MDOT

Research on Non-Destructive Evaluation - Workshop

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16. Abstract

The workshop held on March 28 at the MDOT Aeronautics Auditorium in Lansing, Michigan, was organized with the goal of providing an overview of readily available and proven NDE technologies and the process of integrating these technologies into the bridge management program. The presentations focused on the NDE technologies that have been successfully evaluated under laboratory and field conditions. Further, the capabilities and limitations of each technology were discussed with respect to the intended applications. Based on the information received during the workshop and the expertise of the authors, a two-tier inspection process and a NDE implementation program is described.

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EXECUTIVE SUMMARY

The workshop was held on March 28 at the MDOT Aeronautics Auditorium in Lansing, Michigan. The workshop was organized with the goal of providing an overview of readily available and proven NDE technologies and the process of integrating these technologies into the bridge management program. The presentations focused on the NDE technologies that have been successfully evaluated under laboratory and field conditions. Further, the capabilities and limitations of each technology were discussed with respect to the intended applications. Based on the information received during the workshop and the expertise of the authors, a two-tier inspection process and a NDE implementation program are presented.

Base on the information presented during the workshop and the subsequently held panel discussion, the following conclusions and associated recommendations are developed.

1) NDE is an indirect measurement of physical features of a structure. The signal transmission is dependent on geometry of the structural component, properties of the structural material and environmental parameters. Since environmental parameters are variable depending on the time of the day and season, use of multiple technologies combined with expertise and experience is required to analyze and interpret the data collected in order to derive meaningful results. Further, intrusive investigations on field specimens are needed in order to first calibrate and validate the NDE technology.

2) GPR is recommended to evaluate the existence of deteriorated concrete which may provide a corrosive environment for reinforcing steel, the potential for delamination due to corrosion of embedded steel, and to map concrete delamination exposed by the presence of a moisture layer. Michigan conditions favor using GPR for the above stated purposes. This GPR data will be useful for developing deck deterioration models. Limited applications of impact echo and phased array ultrasonic are also recommended for verifying the GPR results.

3) IR can be a supplemental technology to GPR as it heavily depends on the boundary conditions and exposure conditions.

4) GPR, combined with IR and laser based imaging systems, is recommended for acquiring deck condition data for program development and project selection during the statewide-scoping process.

5) GPR, combined with ultrasonic echo, is recommended for locating steel post-tensioning ducts (GPR) and to identify grout voids (ultrasound).

6) Laser scanning (LiDAR) is recommended for documenting visible bridge component and structural geometric information.

7) Ultrasonic pulse velocity (UPV) and ultrasonic surface waves (USW) are recommended for assessment of concrete soundness and quality based on their near surface permeability, freedom from cracking, and modulus of elasticity.

Finally, the following recommendations are developed in order to enhance awareness, build confidence, and develop a workforce for the effective implementation of NDE in the MDOT bridge management system.

1) MDOT needs to develop an action plan for a comprehensive NDE implementation program. The action plan needs to include the use of implementation-ready NDE technology and associated research, calibration and validation needs. The action plan needs to describe the development of a systematic approach in the bridge management process for including the use of specific NDE techniques including expected results, performance measures, challenges and resource needs. The NDE implementation program outlined in Section 4.2 may be a part of the action plan.

2) MDOT bridge operations will greatly benefit by enhancing the partnership with the FHWA Long Term Bridge Performance Program (LTBPP). Rutgers University, Center for Advanced Infrastructure and Transportation, is the principal agency of the LTBPP which indicated that a bridge cluster in Michigan has been identified for inclusion in the programs during its next five-year phase. A direct benefit of this partnership is to expose Michigan to NDE technologies utilized for condition documentation of the bridges on the LTBPP sample list, and utilize the data collected by the LTBPP for training and education. A specific application can be the use of the deck condition assessment robotic system on Southwest region bridges that are being evaluated by a consultant using the IR system.

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1 INTRODUCTION

1.1 OVERVIEW

The Michigan Department of Transportation (MDOT) strives to assure mobility while maintaining a safe and serviceable highway infrastructure. Bridges are the key nodes within the highway infrastructure. In providing services to assure mobility, today's restrictions create an environment for MDOT to be faster, cheaper, safer and smarter. Within that concept the use of technology is essential to improve the efficiency of the operation. However, adapting technologies without a path of integration to the operation of the agency will not improve efficiency. MDOT, desiring to integrate technology the right way, wanted to learn about the national and international experience on nondestructive evaluation technologies and the process required for their integration into the bridge management process.

The workshop was held on March 28 at the MDOT Aeronautics Auditorium in Lansing, Michigan. The NDE workshop was organized in response to the MDOT desire to learn more about the emerging state of the art non-destructive testing techniques for bridges to increase agencies' capability to evaluate assets, understand their condition, and enhance the management process. MDOT interests included understanding the uses, post processing techniques, and interpretation of non-destructive evaluation (NDE) results. MDOT's interests also included techniques that can produce rapid inspection to facilitate a reduction in lane closures and time of closure. Above all MDOT's need is to obtain an accurate assessment of bridge conditions for:

- developing a 5 year plan,
- forecasting future condition, and
- developing "mix of fixes" strategies for the 5 year plan, or emergency situations, or as needed.

MDOT uses four types of bridge fixes. They are as follows:

- Replacement and rehabilitation (R&R),
- Capital preventive maintenance (CPM),
- Capital schedule maintenance (CSM), and
- Reactive maintenance (RM).

MDOT biennially collects safety inspection data for the bridge management system. The bridge safety inspection report contains the National Bridge Inspection Standard (NBIS) rating for three major elements of a bridge: the deck, the superstructure, and the substructure. With the biennial inspection, MDOT also collects data on over 20 Michigan-specific condition ratings using the NBIS rating scale. Based on the condition rating, a project is planned, and bridge scoping inspection is conducted to collect condition data to develop "mix of fixes" strategies. The most common condition data used in the BMS are cracking, delamination, spall, and patched area. In addition, documenting as-built details such as connection details between prefabricated bridge elements; location of critical steel reinforcement, pre-stressing strands, and post-tensioning ducts; grout voids in post-tensioning ducts; and material properties, such as strength and permeability, are needed. Also, documenting the corrosion state of steel reinforcement, prestressing and post-tensioning strands, and the integrity of welded connections is needed for designing the right fix.

1.2   WORKSHOP GOALS

The specific goals of the NDE workshop were as follows:

- Identify NDE procedures suitable for purposes identified in the bridge management system. Classify the readiness for implementation of NDE procedures as field verified and lab verified.
- Evaluate the value and propose a road map for the integration of NDE within the Michigan Bridge Management System (BMS) Process.
- Identify and describe research needs for verifying and calibrating promising NDE technologies suitable for integration to the BMS. Additionally, define the process of validating these technologies prior to implementation.

1.3   WORKSHOP PRESENTERS

The workshop presenters were identified with expertise in the development and assessment of NDE procedures for bridge assessment. The workshop was a day long and included four morning and three afternoon presenters followed by a question and answer session. The first presenter was Matthew J. Chynoweth, P.E. from MDOT, Engineer of Bridge Field Services,

who discussed the current use of NDE for bridge condition assessment. He was followed by Dr. Herbert Wiggenhauser from German Bundesanstalt für Materialforschung und-prüfung: that translates as Federal Institute for Materials Research and Testing. Since 1999 he has been the Head of Division for Non-Destructive Testing in Civil Engineering. The third presenter was Professor Jerome Lynch of University of Michigan. He is the director of the Laboratory for Intelligent Systems and Technologies. His expertise is in sensors for structural health monitoring. The fourth morning presenter was Professor Tess Ahlborn of Michigan Technological University. Dr. Ahlborn's presentation was the description of the findings of the USDOT project on bridge condition assessment using remote sensors. This presentation included an evaluation of state of the practice optical, laser and thermographic imaging systems for bridge condition assessment.

The afternoon session's first speaker was Professor Ali Maher of Rutgers University. He is the director of the Center for Advanced Infrastructure and Transportation (CAIT) and also serves as the principal investigator of the FHWA project on Long Term Bridge Performance Program (LTBPP). The project's goal is to improve bridge asset management. His presentation included the LTBP project results and potential collaboration and partnership with MDOT during the project's second five-year phase. The second afternoon presenter was also from Rutgers University. Professor Nenad Gucunski is the chair of the civil engineering program and the director of CAIT's Infrastructure Condition Monitoring Program (ICPM) and the principal investigator of the automated nondestructive evaluation and rehabilitation system for bridge decks. The last presenter was the Professor Haluk Aktan of Western Michigan University. His presentation was NDE techniques for early age assessment of concrete durability. He also discussed the methodology of evaluating NDE measurement reliability.

1.4   REPORT ORGANIZATION

The report contains six chapters and three appendices.

Chapter 1 provides an overview of the NDE needs and goals of the workshop.

Chapter 2 describes the structural condition assessment data requirements specific to highway bridges.

Chapter 3 provides a list of technologies discussed in the workshop with a few visuals. Also, technology implementation status, applications, and a few remarks made by each presenter are briefly presented.

Chapter 4 presents the field ready NDE technologies. It is worth stating here that these technologies are not all created equal but have varying accuracies and defect detection reliabilities. Also, an example data structure for effective bridge management is presented. Finally, the recommended NDE implementation program is presented.

Chapter 5 presents a summary, conclusions, and recommendations. The conclusions and associated recommendations were developed based on the workshop presentations. In addition, a list of specific recommendations were also developed to enhance awareness, build confidence, and develop a workforce for the effective implementation of NDE in the MDOT bridge management system.

Chapter 6 presents the list of references.

Appendix A provides detailed summaries of each presentation.

Appendix B provides a list of questions asked during the panel discussion held at the conclusion of the workshop and the answers provided by the panel members.

Appendix C lists workshop participants' names, affiliations, and contact information.

2 STRUCTURAL CONDITION ASSESSMENT DATA REQUIREMENTS

The purpose of the bridge management system (BMS) is to provide a framework for maintaining the good condition of bridges. The goal of BMS is the preservation of infrastructure investment for enhancing the performance and extending the useful life of the highway bridge infrastructure. BMS components include inspection, evaluation, and maintenance of bridges; asset management; capital programming and funding; and resource management. Preservation requires obtaining timely information on bridge conditions in order to develop and implement a planned strategy to maintain and extend the useful life of a bridge.

The components of BMS, requiring the knowledge of a bridge's condition, are (1) biennial inspections for assigning NBI condition ratings to components, (2) rehabilitation projects requiring accurate knowledge of bridge elements and components so that repairs can be designed to restore structural integrity, and (3) specification of condition-based preventive maintenance activities. As an example, biennial inspection of bridge decks is performed to evaluate the condition and proper functioning of the deck. Inspection is performed at the top surface of the deck, including patched areas, cracking, scaling, spalling, and delamination. The deck's bottom surface is inspected for cracking, scaling, spalling, leaching, delamination, and full or partial depth failures (MDOT 2011a). Bridge management decisions on "mix of fixes" strategies Capital Preventive Maintenance (CPM), Capital Scheduled Maintenance (CSM), Rehabilitation and Replacement (R&R), and Reactive Maintenance (RM) are taken based on the criteria given in the MDOT Bridge Deck Preservation Matrix (MDOT 2011b; MDOT 2011c; Juntunen 2009). These decisions are based on the deck top and bottom surface condition ratings (BSIR #58a and BSIR #58b) and the percent of deficiencies noted in the inspection reports. The percent of deficiencies of the top surface is defined as "the percent of deck surface area that is spalled, delaminated, or patched with temporary patch material." The percent of defects of bottom surface that is not concealed by the stay-in-place forms is defined as "the percent of deck underside area that is spalled, delaminated or map cracked."

Table 1 lists the data needs. NDE procedures may be useful to supplement visual inspection procedures. In fact, the FHWA Preservation Guide indicated one of the attributes of a successful BMS as the "availability of tools and resources to conduct bridge inspections and evaluation."
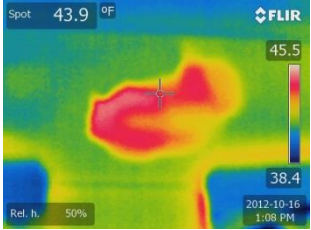
Table 1. Structural Condition Assessment Data Needs

Component		Data
Deck	Top surface	• Delamination • Spall • Patch
	Bottom surface	• Delamination • Spall • Map cracking
	Fascia	• Cracking • Spall
Reinforced concrete railing		• Corrosion • Cracking • Surface scaling • Spall
Substructure		• Delamination • Spall
Other data needs		• Component dimensions to check as-built against as-designed • Component dimensions to check compliance with current standards • Steel reinforcement location and cover • Prestressing strand location • Post-tensioning duct locations and grouting condition • Prefabricated component connection details • Corrosion state of steel reinforcement and strands • Concrete properties (strength, modulus, and transport) • Soundness (freedom from cracking) of recently placed decks

3   NONDESTRUCTIVE TESTING TECHNOLOGY PRESENTED

As mentioned above, the goal of the NDE workshop was to provide an overview of readily available and proven NDE technologies and the process of integrating the technologies into the bridge management program. The presentations focused on the NDE technologies that have been successfully implemented by other Highway Agencies and their capabilities and limitations with respected to the intended applications. A summary of each presentation is provided in Appendix A. Also, Appendix A presents specific examples of success stories including information on cost or user impacts or savings; how the NDE was used as part of a successful bridge management program; the level of difficulty or specialized training needed for operation and data interpretation; and lessons learned. Appendix B provides a summary of the questions and answers session. Table 2 provides a list of technologies discussed in the workshop with a few visuals. Table 3 lists all the technologies discussed during the workshop, implementation status, applications, and a few remarks made by each presenter. Finally, Appendix C lists the workshop attendees and contact information.

Table 2. NDE Technologies Presented at the Workshop

Presenter	Technology		
MDOT – Bridge Field Services	Infrared Thermography	Thermal Imaging Camera	Thermal image
	Ultrasonic Testing Probe (Thickness gauge)		
Herbert Wiggenhauser – BAM	Acoustic Emission		

Herbert Wiggenhauser – BAM	Ground Penetrating Radar	
	Impact Echo	 Impact Echo System
	Infrared Thermography	 Infrared Camera on Movable Frame

Herbert Wiggenhauser – BAM	Phased Array Ultrasonic Testing	Phased Array UT for Metals	Phased Array UT for Concrete
	Ultrasonic Echo	Ultrasound Through Transmission Technique	Ultrasonic Echo Technique
	Ultrasound with Array Technique	Ultrasonic Echo with Array Technique Ultrasonic Linear Array (Shear Wave Transducers)	Ultrasound Sensors on Vacuum Frame
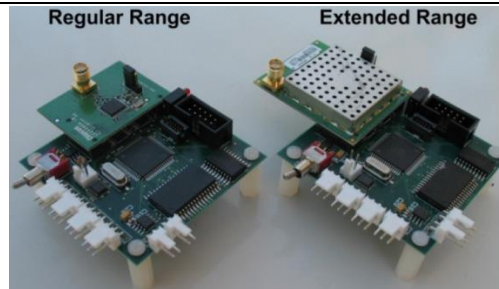
| Jerome P. Lynch – University of Michigan | Narada Wireless Sensor with Amplified Radio | Narada Wireless Sensors |
| | Communication Base Station | Communication Base Station |
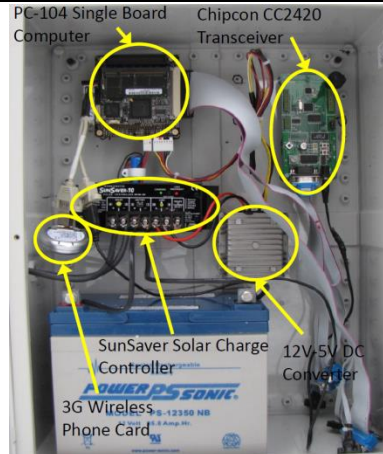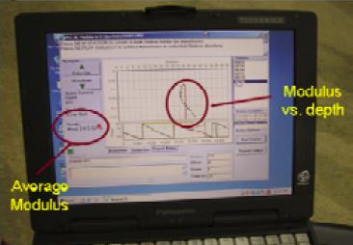
Tess Ahlborn – Michigan Technological University	3D optical bridge evaluation system (3DOBS)	3D Optical Bridge Evaluation System
	Bridge Viewer Remote Camera System (BVRCS)	Bridge Viewer Remote Camera System
	Digital Image Correlation	Digital Image Correlation
	GigaPan	GigaPan

Tess Ahlborn – Michigan Technological University	Infrared Thermography (Thermal IR)	Thermal Infrared Imagery
	LiDAR	LiDAR (Laser Scanner)
	Synthetic Aperture Radar (SAR) 2D and 3D	Lateral translator and radar equipment

