INTRODUCTION

Northwestern University's Infrastructure Technology Institute supports research projects on an annual cycle. Proposals are solicited from principal investigators currently funded by the Institute. Proposals from other Northwestern researchers are accepted and evaluated throughout the year. Researchers are required to report monthly on their progress at meetings of the Institute’s Research Associates group. In addition, the Infrastructure Knowledge Manager works with each researcher to put news about research projects and research end-products on the Institute’s Web site. This report constitutes a summary of progress for each Institute-funded research project for calendar 2001.

MINIMIZING SHRINKAGE AND CREEP DAMAGE TO CONCRETE BRIDGES

Principal Investigator: Prof. Zdenek P. Bazant

Introducing new research results into the codes and recommendations governing concrete bridges is a twofold problem: Formulate improved recommendations or code articles, and convince the appropriate technical committees to enact them. During the last year, significant progress has been achieved on both fronts.

A modified first part of a new draft of standard recommendations, dealing with the basic concepts of modern design for creep and shrinkage, has been formulated, with significant input from the principal investigator, within American Concrete Institute (ACI) Committee 209 on Creep and Shrinkage, which is in charge of a report to go into the ACI Manual of Concrete Practice. The good news is that the first part of this new draft is no longer in conflict with the results of previous National Science Foundation-supported research at Northwestern (model B3), but mostly agrees with it. This is a major breakthrough, which has led to a more cooperative atmosphere within the committee, a necessary condition for eventual positive outcome.

Work is proceeding, again with significant involvement of the principal investigator, on a new draft of the second part of this report, dealing with detailed mathematical formulation for the effects of creep and shrinkage, and looks promising that an agreement could finally be reached on a progressive formulation.

A further effort concerned the proposal for a new improved standard for the testing of creep and shrinkage which Bazant has made to ASTM Committee C09 concerned with concrete, of which the principal investigator is also a member. After spending considerable inactive time in the hands of the committee chair, the proposal has finally moved into
the subcommittee on creep. At the time of writing, this proposal is now under discussion in that subcommittee, and it is too early to promise a positive result. As reported earlier, a very similar previous proposal, prepared largely under Infrastructure Technology Institute support, was previously approved by 'Réunion Internationale des Laboratoires d'Essais et de recherche sur les Matériaux et les Constructions' (RILEM), the International Association for Building Materials and Structures, as a new international recommendation. However, this success does not guarantee approval by ASTM, and it will be necessary to work hard to win that approval. Finally it may be mentioned that the website including a program for applying model B3, prepared with M. Kristek, is active and is being used by various design firms.
COMMERCIALIZATION OF INSTRUMENT FOR MICRO-INCH MEASUREMENT OF CRACK WIDTH IN SUPPORT OF CONTINUOUS REMOTE MONITORING FOR BRIDGE MANAGEMENT

Principal Investigator: Prof. Charles Dowding

In the spring of 2001, an Autonomous Crack Monitoring (ACM) system was installed at a vibrationally-critical location for the Minnesota Department of Transportation (MNDOT). The instrumented funeral chapel in Figures 1 and 2 below is within 100 ft of piles to be driven in conjunction with reconstruction of I-35 in Minneapolis. Response of this building to weather effects can be seen over the Internet at http://www.iti.northwestern.edu/acm. While the data are password protected, interested infrastructure agency personnel should contact Chuck Howe of MNDOT at Charles.Howe@dot.state.mn.us for the login and password.

Figure 1. Exterior of Chapel   Figure 2. Interior with Instrumented Archway

This ACM system was installed with a second-generation field Somat eDAC computer that transmits data digitally in packets and should allow direct connection via the Internet. The computer and associated electronics were installed unobtrusively under a chapel pew seat as shown in Figure 3.

Figure 3. Unobtrusive Installation of Electronics

This ACM system was installed to test its ability to provide graphical
vibration information to concerned neighbors. As explained on the ACM web site: http://www.iti.northwestern.edu/acm, the instrumentation is capable of providing real time comparisons of vibratory and weather responses of cracks. This comparison provides concerned neighbors a means of comparing everyday — but silent— effects (weather) with short lived — but noisy — construction effects (vibratory). The system is capable of displaying results directly over the Internet as demonstrated at the ACM web site.

The special web site shown in Figure 4 has been developed for Internet interaction with the ACM technology. This site can be employed for both research and public education by password protecting research sites.

Figure 4. Autonomous Crack Measurement Web Site

For instance, the general public can access all options on the left side; “Publications”, etc. “Operational Sites” allows access to the three active sites and one archive. The two research sites are password protected and the third is open to the public at large. This format has been adopted for the TDR project as described below.

Five reports and presentations resulted from the ACM project during 2001:


“Monitoring and Control of Construction Vibration Effects,” Metropolitan (New York City) Section of the American Society of Civil Engineers, Dec 2001.

Graduate Students Laureen McKenna and Mickey Snider are working on measurements of the response of atypical structures and testing of specialty sensors. McKenna’s MS Thesis is to be published in 2002; Snider’s in 2003. Laureen McKenna was the 2001 recipient of the Infrastructure Technology Institute Student of the Year Award.

