducted on fracture-critical bridges: those with non-redundant steel tension components, the fracture of which would likely cause catastrophic failure.

Fracture-critical members (FCMs) are subject to special inspections at least every two years. Bridges containing FCMs of particular concern, such as those with fatigue-prone details, are typically inspected more frequently. FCM inspections often employ special non-destructive testing techniques to detect cracks. Techniques used on accessible surfaces include dye penetrant and magnetic particle testing, which make tiny cracks more visible through the use of brightly-colored dyes and patterns of iron particles in a magnetic...
field, respectively. Some FCMs have details in which only one side of an element is accessible. In these cases, non-visual methods must be used. A common option is ultrasonic testing, in which a highly-trained, certified operator interprets the reflection of high-frequency sound waves projected into the element. Both the visual inspection and instrument-based non-destructive testing methods require up-close access to the elements in question, and thus, FCM inspections are often called “arm’s length” inspections.

Instrument-based assessment methods can extend the range and depth of hands-on inspection to answer very specific questions about bridge element condition. The most common instrument-based methods deployed on bridges include well-known non-destructive evaluation (NDE) techniques such as ultrasonic testing, eddy-current testing, in which electric signals are used to detect flaws, and radiography, in which high-energy X- or gamma rays create an image of the internal structure of an element on film. These techniques are employed on specific areas of a structure where cracking is suspected. This is done for economy, but also because it is simply not practical to conduct these tests on all parts of a bridge. Therefore, thorough knowledge of the theory and
practice of bridge design and maintenance is critical to the effective deployment of NDE and SHM technologies on bridges – engineers must know where to look for trouble.

New sensing techniques suitable for bridges are developing rapidly. From new sensors based on nanotechnology to self-assembling wireless sensor networks, a wide variety of options for sensor-based monitoring will be available to bridge engineers in the near future. In particular, wireless sensor networks promise to enable more widely distributed sensing throughout a structure, increasing the number of sites where measurements may be taken. Still, visual inspection will remain the foundation of structural health monitoring. Visual inspection provides a synoptic view of bridge condition. Inspectors are able to identify a wide range of threats to bridge safety, including damage in unanticipated areas and issues not intrinsic to the structure, such as stream channel changes; furthermore, inspectors can identify details where the application of advanced inspection and testing techniques might be particularly instructive. Comprehensive, integrative assessments by trained bridge inspectors will continue to provide most critical safety and serviceability data for the nation’s highway bridges. Continuous sensor-based structural health monitoring should supplement inspection data by measuring quantities that cannot be otherwise observed and by gauging a structure’s performance over time and between inspections.

No single method or technology can provide the condition information needed to ensure the safety and serviceability of the nation’s bridges. The careful integration of sensing technology with traditional inspection techniques, however, will provide the data that engineers and policymakers need to manage the structures that serve as the connective tissue of our society.
LIVE STRAIN MEASUREMENT AIDS INTERSTATE BRIDGE REPAIRS
The John F. Kennedy Memorial Bridge, opened in 1963, carries Interstate 65 over the Ohio River between Louisville, Kentucky and Jeffersonville, Indiana. Over 120,000 vehicles travel the bridge on an average day. Four bearings on the large through-truss structure are designed to resist substantial upward forces that might otherwise lift the bridge off its supports. In a 2006 inspection, one of the four anchor bolts restraining one of these bearings was found to have fractured. Since the performance of the uplift bearings is critical to the safety and serviceability of the bridge, the Kentucky Transportation Cabinet was eager to gain insight into the behavior of the compromised bearing assembly prior to designing a retrofit.

During the summer and fall of 2007, the Kentucky Transportation Cabinet engaged ITI’s Research Engineering Group (ITI-REG) to help investigate the anchor bolt failure. As part of a multi-party effort, the ITI team worked closely with Cabinet personnel, University of Kentucky researchers, and consultants. ITI engineers deployed strain gauges, displacement transducers, and accelerometers on all four bearings to compare the behavior of bearings with intact bolts to that of the bearing with the fractured bolt. Each site was monitored under live traffic for several hours during both daytime and evening. The data revealed that the strain in the three remaining anchor bolts restraining the compromised bearing was much greater than those in the four anchor bolts on the other bearings.

The compromised bearing assembly was retrofitted with a replacement anchor bolt in late October 2007. Prior to installation, ITI engineers instrumented the replacement bolt with strain gauges to measure its performance. Using a computer-controlled data acquisition system, the ITI team observed and recorded the behavior of the replacement bolt during installation and tightening and for twelve hours overnight following installation. The data showed that the strains in the replacement bolt and the three original bolts on the compromised bearing were more appropriately distributed after the retrofit. Members of the ITI-REG presented their findings to the Kentucky Transportation Cabinet at their headquarters in April 2008.