Nenad Gucunski – Rutgers University	Electrical Resistivity	Resistivity Probe	
	Ground Penetrating Radar	Ground Coupled GPR System	Air-Coupled Antenna GPR System
	Half-Cell Potential	Half-Cell Potential	
	Impact Echo	Delamination Detection by Impact Echo	

Nenad Gucunski – Rutgers University	Moist Scan Survey (Relative Moisture)	
		Moist Scan
	Ultrasonic Surface Waves (USW)	

| Nenad Gucunski – Rutgers University | Robotic System | |

Haluk Aktan – Western Michigan University	Resistivity Meter	Wenner Array Probe
	Porosiscope (Figg's test)	Porosiscope – Concrete Air/Water Permeability Tester
	Ultrasonic Pulse Velocity (UPV) – paste quality assessment	UPV Testing (Laboratory) UPV array technique – field implementation

Table 3. NDE Technology, Implementation Status, Applications, and Remarks

Technology	Implementations		Applications	Remarks
	Lab	Field		
Presenter: Matt Chynoweth, MDOT				
Infrared Thermography	☑	☑	• Detect delamination on the deck surface and soffits.	Deployable at near highway speed.
Ultrasonic Testing Probe (Thickness gauge)	☑	☑	• Detect the section loss of steel components due to corrosion. • Verify soundness of anchor bolts that are intended to be reused in foundations. • Test the welds at prefabrication plants.	Training for operation of the equipment and data interpretation is necessary.
Presenter: Herbert Wiggenhauser, BAM, Germany				
Acoustic Emission	☑		• For detecting initiation and propagation of cracks in concrete due to many reasons such as expansion of corroding steel reinforcement.	The success of this technology, in concrete decks, is limited to laboratory applications.
Ground Penetrating Radar	☑	☑	• For identifying embedded objects with different dielectric constants than its surrounding media (e.g. steel reinforcement, prestress strands, and/or post-tensioning ducts in concrete).	Not recommended for evaluating grout condition in metal tendon ducts. Reliable in locating steel tendon ducts.
Impact Echo	☑	☑	• For measuring the thickness of a component.	
	☑		• For testing tendon duct defects in the laboratory specimens. The study was to locate the ducts by identifying the back side echo shift.	When detecting tendon duct defects, B-scan and C-scan of the specimen are obtained to get the visual of the flaw, rather than interpreting the frequency peaks
Infrared Thermography	☑	☑	• Used for detecting shallow delamination in	It is established technology with an

			concrete bridge decks.	ASTM standard. The technique is very much dependent on the time of measurement and conditions at that time. Thus, multiple measurements of the same surface need to be obtained at various times/exposure histories. It is further recommended to verify IR observations by other methods, such as sounding or GPR. The points of concern are: (1) IR is a quasi static measurement, thus, the temperature (solar radiation) history must be considered for making inferences, and (2) it requires an experienced operator.
Phased Array Ultrasonic Testing	☑	☑	• Can detect deep delamination in concrete bridge decks. • Can be used for real-time imaging of concrete deck interior with precision.	Tested on lab specimens for detection of shallow delamination. Deep delamination detection capability is superior to impact echo. Limitations include high initial equipment cost, blind zone near the surface, slow process because of manual testing using contact sensors, and need for traffic control.
Ultrasonic Echo (imaging)	☑	☑	• Used for detecting tendon duct grout defects (i.e., honey-comb defects) in slabs	Data-fusion of Ultrasonic Echo and GPR is being explored. The benefit

			with heavy and low steel reinforcement.	is GPR is good at locating steel tendon duct and Ultrasonic Echo is good at penetrating into the duct.
Ultrasound with Array Technique	☑	☑	• Ultrasound with through transmission and array technique is used for the asphalt porosity measurements. • Ultrasound with array technique using shear wave probes can quantify asphalt porosity.	The back-side echo signal plays a crucial role in the determination of asphalt porosity and its extent.
Presenter: Jerome P. Lynch, University of Michigan				
Narada Wireless Sensor with Amplified Radio	☑	☑	• Capable of collecting data from multiple sensors, such as accelerometers, wind vanes, anemometers, thermistors, potentiometers, and strain gauges. • Applied in the field for the measurement of seismic performance data from Carquinez Bridge located in Vallejo, CA.	The sensors are powered using small solar panels.
Communication Base Station	☑	☑	• Used for communicating with all the sensors on site and transfer data to the repository (data storage location).	Consists of single board computer that runs Linux, a cellular modem, a lead acid rechargeable battery with solar panels, and a transceiver.
Cyber Infrastructure (Internet-enabled cyber environment)	☑	☑	• The environment is capable of extracting the modal characteristics of the bridge, generating ADINA input file, and running the FE analysis. The FE model is calibrated and updated using the sensor data from the repository.	This enables the obtained data, from the sensors, to be disseminated online. The data is then combined with analytical tools (data processing clients) for information discovery.
Presenter: Ali Maher, Rutgers University				
Bridge Portal	☑		• The data obtained from bridge evaluation, testing, and long-term data collection under	The data that will be made available from this repository is suitable for

			the Long-Term Bridge Performance Program (LTBPP) is achieved in this *online repository*.	developing deterioration models and life-cycle cost models, forecasting, and bridge management at program and network level.
Presenter: Tess Ahlborn, Michigan Technological University				
3D optical bridge evaluation system (3DOBS)	☑		• Capable of creating high-resolution 3D images for spall detection. • Technology is near-ready for field implementation.	Applicable for surface measurements. Several digital images of the bridge are acquired at near highway speed. The process uses stereo overlapping of images to produce the final high-resolution 3-D image.
Bridge Viewer Remote Camera System (BVRCS)	☑		• Capable of obtaining a complete surround image of the bridge including information at critical locations. • Technology is near-ready for field implementation.	Similar to the street-view style imaging of Google Maps®; however, captures additional information about the images.
Digital Image Correlation	☑		• Can quantify load induced stresses in a bridge. • Used to measure strain fields and vibrations.	Limited to lab implementation. Exposure conditions can affect data accuracy in the field. Requires significant technology improvements prior to deployment in the field. Complementary technologies such as laser vibrometer, LiDAR, etc. should be considered in parallel.
GigaPan	☑		• Used to obtain high-resolution digital image inventories of bridges. • Technology is near-ready for field implementation.	The images are stitched together to provide a high-resolution image of a complete bridge.

Ground Penetrating Radar			• Used for detecting delamination in concrete decks.	The cost is very high and requires traffic control.
Infrared Thermography (Thermal IR)	☑	☑	• Used to detect shallow delamination in the concrete decks from top.	The passive thermal IR requires the bridge deck exposed to solar radiation. An ASTM standard is also available. The technology is being deployed at near-highway speed. The active thermal IR, which requires mechanical heating of components to enhance thermal IR output, is limited to lab implementation.
LiDAR	☑		• Can be used to measure the surface condition such as percentage area of spall, location, and volume of spalls using composite intensity image of the bridge.	The global features such as static deflection, high load hits, etc., can also be determined. However, measurements are slow and require time. The equipment is costly and needs to be appropriately integrated in the bridge condition assessment framework.
Synthetic Aperture Radar (SAR) 2D and 3D	☑		• Can detect spall, delamination, and subsurface defects. • Only the 2D is currently available and is near-ready for field implementation.	This technology varies from GPR as it uses low cost components, single antenna, and ultra-wide band to assist the resolution/penetration tradeoffs. The system could be adapted for use on a moving vehicle using a *lateral translator*. Research is underway to develop this technology for 3D imaging.

Presenter: Nenad Gucunski, Rutgers University				
Chain Drag/Hammer Sounding	☑	☑	• Used for detecting delamination at its final stages.	Conventional technique.
Electrical Resistivity	☑	☑	• Used for detecting sign of corrosion initiation. • Used for detecting the potential for corrosive environment.	Low resistivity indicates highly corrosive environment, and vice-versa. The Corrosion Rate is qualitative and classified as: (1) very high, (2) high, (3) moderate-low, and (4) low.
Ground Penetrating Radar	☑	☑	• Used for detecting the presence of a corrosive environment for steel. • Used for detecting delamination due to corrosion of embedded steel. • Used to detect likelihood of concrete deterioration.	The technology is deployed on bridge decks using ground coupled antenna as well as air-coupled (horn) antenna. The air-coupled GPR survey is conducted at a speed of 30mph.
Half-Cell Potential	☑	☑	• Used for detecting the corrosion activity. • Used for detecting the likelihood of active corrosion.	The technology is being used in the field, and an ASTM standard is also available for its deployment.
Impact Echo	☑	☑	• Used for detecting delamination at its initial and final stages.	The data obtained is highly accurate and can be validated using coring operation.
Infrared Thermography	☑	☑	• Used for detecting shallow delamination at its final stages.	It is established technology and an ASTM standard is also available.
Moist Scan Survey (Relative Moisture)	☑	☑	• Used for detecting zones of moisture concentration. • Currently, the technology is deployed to provide relative moisture measurements, i.e., low or high moisture.	This technology is not used on a regular basis. Research is in progress for calibrating the equipment for absolute moisture content measurements.

Ultrasonic Echo	☑		• Used for detecting delamination at its initial and final stages.	The process requires expertise. Data collection and analysis is time consuming.
Ultrasonic Surface Waves (USW)	☑	☑	• Used for detecting concrete degradation by measuring the elasticity modulus.	The surface wave velocity is measured and is directly correlated with the modulus. The device can obtain several measurements in relatively short amount of time, ranging from 100 to 120 measurements per hour.
Presenter: Haluk Aktan, Western Michigan University				
Resistivity Meter (Wenner Array Probe)	☑	☑	• Used for measurement of concrete permeability in relation to concrete resistivity.	Resistivity is considered as an electrical indicator of concrete permeability.
Porosiscope (Figg's test)	☑	☑	• Used for measuring near surface air and water permeability in concrete.	This requires drilling 3/8 inch diameter holes in the concrete deck and pumping water or air to measure the permeability.
Ultrasonic Pulse Velocity (UPV) to measure permeability	☑	☑	• Used for measuring permeability in terms of paste quality loss to quantify the deck soundness.	The lab and field instrumentation had been developed and tested for rapid processing of UPV measurements. The technology is ready for implementation with most recent instrumentation, such as dry contact transducers.

4 NDE TECHNOLOGIES AND IMPLEMENTATION TO SUPPORT BMS ACTIVITIES

4.1 TWO-TIER INSPECTION PROCESS

MDOT bridge management decisions are initiated through the statewide scoping process. The data acquired during this process is the basis for program development. Once, the bridges included in the program are identified, further data is acquired for project scoping.

The following NDE technologies are identified as suitable for data collection during statewide and project scoping based on expert presentations and the subsequent discussions.

Table 4. Field Implementation Ready NDE Technologies

Technology	Application
Ground Penetrating Radar	Map steel reinforcement details. Map post-tensioning steel duct locations. Map concrete delamination in the presence of moisture. Map deteriorated concrete areas with possible corrosion vulnerability.
Infrared Thermography	Map shallow delamination in concrete & asphalt.
Impact Echo	Map shallow delamination in concrete. Measure component thickness.
LiDAR	Document bridge component and structural geometric information.
Phased Array Ultrasonic	Map deep delamination in concrete. Locate tendon duct and grouting defects.
Ultrasonic Echo (imaging)	Evaluate tendon duct grout defects.
Ultrasonic Pulse Velocity	Measure near surface permeability properties.
Ultrasonic Surface Waves (USW)	Evaluate modulus of elasticity of concrete.

The NDE technologies classified as field ready in Table 4 are not all created equal but have varying accuracies and defect detection reliabilities. However, all these NDE technologies can be useful within the bridge management process. An example data structure for effective bridge management is shown in Figure 1. This documents the early-age health of a bridge; as-built geometric and condition data can be collected shortly after construction. In-service data (later collected for planning maintenance, repair, rehabilitation, and/or replacement activities) can be grouped under a two-tier process: statewide and project levels as shown in Figure 1. Different NDE technology would be used based on defect detection reliability specified for each tier of condition data collection. Moreover, NDE technology reliability specified under each tier would be based on the associated risk. For example, the NDE data

for statewide scoping may be less reliable then the NDE data required for project level. Thus, NDE technologies, for example at the statewide level, based on speed of inspection may be.
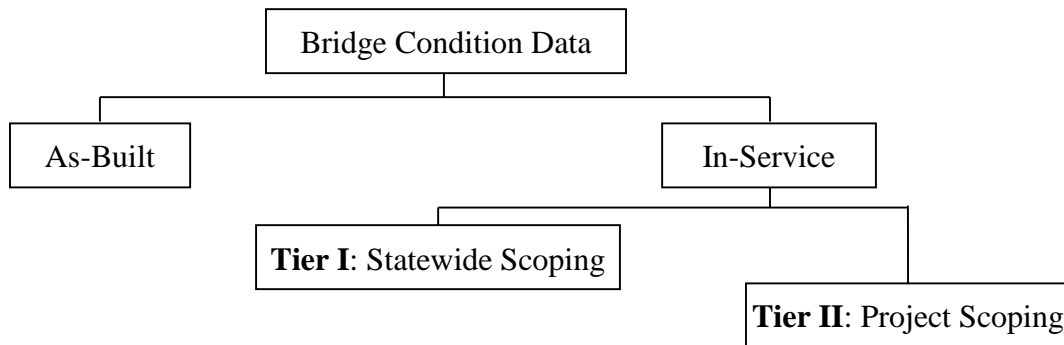

Figure 1. Two-tier data collection process

A more detailed description of NDE technologies that are appropriate for as-built and in-service bridge topological and condition data collection is presented in the following sections.

4.1.1 As-Built Topologic and Condition Data

Table 5 lists the NDE technologies and as-built condition data that can be integrated into the bridge management system for evaluating the 'at-birth' health of the bridge. At-birth health data is useful for developing proactive maintenance decisions (such as CPM). Further, documenting as-built details will greatly help in the interpretation of future condition data. Moreover, data can be collected before the bridge is opened to traffic, and NDE technologies capable of providing accurate and reliable data, though time-consuming in data collection, can be implemented.

Table 5. Field Implementation Ready NDE Technologies for Documenting As-Built Data

Technology	Application
Ground Penetrating Radar	Map post-tensioning steel duct locations. Map steel reinforcement details.
Impact Echo	Map component thickness.
LiDAR	Document bridge component and structural geometric information.
Ultrasonic Echo (imaging)	Evaluate tendon duct grout defects.
Ultrasonic Pulse Velocity	Measure near surface permeability properties and soundness of deck concrete.
Ultrasonic Surface Waves (USW)	Evaluate modulus of elasticity of concrete.

4.1.2 Statewide Scoping Data

In general, bridge deck condition controls the decision on "mix of fixes" strategies that are currently being implemented by MDOT. Hence, data collection can be limited to bridge decks. The data collection can be implemented using technologies with minimum impact on mobility. These NDE technologies that are implemented on mobile systems to operate at near highway speed often provide data at lower reliabilities. The technologies listed in Table 6 are suitable for statewide scoping data collection.

Table 6. Field Implementation Ready NDE Technologies for Statewide Scoping Data Collection

Technology	Application
Ground Penetrating Radar	Map steel reinforcement location and cover. Map concrete delamination with water intrusion. Map deteriorated concrete areas with potential corrosion environment.
Infrared Thermography	Map shallow delamination in concrete.
Laser based Image Systems	Map surface defects of spall, patch, and cracking.

The data inputs for bridge management decisions are the delaminated, spall, and patched deck areas. As described during the workshop, Michigan exposure conditions favor implementing GPR to identify the presence of a corrosive environment for steel as well as the potential for delamination due to corrosion of embedded steel. Further, with the presence of moisture, GPR has the indirect capability to detect delamination.

Infrared thermography (IR) is also a technology for detecting shallow delamination. Measurement reliability of IR is low due to several limitations for its field use. Laser illuminated image systems are also being implemented to document pavement surface conditions; although, they were not discussed during the workshop. The GPR and laser based image systems for surface condition evaluation can be implemented during day or night while IR necessitates making measurements only during a specific time window of the day and under specific exposure conditions. In order to overcome the limitations inherent to each technology and to improve defect measurement reliability, an implementation of a combined technology of GPR, laser based image systems, and infrared thermography would be most appropriate for statewide scoping condition data collection on bridge decks. Additionally, the combined NDE technology is also capable of indicating the presence of a corrosive

environment and the potential for causing delamination due to steel corrosion. Thus, the collected data for statewide scoping is also suitable for developing deck deterioration models.

4.1.3 Project Scoping Data

Bridge scoping inspection is performed to collect condition data for repair and rehabilitation decisions. At this level, the accuracy and reliability of condition data is critical. For this reason, the use of NDE technologies that can provide accurate and reliable condition data needs to be specified. The decision in selecting the appropriate NDE technology, at this level, should also consider load path. A prudent approach would be to divide the bridge components into segments based on their significance to the load path (or rating), surface area or volume, or maintenance significance. For each segment, a single or a combined system of technologies listed in Table 4 can be specified considering associated NDE reliability.