Dave Kosnik, Sophomore-Junior at Northwestern University has been working with the Institute’s ACM team since the summer before his freshman year to develop JAVA server side programs that are critical to the success of this project. Matt Kotowsky, Sophomore-Junior at the University of Illinois has joined the team to speed the development of server side programs.

This ACM project has led the way to a new concept of Internet broadcast of instrumentation response for public consumption. Software developed for this thrust will be transportable to other types of instrumentation on bridges, which may eventually lead to Internet presentation of the response of ITI instruments around the country. Such Internet presentation provides a unique method of public interaction and education. However, critical to the realization of this public interaction is the expansion of resources expended in the area of knowledge management and server programming.
In the summer of 2001, horizontal Time Domain Reflectometry (TDR) cables were installed for the Florida Department of Transportation (FLDOT) for surveillance of the expansion of sinkhole induced roadway instability as indicated in Figure 5. This installation is the first time that TDR cables have been installed horizontally. Two sites, SR 27 and SR 66, were instrumented through the joint efforts of ITI, FLDOT, and consultants PSI and Geotechnical Consultants Inc. (GCI).

**Figure 5. Plan View of Horizontal & Vertical TDR Cables for FLDOT**

The installed land bridge over the sinkhole under SR 66 and the accompanying TDR instrumentation is shown in the figure above. The sinkhole is shown in the middle of the "land bridge" and the installation of the horizontal cables is shown in the Figure 6.

**Figure 6. Installation of TDR Cable**
As described on the TDR web site: http://www.itinorthwestern.edu/TDR, TDR cables are installed to provide a quick means of determination of deformation that may occur anywhere in a large volume. As shown in Figure 1, the cable stretches the entire length of the land bridge to monitor for deformation that may occur anywhere along the cable. Another attractive feature of TDR instrumentation is that it’s digital nature means that it can be easily monitored remotely without the presence of personnel at the site.

In September 2001, over 100 researchers, scientists, and engineers from around the world gathered at Northwestern University to present progress in TDR research since the last TDR symposium (also at Northwestern) was held in 1994. Special short courses were given the day before for members of State DOT’s. The courses were focused upon

TDR Technology in Surveillance and Measurement,
Automated and Remote Monitoring,
Water Content and Density by TDR (The Purdue Method)

Proceedings of the symposium, the cover of which is shown as Figure 7, can be downloaded for free from: http://www.itinorthwestern.edu/TDR, in the section labeled “symposium”. The proceedings volume was produced entirely electronically, which lowered its cost by nearly an order of magnitude and allowed it to be distributed for free in digital form. Papers in the proceedings included use of TDR to measure roadway moisture content, melting of frozen subgrade, surveillance of roadway landslides, movement of bridge abutments, etc.

Figure 7. Proceeding of TDR 2000 Conference
Importance of the ITI/Northwestern designed compliant TDR cable has been verified through a unique 3D finite element analysis. Use of this cable, shown in Figure 8, will improve the TDR detection of shearing in soft soils necessary for remote surveillance of roadway embankments built on soft clays.

![ITI Developed Compliant TDR Cable](image)

**Figure 8. Institute-Developed Compliant TDR Cable**

An advanced 3D model was employed to link field observation of TDR response to the failure of the embankment fill on soft clay in Figure 9 with laboratory measurements of the response of various TDR cable/grout composites. The work was conducted by Tanner Blackburn, one of the MS/PhD students in Civil Engineering supported by an ITI fellowship. This work will be expanded as a PhD thesis. A special article on this pioneering work is in preparation for publication in 2002.

![TDR Drill Rig](image)

**Figure 9. Installation of TDR Cable in Failing Fill**
Figure 10 shows the installation of TDR cables and tiltmeters at a test site on SR 62 over the Little Blue River for the Indiana Department of Transportation (InDOT). This instrumentation was rendered remotely operable and viewable this November.

Figure 10. Installation of TDR Cables & Tiltmeters over the Little Blue River

Data can be accessed either by modem or by Internet. Internet available data are updated daily and can be viewed at http://www.iti.northwestern.edu/TDR. This remote view capability allows InDOT personnel to monitor performance with any publicly accessible Internet connection or browser, and thus eliminates the need for special computers and software.

A similar capability was also installed this fall for the Ohio Department of Transportation for their surveillance of potential subsidence. It too can be accessed via the Internet at the same address.

Figure 11 is from the TDR web site for Indiana SR 62 and compares TDR cable responses. These data are password protected but can be accessed by requesting permission from Dan Chase of InDOT DCHASE@indot.state.in.us.
Three reports and presentations were developed under the TDR project during 2001:

“Real-Time Monitoring of Subsidence along I-70 in Washington, PA" (w/ O’Connor, K.M. and PennDOT personnel) TRB meeting January 2001. *This paper was highlighted in catalog of practical papers of immediate value to transportation engineers.*


“TDR 2001: The Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Applications, Northwestern University, Infrastructure Technology Institute, [http://www.itinerary.northwestern.edu/TDR](http://www.itinerary.northwestern.edu/TDR), 400pps

Graduate student Tanner Blackburn, recipient of the 2001–2002 ITI scholarship, is finishing his thesis that is described in the section above, ITI Specialty TDR Cable and 3D TDR Analysis.