Once a more permanent retrofit is in place, the ITI-REG will install a system for the continuous remote monitoring of live strains, displacement, and acceleration at the bearing assembly. This system will help characterize the long-term behavior of the anchor bolts and aid in evaluation of the retrofit. Data will be autonomously delivered to researchers and Cabinet engineers for analysis via Internet display technology previously developed at ITI.
ITI-sponsored research was prominently featured in the program of the 7th International Symposium on Field Measurements in Geomechanics (FMGM), a technical conference presented by the Geo-Institute of the American Society of Civil Engineers (ASCE). The symposium was held September 24-27, 2007, in Boston, Massachusetts. ITI researchers contributed six technical papers, authored by Professors Charles Dowding and Richard Finno and research engineers David Kosnik and Mathew Kotowsky. Professor Finno presented an invited theme lecture and Professor Dowding served as vice chair of the conference organizing committee.

Professor Finno’s invited theme lecture, “Use of Remote, Real-Time Monitoring Data for Supported Excavations,” summarized advances in the theory and practice of design and performance evaluation of supported excavations. The technique, called “inverse analysis,” uses intelligent updating with real-time data to improve the ability of numerical models to predict soil deformation around an excavation. Improved performance models will help anticipate and prevent disruptions to transportation infrastructure facilities, such as roads, railroads, and pipelines, due to nearby excavations. Finno also presented a technical paper, “Real Time Monitoring at the Olive 8 Excavation,” which described the use of an automated survey instrument to measure the performance of a deep excavation with an unusual support system.

Professor Dowding presented “Response of Historic Structure to Long-term Environmental and Construction Vibration Effects” and “Multi-Hop Wireless Crack Measurement for Control of Construction Vibrations.” These respectively described wired and wireless approaches to quantifying the effect of construction vibrations on adjacent structures.
ITI research engineer David Kosnik presented “Internet-Enabled Geotechnical Data Exchange” and “Case Studies in Integrated Autonomous Remote Monitoring,” which described ITI’s techniques and experience in data acquisition, communication, and autonomous data archiving and display over a wide range of infrastructure instrumentation projects. Mr. Kosnik emphasized the importance of robust communication systems and the value of autonomous Internet-enabled data display techniques, such as those developed at ITI.

When not presenting papers or attending sessions, ITI research engineers David Kosnik, Mathew Kotowsky, and Daniel Hogan staffed an information booth in the exhibit area, showcasing ITI’s work and soliciting new external deployment partners for ITI research.

ITI publications from FMGM 2007

All papers are found in Proceedings of the 7th International Symposium on Field Measurements in Geomechanics, Boston, Massachusetts American Society of Civil Engineers, 2007.

Dowding, C.H., Marron, D.R., and Baillot, R. Response of historic structure to long-term environmental and construction vibration effects.


Finno, R.J. (Invited lecture). Use of remote, real-time monitoring data for supported excavations.


Kosnik, D.E. Internet-enabled geotechnical data exchange.

In the summer of 2007, the ITI team drew on experienced gained during the construction of the Olive8 development in downtown Seattle in 2006 to design and deploy an even more sophisticated system for monitoring the effects of excavation on nearby structures. The Museum of Fine Arts (MFA) in Boston is undergoing a complex construction project in which a new section of the building will be built upon what had previously been a courtyard.

Because of the proximity of the excavation to the existing structure and the fragility of the collections contained therein, ITI has teamed with the Schnabel Foundation Company to install an automated motorized total station (a type of surveying instrument) and an Internet-accessible camera to monitor the effect of the excavation on the adjacent building. The restrictions on the movement of this structure, imposed by the structure owner, its neighbors, and operators of nearby utility infrastructure, are similar to those for excavations that border transportation infrastructure such as tunnels and rail lines. To track building movement, the total station measures the precise bearing and distance from itself to twelve targets installed on the construction site as well as to four additional targets.
located sufficiently far from the construction site that they could be assumed to be fixed. These data are collected every two hours and immediately transferred to the ITI data center on Northwestern’s Evanston campus where they are integrated with historic data and immediately made available over the Internet to authorized parties. Schnabel, the MFA, and ITI are also able to view real-time, full-motion video from the construction site.

This construction site presented a unique challenge to the ITI engineering staff because the sensitive electronic equipment had to be placed high above the construction site with no convenient access for a technician to perform system maintenance after installation. To address this issue, ITI engineers designed, built, and installed a rigid, lightweight mounting apparatus that would hold the equipment perfectly level while protecting it from the elements and the construction activity below. ITI engineers also deployed a new commercially-available wireless communication system with a custom Internet-enabled software package to control the total station using a wireless PDA on-site or from the ITI laboratory at Northwestern. This secure Internet-accessibility combined with the system’s on-site intelligence represent a significant innovation in the field of autonomous surveying.