4.2 NDE IMPLEMENTATION PROGRAM

It is envisioned that the goal is to incorporate NDE technology as part of scoping inspections in order to complement and enhance inspection process with accurate and reliable quantitative data. However, before introducing the implementation-ready technologies into inspection procedures, a strategy needs to be developed and applied that incorporates the following activities;

- Develop a specimen library from laboratory-fabricated specimens with embedded defects, field specimens with defects obtained from decommissioned bridges, and a list of in-service bridges on low-volume roads.
- Calibrate and validate NDE procedures on the specimen library.
- Conduct education and hands on training sessions with the recommended NDE technologies.
- Develop guidelines for field implementation followed by periodic revisions based on feedback from users and manufacturers.
- Develop and support an NDE operator certification program in partnership with an industry association such as the American Council of Engineering Companies (ACEC).

Most of these programs can be developed through State Highway Program Research. As new NDE or other inspection technologies become available for field implementation, the above steps again need to be followed before being introduced into inspection procedures.

5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 SUMMARY AND CONCLUSIONS

The goal of the workshop was to provide an overview of available and proven NDE technologies and the process of integrating the technologies into the bridge management system. The presentations focused on the NDE technologies that have been successfully evaluated under laboratory and field conditions. Further, the capabilities and limitations of each technology were discussed with respect to the intended applications. Based on the information received during the workshop and the expertise of the authors, a two-tier inspection process and a NDE implementation program are presented. The following conclusions are developed based on the workshop presentations and subsequent discussions.

1) NDE is an indirect measurement of physical features of a structure. The signal transmission is dependent on geometry of the structural component, properties of the structural material and environmental parameters. Since environmental parameters are variable depending on the time of the day and season, use of multiple technologies combined with expertise and experience is required to analyze and interpret the data collected in order to derive meaningful results. Further, intrusive investigations of the structure are needed in order to first calibrate the NDE technology.

2) GPR is applicable for evaluating deteriorated areas of concrete which are vulnerable for steel reinforcement corrosion. GPR can also be used to map concrete delamination depicted by the presence of a moisture layer. Michigan conditions favor using GPR for the above stated purposes. This GPR data will be useful for developing deck deterioration models. Limited applications of impact echo and phased array ultrasonic are also applicable for verifying the GPR results.

3) IR can be a supplemental technology to GPR as it heavily depends on the boundary conditions and exposure conditions.

4) GPR, combined with IR and laser based imaging systems, is applicable for obtaining deck condition data for statewide scoping.

5) GPR, combined with ultrasonic echo, is applicable for locating steel post-tensioning ducts and to identify grout voids.

6) Laser scanning (LiDAR) is applicable for documenting bridge component and structural topologic information.

7) Ultrasonic pulse velocity (UPV) and ultrasonic surface waves (USW) are applicable for assessment of concrete soundness and quality based on their near surface permeability, freedom from cracking, and modulus of elasticity.

5.2   RECOMMENDATIONS

The following recommendations are also developed in order to enhance awareness, build confidence, and develop a workforce for the effective implementation of NDE in the MDOT bridge management system.

1) MDOT needs to develop an action plan for a comprehensive NDE implementation program. The action plan needs to include the use of implementation-ready NDE technology and associated research needs. The action plan needs to describe the development of a systematic approach in the bridge management process for including the use of specific NDE techniques including expected results, performance measures, challenges and resource needs. The NDE implementation program outlined in Section 4.2 may be a part of the action plan.

2) MDOT bridge operations will greatly benefit by enhancing the partnership with the FHWA Long Term Bridge Performance Program (LTBPP). Rutgers University, Center for Advanced Infrastructure and Transportation (CAIT), is the principal agency of the LTBPP which indicated that a bridge cluster in Michigan has been identified for inclusion in the programs during its next five-year phase. A direct benefit of this partnership is to expose Michigan to NDE technologies utilized for condition documentation of the bridges on the LTBPP sample list, and utilize the data collected by the LTBPP for training and education. A specific application can be the use of the deck condition assessment robotic system on Southwest region bridges that will be assessed by a rapid IR system.

6 REFERENCES

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APPENDIX A: WORKSHOP PRESENTATION SUMMARIES

MR. MATTHEW J. CHYNOWETH – PRESENTATION SUMMARY

Mr. Matthew J. Chynoweth, P.E., Engineer of Bridge Field Services, discussed the current use of NDE for bridge condition assessment.

LIST OF TECHNOLOGIES

- Infrared Thermography (IR): FLIR T640 and FLIR T420
- Ultrasonic Testing (UT) Probe

IMPLEMENTATIONS

Field

Infrared Thermography

- Handheld FLIR systems are used to detect delamination on the deck surface and soffits.
- FLIR T640 is suitable for measuring concrete defects of less than 1 sq ft; whereas, the FLIR T420 is not.
- IR is currently being used in the MDOT Superior region, University region, and Metro region.
- Technology has been developed to a state of implementation at highway speed.

Ultrasonic Thickness Gauge (UT Probe)

- The UT probe is used to (1) measure wall thickness of hollow metal light poles to check if corroding from inside, (2) verify the soundness of anchor bolts that are intended to be reused in foundations, and (3) test the welds (flange and web welds) at fabrication plants.

STATUS

Infrared Thermography using the FLIR system is currently being implemented under field conditions. Jason DeRuyver and his group at MDOT are in the process of training the bridge inspectors to use the FLIR system. Guidelines for thermographic inspection of concrete bridges components and an online application (http://zlmoment.appspot.com) are also made available by the University of Missouri-Rolla under a pool-fund study. The online application with the current weather data advises on the timing of the IR scanning of a bridge at a particular location.

The UT Probe, also known as *Thickness Gauge*, has been successfully evaluated and is being implemented in the field.

RECOMMENDATIONS

Infrared Thermography with the FLIR system

In order to acquire reliable IR data on delamination of a bridge deck, the deck needs to be exposed to solar radiation for about 2 hrs. On the other hand, for the deck soffit IR inspection, a temperature gradient of at least 15°F is required. Further, wind speed also needs to be considered for obtaining accurate results, because wind cools the surface, leading to a false IR image.

Ultrasonic Testing (UT) Probe/Thickness Gauge

Training is essential prior to using the device, reading signals and interpreting the results.

DR. HERBERT WIGGENHAUSER – PRESENTATION SUMMARY

Dr. Herbert Wiggenhauser from German Bundesanstalt für Materialforschung und –prüfung: that translates as Federal Institute for Materials Research and Testing (or commonly known as BAM) presented the technologies listed below. Since 1999 Dr. Wiggenhauser has been the Head of Division for Non-Destructive Testing in Civil Engineering.

LIST OF TECHNOLOGIES
- Acoustic Emission (AE)
- Impact Echo
- Ground Penetrating Radar (GPR)
- Ultrasonic Echo
    - Dual Probe
    - Array Technique
    - Phased Array
- Ultrasound with Array Technique
- Infrared Thermography

Commonly Used Technologies

- Electro-Magnetic Method: Radar
    - Analysis of reflected waves from interfaces of materials with different dielectric properties
    - Antenna: 500 MHz and 1.5 GHz
- Ultrasonic Pulse Echo Measurement System
    - Pulse Echo is commonly used rather than linear array
    - Shear wave transducers: frequency = 50 kHz
    - Measurement head: 24 point dry contact transducers
- Impact Echo
    - Frequency range: 1Hz to 40 kHz
    - Frequency spectrum analysis: multiple reflections recorded in time domain
- Scanner systems with Ultrasonic Probes
    - A frame with suction cups is used to mount the scanner, for upside down use, to the deck soffit.

o The time for ultrasonic scanning is much longer than the time required by Radar.

IMPLEMENTATIONS

Lab

<u>Impact Echo</u>

- The traditional implementation of Impact Echo to analyze signals in the frequency domain has been modified by BAM to Impact Echo imaging (3-D image representation). The BAM process is to obtain a B-scan and C-scan of the specimen similar to scans obtained using the UT technique. The scanning procedures eliminate the need for interpreting the frequency peaks in order to detect the flaw. The images enable the operator to distinguish between a point event (most likely false reading) and a reading which is similar as neighboring measurements.

- Tendon ducts: The research studies recognized a shift in the back side echo at locations of un-grouted tendons. Predefined defects in tendon ducts were located very precisely in the laboratory by the shift in the back side echo.

- Geometry Effects: On a surface with nearby edges and internal retro-reflective edges, additional peaks in the impact-echo frequency analysis appear. These are only due to the limited size of the surface. These effects can only be separated from true IE signals through scanning measurements.

<u>Phased Array UT</u>

- The synthetic aperture focusing technique is used to detect the flaws in a test specimen. Several test specimens with defects were successfully tested in the laboratory.

- The device makes measurements along a line on the specimen. The 3D data that is obtained from that line measurement is divided into B-Scans and C-Scans. These scans provide the 2D images (point-by-point summary) of the specimen across the section of the line measurement.

- Continuous 3D measurements will provide more accurate images showing information of the defects in the test specimen. However, the phase shift needs to be evaluated manually. The automation of this process is still under research development.

- Deep delaminations can be accurately located and directly characterized. However, the shallow delaminations could be indirectly detected for the built-in defects only, because of missing back-wall reflections and/or multiple reflections (i.e., phase shift).

GPR and Ultrasonic Echo

- A large concrete slab was used for validation and reference. Three honey-combs were generated in to the slab. The slab was then tested using Impact Echo and GPR. Contrary to the expectations, the honey-combs were not detected with GPR. Ultrasonic Echo (Ultrasonic Imaging) of 55 kHz was used. Densely spaced grid measurements and thorough data analysis could locate two of the honey-combs.

Ultrasound Transmission

- This technology is used to measure asphalt porosity using the through transmission technique (longitudinal wave probes, $f = 100$ kHz) and echo technique (longitudinal wave probes, $f = 85$ kHz). To reduce the noise and other effects in the signal, the "array technique" (longitudinal wave probe, $f = 100$ k Hz) was preferred.
- The Ultrasound with Array Technique with shear wave probes, $f = 50$ kHz, was successfully used to identify the extent of porosity in asphalt. This is achieved by measuring the variation in the back-side signal.

Field

Impact Echo

- Used to measure thickness

Phased Array UT

- Applied for detecting delamination in concrete bridge decks
- Deep delaminations could be accurately located and directly characterized. However, the shallow delaminations could not be directly detected under field conditions.

Infrared Thermography

- The technology is explored for detecting shallow delaminations in concrete decks. Further studies are not being conducted on this technology, because it is a well-developed technique

and suitable for field implementation. An ASTM standard D4788 – 03 is also available for this purpose.

- IR is an imaging method that generates images for visual analysis, and can be used easily for remote sensing providing real time results. However, quasi static measurements are made; thus, the thermal time history needs to be considered before making inferences. The operator needs to be experienced.

GPR, Impact Echo and Ultrasonic Echo

- Field application was completed on a segmental concrete box bridge with post-tensioning to obtain a condition data of the webs and the deck slab interior. The length of the bridge was 400 m and was post-tensioned in longitudinal and transverse directions. The bridge was constructed in 1966 and decommissioned in 2004 because of condition. A surface area (10mx4m) of the bridge deck was investigated using GPR, Impact Echo and Ultrasonic Echo technologies.

- The GPR data acquired from top and underside was superimposed to obtain a visual of the deck interior. Duct investigation with Ultrasonic Echo was also successful even in identifying minute defects.

- The GPR and Ultrasonic Echo were successful in locating the top and bottom reinforcement, tendon duct locations, and defects in the tendon ducts. Also, Impact Echo was successful in detecting the thickness of the deck. The tendon duct locations were indicated by an apparent shift of the Impact Echo signal, but grouting defects in the tendon ducts could not be detected. The challenge was that the tendon ducts were not parallel to the deck surface.

- Data-fusion of GPR and Ultrasonic Echo was explored. GPR is capable of identifying any metal (ducts) inside concrete but is unable to look inside the metal (ducts). On the other hand, Ultrasonic Echo signals can penetrate through the metal (ducts). Thus, in bridge investigations, the tendon grout defects were evaluated using the combination of GPR and Ultrasonic Echo.

STATUS AND RECOMMENDATIONS

Primarily visual inspection is used for bridge inspection. NDE is specified only for special cases where damage cannot be identified or accessed using visual inspection.

Acoustic Emission (AE)

AE is used for detecting cracking, friction between surfaces during crack movement, and expansion of a corroding rebar. AE applications for detecting concrete delamination in field haves not shown successful results. However, AE application for detecting concrete delaminations in a laboratory where those effects can be localized has been successful.

Impact Echo

Lab tests were successful in identifying predefined tendon duct grouting defects. However, using Impact Echo in the field to detect tendon duct grouting defects is not recommended, because controlled lab conditions could not be achieved. Only a measurement of thickness with Impact Echo is recommended.

A 2D time-frequency analysis technique is used to detect delamination in bridge decks using Impact Echo. Here the pattern of the signal is investigated and compared with predefined signatures to evaluate the severity of delamination, such as good condition (intact or no debonding), fair (initiation of debonding), poor (progressed debonding), and severe (fully debonded).

Phased Array UT

Phased array Ultrasonic Testing (UT) for testing metals is well established. The Phased Array UT technique for concrete is a sampling phased array rather than electronic phased array. The measurements require 3 seconds for one B-Scan. The Phased Array UT technique for detecting delamination in concrete bridge decks showed better success than Impact Echo.

The capabilities include real-time imaging of slab interior, accuracy, precision, and ease of use; whereas, the limitations are high initial cost, blind zone near the surface, and a slow data acquisition process because of manual testing using dry contact sensors.

The technology is suitable for in-depth investigation of a limited part of a component.

GPR and Ultrasonic Echo

The GPR or Ultrasonic Echo could detect a honey-comb if the defect is parallel to the surface where waves can reflect. Also, the defects can be detected if the defect surface is highly irregular, or if it consists of large voids which acoustic waves could not propagate. However, there is a need for additional research in this area.

For a RC slab containing heavy reinforcement and defects, Impact Echo, Infrared, and GPR all were not able to detect the defects; whereas, defects could be identified and located by using Ultrasonic Echo (ultrasound imaging). Further, Ultrasonic Echo could detect the defects with high reliability in slabs with low reinforcement. It is the recommended NDE method to detect defects, such as honeycombs (voids).

Ultrasound with Array Technique

The ultrasound with through transmission and array technique is recommended for the asphalt porosity assessment. Radar (GPR) could not be used reliably to assess asphalt porosity as the dielectric constant of the medium is not sensitive enough to porosity.

Infrared (IR) Thermography

The technique is very much dependent on ambient conditions and the time of measurement. Thus, repeated measurements of the same defect need to be imaged at different times and different exposure histories. It is further recommended to consider the IR result as a potential, and verify the defect using other methods, such as sounding, GPR, etc.

IR thermography was used reliably to detect asphalt overlay delamination on a concrete deck by allowing the deck to absorb heat under solar radiation (passive thermography) and by artificially heating the surface using (active thermography). The IR image time histories are then generated and analyzed in time domain and frequency domain. Another analysis option which is being researched is to analyze the selective reflectivity from the heated deck surface.

General Comments

Proactive NDE is always the best approach to test the construction quality immediately after construction and identify any imperfections that can affect service life of a component. Further, highly accurate NDE techniques are not necessary, as long as the method is accepted as a QC method and the inspectors trust the technique is able to detect the flaws.

There are several successful NDE applications. However, these applications at this time are lacking in standards. NDE is not implemented within the scheduled inspection process; it is rather requested only on exceptional bridge inspection cases.

For successful NDE implementation in bridge management, the agency needs to invest in

(1) **experts,**

(2) **purchasing a pool of expensive equipment,**

(3) **integration of techniques into routine tasks,**

(4) gaining experience through routine applications, and

(5) **training/education.**

To move directly from *newly developed NDE methods* to *practical use* is not preferred. Rather, the steps that need to be followed are:

(1) **lab verification,**

(2) **pilot field application,**

(3) **training/education, and**

(4) **developing guidelines/certifications** before incorporating into field practice.

RELIABILITY OF NDE DATA

Impact Echo

When testing a specimen with finite geometry using Impact Echo, a large amount of disturbance is created due to the reflection of waves from the corners as well as from the surface (retro reflected at corners). For example, if a compression wave is created on the specimen, about 70 % and 23 % of the energy is converted into the surface waves and shear wave respectively. The compression waves, which are the signals of interest, receive the remaining 7 % energy. Hence, boundary effects need to be considered.