Work of undergraduates David Kosnik and Matt Kotowsky have direct application to TDR as well as ACM web presentation. Their work has led to the automation of TDR sites for Ohio and Indiana DOT’s. They have been working with the ITI/ACM/TDR team to develop JAVA server side programs that are critical to the success of the automation project. Dave and Matt are sophomore-juniors at Northwestern and University of Illinois respectively.
Shanna McGarry and Cristin Dziekonski were hired during the summer as ITI Summer Interns. Shanna is a Journalism/Marketing major at Northwestern and assisted with the production of the CD based Proceedings of TDR 2000. Cristin is an Electrical Engineering major at NU and has been invaluable in preparing instruments for bridge monitoring as well as TDR data acquisition.
COMMERCIALIZATION OF NUCu STEEL

Principal Investigators: Prof. Morris Fine, Dr. Semyon Vaynman

NUCu steel is a hot-rolled, air-cooled 70-ksi copper-precipitation-hardened steel with better weldability, fracture toughness (especially at very low temperatures) and corrosion resistance than any other structural steel.

During 2001, commercialization of NUCu steel continued. The Illinois Department of Transportation (IDOT) has specified NUCu steel for a bridge to be constructed in 2002. The research team communicated extensively with steel producers and steel users. This effort resulted in participation of a number of entities such as US Steel Company, North Star Steel Company, Caterpillar, IDOT, Ohio Department of Transportation, Stupp Bridge Company in further production, testing, standardization and commercialization of NUCu steel. The research team participated in the meetings of Federal Highway Administration/American Iron and Steel Institute/US Navy Committee on High Performance Steels. Also, corrosion tests of painted NUCu and other construction steels were done. They demonstrated the superiority of NUCu steel.

Highlights of 2001 accomplishments include:

- IDOT has specified NUCu steel for a bridge to be constructed in 2002.
- US Steel Company has begun to promote marketing of NUCu steel. The US Steel Research Laboratory, Monroeville, Pennsylvania, first assured castability of NUCu steel by their melting and casting practice.
- North Star Steel Company paid for 8.4 tons of that steel. It was rolled to 4-inch-thick plates by US Steel, Gary. North Star will roll further and evaluate steel for applications such as light and power poles and hoist and derrick beams. Their interest is in achieving high strength by less costly and more energy efficient processing than quench and tempering or TMCP.
- Caterpillar has ordered from US Steel Company and North Star ½-ton of plates for evaluation of laser welding and laser cutting for possible application in heavy machinery they produce.
- On request from Ohio DOT, Stupp Bridge Company, Bowling Green, KY will conduct in February 2002 a PQR welding test without pre-heat or post-heat before considering NUCu steel for use in bridges. ¼-ton of steel was already provided by US Steel Company for this test.
- Together with Illinois DOT the research team worked on proposal for including NUCu steel into an ASTM Standard. The relevant sub-committee approved the proposal in September 2001. Final approval of a revised A710 ASTM Standard to include NUCu steel (A710B by their designation) is expected in May 2002.
The research team prepared an abstract for an International Iron and Steel Society Symposium on Microalloyed Steels that will be held in October 2002. A paper will be prepared for the Symposium. Two US Steel Company engineers will participate as co-authors.

Corrosion tests performed on painted NUCu steel and some other construction steels commonly used in bridges demonstrated a significant superiority of NUCu steel over all the other steels tested. Figure 12 shows results for painted and scratched panels. The amount of corrosion at the scratch was much less for NUCu steel than the other weathering steels tested including the quench and tempered weathering 70 Ksi yield strength steel developed under the AISI/Navy/FHWA program. Reducing the amount of repainting and touch-up is of considerable current interest.

Figure 12. Painted and Scratched Steel Panels after 3 Week, 35°C Exposure in Salt-Fog Chamber. Steels (from left to right): A36, A588, A709 HPS70W and NUCu.
ANALYSIS OF THE PERFORMANCE OF THE REHABILITATION OF THE CHICAGO-STATE SUBWAY STATION AND ITS EFFECTS ON ADJACENT STRUCTURES

Principal Investigator: Prof. Richard Finno

In 1999, the Department of Transportation of the City of Chicago (Chicago DOT) undertook the rehabilitation of the existing subway station at the corner of Chicago Avenue and State Street. The attendant excavation presented a number of challenges, including excavating through 13 m of soft to medium stiff glacial clay while minimizing associated ground movements so that damage to the adjacent St. Frances Xavier Warde School and Holy Name Cathedral would be minimized. See Figure 13 for photos during construction of the excavation support system.

![Installing Second Level Tiebacks](image1) ![Base and Mezzanine Slabs Placed](image2)

**Figure 13. Site Conditions during Various Stages of Chicago-State Subway Station Construction**

The purpose of this project is to use the data obtained from the monitoring effort to check methods of predicting ground movements arising from supported excavations in soft clay and to evaluate the soil-structure interaction between the adjacent buildings and the deforming soils. Results of the field instrumentation indicated that the support system performed as it was designed. As planned in the design, minor damage occurred to non-load bearing portions of the school.