The system operated continuously for the entire 10 months of the project’s excavation, providing the engineers with real-time feedback on the effectiveness of their soil stabilization and construction techniques as well as the ability to analyze the construction process after the project is complete. The technique developed and tested at the MFA has immediate practical applications for the monitoring of sensitive urban transportation infrastructure located near excavations or other construction projects.
Opportunities for technology transfer often arise in unexpected ways. In December 2007, ITI technology originally developed for monitoring of construction and mining vibration was successfully adopted for commercial use by a spinoff company and a structural engineering firm for an unlikely purpose: structural crack monitoring of an historic church.

As the congregation of Grace Episcopal Church in Charleston, South Carolina, prepared to build a major addition, an engineering survey of the 160-year-old church revealed serious cracking and differential settlement in both the bell tower and the nave. The addition project was suspended and attention was focused on rehabilitation of the historic structure.

As the project engineers, Charleston-based 4SE, Inc., searched for instrumentation solutions, they discovered articles on Autonomous Crack Monitoring (ACM) technology on the ITI web site. A team led by ITI-sponsored researcher Professor Charles Dowding originally developed ACM technology as a fully automated Internet-enabled system for measurement of cracks in structures subject to construction and mining vibration. Data are aggregated and displayed on a web site in near-real time for review and archiving. Search tools enable users to find data of interest within months or years of readings. 4SE contacted Dowding to explore how ACM technology could be applied to the situation at Grace Church.

From the beginning, ITI’s goal in the Grace Church project was to demonstrate that a private engineering company could successfully employ an ACM system to meet its own project needs. The ACM...
system at Grace Church comprises crack displacement sensors throughout the tower and nave attic and a central computer-controlled data acquisition system. ITI engineers taught 4SE personnel to install and operate the sensors and data acquisition equipment and provided one year of occasional technical support. 4SE engaged Civil Data Systems, a private company chartered to commercialize Internet-enabled remote monitoring technology developed at ITI, to archive and display project data on a web site for review by 4SE and concerned parishioners.

The year of informal ITI technical support for the Grace Church project ended in December 2007. Since then, 4SE has continued to employ the crack monitoring system and Internet data display independently. The increased quantitative knowledge of the structural cracking afforded by the Autonomous Crack Monitoring system grants 4SE greater assurance of the building’s stability on a daily basis. Without the data provided by the monitoring system, 4SE and the Grace Church leadership would likely have been forced to close the nave and hold church services elsewhere during the building’s rehabilitation. As a courtesy, 4SE provides ITI with access to its monitoring web site and all data collected from this system for use in the Institute’s educational and research programs. The continued success of this unique ACM installation illustrates the commercial value of technologies developed at ITI.
In 2003, ITI-sponsored researchers Professors Charles Dowding and Roberta Massabò proposed to use an Internet-connected camera overlooking a construction site as a teaching tool for students of transportation engineering, structural engineering, and project management. Once the camera was installed on the roof of a high-rise building overlooking the construction of the 11th Street pedestrian bridge in downtown Chicago, however, it became apparent that the technology would be just as useful to practicing engineers and project managers as a mechanism for keeping a visual record of construction activity and staging.

In the fall of 2007, Civil Data Systems, a private company chartered specifically to bring ITI technologies to market, was engaged by Hayward Baker, a major geotechnical contractor, to provide construction surveillance cameras on two worksites in downtown Chicago: an office building on Wacker Drive, and the Chicago Spire, a lakefront condominium development by architect-engineer Santiago Calatrava, which will be the tallest building in North America when complete. In each case, Civil Data Systems built a customized bracket and enclosure to mount the camera and communication equipment on the roof of an adjacent building. The brackets attach to the parapet wall of the existing building to support the camera safely in all weather conditions without damage or any modification to the parapet or roof. Civil Data Systems’ unique ability to utilize a wide array of robust wireless Internet...
connections allows for real-time remote control of the pan-tilt-zoom cameras, while on-site computer control captures a time-lapse photographic record of construction progress at each area of interest on the site. The use of flexible and robust wireless communication hardware, installation of the equipment without any modification to host structure, and customized integration of off-the-shelf components keeps the costs far lower than those to install and maintain their traditional wired counterparts.

As construction projects become more complex and schedules tighten, demand for this innovative project management tool is expected to increase.
Several ITI-affiliated students at Northwestern University have recently won a variety of prestigious awards. These undergraduate and graduate students work closely with ITI-affiliated faculty in the completion of their coursework, research, and extracurricular projects and activities.

Zitao Zhang, a second-year Civil Engineering graduate student in transportation, won the ASCE Illinois Section Transportation Engineering Scholarship. Mr. Zhang is a graduate of Tsinghua University in Beijing and was the first undergraduate president of the ASCE Student Chapter in mainland China. In the summer of 2008, Mr. Zhang will be an intern with Northwest Airlines.