The method is reliable if used for the correct purpose, such as thickness measurement preferably of a large slab. Do not push the technique beyond what it is designed for. The thickness results obtained are very reliable; this was proved by using a test specimen with varying thickness and obtaining a 3-D plot of it by obtaining several single thickness measurements (~40,000).

Phased Array UT

When a mechanical wave is reflected from a soft surface, there is a phase shift observed in the data; whereas, if the wave is reflected from a hard surface, the phased shift is not observed.

Measurements are highly repeatable and reasonably accurate. However, placing the array over the edge of the delaminated area may lead to ambiguous results. This becomes challenging because the boundaries of the delaminated are not visually defined before implementing the technology.

If a prismatic test specimen is tested from the sides, then 94 % of the time flaws are detected and accurate characterization occurs at 92 %. When the specimen is tested from the top, then flaw detection decreased to 92 % and characterization to 91 %.

The phase array system is reliable. Repeatable data is obtained, even if the testing is performed under different conditions.

Infrared Thermography

Active thermography (i.e., heating the deck surface using large heaters) is more reliable than the passive thermography (i.e., allowing the deck to be heated up by solar radiation).

DR. JEROME P. LYNCH – PRESENTATION SUMMARY

Dr. Jerome Lynch is the director of the Laboratory for Intelligent Systems and Technologies at the University of Michigan.

LIST OF TECHNOLOGIES

- Narada Wireless Sensor with Amplified Radio
    - Developed by the University of Michigan in 2005 (Cost: $175 per unit; Energy source: 5AA batteries; Active power: 200mW; Data rate: 250 kB/s; Sample rate: 100 kHz)
    - 16-bit ADC resolution on 4 channels capable of acquisition rates (100kHz)
    - Equipped with a radio that allows interoperability with other sensors. Further, the radio is amplified by power amplifier circuit designed to achieve 10dBm output gain and a communication range of 700m
    - Includes an embedded processor with algorithms to perform sensor-based data processing – implements *rain flow counting* algorithms by Downing and Socie (1982)
- Communication Base Station
    - Designed to communicate with all the sensors on the structure and transfer data to the repository (data storage location)
    - Consists of single board computer that runs Linux, a cellular modem to transfer data, a lead acid rechargeable battery that is charged using solar panels, and a transceiver that communicates with all the Narada wireless sensors on the bridge
- Cyber Infrastructure (Internet-enabled cyber environment.)
    - Combines data with structural analytical tools for information discovery

IMPLEMENTATIONS

Field

Narada Wireless Sensor Implementation in California

- 28 Narada wireless sensors were installed on the Carquinez Bridge located in Vallejo, CA, to measure the seismic performance of the bridge. The bridge length is 1056 m with main span of 728 m and was constructed in 2003.

- The bridge consists of steel orthotropic box girders deck, hollow concrete tower legs and prestressed link beam.
- The 28 sensors collect data from following 81 channels:
  - 19 **tri-axial accelerometers** measuring the main deck,
  - 3 **tri-axial accelerometers** measuring vibrations at tower top,
  - **A wind vane, anemometer and temperature sensor** in three locations,
  - 3 **string potentiometers** to measure deck movement relative to tower.

Narada Wireless Sensor Implementation in Michigan

- 31 Narada wireless sensors for fatigue assessment are installed on the Telegraph Road Bridge located in Monroe, MI. The bridge was constructed in 1973.
- **strain gauges** were installed at various locations of the pin and hanger connection to identify states of strain in the hanger plates, to track fatigue accumulation, and to calculate moments due to corrosion and locking. From the measurements, a compressive-tensile strain difference in the pin and hanger plate was observed. That strain difference may be due to a flexural moment. However, the flexural moment could be caused either because of locking in the hanger plate or because of bridge skew, which requires further investigation.
- The sensors monitored **strains and temperatures along girders at deck level** and correlated with deck crack zones.
- They measured **strains** along typical cross-sections and evaluated composite action of the superstructure.
- The 31 sensors collected data from the following 57 channels:
  - 15 **uni-axial accelerometers** for modal analysis and model updating,
  - 36 **strain gauges** (24 for beam strain profile and 12 for link plate strain), and
  - 6 **thermistors** to assess temperature load and for thermal corrections.

STATUS

Narada Wireless Sensor – Accelerometer

The sensors are powered using small solar panels and are magnetically mounted on the steel girders.

Narada Wireless Sensor – Strain Gauge

The sensor consists of a metal foil strain gauge that is physically bonded using epoxy. The sensors are powered using small solar panels. The area for the strain gauge is sanded first, and then the strain gauge is bonded and covered using powder paste protection to make the respective area waterproof.

Based on the Finite Element Model of the bridge, the strain gauges were mounted on two critical pin and hanger plates (i.e., with high levels of stress).

The strain is measured through the depth of a girder web as well as in the deck. These strain measurements were used to determine the location of the neutral axis and evaluate the composite action. The automated data processing in the sensor network compares the calculated neutral axis with the theoretical axis location. The location of the neutral axis is considered as a good indicator of deck/girder deterioration.

Cyber Infrastructure – Data Processing Clients

Several data processing clients were developed that automatically extract the modal characteristics. Although modal characteristics are not for health monitoring purposes (because they are not a good indicator of bridge deterioration), they play a very important role in the Finite Element model updating process that plays a major role in structural health monitoring strategies.

A data processing client was developed that extracts the modal data from the repository (database), automatically generates the ADINA input file for the bridge, runs the FE analysis, and then performs FE model updating using the sensor data that is also embedded in the repository. The FE model updating process is performed frequently so that the FE model modal characteristics match closely with the actual bridge. The FE model updating is performed considering 4 structural parameters: (1) Mass of deck overlay, (2) Strength of concrete in deck slab, (3) Thickness of concrete, and (4) Stiffness of springs simulating composite action.

Other data processing clients automatically generate the mode shapes of the bridge using the automatically extracted model characteristics. The frequency domain decomposition (FDD) is performed within the sensors as well as the repository.

The sensors at the pin and hanger connection are embedded with data processing clients that perform the *rain flow counting* and plot histograms of the strain response. The peak strains

are identified and processed using models that determine cumulative fatigue damage in the components.

RELIABILITY ANALYSIS

Reliability analysis is performed for all the collected data. The capacity that is embedded within the structure is compared with the estimated demand from vehicle loads, thermal loads, etc. The capacity is measured by structural response from the instrumentation; whereas, the demand is measured considering the actual traffic loads and temperature loads. For example, consider the evaluation of composite action using the process for determination of the neutral axis location. Limits on the location of neutral axis were established, and the measured location using sensor data was subjected to a reliability approach to determine how well it falls within those limits. The FORM (First Order Reliability Method) reliability index is calculated as shown below (Eq. 1) and is used in the decision making process.

$$\beta = \beta(t) = \frac{\mu_{d\,(intended)} - \mu_{d\,(measured)}}{\sqrt{\sigma^2_{d(intended)} + \sigma^2_{d(measured)}}} \tag{1}$$

where: *"measured"* is providing the capacity of the structure, and *"intended"* is from the demand side of the structure.

For the bridge decks, the total deck response and temperature are considered under *measured,* and dead load and live load are considered under *intended/computed*.

The influence lines of the bridge are developed for each sensor location and stored in the repository. The influence lines are combined with the Weigh-in-Motion (WIM) data to obtain the demand that is deployed on the analytical model to obtain the expected response of the bridge. The expected response of the structure, in the form of probability density function, is mapped with the sensor data to estimate the reliability index for that corresponding component (essentially the sensor location on a component).

DR. ALI MAHER – PRESENTATION SUMMARY

Dr. Ali Maher of Rutgers University is the director of the Center for Advanced Infrastructure and Transportation (CAIT). He is the principal investigator of the FHWA project on Long-Term Bridge Performance Program (LTBPP).

Long-Term Bridge Performance Program (LTBPP)

The LTBP program serves as the national platform for (1) improving bridge health and effective management, (2) standardizing and enhancing inspection techniques, and (3) enhancing design, construction, preservation and operation practices from data-driven tools.

The research approach included (1) Defining bridge performance, (2) Determining high priority performance related issues, (3) Designing an experiment for identifying bridges for data collection, and for referencing the cluster concept, (4) Providing data analysis (portal platform), and (5) Verifying data collection protocols using the pilot program. The bridge performance related priorities were identified from the focus group interviews with 15 state DOTs, geotechnical issues workshop, state coordinators, and the input from a stakeholder advisory board and expert task group (ETG) committees.

The high priority topics considered were (1) Untreated/Treated concrete bridge decks, (2) Bridge deck joints, (3) Bridge bearings, (4) Coatings for steel superstructure elements, and (5) Prestressing strands. For the design of experiments, the primary experimental variables were identified from the intrinsic characteristics such as age, main span length, bridge type, etc.; and external characteristics such as, climate, ADTT, state's preservation policy, etc. In the next step, for each high priority topic, an experiment was designed by allowing some of the primary experimental variables to vary while keeping the others constant. Afterwards, for the experiment designed under each high priority topic, bridge clusters were developed that fit into that experiment. Further, corridor candidates were identified for each of the high priority topics by considering the experimental variables that are neither *constant* nor *variable*, such as state policies, etc. Finally, clusters of candidate bridges were developed by overlapping the bridge clusters and corridor candidates on the U.S. map.

Michigan is one of the test beds where the LTBPP needs to be implemented. The bridge clusters identified from the first step of design of experiments were around 5000-6000 bridges. After overlapping those bridge clusters with the corridor candidates through Michigan, clusters

of candidate bridges were developed that totaled to around 400-500 bridges. This population of bridges was considered as the sample that is statistically significant to provide reasonable judgments for the total population of 5000 to 6000 bridges.

The clusters of candidate bridges were again evaluated to identify a *reference bridge* that closely represents the characteristics of the nearby candidate bridges within that cluster. The *reference bridges* from all the clusters will be used for visual inspection, non-destructive evaluation, global testing, materials testing, and long-term data collection under the LTBP program. For example, the clusters of candidate bridges (500-600 bridges) in Michigan may be reduced to around 10-20 reference bridges. The information obtained from the evaluation of a reference bridge could be used to infer the information of other nearby candidate bridges in that particular cluster.

The data that will be obtained from the evaluation, testing and long-term data collection under the LTBP program will be stored in a *Bridge Portal*, which is a repository. The data infrastructure platform of *Bridge Portal* was developed by Siemens Cooperation under a LTBP program sub-contract. All the Meta data that will be made available by the *Bridge Portal* could be used for (1) developing deterioration models and life-cycle cost models, (2) forecasting, and (3) bridge management at program and network levels.

DR. TESS AHLBORN – PRESENTATION SUMMARY

Dr. Tess Ahlborn of Michigan Technological University presented the findings of the USDOT project on bridge condition assessment using remote sensors. This presentation included an evaluation of state of the practice optical, laser and thermographic imaging systems for bridge condition assessment.

LIST OF TECHNOLOGIES

- Ground Penetrating Radar (GPR)
- 3D optical bridge evaluation system (3DOBS)
- Bridge Viewer Remote Camera System (BVRCS)
- GigaPan
- Infrared Thermography (Thermal IR)
- Synthetic Aperture Radar (SAR) 2D and 3D
- Digital Image Correlation
- LiDAR

STATUS

Ground Penetrating Radar (GPR)

The cost is very high and requires traffic disruption; thus it is used rarely.

3D optical bridge evaluation system (3DOBS)

The 3DBOS acquires several images of a bridge at highway speed. The processing of the images by stereo overlapping creates high-resolution 3D image for spall detection and characterization at 2mm resolution. The 3DBOS data is fed into the ArcGIS analysis software for detecting the percent spalled area using its automated spall detection algorithm.

The 3DOBS also consists of a digital elevation model that can zoom onto the locations, such as wheel path, on the 3D image. Thus, the International Roughness Index (IRI) could also be evaluated for different wheel paths. However, the technology currently works on near-highway speed, and investigations are in progress to achieve highway speed data collection.

Bridge Viewer Remote Camera System (BVRCS)

This technology is similar to the street-view style photography of Google Maps®. It captures more information about the images as images of a component are acquired from different angles. The images are finally stitched using stereo overlapping patterns to obtain a complete rendering of the bridge including information at critical locations.

GigaPan

This technology is being used to obtain high resolution photo inventories of bridges. It consists of a DSLR camera mounted on a rotating arm that takes a series of images. These images are stitched together to provide a high-resolution photo of the complete bridge. The bridge image could be enlarged to obtain the component view with about 5mm resolution. The resolution is still being investigated for increasing to 1mm.

Infrared Thermography (Thermal IR)

The passive thermal IR is implemented on the bridge deck to detect delaminations, which requires the bridge deck to be heated up under the passive solar radiation. The technology is ready for field implementation. There is also an ASTM standard for deployment of this technology. The data can be processed using Microsoft Excel to identify the delaminations using the thermal images.

The active thermal IR is essential for the underside of the bridge deck or the fascia-wherein sunlight cannot reach. Here, the component needs to be heated actively to enhance thermal IR output. Currently, the implementation of active thermal IR is limited to lab applications on small specimens.

Synthetic Aperture Radar (SAR) 2D and 3D

The technology is used for detecting spall and delamination. The technology can also detect subsurface defects. The instrument consists of radar equipment and a lateral translator. This is different from GPR as low cost components are used with an ultra-wide band system and a single antenna to assist the resolution/penetration tradeoffs.

Digital Image Correlation

This technology has been implemented in Aerospace engineering. However, its implementation was performed in a controlled environment. There was limited implementation

of this technology to detect load induced stresses in a bridge; however, several environmental factors affected the accuracy of data. Research is in progress to bring this technology into regular bridge assessment.

Benefits that can be drawn from this technology are:

1) Remotely captures deflection, and
2) Measures strain field and vibrations.

Limitations of this technology are:

1) A significant amount of error induced by wind and traffic flow, and
2) Suited only for controlled environments in the current state.

<u>LiDAR</u>

The LiDAR is usually used for surveying, measuring the as-built construction, etc. For the NDE, the system is used to measure the surface condition such as percentage area of spall, along with the location and volume of spalls using a composite intensity image of the bridge deck. Using LiDAR, the global features (such as static deflection, high load hits, etc.) can also be determined. However, the technology is time consuming and costly.

RECOMMENDATIONS

<u>3DOBS, BVRCS, and GigaPan</u>

1) These technologies require low cost components, can be deployed rapidly, and consume a limited time for collecting data; thus, they can be deployed to detect the percentage area/volume and location of spalls, and the International Roughness Index (IRI). They can also begeo-tagged and provide a very high-resolution photo inventory.
2) The automation of the data analysis is required. Further, the data storage capability, for the high resolution images, needs to be considered.
3) The technologies are near-ready for field deployment.

<u>Infrared (IR) Thermography</u>

1) The technology is being deployed at near-highway speed (45mph).
2) The IR has equal reliability to chain dragging in detecting the delaminations. Further, the data is 60-70 % accurate with respect to actual delaminations verified by bridge coring.

3) The technology is field ready at near-highway speed; however, a manual for its deployment is required.

Synthetic Aperture Radar (SAR) 2D and 3D

1) The technology can be adapted for use on a moving vehicle using a *lateral translator*.

2) The data collection time and the data processing and user interpretation needs to be considered.

3) Correlations of deviation in obtained data with actual defects need to be investigated for subsurface defects. This will allow identification of the defects accurately. Moreover, development of this technology to 3D is necessary to compete with commercially available 3D GPR.

Digital Image Correlation

1) This is not ready to be deployed in the field without significant technology improvements such as gyroscopic compensation, rigid mount, etc.

2) Complementary technologies such as laser vibrometry, LiDAR, etc. should be considered along with the Digital Image Correlation.

LiDAR

1) LiDAR access range is about 55-56 ft. Thus, for scanning the bridge deck, the LiDAR needs to be setup at multiple locations.

2) The technology needs to be appropriately integrated in the bridge condition assessment framework.

3) Mobile LiDAR that is under implementation in other industries can be considered as a practical future platform in bridge assessment. However, Mobile LiDAR needs a manual for deployment in bridge condition assessment process.

4) The point cloud density of LiDAR needs to be considered for collecting bridge condition assessment data.

DR. NENAD GUCUNSKI – PRESENTATION SUMMAR

Dr. Nenad Gucunski is the chair of the civil engineering program at the Rutgers University. He is the director of CAIT's Infrastructure Condition Monitoring Program (ICPM) and the principal investigator of the automated nondestructive evaluation and rehabilitation system for bridge decks.

OVERVIEW

Almost 80 % of rehabilitation cost spent on bridges in the country is on bridge decks. The annual rehabilitation cost spent on bridge decks nationally totals to about $5 billion. This expenditure can be reduced by changing the way of evaluating the bridge decks and providing timely rehabilitation of the bridge decks.