Laboratory evaluations of the behavior of the three compressible glacial clay strata at the Chicago-State site have been completed. In each layer index property, consolidation, drained and undrained triaxial compression, and drained triaxial extension tests have been conducted. These results are used to determine the effective stress soil parameters for use in the constitutive models.

The finite element work has progressed significantly during this period. An existing code developed by the US Geological Survey, called UCODE, has been coupled with two finite element codes, JFEST, co-written by the principal investigator, and PLAXIS, a commercially available code for geotechnical analysis. The combinations allow one to automatically optimize the input parameters to obtain the best fit for a specific output of the finite element code. After testing the numerical procedures by determining parameters for several constitutive models of Chicago clays, the procedure was used to determine soil model parameters that best fit the extensive inclinometer data obtained as the Chicago-State excavation was made. The research team showed that the numerical procedure could be used to produce, without operator intervention, faithful representations of the distribution of lateral movements throughout construction. Hence, the research team has developed a working model that will automatically update determine parameters to accommodate new information that is collected during construction, and use this new data to make more accurate predictions of ground movements caused by additional excavation. The support of the Infrastructure Technology Institute over the last two years has been instrumental in developing a proposal that was funded by the National Science Foundation to further develop this numerical scheme.

The procedure is currently being used to predict and eventually monitor the progress of an excavation for the Lurie Research Building in Chicago. Working with Case Foundation Company, predictions of movements of a 42 ft deep tied back excavation were made. The ground deformations will be monitored as part of the contract documents, and updated predictions will be made based on the recorded data. Depending on the observed and subsequently updated performance predictions of the system, the design of the support system may be changed as the excavation proceeds. The research team secured the in-kind support of Case Foundation, STS Consultants and GeoSyntec Consultants to pursue this type of updated performance predictions for other projects as they develop in the near future.

EVALUATION OF CAPACITY OF MICROPILES EMBEDDED IN ROCK

Principal Investigator: Prof. Richard Finno

This project is a joint effort between Northwestern University and TCDI – Division of Hayward Baker, a specialty geotechnical contractor. The test micropiles consisted of 178 mm diameter piles with a wall thickness of 13 mm. Four test piles were drilled into rock with sockets that varied in length from 0.3 to 2 m, were tremie-filled, and then grouted with pressures of about 350 kPa. Axial compressive tests were conducted on each of the four piles instrumented with pairs of strain gages spaced every 0.6 m to determine axial load distributions and load transfer characteristics. Additionally, embedment gages were installed in the grout in two of the test piles. A view of the load testing system is shown in Figure 14.

![Micropile Load Test System](image)

**Figure 14. Micropile Load Test System**

The test piles were able to sustain much higher axial loads than allowed by applicable building codes when the piles were tip in relatively good quality rock. The strain gage data collected during testing allowed one to analyze the load transfer characteristics of this micropiles. The strain gage data were analyzed to account for the non-linearity in the stress-strain response of the micropiles. The
piles are flexible relative to conventional piles because of their small cross-section, and as a result of the high axial loads exhibited relatively large non-linearities. Based on consideration of the strain-dependence of the moduli, the unit side resistance, $f_s$, is plotted versus pile head displacement for all micropiles in Figure 15. Examination of the piles after extraction, and supporting finite element studies, showed that the interface which determined the distribution of axial load transfer with depth was not the interface between grout and rock, but the interface between the outside diameter of the steel and the grout. Because of the small annulus between the steel casing and the rock, and the low grout pressures necessitated by the shallow depth of the piles, side resistance did not develop above an embedded depth of approximately 1 m, as shown in Figure 2. Below 1 m, the mobilized friction was substantial, but was limited to that which can develop at the interface of steel casing and grout, and was approximately equal to that estimated based on pullout tests of smooth steel rebar from blocks of concrete. In production piles of lengths up to 30 m, the data suggests that the settlements caused by elastic compression of the pile, and not the axial capacity determined by considerations of load transfer to the rock, will limit the capacity of the piles while supporting buildings. Opportunities for conducting full-scale tests may arise as Soldier Field is reconstructed.

![Figure 15. Mobilized Unit Side Resistance versus Displacement](image)

Congress sponsored by the GeoInstitute of ASCE, and will be presented in February 2002.
IMPROVED CONDITION MONITORING OF BRIDGES: NONDESTRUCTIVE EVALUATION OF FOUNDATIONS

Principal Investigator: Prof. Richard Finno

The purpose of this project is to develop methods to non-destructively evaluate the condition of existing deep foundations and bridge piers. A theory based on guided waves, describing the relation between frequency and group velocity of frequency-controlled excitations, has been developed to allow higher frequencies to be used to evaluate shafts, and, consequently, to identify smaller defects than possible with conventional techniques. After developing an experimental system for inducing high frequencies bursts of energy, the research team conducted the laboratory tests on concrete piles in a free condition, i.e., no soil surrounding the concrete, and field tests on prototype piles installed at the Northwestern National Geotechnical Experimentation Site (NGES) to verify the theoretical solution and evaluate the test equipment. The laboratory set-up is shown in Figure 16.