Mark Ahasic was selected for an Eno Leadership Conference Fellowship Award. The Eno Leadership Conference selects a group of top transportation graduate students to come to Washington D.C. to learn about the United States’ transportation policy process by meeting with key government, association, and industry leaders. Mr. Ahasic, a former JetBlue employee, is a student in Northwestern University’s Kellogg School of Management and a graduate of Northwestern University’s Industrial Engineering program. He is also currently serving as the Chair of the Northwestern University Transportation Club.
Pattharin Sarutipand, a Civil and Environmental Engineering Ph.D. candidate working with ITI researcher Professor Pablo Durango-Cohen, won an International Road Federation Executive Leadership Fellowship. This award brings together outstanding international students to foster the importance of leadership while developing a better understanding of the transportation industry in the United States as well as the benefits and merits of the International Road Federation. Executive Fellows are nominated by their professors and must demonstrate great educational accomplishments as well as a strong desire to use their education in their home countries.

Emily Kushto, a first-year Civil Engineering graduate student in Transportation, won a scholarship from the Illinois Section of the Institute Of Transportation Engineers. Ms. Kushto is a graduate of Bucknell University and a registered professional engineer. Ms. Kushto previously held the position of Senior Engineer at Edwards and Kelcey in New York.

Mackenzie Nicholson, a senior Civil Engineering student, and Laura Riegel, a senior Industrial Engineering student, received scholarships from the Women’s Transportation Seminar. Ms. Nicholson has worked for Kittelson Associates in Portland as well as for a consulting firm in Australia. Ms. Riegel completed an undergraduate research study examining the carbon footprint of logistics operations at Philips Electronics.
ITI Director Professor Joseph Schofer teamed with Civil Engineering Professor Charles Dowding to teach the ITI-developed Infrastructure Facilities and Systems course in the spring of 2008. This course continues to serve as the capstone design experience in Northwestern’s Department of Civil and Environmental Engineering, but enrollment includes seniors from other fields, particularly those pursuing an undergraduate minor in Transportation and Logistics.

Among the weekly field trips this year are visits to the $15 billion O’Hare Airport Modernization Project, the classification yard and shops of the Belt Railway of Chicago, and the Illinois State Toll Highway Authority widening project on I-294.

The O’Hare project involves the addition of 4 parallel runways, the removal of two existing runways, construction of a new, western terminal and access roads, and a rail transit link under the airport.

The class toured the active airfield and observed runway extensions and new construction projects.

The toll road project includes addition of two lanes in each direction, built under service. Creative traffic management schemes and the use of advanced paving materials and concepts are special features of this project. Students observed installation of bridges and retaining walls, preparations for slip-form paving, and removal of existing pavements.

The Belt Railway visit is always a favorite of the course. This largely automated yard relies on robotic locomotive operations and computer-based management of inbound and outbound freight cars.

In the design portion of the course, two multidisciplinary student teams are designing a green municipal service building to be constructed on top of a land fill near Northwestern’s Evanston campus.
In the summer of 2007, the ITI Research Engineering Group found itself overwhelmed with a continuous flow of projects, and hired Meredith Chow as a student employee to help pick up some of the load. They quickly found Meredith to be an invaluable aid in ways not generally expected of most student workers, and especially an underclassman.

“It was critical to find a student who could take on new tasks with minimal instruction,” says Dan Marron, ITI’s Chief Research Engineer. “The REG is a small group, and Meredith has helped immensely by providing another pair of competent hands.”

Originally from Miami, Florida, Meredith is a sophomore studying electrical engineering at Northwestern. She excelled in math and science in high school, and decided to follow that path into engineering in college. While in her freshman year, Meredith found herself looking for a job on campus and a friend of hers happened to know ITI Research Engineer Daniel Hogan. Meredith contacted him and ended up being hired by ITI. Since then, she has been included in a wide range of engineering projects.

“Meredith fearlessly and enthusiastically went to work on a number of projects,” says ITI Research Engineer David Kosnik. “She assembled field computer components, lab-tested a strain gauge array, and worked tirelessly in challenging field conditions to help with installation of strain gauges.”

“It was critical to ensure that the sensor layout and electronics were correct before deployment on the actual bridge,” says Marron. “The complex arrangement of strain gauges simultaneously measured axial loading, torque, and bending in two directions. She did an excellent job.”

Meredith responds that she has learned a great deal working for ITI.

“It has given me the opportunity to get practical experience and firsthand knowledge of what engineers do in the real world that I can’t get in academia. I’ve actually been putting concepts I learned in school into practice and learning some new engineering skills along the way.”

The REG is hoping Meredith will stick around for a while as she continues her studies at Northwestern. This summer, Meredith will have an internship at Massachusetts Electric Company.
Students in the Infrastructure Facilities and Systems course tour Chicago's O'Hare Airport Modernization Project.

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