The topic was focused on bridge deck evaluation and the means of improving using automation. Also discussed were customized bridge deck rehabilitation procedures.

TYPES OF BRIDGE DECK DETERIORATION OF INTEREST

- Deck Delamination
- Rebar Corrosion
- Concrete Degradation
- Deck Cracking (Vertical)

LIST OF TECHNOLOGIES

- Electrical Resistivity
  - To detect the signs of corrosion initiation
  - To detect the potential for corrosive environment
- Half-Cell Potential
  - To detect the corrosion activity
  - To detect the likelihood of active corrosion
- Ground Penetrating Radar (GPR)
  - To detect the potential for corrosive environment

- To detect delamination at its initial stages, but only in cases where the delamination is induced due to corrosion (i.e., detect the likelihood of delamination in highly attenuated areas)
  - To detect the likelihood of concrete deterioration
- Impact Echo
  - To detect delamination during early and late stages
- Infrared Thermography
  - To detect delamination near its late stages
- Chain Drag/Hammer Sounding
  - To detect delamination near its late stages
- Ultrasonic Surface Waves (USW)
  - To detect the concrete degradation by identifying the modulus degradation
- Moist Scan Survey (Relative Moisture)
  - To detect zones of moisture concentration

STATUS

Electrical Resistivity

The technology is being deployed in the field. The available literature defines the relationship between resistivity and corrosion rate. The corrosion rate is classified as (1) very high, (2) high, (3) moderate-low, and (4) low.

Recent studies show that 40 kOhm-cm is the threshold resistivity between a corrosive and non-corrosive environment. Low resistivity indicates a highly corrosive environment and vice-versa.

Half-Cell Potential

The technology is being used in the field, and an ASTM standard (ASTM C875) is also available.

Moist Scan Survey (Relative Moisture)

This technology is not used on regular basis. It uses micro-wave technology to identify the zones of moisture concentrations. Currently, the technology is deployed to provide relative moisture measurements, i.e., low moisture or high moisture.

Research is in progress for calibrating the equipment to obtain absolute moisture content measurements.

Impact Echo

This technology is being used in the field. The data obtained is highly accurate and was validated by identifying delamination using a coring operation.

Ground Penetrating Radar (GPR)

This technology is being used in the field. It is deployed on the bridge deck using ground coupled antenna as well as air-coupled (horn) antenna. The air-coupled GPR survey is conducted at a speed of 30mph.

The ground-coupled GPR is more advantageous as it provides higher quality and detailed data. The use of ground-coupled GPR is recommended. However, air-coupled GPR could be deployed to obtain an estimate of delaminations on a roadway network.

The materials that represent the bridge deck makeup need to be considered, and their respective dielectric constants (K^*) should be known. Also, the presence of moisture can significantly increase the dielectric constant and reduce penetration.

The concrete with voids will have less attenuation, and thus the dielectric constant is low compared to dense concrete. The attenuation in this case indicates possible change in concrete quality, but it may not be detectable. However, for water/chloride filled voids and contaminated concrete, the attenuation is significantly high (i.e., chlorides significantly more conductive than concrete) and thus the dielectric constant is high compared to concrete. The attenuation in this case indicates significant change in concrete quality and can be detected easily.

The data provided as an attenuation map needs to be corrected for depth of rebars. The depth that is considered in this case includes approximate thickness of overlay and original deck concrete cover. This allows generating a map of current concrete cover that can be used to identify potential locations of deterioration.

Ultrasonic Surface Waves (USW)

This technology is being implemented in the field to detect concrete quality/degradation. Here the velocity of surface wave propagation is measured and is directly correlated with the

modulus. The device can obtain several measurements in a relatively small amount of time, ranging from 100 to 120 measurements per hour.

During the field implementation of this technology, it was observed that the modulus of elasticity has high variability in bridge decks. This phenomenon was observed in newly built bridge decks. Variability in the modulus cannot be a direct indication of bridge deck deterioration. To assess bridge deck deterioration using the modulus of elasticity measurement, periodical measurements can be performed, and the changes can be related to changing deck condition.

<u>Additional Information</u>

- The typical inspection rate with the use of NDE technologies presented ranges from 1000 to 1500 sq. ft per hour.

- GPR and Electrical Resistivity measurements show good correlation. This is because the same factors influence the measurements with these two technologies.

- GPR is not useful to identify delamination when the cause of delamination is not rebar corrosion. Impact Echo can identify the delaminations with some uncertainty.

- The quantitative nature of NDE can be utilized to reduce inspection subjectivity and enable an objective rating of bridge decks. Here, the bridge deck is divided into several sectors, and the rating is based on the percentage of delamination, percentage of corrosion, and percentage of concrete degradation. The overall condition rating of the bridge deck with respect to delamination, corrosion, and degradation is calculated independently from NDE measurements. Finally, a combined rating for the bridge deck is obtained by averaging the three overall ratings (i.e., delamination, corrosion, and degradation ratings). The combined condition rating can be used to develop deterioration progression models. Further, individual overall ratings for delamination, corrosion, and degradation can be used to develop distress based degradation models.

- Automated NDE is required because of the size and count of bridge decks that need to be evaluated.

- In the future, continuous health monitoring of the bridge decks shall be performed in order to deploy preventive maintenance activities. To achieve this, a Robotic system is developed that includes the following technologies: (1) GPR arrays, (2) Acoustic arrays,

(3) Resistivity (Wenner) probes, (4) Laser scanners, and (5) a Panoramic (360°) camera. The main components of the Robotic System are a global positioning system (GPS), a wheel encoder for distance measurement, and an inertial measurement unit (IMU) working as gyroscope.

- Implementing an integrated approach of early distress detection and proactive rehabilitation will articulate NDE benefits.

DR. HALUK AKTAN – PRESENTATION SUMMARY

Professor Haluk Aktan is the director of Center for Structural Durability at Western Michigan University. His presentation was on NDE techniques for early age assessment of concrete durability. He also discussed the methodology of evaluating NDE measurement reliability.

LIST OF TECHNOLOGIES

- Resistivity Meter (Wenner Array Probe)
  - Concrete resistivity is considered as an electrical indicator of its permeability.
- Porosiscope (Figg's Device)
  - For measuring near surface air and water permeability in concrete
- Ultrasonic Pulse Velocity (UPV)
  - Used as a predictor of permeability and concrete soundness

EARLY AGE QUALITY ASSESSMENT

Early age health assessment of RC bridge decks will be useful in establishing a continuous quality improvement tool. The tool could assist in understanding the structure, materials, and construction quality, so as to improve the design procedures, material specification, and construction procedures. The need for an early age health assessment tool is expressed by the fact that current practice is not able to control or attain most durability indices, such as cracking, crack width, permeability, time to corrosion, delamination, time to spall, etc. Nevertheless, there is a definite need to develop measures for assessing the overall quality of newly constructed concrete decks.

The construction processes and material specifications involved in the bridge deck replacement are much regimented. However, significant variability exists in the performance of RC bridge decks constructed using the same materials and construction processes. In order to understand the reasons for the variability and for controlling the quality of bridge decks, measures are being developed. In 1992, the Florida Department of Transportation (DOT), followed by other DOTs, identified permeability of concrete as the performance measure.

Generally, the methods used to test the permeability have drawbacks: they are destructive; time consuming, and the variability of their results are high. Concrete permeability is usually determined by taking a core from the bridge deck. Thus, measurements can only

represent the permeability of the core location. As a complete smeared measure for a bridge deck, the *Soundness* is a better representation. To accomplish this, permeability and Ultrasonic Pulse Velocity (UPV) measurement technologies had been integrated to assess the distributed durability of the concrete deck. Here, a fundamental relationship between permeability and UPV was identified. The exception is that UPV is affected by properties of concrete ingredients such as aggregate; thus, cannot be used as an absolute measure, rather it is a relative measure. Considering these aspects, a UPV test has been developed to measure the soundness of RC bridge deck based on the permeability measure.

IMPLEMENTATIONS

Lab

UPV measurements (V_s) are taken on standard concrete specimens prepared during the deck placement. V_s is considered as the benchmark UPV. Following the completion of deck curing, the UPV is measured in the field (V_f). The soundness is measured by a parameter called the Paste Quality Loss (PQL). PQL is a measure of the reduction of soundness between the standard specimens and the deck concrete. PQL representation is shown below based on the reduction of UPV.

$$PQL = \frac{\alpha(V_s - V_f)}{V_s} \qquad\qquad (2)$$

where: α is the statistical distribution factor and is given by $\alpha = 0.954 / P_F$; P_F is the probability of V_f to be between $\pm 2\sigma$.

UPV measurements were performed on the following specimens: (1) Standard specimens, (2) Controlled field specimens, and (3) Field specimens with substandard curing. The PQL obtained for the respective specimens is shown in Table A-1.

Table A-1. Paste Quality Loss (PQL) of Test Specimens

Specimen	28 days			90 days		
	UPV (m/s)		PQL	UPV (m/s)		PQL
	Mean	COV (%)	(%)	Mean	COV (%)	(%)
Standard specimen	4820	1.2		4760	1.0	
Controlled field specimen	4440	1.3	**8**	4490	2.4	**9**
Field specimen without curing	4390	2.0	**10**	4400	3.8	**16**

Field

The field implementation was performed on three bridge or deck replacements in the Metro region. The bridge projects were (1) Scotten St. over Michigan Ave, (2) Oakman Avenue over Lodge Freeway (M-10), and (3) I-75 NB to I-94 EB. *Standard specimens* were prepared during concrete placement and tests were conducted on those specimens to document: (1) f'_c, (2) E, (3) UPV, and (4) air permeability.

Afterwards, UPV and Figg's permeability tests were conducted on the aforementioned bridges (decks) at 14, 28, and 56 days. The results from the Figg's permeability test were categorized into 5 rating groups: namely, (1) 0-poor, (2) 1-not good, (3) 2-fair, (4) 3-good, and (5) 4-excellent. Further, the PQL for each of the three decks was identified.

STATUS

Ultrasonic Pulse Velocity (UPV) is considered as a good predictor of permeability, and the Paste Quality Loss (PQL) relation quantifies deck soundness. The lab and field instrumentation had been developed and tested for rapid processing of UPV measurements.

Further, the instruments used for UPV have been improved. For example, the conventional process required surface preparation for UPV measurement. Now, dry contact transducers are available and can be used without a need for surface preparation.

RELIABILITY OF NDE

The reliability of a non-destructive test is composed of three attributes: namely, (1) intrinsic capability, for example, physical and technical principles behind the detection, ultrasonic pulse velocity in relation to elasticity modulus, etc; (2) application factors, for example, realistic circumstances during measurement, transducer coupling, moisture, noise, etc; and (3) human factors, for example, operator use and recording measurements, procedure clarity, inspector training, etc.

Reliability in the measurement sense is repeatability or consistency of measurements. A measurement is considered reliable if the same value is obtained over and over again. The reliability (R) for a measurement and its associated estimate (β) can be described as shown in Eq. 3 below.

$$R = \frac{\text{True level on the measure (T)}}{\text{Entire measure (X)}}$$

$$\beta = \frac{\sigma^2(T)}{\sigma^2(X)}$$

$$X = T + E \rightarrow \sigma^2(X) = \sigma^2(T) + \sigma^2(E) \tag{3}$$

$$\beta = 1 - \frac{\sigma^2(E)}{\sigma^2(X)}$$

where: R is Reliability, β is Reliability Estimate, T is True Result/Score, X is Observed Result/Score, E is Error, σ is Standard Deviation, and σ^2 is Variance.

The reliability estimate, β, is a dimensionless number between 0 and 1; where, $\beta=0$ indicates that none of the measurements are true, and $\beta=1$ indicates that all measurements are true. For example, if $\beta=0.5$ signifies that 50% of the variance of measurements are *true*, and the remaining 50% is in error. Therefore, β can be described as the indicator of proportion of variability in the result attributable to the *true result*.

The error component in the measurements includes random error and systematic error. The random error is due to factors that affect the measurement around the mean. Systematic error is due to factors that systematically affect the measurement across the sample. Here the factors shift the mean from its *true* value.

As the *true* measurements (i.e., without error) are unknown, calculating $\sigma^2(T)$ for obtaining β may not be possible. However, β may be estimated by the variability of *true results* by considering two sets of measurements as shown in Eq. 4 below.

$$\mathbf{X}_1 = \mathbf{T} + \mathbf{E}_1$$
$$\mathbf{X}_2 = \mathbf{T} + \mathbf{E}_2 \tag{4}$$

where: $\mathbf{X}_1$ and $\mathbf{X}_2$ are two sets of measurements of the same test, with $\mathbf{T}$ as *true measurements* and $\mathbf{E}_1$ and $\mathbf{E}_2$ as respective errors. The correlation between $\mathbf{X}_1$ and $\mathbf{X}_2$ can be used as the estimate of reliability and can be expressed as shown in Eq. 5 below.

$$\beta = \frac{Cov(X_1, X_2)}{\sqrt{\sigma^2(X_1) * \sigma^2(X_2)}}$$

$$\text{where}: Cov(X_1, X_2) = \frac{1}{n} \sum_{i=1}^{n} \left(\left(X_{1_i} - \overline{X_1} \right) \left(X_{2_i} - \overline{X_2} \right) \right) \tag{5}$$

where: $Cov(X_1, X_2)$ is the covariance among data sets X_1 and X_2; n is the number of measurements in each data set; $\overline{X_1}$ and $\overline{X_2}$ are means of the respective data sets. The covariance is a measure of association between two data sets. If the two data sets represent measurement of the same parameter, then $Cov(X_1, X_2)$ is positive; whereas, if the $Cov(X_1, X_2)$ is negative, then the data is considered as invalid, i.e., the measurements are completely distinct.

RECOMMENDATIONS

- The PQL is a measure of final product quality of newly placed concrete decks and can be used to contemplate the construction process as a total quality management tool.
- Following appropriate lab and field studies to document the application factors that impact the measurements, NDE can be integrated in the bridge management system.
- In adopting NDE in bridge management, one must develop clear measurement protocols and train operators to follow the standards specific to the agency. These protocols and standards could supplement ASTM standards (if applicable), because the situations differ from agency to agency.
- The agency also needs to establish a reliability index for the NDE tests considered in the bridge management process. This is because the reliability index can be different for different components of a bridge management system, such as NBI inspection, scoping inspection, planning, etc.

APPENDIX B: WORKSHOP QUESTION/ANSWER SESSION SUMMARY

Q. David Juntunen: What kind of NDE techniques does the German Federal Highway Department regularly use?

A. Herbert Wiggenhauser: For concrete inspection, the cover meter is the standard technology, and for the rebar corrosion detection, the Electro Chemical Potential is the standard technology.

Q. Matt Chynoweth: What is the standard inspection frequency in Germany, and when is it customized (i.e., increased or decreased based on deterioration, etc.)?

A. Herbert Wiggenhauser: Every 3 years the bridges are inspected in Germany, among which every second inspection (every 6 years) is an in-depth inspection. The special inspections are performed only under special circumstances.

Q. How long did it take to perform the inspection of a box girder using NDE technologies in regards to the investigation performed in Germany? Also, how far is it feasible to take the technology to field, for example locating tendon ducts in the field?

A. Herbert Wiggenhauser: The inspection of the box girder (inner up) was part of a research project and took almost a week. However, if all things go right, then the NDE inspection could be completed within 1 or 2 days. The inspection time for 1 square meter for ultrasonic echo is about 1 hr (i.e., approximately same as the time required by any NDE technology that requires a physical contact), and 5 minutes for Radar (i.e., approximately same as the time required by any NDE technology using scanning device).

The data processing requires additional time. Currently, there are no professional data processing softwares available. In the future, if there is high demand for such softwares and they are made available, then the NDE technology could be deployed along with field data processing (e.g., identifying the location of a tendon duct in the field).

Q. Herbert Wiggenhauser: Ten years ago IR research was discontinued because of reliability issues with the field use of the technology. MDOT appears to have made an investment in this area. Regarding the usage of IR Thermal cameras by MDOT, what are the experiences?

A. Jason DeRuyver: It is not recommended to collect the data of the deck during traffic. After numerous uses, the technicians are gaining confidence. Before the equipment investment, the expectations were very high. Following its use for a while, the expectations were lowered. Further, the use guidelines and procedures that are included with the camera are not really

followed at all the times. This is because of factors such as climate conditions, exposure, and time of day. The data require interpretation based on the measurement conditions.

Q. Sudhakar Kulkarni: Following construction of new bridges, within a month or so, cracks are observed on the bridge deck. TRB and other researchers identified the cause as drying shrinkage. Thus, MDOT started pouring decks at night to control the evaporation. Still decks crack. Will the *rapid bridge deck testing facility* that is planned, as part of the LTBPP, investigate measures to reduce early age cracking of bridge decks?