![Experimental Setup in Laboratory](image)

**Freestanding “Prototype” Concrete Pile**  **Vibrator and Accelerometers**

*Figure 16. Experimental Setup in Laboratory*

Six prototype piles were installed at the NGES. The piles ranged from 12 to 18 inches in diameter, and are made of either concrete or grout. Grout with an unconfined compressive strength of about 1000 psi was used so that the ratio of the shear wave velocity of the pile to that of the soil could be varied. The smaller this shear wave velocity ratio, the higher the attenuation due to geometric damping.

Testing has focused on:
(1) developing a method for consistently generating the input waveform for use in frequency-controlled testing,

(2) using numerically-computed modal shapes to find the best place to place a transducer so that a particular frequency can be identified. Prototypes piles of 8, 10, 12 and 18 inches have been tested to verify that the theoretical locations agree with the actual test data,

(3) evaluating the frequency-dependent material attenuation, and,

(4) evaluating the effect of aging on the observed propagation velocities in the free-field condition as a function of frequency.

In addition to the guided wave work, the research team has developed new methods to test piles in the field, termed longitudinal wave identification (LWI) and shear wave identification (SWI) tests, where intervening structure prevents use of impulse response techniques. This condition is quite common in bridge piers and wharf structures when the intervening structure between the top surface and the pile is too large. The research team has recently completed a project with the US Navy where the research team tested this new approach at their Port Hueneme facility. Figure 17 shows conditions at the dock structure where the research team did its work.

![Figure 17. Conditions at Port Hueneme Test Facility](image-url)
The test requires that multiaxial accelerometers be attached at two locations along the length of the pile. In the LWI test, the structure above the pile is impacted, and the vibrations transmitted along the length of the pile are recorded by the accelerometers. The compression wave is identified in the acceleration versus time (and frequency) data and used to calculate distances to source(s) of reflection. In the LWI test, the piles are impacted above the location of the two transducers and the flexural wave is identified in the data and used to calculate distances to sources(s) of reflection. In both tests, the propagation velocities of the stress waves are directly measured, an improvement over the impulse response test wherein that value must be assumed. Figure 18 shows the research team conducting an SWI test at Port Hueneme.

![Figure 18. Conducting Flexural Wave Identification Test at Port Hueneme](image)

The structure geometry, L/D ratio, and soil conditions all limit the effective depth of the impulse response test. The slab and grade beam on the piles will limit the amount of energy transmitted to the piles, and hence it is advantageous to measure the responses of the piles directly, as was done in the LWI and SWI tests. The piles have embedded L/D ratios of 35, which is near the limit where these methods can be expected to be of use in the soil conditions encountered at the test site.
For the piles in which the bottom was identified, the length was calculated to be within the experimental error of the expected length of 50 ft when the length was computed by the average of the three tests. No significant defects were identified, which was expected since the structure is relatively new and lightly loaded, and the quality of the concrete was good as indicated by the observed longitudinal propagation velocities. Changes in soil conditions were identified at a depth of about 30 ft below the top of the slab, likely representing the interface between the loose, unconsolidated sediments and the underlying dense alluvial sands and gravels.

The combination of the LWI, SWI and impulse response tests represents an improvement over the use of the impulse response method alone. Furthermore, the probability of successful application of these nondestructive techniques is proportional to the amount of information concerning the subsurface conditions at a particular site.

The paper, “Guided Wave Interpretation of Surface Reflection Techniques for Deep Foundations,” was published in the Italian Geotechnical Journal. The paper, “Non-destructive Evaluation of Drilled Shafts at the Amherst NGES Test Section” has been accepted for presentation and publication in the 2002 International Deep Foundation Congress sponsored by the GeoInstitute of ASCE. Professor Finno also will serve as a panel member for a session concerning Lessons Learned from the Nondestructive Test Section at the UMASS National Geotechnical Experimentation Site at this Congress. A report was written to the Navy summarizing the results of the evaluations at Port Heuneme.
The objective of the research project is to develop an understanding of failure mechanisms in pin and hanger joint connections in steel bridges. When functioning as designed, the joints rotate freely under applied loads, which include thermal expansion or contraction and dead weight. From field observations it is found that pin and hanger connections in aging bridges are susceptible to partial or full lock-up due to pack-rust formation. This can cause unintended stresses by inhibiting superstructure movement. In order to investigate these effects, the research team has carried out a series of finite element analyses. Previously, the research team analyzed the problem by assuming linear elastic material behavior with various values of friction between the contacting surfaces. The nonlinearities in the problem were as a result of friction and changing contact conditions. Results for the stresses in the pin and hanger were within the American Association of State Highway and Transportation Officials (AASHTO) standard specifications when the coefficient of friction was small and exceeded these specifications when frictional lock-up was approached. This report presents results obtained using elastic-plastic material behavior, again for a range of friction parameters.

The cantilever and suspended spans of the bridge are 61 ft long and 8 ft 1/4 in. in height. The pin has a diameter of 6.5 in. The entire bridge is made of the same construction steel (ASTM A36), with an initial flow stress of 248 MPa (36 Ksi), Young’s modulus E = 29,000 Ksi, and Poisson’s ratio $\nu = 0.3$. The model consists of three-dimensional brick finite elements (Figure 19). There are 75,000 degrees of freedom in the model. The analysis consists of two steps. In the first step, a dead load of 294 KN (268 Klb) is applied. In the second step, the temperature (Figure 20) is ramped up to 45°C and then cooled back to the reference temperature. The dead load is maintained throughout this procedure.

As can be seen from the Table 1, the deformation under the dead load and thermal loading is purely elastic for friction values up to 0.8. The quantity termed “Peeq” is the “equivalent plastic strain”, while “Mises” is the “equivalent von Mises stress”. For a friction value of 2.0, when lock-up occurs, plastic yield is reached and plastic strains are induced. The implications for structural integrity are being explored and other temperature profiles – including cooling from the reference temperature are being considered.

Future work will also include the investigation of fatigue crack growth in the pin as an alternative failure mechanism.
Figure 19 – Detail of the Joint Connection Mesh

![Diagram of joint connection mesh]

Figure 20 – Temperature Profile

![Graph showing temperature profile with peak at 45°C over a 1.0 time period]

T (°C)

0 1.0 Time period

45

Figure 20 – Temperature Profile
Table 1 – Finite element results

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<th>PIN Mises ($\times 10^8$Pa)</th>
<th>PIN Peeq ($\times 10^{-3}$)</th>
<th>HANGER Mises ($\times 10^8$Pa)</th>
<th>HANGER Peeq ($\times 10^{-3}$)</th>
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On December 13, 2000, the Hoan Bridge (I-794 Milwaukee Harbor) suffered a major structural failure (Figure 21). Two girders in a three-girder approach span failed. The deck dropped approximately 5 feet and the bridge was immediately closed to traffic. The Wisconsin Department of Transportation (WisDOT) assembled a team of experts to determine the nature and cause of the failure and to recommend retrofit or replacement strategies. The team included, Lichtenstein Engineers, Lehigh University, Federal Highway Administration, University of Michigan and Northwestern University. The Infrastructure Technology Institute (ITI) was chosen to instrument a twin to the failed span to allow Lichtenstein to perform load tests as part of the failure analysis effort. During February 2001, engineers from ITI installed and wired 48 strain gages along with wind and temperature sensors. Following the installation of the sensors and data acquisition system, ITI recorded the data through a series of static and dynamic load tests in addition to monitoring the structure over several multi-day periods to assess the response of the bridge to environmental conditions. This work was done under very severe weather conditions with temperatures hovering in single digit readings and high winds of 15 to 35 mph.

ITI installed a total of 48 strain gages, two thermocouples, and one ultrasonic wind speed and direction sensor during the period February 13 to March 1. The
installation was performed from a “stripper” type scaffolding platform suspended under the bridge.

The environmental conditions were extremely unfavorable for the application of strain gages. Temperatures regularly hovered at 20 degrees F or lower with high winds and blowing snow. ITI engineers used radiant and direct propane heaters to locally heat the bridge steel to 80 degrees F for installation of the gages. All instrumentation, enclosures, and wiring were affixed to the bridge steel with c-clamps, l-beam clamps, and nylon wire ties.

Four types of resistance strain gages were used during this testing. The first and most used type (27 gages) was a uniaxial-weldable strain gage with a gage length of 0.250 inches. These gages were manufactured with 25 feet of pre-attached instrumentation wiring. The next type (7 gages) was a uniaxial adhesive bonded gage with a gage length of 1/8 inch. Two strip gages (10-element gages) installed were the adhesive bonded, 120-ohm, ten-element type, with an element gage length of 0.020 inches. Only six elements on each strip gage were used. The final type of strain gage used (2-element gage) was a welded double gage with a 90-degree orientation with a gage length of 0.230 inches.

Air and steel temperatures were measured with standard type “J” thermocouples. The air temperature thermocouple consisted of a ¼” diameter by 12” long probe with a vented PVC shroud. The steel temperature thermocouple was an adhesive mounted thin foil thermocouple. The ultrasonic wind speed and direction sensor was a model 50.5 manufactured by MetOne Instruments Inc.

All signal conditioning and data recording was performed using the modular 2100 field computer system from Somat Corporation of Champaign, Illinois. The ITI team used four stacks in a hard-wired network configuration to sample all channels on the same time base. The wire lengths necessary to bring all strain gage signals to a single location would have been too long. The maximum strain gage wire length is limited by available instrumentation gain and ambient electrical interference. By separating the data acquisition system into four stacks distributed across the panel point, the strain gage wires were kept to a maximum of 25 feet. Communication between the master stack and the laptop PC was made via radio using 900MHz spread spectrum serial data transceivers.