A. Nenad Gucunski: Regarding the project that Rutgers is initiating with NJDOT, they have few concerns regarding high-performance concrete bridge decks. They want to identify the current condition of those bridge decks, and if cracks are present, they want to understand the impact. In order to address their concerns, Rutgers will be assessing the overall condition of those bridge decks. The project will work on identifying crack depths and establish correlation between crack depth and deterioration. Further, new bridges constructed in NJ are to be investigated with various techniques. For example, curing will be monitored after 1 or 2 days of casting the deck, the concrete modulus will be investigated, any cracks that are developed will be characterized, and investigation will be performed to identify the consequences of crack propagation.

Q. David Juntunen: The damage evaluation worksheet shown by Dr. Ahlborn, which involves different elements and their condition, is of interest in bridge preservation and maintenance. In bridge preservation, for a given condition state of the bridge, the corrective action is decided based on a similar worksheet that MDOT developed. Can the worksheet that Dr. Ahlborn's team developed be shared with MDOT?

A. Tess Ahlborn: The worksheet is the part of RITA project deliverable. The final report is published and available on the RITA website. The worksheet is public information and is available to MDOT. The worksheet needs to be reassessed for use in bridge preservation, because it is about health indicators. Based on the type of defect and its extent, the health indicators may change and affect the condition states. This will be a next step for advancing that worksheet.

Q. David Juntunen: Regarding the database that Ali Maher and his team is working on, AASHTO in parallel is updating the national bridge elements and defining the condition states as good, fair, or severe. Is there any coordination between what Ali Maher's team is doing and AASHTO?

A. Ali Maher: The Rutgers team regularly briefs various AASHTO committees. The way that FHWA LTBPP set up the project is that in the long-term (i.e., 20 years) process of data collection, there is the expectation to identify relationships for the performance indicators. However, there are also short-term objectives for the FHWA LTBPP to address. From the AASHTO standpoint, the message is quite different where short-term results need to be produced by testing etc., through complementing projects for providing data in updating the national bridge elements and their condition states.

Q. David Juntunen: This is in Regard to the animation that Nenad Gucunski showed, which presented the future delamination growth in a component with time. Here in Michigan, MDOT tries to preserve the bridges as long as economically feasible. For bridge deck rehabilitation, first the quantity of bridge deck that is delaminated and spalled is calculated. Then an appropriate rehabilitation procedure is performed to stop the deterioration. MDOT is interested in knowing if there is possibility to identify the time duration from delamination to spall (using the animation showed in the presentation) so that corrective actions could be scheduled proactively.

A. Nenad Gucunski: The animation presented utilized data from GPR. The research team needs to obtain more data through LTBPP; then the deterioration curves could be developed that can better predict the time of progression from one stage of deterioration to the next. Also, the bridge assessment project that is being developed under FHWA funding identifies the delaminated or any other deteriorated areas in the bridge deck. It then transfers respective coordinates to another robot that Rutgers is currently developing. This robot is expected to take action to stop the deterioration, similar to welding a crack to stop its propagation.

A. Ali Maher: This is a fundamental question that constantly drives the LTBPP, and it is among the primary questions that were obtained from discussions with several stakeholders. There are around 1000 bridges distributed around the US under periodic monitoring among which Michigan bridges would be prominently represented. Ultimately, those bridges will be

instrumented, and we could obtain more data points to develop the deterioration curves for Michigan bridges. However, this process will take time as these come under the long-term objectives of the LTBPP. Clearly, it is challenging to manage the long-term objectives with the intermittent short-term expectation of the LTBPP.

APPENDIX C: WORKSHOP PARTICIPANTS

Table B-1. List of Attendees (Non-Destructive Testing of Highway Bridge Assets- March 28, 2013- Lansing)

Last Name	First Name	Account Name	E-mail
Adefeso	Olukayode	MDOT – Metro Region	adefesoo@michigan.gov
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Aktan	Haluk	Western Michigan University	haluk.aktan@wmich.edu
Attanayake	Upul	Western Michigan University	Upul.attanayake@wmich.edu
Beck	Steve	MDOT	becks2@michigan.gov
Bruinsma	Jon	MDOT – Grand Region	bruinsmaj@michigan.gov
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APPENDIX A: WORKSHOP PRESENTATION SUMMARIES

MR. MATTHEW J. CHYNOWETH – PRESENTATION SUMMARY

Mr. Matthew J. Chynoweth, P.E., Engineer of Bridge Field Services, discussed the current use of NDE for bridge condition assessment.

LIST OF TECHNOLOGIES

- Infrared Thermography (IR): FLIR T640 and FLIR T420
- Ultrasonic Testing (UT) Probe

IMPLEMENTATIONS

Field

Infrared Thermography

- Handheld FLIR systems are used to detect delamination on the deck surface and soffits.
- FLIR T640 is suitable for measuring concrete defects of less than 1 sq ft; whereas, the FLIR T420 is not.
- IR is currently being used in the MDOT Superior region, University region, and Metro region.
- Technology has been developed to a state of implementation at highway speed.

Ultrasonic Thickness Gauge (UT Probe)

- The UT probe is used to (1) measure wall thickness of hollow metal light poles to check if corroding from inside, (2) verify the soundness of anchor bolts that are intended to be reused in foundations, and (3) test the welds (flange and web welds) at fabrication plants.

STATUS

Infrared Thermography using the FLIR system is currently being implemented under field conditions. Jason DeRuyver and his group at MDOT are in the process of training the bridge inspectors to use the FLIR system. Guidelines for thermographic inspection of concrete bridges components and an online application (http://zlmoment.appspot.com) are also made available by the University of Missouri-Rolla under a pool-fund study. The online application with the current weather data advises on the timing of the IR scanning of a bridge at a particular location.

The UT Probe, also known as *Thickness Gauge*, has been successfully evaluated and is being implemented in the field.

RECOMMENDATIONS

Infrared Thermography with the FLIR system

In order to acquire reliable IR data on delamination of a bridge deck, the deck needs to be exposed to solar radiation for about 2 hrs. On the other hand, for the deck soffit IR inspection, a temperature gradient of at least 15°F is required. Further, wind speed also needs to be considered for obtaining accurate results, because wind cools the surface, leading to a false IR image.

Ultrasonic Testing (UT) Probe/Thickness Gauge

Training is essential prior to using the device, reading signals and interpreting the results.

DR. HERBERT WIGGENHAUSER – PRESENTATION SUMMARY

Dr. Herbert Wiggenhauser from German Bundesanstalt für Materialforschung und –prüfung: that translates as Federal Institute for Materials Research and Testing (or commonly known as BAM) presented the technologies listed below. Since 1999 Dr. Wiggenhauser has been the Head of Division for Non-Destructive Testing in Civil Engineering.

LIST OF TECHNOLOGIES
- Acoustic Emission (AE)
- Impact Echo
- Ground Penetrating Radar (GPR)
- Ultrasonic Echo
    - Dual Probe
    - Array Technique
    - Phased Array
- Ultrasound with Array Technique
- Infrared Thermography

Commonly Used Technologies

- Electro-Magnetic Method: Radar
    - Analysis of reflected waves from interfaces of materials with different dielectric properties
    - Antenna: 500 MHz and 1.5 GHz
- Ultrasonic Pulse Echo Measurement System
    - Pulse Echo is commonly used rather than linear array
    - Shear wave transducers: frequency = 50 kHz
    - Measurement head: 24 point dry contact transducers
- Impact Echo
    - Frequency range: 1Hz to 40 kHz
    - Frequency spectrum analysis: multiple reflections recorded in time domain
- Scanner systems with Ultrasonic Probes
    - A frame with suction cups is used to mount the scanner, for upside down use, to the deck soffit.

o The time for ultrasonic scanning is much longer than the time required by Radar.

IMPLEMENTATIONS

Lab

Impact Echo

- The traditional implementation of Impact Echo to analyze signals in the frequency domain has been modified by BAM to Impact Echo imaging (3-D image representation). The BAM process is to obtain a B-scan and C-scan of the specimen similar to scans obtained using the UT technique. The scanning procedures eliminate the need for interpreting the frequency peaks in order to detect the flaw. The images enable the operator to distinguish between a point event (most likely false reading) and a reading which is similar as neighboring measurements.

- Tendon ducts: The research studies recognized a shift in the back side echo at locations of un-grouted tendons. Predefined defects in tendon ducts were located very precisely in the laboratory by the shift in the back side echo.

- Geometry Effects: On a surface with nearby edges and internal retro-reflective edges, additional peaks in the impact-echo frequency analysis appear. These are only due to the limited size of the surface. These effects can only be separated from true IE signals through scanning measurements.

Phased Array UT

- The synthetic aperture focusing technique is used to detect the flaws in a test specimen. Several test specimens with defects were successfully tested in the laboratory.

- The device makes measurements along a line on the specimen. The 3D data that is obtained from that line measurement is divided into B-Scans and C-Scans. These scans provide the 2D images (point-by-point summary) of the specimen across the section of the line measurement.

- Continuous 3D measurements will provide more accurate images showing information of the defects in the test specimen. However, the phase shift needs to be evaluated manually. The automation of this process is still under research development.

- Deep delaminations can be accurately located and directly characterized. However, the shallow delaminations could be indirectly detected for the built-in defects only, because of missing back-wall reflections and/or multiple reflections (i.e., phase shift).

GPR and Ultrasonic Echo

- A large concrete slab was used for validation and reference. Three honey-combs were generated in to the slab. The slab was then tested using Impact Echo and GPR. Contrary to the expectations, the honey-combs were not detected with GPR. Ultrasonic Echo (Ultrasonic Imaging) of 55 kHz was used. Densely spaced grid measurements and thorough data analysis could locate two of the honey-combs.

Ultrasound Transmission

- This technology is used to measure asphalt porosity using the through transmission technique (longitudinal wave probes, f = 100 kHz) and echo technique (longitudinal wave probes, f = 85 kHz). To reduce the noise and other effects in the signal, the "array technique" (longitudinal wave probe, f = 100 k Hz) was preferred.
- The Ultrasound with Array Technique with shear wave probes, f = 50 kHz, was successfully used to identify the extent of porosity in asphalt. This is achieved by measuring the variation in the back-side signal.

Field

Impact Echo

- Used to measure thickness

Phased Array UT

- Applied for detecting delamination in concrete bridge decks
- Deep delaminations could be accurately located and directly characterized. However, the shallow delaminations could not be directly detected under field conditions.

Infrared Thermography

- The technology is explored for detecting shallow delaminations in concrete decks. Further studies are not being conducted on this technology, because it is a well-developed technique

and suitable for field implementation. An ASTM standard D4788 – 03 is also available for this purpose.

- IR is an imaging method that generates images for visual analysis, and can be used easily for remote sensing providing real time results. However, quasi static measurements are made; thus, the thermal time history needs to be considered before making inferences. The operator needs to be experienced.

GPR, Impact Echo and Ultrasonic Echo

- Field application was completed on a segmental concrete box bridge with post-tensioning to obtain a condition data of the webs and the deck slab interior. The length of the bridge was 400 m and was post-tensioned in longitudinal and transverse directions. The bridge was constructed in 1966 and decommissioned in 2004 because of condition. A surface area (10m×4m) of the bridge deck was investigated using GPR, Impact Echo and Ultrasonic Echo technologies.

- The GPR data acquired from top and underside was superimposed to obtain a visual of the deck interior. Duct investigation with Ultrasonic Echo was also successful even in identifying minute defects.

- The GPR and Ultrasonic Echo were successful in locating the top and bottom reinforcement, tendon duct locations, and defects in the tendon ducts. Also, Impact Echo was successful in detecting the thickness of the deck. The tendon duct locations were indicated by an apparent shift of the Impact Echo signal, but grouting defects in the tendon ducts could not be detected. The challenge was that the tendon ducts were not parallel to the deck surface.

- Data-fusion of GPR and Ultrasonic Echo was explored. GPR is capable of identifying any metal (ducts) inside concrete but is unable to look inside the metal (ducts). On the other hand, Ultrasonic Echo signals can penetrate through the metal (ducts). Thus, in bridge investigations, the tendon grout defects were evaluated using the combination of GPR and Ultrasonic Echo.

STATUS AND RECOMMENDATIONS

Primarily visual inspection is used for bridge inspection. NDE is specified only for special cases where damage cannot be identified or accessed using visual inspection.

Acoustic Emission (AE)

AE is used for detecting cracking, friction between surfaces during crack movement, and expansion of a corroding rebar. AE applications for detecting concrete delamination in field haves not shown successful results. However, AE application for detecting concrete delaminations in a laboratory where those effects can be localized has been successful.

Impact Echo

Lab tests were successful in identifying predefined tendon duct grouting defects. However, using Impact Echo in the field to detect tendon duct grouting defects is not recommended, because controlled lab conditions could not be achieved. Only a measurement of thickness with Impact Echo is recommended.

A 2D time-frequency analysis technique is used to detect delamination in bridge decks using Impact Echo. Here the pattern of the signal is investigated and compared with predefined signatures to evaluate the severity of delamination, such as good condition (intact or no debonding), fair (initiation of debonding), poor (progressed debonding), and severe (fully debonded).

Phased Array UT

Phased array Ultrasonic Testing (UT) for testing metals is well established. The Phased Array UT technique for concrete is a sampling phased array rather than electronic phased array. The measurements require 3 seconds for one B-Scan. The Phased Array UT technique for detecting delamination in concrete bridge decks showed better success than Impact Echo.

The capabilities include real-time imaging of slab interior, accuracy, precision, and ease of use; whereas, the limitations are high initial cost, blind zone near the surface, and a slow data acquisition process because of manual testing using dry contact sensors.

The technology is suitable for in-depth investigation of a limited part of a component.

GPR and Ultrasonic Echo

The GPR or Ultrasonic Echo could detect a honey-comb if the defect is parallel to the surface where waves can reflect. Also, the defects can be detected if the defect surface is highly irregular, or if it consists of large voids which acoustic waves could not propagate. However, there is a need for additional research in this area.

For a RC slab containing heavy reinforcement and defects, Impact Echo, Infrared, and GPR all were not able to detect the defects; whereas, defects could be identified and located by using Ultrasonic Echo (ultrasound imaging). Further, Ultrasonic Echo could detect the defects with high reliability in slabs with low reinforcement. It is the recommended NDE method to detect defects, such as honeycombs (voids).

Ultrasound with Array Technique

The ultrasound with through transmission and array technique is recommended for the asphalt porosity assessment. Radar (GPR) could not be used reliably to assess asphalt porosity as the dielectric constant of the medium is not sensitive enough to porosity.

Infrared (IR) Thermography

The technique is very much dependent on ambient conditions and the time of measurement. Thus, repeated measurements of the same defect need to be imaged at different times and different exposure histories. It is further recommended to consider the IR result as a potential, and verify the defect using other methods, such as sounding, GPR, etc.

IR thermography was used reliably to detect asphalt overlay delamination on a concrete deck by allowing the deck to absorb heat under solar radiation (passive thermography) and by artificially heating the surface using (active thermography). The IR image time histories are then generated and analyzed in time domain and frequency domain. Another analysis option which is being researched is to analyze the selective reflectivity from the heated deck surface.

General Comments

Proactive NDE is always the best approach to test the construction quality immediately after construction and identify any imperfections that can affect service life of a component. Further, highly accurate NDE techniques are not necessary, as long as the method is accepted as a QC method and the inspectors trust the technique is able to detect the flaws.

There are several successful NDE applications. However, these applications at this time are lacking in standards. NDE is not implemented within the scheduled inspection process; it is rather requested only on exceptional bridge inspection cases.

For successful NDE implementation in bridge management, the agency needs to invest in

(1) **experts,**

(2) **purchasing a pool of expensive equipment,**

(3) **integration of techniques into routine tasks,**

(4) gaining experience through routine applications, and

(5) **training/education.**

To move directly from *newly developed NDE methods* to *practical use* is not preferred. Rather, the steps that need to be followed are:

(1) **lab verification,**

(2) **pilot field application,**

(3) **training/education, and**

(4) **developing guidelines/certifications** before incorporating into field practice.

RELIABILITY OF NDE DATA

Impact Echo

When testing a specimen with finite geometry using Impact Echo, a large amount of disturbance is created due to the reflection of waves from the corners as well as from the surface (retro reflected at corners). For example, if a compression wave is created on the specimen, about 70 % and 23 % of the energy is converted into the surface waves and shear wave respectively. The compression waves, which are the signals of interest, receive the remaining 7 % energy. Hence, boundary effects need to be considered.

The method is reliable if used for the correct purpose, such as thickness measurement preferably of a large slab. Do not push the technique beyond what it is designed for. The thickness results obtained are very reliable; this was proved by using a test specimen with varying thickness and obtaining a 3-D plot of it by obtaining several single thickness measurements (~40,000).

Phased Array UT

When a mechanical wave is reflected from a soft surface, there is a phase shift observed in the data; whereas, if the wave is reflected from a hard surface, the phased shift is not observed.

Measurements are highly repeatable and reasonably accurate. However, placing the array over the edge of the delaminated area may lead to ambiguous results. This becomes challenging because the boundaries of the delaminated are not visually defined before implementing the technology.

If a prismatic test specimen is tested from the sides, then 94 % of the time flaws are detected and accurate characterization occurs at 92 %. When the specimen is tested from the top, then flaw detection decreased to 92 % and characterization to 91 %.

The phase array system is reliable. Repeatable data is obtained, even if the testing is performed under different conditions.

Infrared Thermography

Active thermography (i.e., heating the deck surface using large heaters) is more reliable than the passive thermography (i.e., allowing the deck to be heated up by solar radiation).

DR. JEROME P. LYNCH – PRESENTATION SUMMARY

Dr. Jerome Lynch is the director of the Laboratory for Intelligent Systems and Technologies at the University of Michigan.

LIST OF TECHNOLOGIES

- Narada Wireless Sensor with Amplified Radio
  - Developed by the University of Michigan in 2005 (Cost: $175 per unit; Energy source: 5AA batteries; Active power: 200mW; Data rate: 250 kB/s; Sample rate: 100 kHz)
  - 16-bit ADC resolution on 4 channels capable of acquisition rates (100kHz)
  - Equipped with a radio that allows interoperability with other sensors. Further, the radio is amplified by power amplifier circuit designed to achieve 10dBm output gain and a communication range of 700m
  - Includes an embedded processor with algorithms to perform sensor-based data processing – implements *rain flow counting* algorithms by Downing and Socie (1982)
- Communication Base Station
  - Designed to communicate with all the sensors on the structure and transfer data to the repository (data storage location)
  - Consists of single board computer that runs Linux, a cellular modem to transfer data, a lead acid rechargeable battery that is charged using solar panels, and a transceiver that communicates with all the Narada wireless sensors on the bridge
- Cyber Infrastructure (Internet-enabled cyber environment.)
  - Combines data with structural analytical tools for information discovery

IMPLEMENTATIONS

Field

Narada Wireless Sensor Implementation in California

- 28 Narada wireless sensors were installed on the Carquinez Bridge located in Vallejo, CA, to measure the seismic performance of the bridge. The bridge length is 1056 m with main span of 728 m and was constructed in 2003.

- The bridge consists of steel orthotropic box girders deck, hollow concrete tower legs and prestressed link beam.
- The 28 sensors collect data from following 81 channels:
  - 19 **tri-axial accelerometers** measuring the main deck,
  - 3 **tri-axial accelerometers** measuring vibrations at tower top,
  - **A wind vane, anemometer and temperature sensor** in three locations,
  - 3 **string potentiometers** to measure deck movement relative to tower.

Narada Wireless Sensor Implementation in Michigan

- 31 Narada wireless sensors for fatigue assessment are installed on the Telegraph Road Bridge located in Monroe, MI. The bridge was constructed in 1973.
- **strain gauges** were installed at various locations of the pin and hanger connection to identify states of strain in the hanger plates, to track fatigue accumulation, and to calculate moments due to corrosion and locking. From the measurements, a compressive-tensile strain difference in the pin and hanger plate was observed. That strain difference may be due to a flexural moment. However, the flexural moment could be caused either because of locking in the hanger plate or because of bridge skew, which requires further investigation.
- The sensors monitored **strains and temperatures along girders at deck level** and correlated with deck crack zones.
- They measured **strains** along typical cross-sections and evaluated composite action of the superstructure.
- The 31 sensors collected data from the following 57 channels:
  - 15 **uni-axial accelerometers** for modal analysis and model updating,
  - 36 **strain gauges** (24 for beam strain profile and 12 for link plate strain), and
  - 6 **thermistors** to assess temperature load and for thermal corrections.

STATUS

Narada Wireless Sensor – Accelerometer

The sensors are powered using small solar panels and are magnetically mounted on the steel girders.

Narada Wireless Sensor – Strain Gauge

The sensor consists of a metal foil strain gauge that is physically bonded using epoxy. The sensors are powered using small solar panels. The area for the strain gauge is sanded first, and then the strain gauge is bonded and covered using powder paste protection to make the respective area waterproof.

Based on the Finite Element Model of the bridge, the strain gauges were mounted on two critical pin and hanger plates (i.e., with high levels of stress).

The strain is measured through the depth of a girder web as well as in the deck. These strain measurements were used to determine the location of the neutral axis and evaluate the composite action. The automated data processing in the sensor network compares the calculated neutral axis with the theoretical axis location. The location of the neutral axis is considered as a good indicator of deck/girder deterioration.

Cyber Infrastructure – Data Processing Clients

Several data processing clients were developed that automatically extract the modal characteristics. Although modal characteristics are not for health monitoring purposes (because they are not a good indicator of bridge deterioration), they play a very important role in the Finite Element model updating process that plays a major role in structural health monitoring strategies.

A data processing client was developed that extracts the modal data from the repository (database), automatically generates the ADINA input file for the bridge, runs the FE analysis, and then performs FE model updating using the sensor data that is also embedded in the repository. The FE model updating process is performed frequently so that the FE model modal characteristics match closely with the actual bridge. The FE model updating is performed considering 4 structural parameters: (1) Mass of deck overlay, (2) Strength of concrete in deck slab, (3) Thickness of concrete, and (4) Stiffness of springs simulating composite action.

Other data processing clients automatically generate the mode shapes of the bridge using the automatically extracted model characteristics. The frequency domain decomposition (FDD) is performed within the sensors as well as the repository.

The sensors at the pin and hanger connection are embedded with data processing clients that perform the *rain flow counting* and plot histograms of the strain response. The peak strains

are identified and processed using models that determine cumulative fatigue damage in the components.

RELIABILITY ANALYSIS

Reliability analysis is performed for all the collected data. The capacity that is embedded within the structure is compared with the estimated demand from vehicle loads, thermal loads, etc. The capacity is measured by structural response from the instrumentation; whereas, the demand is measured considering the actual traffic loads and temperature loads. For example, consider the evaluation of composite action using the process for determination of the neutral axis location. Limits on the location of neutral axis were established, and the measured location using sensor data was subjected to a reliability approach to determine how well it falls within those limits. The FORM (First Order Reliability Method) reliability index is calculated as shown below (Eq. 1) and is used in the decision making process.

$$\beta = \beta(t) = \frac{\mu_{d\ (intended)} - \mu_{d\ (measured)}}{\sqrt{\sigma^2_{d(intended)} + \sigma^2_{d(measured)}}} \tag{1}$$

where: *"measured"* is providing the capacity of the structure, and *"intended"* is from the demand side of the structure.

For the bridge decks, the total deck response and temperature are considered under *measured,* and dead load and live load are considered under *intended/computed*.

The influence lines of the bridge are developed for each sensor location and stored in the repository. The influence lines are combined with the Weigh-in-Motion (WIM) data to obtain the demand that is deployed on the analytical model to obtain the expected response of the bridge. The expected response of the structure, in the form of probability density function, is mapped with the sensor data to estimate the reliability index for that corresponding component (essentially the sensor location on a component).

DR. ALI MAHER – PRESENTATION SUMMARY

Dr. Ali Maher of Rutgers University is the director of the Center for Advanced Infrastructure and Transportation (CAIT). He is the principal investigator of the FHWA project on Long-Term Bridge Performance Program (LTBPP).

Long-Term Bridge Performance Program (LTBPP)

The LTBP program serves as the national platform for (1) improving bridge health and effective management, (2) standardizing and enhancing inspection techniques, and (3) enhancing design, construction, preservation and operation practices from data-driven tools.

The research approach included (1) Defining bridge performance, (2) Determining high priority performance related issues, (3) Designing an experiment for identifying bridges for data collection, and for referencing the cluster concept, (4) Providing data analysis (portal platform), and (5) Verifying data collection protocols using the pilot program. The bridge performance related priorities were identified from the focus group interviews with 15 state DOTs, geotechnical issues workshop, state coordinators, and the input from a stakeholder advisory board and expert task group (ETG) committees.

The high priority topics considered were (1) Untreated/Treated concrete bridge decks, (2) Bridge deck joints, (3) Bridge bearings, (4) Coatings for steel superstructure elements, and (5) Prestressing strands. For the design of experiments, the primary experimental variables were identified from the intrinsic characteristics such as age, main span length, bridge type, etc.; and external characteristics such as, climate, ADTT, state's preservation policy, etc. In the next step, for each high priority topic, an experiment was designed by allowing some of the primary experimental variables to vary while keeping the others constant. Afterwards, for the experiment designed under each high priority topic, bridge clusters were developed that fit into that experiment. Further, corridor candidates were identified for each of the high priority topics by considering the experimental variables that are neither *constant* nor *variable*, such as state policies, etc. Finally, clusters of candidate bridges were developed by overlapping the bridge clusters and corridor candidates on the U.S. map.

Michigan is one of the test beds where the LTBPP needs to be implemented. The bridge clusters identified from the first step of design of experiments were around 5000-6000 bridges. After overlapping those bridge clusters with the corridor candidates through Michigan, clusters

of candidate bridges were developed that totaled to around 400-500 bridges. This population of bridges was considered as the sample that is statistically significant to provide reasonable judgments for the total population of 5000 to 6000 bridges.

The clusters of candidate bridges were again evaluated to identify a *reference bridge* that closely represents the characteristics of the nearby candidate bridges within that cluster. The *reference bridges* from all the clusters will be used for visual inspection, non-destructive evaluation, global testing, materials testing, and long-term data collection under the LTBP program. For example, the clusters of candidate bridges (500-600 bridges) in Michigan may be reduced to around 10-20 reference bridges. The information obtained from the evaluation of a reference bridge could be used to infer the information of other nearby candidate bridges in that particular cluster.

The data that will be obtained from the evaluation, testing and long-term data collection under the LTBP program will be stored in a *Bridge Portal*, which is a repository. The data infrastructure platform of *Bridge Portal* was developed by Siemens Cooperation under a LTBP program sub-contract. All the Meta data that will be made available by the *Bridge Portal* could be used for (1) developing deterioration models and life-cycle cost models, (2) forecasting, and (3) bridge management at program and network levels.

DR. TESS AHLBORN – PRESENTATION SUMMARY

Dr. Tess Ahlborn of Michigan Technological University presented the findings of the USDOT project on bridge condition assessment using remote sensors. This presentation included an evaluation of state of the practice optical, laser and thermographic imaging systems for bridge condition assessment.

LIST OF TECHNOLOGIES

- Ground Penetrating Radar (GPR)
- 3D optical bridge evaluation system (3DOBS)
- Bridge Viewer Remote Camera System (BVRCS)
- GigaPan
- Infrared Thermography (Thermal IR)
- Synthetic Aperture Radar (SAR) 2D and 3D
- Digital Image Correlation
- LiDAR

STATUS

Ground Penetrating Radar (GPR)

The cost is very high and requires traffic disruption; thus it is used rarely.

3D optical bridge evaluation system (3DOBS)

The 3DBOS acquires several images of a bridge at highway speed. The processing of the images by stereo overlapping creates high-resolution 3D image for spall detection and characterization at 2mm resolution. The 3DBOS data is fed into the ArcGIS analysis software for detecting the percent spalled area using its automated spall detection algorithm.

The 3DOBS also consists of a digital elevation model that can zoom onto the locations, such as wheel path, on the 3D image. Thus, the International Roughness Index (IRI) could also be evaluated for different wheel paths. However, the technology currently works on near-highway speed, and investigations are in progress to achieve highway speed data collection.

Bridge Viewer Remote Camera System (BVRCS)

This technology is similar to the street-view style photography of Google Maps®. It captures more information about the images as images of a component are acquired from different angles. The images are finally stitched using stereo overlapping patterns to obtain a complete rendering of the bridge including information at critical locations.

GigaPan

This technology is being used to obtain high resolution photo inventories of bridges. It consists of a DSLR camera mounted on a rotating arm that takes a series of images. These images are stitched together to provide a high-resolution photo of the complete bridge. The bridge image could be enlarged to obtain the component view with about 5mm resolution. The resolution is still being investigated for increasing to 1mm.

Infrared Thermography (Thermal IR)

The passive thermal IR is implemented on the bridge deck to detect delaminations, which requires the bridge deck to be heated up under the passive solar radiation. The technology is ready for field implementation. There is also an ASTM standard for deployment of this technology. The data can be processed using Microsoft Excel to identify the delaminations using the thermal images.

The active thermal IR is essential for the underside of the bridge deck or the fascia-wherein sunlight cannot reach. Here, the component needs to be heated actively to enhance thermal IR output. Currently, the implementation of active thermal IR is limited to lab applications on small specimens.

Synthetic Aperture Radar (SAR) 2D and 3D

The technology is used for detecting spall and delamination. The technology can also detect subsurface defects. The instrument consists of radar equipment and a lateral translator. This is different from GPR as low cost components are used with an ultra-wide band system and a single antenna to assist the resolution/penetration tradeoffs.

Digital Image Correlation

This technology has been implemented in Aerospace engineering. However, its implementation was performed in a controlled environment. There was limited implementation

of this technology to detect load induced stresses in a bridge; however, several environmental factors affected the accuracy of data. Research is in progress to bring this technology into regular bridge assessment.

Benefits that can be drawn from this technology are:

1) Remotely captures deflection, and
2) Measures strain field and vibrations.

Limitations of this technology are:

1) A significant amount of error induced by wind and traffic flow, and
2) Suited only for controlled environments in the current state.

LiDAR

The LiDAR is usually used for surveying, measuring the as-built construction, etc. For the NDE, the system is used to measure the surface condition such as percentage area of spall, along with the location and volume of spalls using a composite intensity image of the bridge deck. Using LiDAR, the global features (such as static deflection, high load hits, etc.) can also be determined. However, the technology is time consuming and costly.

RECOMMENDATIONS

3DOBS, BVRCS, and GigaPan

1) These technologies require low cost components, can be deployed rapidly, and consume a limited time for collecting data; thus, they can be deployed to detect the percentage area/volume and location of spalls, and the International Roughness Index (IRI). They can also begeo-tagged and provide a very high-resolution photo inventory.
2) The automation of the data analysis is required. Further, the data storage capability, for the high resolution images, needs to be considered.
3) The technologies are near-ready for field deployment.

Infrared (IR) Thermography

1) The technology is being deployed at near-highway speed (45mph).
2) The IR has equal reliability to chain dragging in detecting the delaminations. Further, the data is 60-70 % accurate with respect to actual delaminations verified by bridge coring.

3) The technology is field ready at near-highway speed; however, a manual for its deployment is required.

Synthetic Aperture Radar (SAR) 2D and 3D

1) The technology can be adapted for use on a moving vehicle using a *lateral translator*.

2) The data collection time and the data processing and user interpretation needs to be considered.

3) Correlations of deviation in obtained data with actual defects need to be investigated for subsurface defects. This will allow identification of the defects accurately. Moreover, development of this technology to 3D is necessary to compete with commercially available 3D GPR.

Digital Image Correlation

1) This is not ready to be deployed in the field without significant technology improvements such as gyroscopic compensation, rigid mount, etc.

2) Complementary technologies such as laser vibrometry, LiDAR, etc. should be considered along with the Digital Image Correlation.

LiDAR

1) LiDAR access range is about 55-56 ft. Thus, for scanning the bridge deck, the LiDAR needs to be setup at multiple locations.

2) The technology needs to be appropriately integrated in the bridge condition assessment framework.

3) Mobile LiDAR that is under implementation in other industries can be considered as a practical future platform in bridge assessment. However, Mobile LiDAR needs a manual for deployment in bridge condition assessment process.

4) The point cloud density of LiDAR needs to be considered for collecting bridge condition assessment data.

DR. NENAD GUCUNSKI – PRESENTATION SUMMAR

Dr. Nenad Gucunski is the chair of the civil engineering program at the Rutgers University. He is the director of CAIT's Infrastructure Condition Monitoring Program (ICPM) and the principal investigator of the automated nondestructive evaluation and rehabilitation system for bridge decks.

OVERVIEW

Almost 80 % of rehabilitation cost spent on bridges in the country is on bridge decks. The annual rehabilitation cost spent on bridge decks nationally totals to about $5 billion. This expenditure can be reduced by changing the way of evaluating the bridge decks and providing timely rehabilitation of the bridge decks.

The topic was focused on bridge deck evaluation and the means of improving using automation. Also discussed were customized bridge deck rehabilitation procedures.