ITI performed several long-term, static, and dynamic tests using the installed sensors and data acquisition system. All tests were documented on digital videotape. All test data appeared reasonable and within the expected ranges. The test data proved useful in both the failure analysis effort and the retrofit design. The retrofit which included replacement of the failed span and complete removal of the lateral bracing system with its associated connections was completed in October of 2001, and the bridge is reopened to traffic.
The team members, including ITI, received FHWA “Strive for Excellence” awards in recognition of their efficient and timely completion of the complex task of safely returning this critical structure to service.

Crack monitoring work is being performed in support of Professor Charles Dowding’s project on Commercialization of Instrument for Micro-Inch Measurement of Crack Width. Vibrations caused by construction or mining operations are of great concern to people who live near these activities. Sometimes homeowners associate the appearance of normal cosmetic cracks in their homes with the construction vibrations they feel and hear. The goal of our project is to compare crack changes produced by short-term construction vibrations with those produced by longer-term environmental effects (temperature/humidity). The research team has installed several onsite remote-monitoring systems, which include temperature, humidity, ground motion, air pressure, and crack displacement sensors. The data collected by these systems is automatically analyzed and presented via a web-based interface (http://iti.birl.northwestern.edu/acm/).

During 2001, the Institute research team has continued to improve the automated data acquisition system and web interface for our Evanston and Milwaukee sites. During the first week of June Institute researchers and NU Civil Engineering graduate students installed another remote crack monitoring system in Minneapolis, Minnesota (Figure 22). This system is located in an active funeral chapel adjacent to a pending interchange reconstruction on I-35. The new system is monitoring four crack gages, three geophones, two temperature, two humidity, and one air pressure sensor. The system is constructed completely of commercially available hardware and software. NU students wrote the data reduction and web posting software in JAVA. This Minneapolis site should provide excellent historical record of crack behavior and environmental conditions prior to, during, and after the interchange construction.

The crack monitoring sites were made “active” sites in October 2001. The web server now automatically checks each remote site for proper operation. If a system malfunction or error is detected, email and pager messages are sent to responsible Institute personnel and civil engineering graduate students. This ensures that a continuous record of all data is available on the website.
The Institute has partnered with the Civil Engineering department to develop the Infrastructure Construction and Condition Monitoring Laboratory (ICCML). This lab contains two state of the art CAD workstations with access to Internet based video monitoring of actual construction sites. The first Internet accessible camera was installed last year and the CAD workstations were installed in May. During the last quarter of 2001 all of the CAD software was upgraded to the latest versions. The Institute has transferred the web-aimable and zoomable Internet camera from its initial test site on the roof of the 1801 Maple building (overlooking the Evanston Research Park construction) to the Hogan building on the NU Campus. This location overlooks the construction of the new nanofabrication laboratory. NU facilities management will be sharing project information and communications with the users of the ICCML. Additionally the Institute plans to install an additional camera at its Sturgeon Bay Wisconsin lift bridge remote monitoring site. Both video and sensor data will be made available to users of the ICCML.

During 2001 the Institute began experimenting with the latest standard in Internet video (H.323) to perform 2-way video conferencing. Two TDR seminars were held. The first utilized PolyCom equipment to provide 2-way video conferencing between Northwestern University and the Ohio Department of Transportation. The second was held as part of the TDR 2001 Symposium and linked the California Department of Transportation, Indiana Department of Transportation, and Northwestern for a one-day seminar covering TDR and remote monitoring using the same technology. The technology has also been successfully
employed to provide participation for state transportation personnel who otherwise would not be able to attend meetings because of travel restrictions. The 2-way technology has been successfully used at two Bridge Maintenance and Inspection Working Group (BMIWG) meetings. Additionally, the Institute in cooperation with Northwestern’s Information Technology group successfully broadcast streaming video from the BMIWG meeting held at Northwestern in December 2001. Selected presentations are being archived and will be available on the Institute’s net site as streaming video or as free CD-ROM’s for people with low bandwidth Internet connections. This technology is in its infancy and new products are becoming available almost daily. The Institute research team sees it as a powerful communications tool that will make a major positive impact on communications between bridge NDE practitioners allowing timely sharing of common problems and solutions.
FEASIBILITY STUDY FOR COMMERCIALIZATION OF A NONDESTRUCTIVE, ULTRASONIC TECHNIQUE FOR MONITORING THE SETTING AND HARDENING OF CONCRETE

Principal Investigator: Prof. Surendra P. Shah

A technique for in-situ monitoring the setting and hardening of concrete was developed at the Center for Advanced Cement Based Materials (ACBM). The experimental procedure is based on high-frequency ultrasonic measurements and consists of monitoring the attenuation of wave reflections at the interface between a steel plate and the hardening concrete. A transverse wave pulse is transmitted into the steel and reflected at the steel-concrete interface. The attenuation of the amplitudes of the first and second reflections due to transmission losses at the interface between the steel and the hydrating concrete is calculated and monitored over time. The reflection process is schematized in Fig 23. The semi portable test setup is presented in Fig 24.

The objective was to develop a method to predict the compressive strength gain of concrete at early ages by means of ultrasonic measurements. Experimental data of strength tests and appropriate wave reflection measurements under controlled temperature conditions were evaluated. Furthermore, an experimental study with six different concrete mixtures tested under outdoor conditions was conducted. Additionally, comparative wave reflection experiments with mortar and concrete were performed.

To investigate the general suitability of the proposed wave reflection method for the strength prediction of concrete, two different concrete mixtures were tested at three different curing temperatures. Strength tests and ultrasonic measurements were performed simultaneously. The development of compressive strength and attenuation is given in Figures 25 and 26. The strength evolution of the concretes start at different ages according to their curing temperature. The same trend could be observed in the development of the attenuation.
The analysis of the correlation between the strength and attenuation has revealed that those quantities are linearly related at early ages (up to 3 days). For the purpose of strength prediction a relationship between strength and the change of attenuation (S-A relationship) for all experiments was established. The change of attenuation is calculated as the difference between a certain attenuation value at time t and the attenuation at that time when strength starts to increase. The S-A relationships for all experiments conducted in this phase are given in Figure 27. Based on those relationships the compressive strength can be predicted from the measured attenuation. The predicted and measured strength values are presented in Figure 28.
compression tests were subjected to the same temperature conditions. The temperature inside the concrete was monitored by embedded thermocouples (Figure 30).

The outdoor experiments have shown that changing environmental temperatures have not influenced the linearity of the S-A relationships for the tested concrete mixtures.

The measured vs. predicted strength values are presented in Figure 31. At the reported state of research, the developed strength prediction procedure requires the determination of one or two compressive strength values at the beginning of the strength development (first day) by compression tests. These experimentally determined strength values have to be used to calibrate the S-A relationship to the specific strength gain of the concrete. Once the S-A relationship is calibrated it can be used to predict the compressive strength from the measured attenuation only.
In order to analyze and compare wave reflection measurements on mortar and concrete experiments with three different batches of one mortar and one concrete mixture were performed under constant temperature conditions. Simultaneously to the wave reflection measurements the compressive strength was determined by compression tests.

The attenuation curves measured on the three different mortar (M-1, 2,3) and concrete batches (C-1, 2,3) are shown in Fig. 32 and 33. It is apparent that the measurements on the mortar samples show a very good repeatability. All three attenuation graphs for mortar are consistent in shape and converge to a unique, material specific asymptote. In contrast to mortar, the attenuation curves for the three tested concrete samples bear resemblance only in respect of their shape. Thus, the different stages of hydration, indicated by the time of occurrence of distinctive points in the attenuation graph are reproduced. But the three samples differ in that all three samples approach three different final values of attenuation.

This result suggests that the homogeneity of the material and the consistency of the final attenuation value are connected. The measurements on the relatively homogeneous mortar give a unique attenuation development, where the experiments with the inhomogeneous concrete are not consistent in the final value. It is assumed that local differences in w/c-ratio, cement and paste content and aggregate dispersion are responsible for this phenomenon.
The same procedure for the strength prediction as described before is applied to the data. The measured vs. predicted strength values are shown in Figure 34. It can be seen from the figure, that the accuracy of the strength prediction for concrete is not influenced by the inconsistency of the attenuation measurements regarding the final value.

![Figure 34. Measured vs. predicted strength values for mortar and concrete experiments](image)

The conclusion of the research to date is compressive strength development and the change of attenuation are linearly related for concrete at early ages. Changing curing temperatures and different concrete mix designs and materials do not affect the linearity of the correlation. Once the attenuation change of the concrete is calibrated to the strength gain of the concrete, it can be used to predict the concrete compressive strength at early ages. Wave reflection measurements on mortar are repeatable concerning shape and final value of the attenuation curve. Measurements on concrete can reproduce the time of occurrence of distinct points in the attenuation graph, but not the final value. Consequently, wave reflection measurements depend on local material properties (such as, coarse aggregate ratio, water to cement ratio) of the material at the measurement point. Homogeneous materials, such as mortar, give a unique attenuation development.

Further research will investigate the microstructural changes in mortar and concrete during hydration. This will help to understand the physical relationship between the attenuation measurements and the hydration process.

Additionally, the repeatability of the proposed strength prediction will be examined with a set of different mix designs. After a sufficient validation of the method, a full-scale test on a concrete slab can be done.

A technical paper which reports on the experiments conducted under controlled temperature and outdoor conditions was submitted for Publication in the RILEM-Journal *Materials and Structures* in October 2001.

A paper dealing with the results of the comparative study with mortar and concrete was submitted to the *ASCE Journal of Materials in Civil Engineering* in February 2002. The paper will be published in a special *NDT-Issue* of the journal.
The success in the research project was presented at the ACI Fall Convention 2001 in Dallas. The presentation was held within the Session “Nondestructive Testing of Early-Age Concrete” organized by the ACI Committee 228 “Nondestructive Testing of Concrete”.

A technical paper about the research presented in this report was accepted for presentation at the 6th International Symposium on Utilization of High Strength/High Performance Concrete. The conference will take place in June 2002 in Germany. The submitted paper will be published in the symposium proceedings.