TYPES OF BRIDGE DECK DETERIORATION OF INTEREST

- Deck Delamination
- Rebar Corrosion
- Concrete Degradation
- Deck Cracking (Vertical)

LIST OF TECHNOLOGIES

- Electrical Resistivity
  - To detect the signs of corrosion initiation
  - To detect the potential for corrosive environment
- Half-Cell Potential
  - To detect the corrosion activity
  - To detect the likelihood of active corrosion
- Ground Penetrating Radar (GPR)
  - To detect the potential for corrosive environment

- o To detect delamination at its initial stages, but only in cases where the delamination is induced due to corrosion (i.e., detect the likelihood of delamination in highly attenuated areas)
  - o To detect the likelihood of concrete deterioration
- Impact Echo
  - o To detect delamination during early and late stages
- Infrared Thermography
  - o To detect delamination near its late stages
- Chain Drag/Hammer Sounding
  - o To detect delamination near its late stages
- Ultrasonic Surface Waves (USW)
  - o To detect the concrete degradation by identifying the modulus degradation
- Moist Scan Survey (Relative Moisture)
  - o To detect zones of moisture concentration

STATUS

Electrical Resistivity

The technology is being deployed in the field. The available literature defines the relationship between resistivity and corrosion rate. The corrosion rate is classified as (1) very high, (2) high, (3) moderate-low, and (4) low.

Recent studies show that 40 kOhm-cm is the threshold resistivity between a corrosive and non-corrosive environment. Low resistivity indicates a highly corrosive environment and vice-versa.

Half-Cell Potential

The technology is being used in the field, and an ASTM standard (ASTM C875) is also available.

Moist Scan Survey (Relative Moisture)

This technology is not used on regular basis. It uses micro-wave technology to identify the zones of moisture concentrations. Currently, the technology is deployed to provide relative moisture measurements, i.e., low moisture or high moisture.

Research is in progress for calibrating the equipment to obtain absolute moisture content measurements.

Impact Echo

This technology is being used in the field. The data obtained is highly accurate and was validated by identifying delamination using a coring operation.

Ground Penetrating Radar (GPR)

This technology is being used in the field. It is deployed on the bridge deck using ground coupled antenna as well as air-coupled (horn) antenna. The air-coupled GPR survey is conducted at a speed of 30mph.

The ground-coupled GPR is more advantageous as it provides higher quality and detailed data. The use of ground-coupled GPR is recommended. However, air-coupled GPR could be deployed to obtain an estimate of delaminations on a roadway network.

The materials that represent the bridge deck makeup need to be considered, and their respective dielectric constants (K^*) should be known. Also, the presence of moisture can significantly increase the dielectric constant and reduce penetration.

The concrete with voids will have less attenuation, and thus the dielectric constant is low compared to dense concrete. The attenuation in this case indicates possible change in concrete quality, but it may not be detectable. However, for water/chloride filled voids and contaminated concrete, the attenuation is significantly high (i.e., chlorides significantly more conductive than concrete) and thus the dielectric constant is high compared to concrete. The attenuation in this case indicates significant change in concrete quality and can be detected easily.

The data provided as an attenuation map needs to be corrected for depth of rebars. The depth that is considered in this case includes approximate thickness of overlay and original deck concrete cover. This allows generating a map of current concrete cover that can be used to identify potential locations of deterioration.

Ultrasonic Surface Waves (USW)

This technology is being implemented in the field to detect concrete quality/degradation. Here the velocity of surface wave propagation is measured and is directly correlated with the

modulus. The device can obtain several measurements in a relatively small amount of time, ranging from 100 to 120 measurements per hour.

During the field implementation of this technology, it was observed that the modulus of elasticity has high variability in bridge decks. This phenomenon was observed in newly built bridge decks. Variability in the modulus cannot be a direct indication of bridge deck deterioration. To assess bridge deck deterioration using the modulus of elasticity measurement, periodical measurements can be performed, and the changes can be related to changing deck condition.

Additional Information

- The typical inspection rate with the use of NDE technologies presented ranges from 1000 to 1500 sq. ft per hour.

- GPR and Electrical Resistivity measurements show good correlation. This is because the same factors influence the measurements with these two technologies.

- GPR is not useful to identify delamination when the cause of delamination is not rebar corrosion. Impact Echo can identify the delaminations with some uncertainty.

- The quantitative nature of NDE can be utilized to reduce inspection subjectivity and enable an objective rating of bridge decks. Here, the bridge deck is divided into several sectors, and the rating is based on the percentage of delamination, percentage of corrosion, and percentage of concrete degradation. The overall condition rating of the bridge deck with respect to delamination, corrosion, and degradation is calculated independently from NDE measurements. Finally, a combined rating for the bridge deck is obtained by averaging the three overall ratings (i.e., delamination, corrosion, and degradation ratings). The combined condition rating can be used to develop deterioration progression models. Further, individual overall ratings for delamination, corrosion, and degradation can be used to develop distress based degradation models.

- Automated NDE is required because of the size and count of bridge decks that need to be evaluated.

- In the future, continuous health monitoring of the bridge decks shall be performed in order to deploy preventive maintenance activities. To achieve this, a Robotic system is developed that includes the following technologies: (1) GPR arrays, (2) Acoustic arrays,

(3) Resistivity (Wenner) probes, (4) Laser scanners, and (5) a Panoramic (360°) camera. The main components of the Robotic System are a global positioning system (GPS), a wheel encoder for distance measurement, and an inertial measurement unit (IMU) working as gyroscope.

- Implementing an integrated approach of early distress detection and proactive rehabilitation will articulate NDE benefits.

DR. HALUK AKTAN – PRESENTATION SUMMARY

Professor Haluk Aktan is the director of Center for Structural Durability at Western Michigan University. His presentation was on NDE techniques for early age assessment of concrete durability. He also discussed the methodology of evaluating NDE measurement reliability.

LIST OF TECHNOLOGIES

- Resistivity Meter (Wenner Array Probe)
  - Concrete resistivity is considered as an electrical indicator of its permeability.
- Porosiscope (Figg's Device)
  - For measuring near surface air and water permeability in concrete
- Ultrasonic Pulse Velocity (UPV)
  - Used as a predictor of permeability and concrete soundness

EARLY AGE QUALITY ASSESSMENT

Early age health assessment of RC bridge decks will be useful in establishing a continuous quality improvement tool. The tool could assist in understanding the structure, materials, and construction quality, so as to improve the design procedures, material specification, and construction procedures. The need for an early age health assessment tool is expressed by the fact that current practice is not able to control or attain most durability indices, such as cracking, crack width, permeability, time to corrosion, delamination, time to spall, etc. Nevertheless, there is a definite need to develop measures for assessing the overall quality of newly constructed concrete decks.

The construction processes and material specifications involved in the bridge deck replacement are much regimented. However, significant variability exists in the performance of RC bridge decks constructed using the same materials and construction processes. In order to understand the reasons for the variability and for controlling the quality of bridge decks, measures are being developed. In 1992, the Florida Department of Transportation (DOT), followed by other DOTs, identified permeability of concrete as the performance measure.

Generally, the methods used to test the permeability have drawbacks: they are destructive; time consuming, and the variability of their results are high. Concrete permeability is usually determined by taking a core from the bridge deck. Thus, measurements can only

represent the permeability of the core location. As a complete smeared measure for a bridge deck, the *Soundness* is a better representation. To accomplish this, permeability and Ultrasonic Pulse Velocity (UPV) measurement technologies had been integrated to assess the distributed durability of the concrete deck. Here, a fundamental relationship between permeability and UPV was identified. The exception is that UPV is affected by properties of concrete ingredients such as aggregate; thus, cannot be used as an absolute measure, rather it is a relative measure. Considering these aspects, a UPV test has been developed to measure the soundness of RC bridge deck based on the permeability measure.

IMPLEMENTATIONS

Lab

UPV measurements (V_s) are taken on standard concrete specimens prepared during the deck placement. V_s is considered as the benchmark UPV. Following the completion of deck curing, the UPV is measured in the field (V_f). The soundness is measured by a parameter called the Paste Quality Loss (PQL). PQL is a measure of the reduction of soundness between the standard specimens and the deck concrete. PQL representation is shown below based on the reduction of UPV.

$$PQL = \frac{\alpha(V_s - V_f)}{V_s} \qquad\qquad (2)$$

where: α is the statistical distribution factor and is given by $\alpha = {0.954}/{P_F}$; P_F is the probability of V_f to be between $\pm 2\sigma$.

UPV measurements were performed on the following specimens: (1) Standard specimens, (2) Controlled field specimens, and (3) Field specimens with substandard curing. The PQL obtained for the respective specimens is shown in Table A-1.

Table A-1. Paste Quality Loss (PQL) of Test Specimens

Specimen	28 days			90 days		
	UPV (m/s)		PQL	UPV (m/s)		PQL
	Mean	COV (%)	(%)	Mean	COV (%)	(%)
Standard specimen	4820	1.2		4760	1.0	
Controlled field specimen	4440	1.3	**8**	4490	2.4	**9**
Field specimen without curing	4390	2.0	**10**	4400	3.8	**16**

Field

The field implementation was performed on three bridge or deck replacements in the Metro region. The bridge projects were (1) Scotten St. over Michigan Ave, (2) Oakman Avenue over Lodge Freeway (M-10), and (3) I-75 NB to I-94 EB. *Standard specimens* were prepared during concrete placement and tests were conducted on those specimens to document: (1) f'_c, (2) E, (3) UPV, and (4) air permeability.

Afterwards, UPV and Figg's permeability tests were conducted on the aforementioned bridges (decks) at 14, 28, and 56 days. The results from the Figg's permeability test were categorized into 5 rating groups: namely, (1) 0-poor, (2) 1-not good, (3) 2-fair, (4) 3-good, and (5) 4-excellent. Further, the PQL for each of the three decks was identified.

STATUS

Ultrasonic Pulse Velocity (UPV) is considered as a good predictor of permeability, and the Paste Quality Loss (PQL) relation quantifies deck soundness. The lab and field instrumentation had been developed and tested for rapid processing of UPV measurements.

Further, the instruments used for UPV have been improved. For example, the conventional process required surface preparation for UPV measurement. Now, dry contact transducers are available and can be used without a need for surface preparation.

RELIABILITY OF NDE

The reliability of a non-destructive test is composed of three attributes: namely, (1) intrinsic capability, for example, physical and technical principles behind the detection, ultrasonic pulse velocity in relation to elasticity modulus, etc; (2) application factors, for example, realistic circumstances during measurement, transducer coupling, moisture, noise, etc; and (3) human factors, for example, operator use and recording measurements, procedure clarity, inspector training, etc.

Reliability in the measurement sense is repeatability or consistency of measurements. A measurement is considered reliable if the same value is obtained over and over again. The reliability (R) for a measurement and its associated estimate (β) can be described as shown in Eq. 3 below.

$$R = \frac{\text{True level on the measure (T)}}{\text{Entire measure (X)}}$$

$$\beta = \frac{\sigma^2(T)}{\sigma^2(X)}$$

$$X = T + E \rightarrow \sigma^2(X) = \sigma^2(T) + \sigma^2(E) \tag{3}$$

$$\beta = 1 - \frac{\sigma^2(E)}{\sigma^2(X)}$$

where: R is Reliability, β is Reliability Estimate, T is True Result/Score, X is Observed Result/Score, E is Error, σ is Standard Deviation, and σ^2 is Variance.

The reliability estimate, β, is a dimensionless number between 0 and 1; where, β=0 indicates that none of the measurements are true, and β=1 indicates that all measurements are true. For example, if β=0.5 signifies that 50% of the variance of measurements are *true*, and the remaining 50% is in error. Therefore, β can be described as the indicator of proportion of variability in the result attributable to the *true result*.

The error component in the measurements includes random error and systematic error. The random error is due to factors that affect the measurement around the mean. Systematic error is due to factors that systematically affect the measurement across the sample. Here the factors shift the mean from its *true* value.

As the *true* measurements (i.e., without error) are unknown, calculating σ^2(T) for obtaining β may not be possible. However, β may be estimated by the variability of *true results* by considering two sets of measurements as shown in Eq. 4 below.

$$\mathbf{X}_1 = \mathbf{T} + \mathbf{E}_1$$
$$\mathbf{X}_2 = \mathbf{T} + \mathbf{E}_2 \tag{4}$$

where: $\mathbf{X}_1$ and $\mathbf{X}_2$ are two sets of measurements of the same test, with $\mathbf{T}$ as *true measurements* and $\mathbf{E}_1$ and $\mathbf{E}_2$ as respective errors. The correlation between $\mathbf{X}_1$ and $\mathbf{X}_2$ can be used as the estimate of reliability and can be expressed as shown in Eq. 5 below.

$$\beta = \frac{Cov(X_1, X_2)}{\sqrt{\sigma^2(X_1) * \sigma^2(X_2)}}$$

$$\text{where}: Cov(X_1, X_2) = \frac{1}{n} \sum_{i=1}^{n} \left(\left(X_{1_i} - \overline{X_1} \right) \left(X_{2_i} - \overline{X_2} \right) \right) \tag{5}$$

where: $Cov(X_1,X_2)$ is the covariance among data sets X_1 and X_2; n is the number of measurements in each data set; $\overline{X_1}$ and $\overline{X_2}$ are means of the respective data sets. The covariance is a measure of association between two data sets. If the two data sets represent measurement of the same parameter, then $Cov(X_1,X_2)$ is positive; whereas, if the $Cov(X_1,X_2)$ is negative, then the data is considered as invalid, i.e., the measurements are completely distinct.

RECOMMENDATIONS

- The PQL is a measure of final product quality of newly placed concrete decks and can be used to contemplate the construction process as a total quality management tool.

- Following appropriate lab and field studies to document the application factors that impact the measurements, NDE can be integrated in the bridge management system.

- In adopting NDE in bridge management, one must develop clear measurement protocols and train operators to follow the standards specific to the agency. These protocols and standards could supplement ASTM standards (if applicable), because the situations differ from agency to agency.

- The agency also needs to establish a reliability index for the NDE tests considered in the bridge management process. This is because the reliability index can be different for different components of a bridge management system, such as NBI inspection, scoping inspection, planning, etc.

APPENDIX B: WORKSHOP QUESTION/ANSWER SESSION SUMMARY

Q. David Juntunen: What kind of NDE techniques does the German Federal Highway Department regularly use?

A. Herbert Wiggenhauser: For concrete inspection, the cover meter is the standard technology, and for the rebar corrosion detection, the Electro Chemical Potential is the standard technology.

Q. Matt Chynoweth: What is the standard inspection frequency in Germany, and when is it customized (i.e., increased or decreased based on deterioration, etc.)?

A. Herbert Wiggenhauser: Every 3 years the bridges are inspected in Germany, among which every second inspection (every 6 years) is an in-depth inspection. The special inspections are performed only under special circumstances.

Q. How long did it take to perform the inspection of a box girder using NDE technologies in regards to the investigation performed in Germany? Also, how far is it feasible to take the technology to field, for example locating tendon ducts in the field?

A. Herbert Wiggenhauser: The inspection of the box girder (inner up) was part of a research project and took almost a week. However, if all things go right, then the NDE inspection could be completed within 1 or 2 days. The inspection time for 1 square meter for ultrasonic echo is about 1 hr (i.e., approximately same as the time required by any NDE technology that requires a physical contact), and 5 minutes for Radar (i.e., approximately same as the time required by any NDE technology using scanning device).

The data processing requires additional time. Currently, there are no professional data processing softwares available. In the future, if there is high demand for such softwares and they are made available, then the NDE technology could be deployed along with field data processing (e.g., identifying the location of a tendon duct in the field).

Q. Herbert Wiggenhauser: Ten years ago IR research was discontinued because of reliability issues with the field use of the technology. MDOT appears to have made an investment in this area. Regarding the usage of IR Thermal cameras by MDOT, what are the experiences?

A. Jason DeRuyver: It is not recommended to collect the data of the deck during traffic. After numerous uses, the technicians are gaining confidence. Before the equipment investment, the expectations were very high. Following its use for a while, the expectations were lowered. Further, the use guidelines and procedures that are included with the camera are not really

followed at all the times. This is because of factors such as climate conditions, exposure, and time of day. The data require interpretation based on the measurement conditions.

Q. Sudhakar Kulkarni: Following construction of new bridges, within a month or so, cracks are observed on the bridge deck. TRB and other researchers identified the cause as drying shrinkage. Thus, MDOT started pouring decks at night to control the evaporation. Still decks crack. Will the *rapid bridge deck testing facility* that is planned, as part of the LTBPP, investigate measures to reduce early age cracking of bridge decks?

A. Nenad Gucunski: Regarding the project that Rutgers is initiating with NJDOT, they have few concerns regarding high-performance concrete bridge decks. They want to identify the current condition of those bridge decks, and if cracks are present, they want to understand the impact. In order to address their concerns, Rutgers will be assessing the overall condition of those bridge decks. The project will work on identifying crack depths and establish correlation between crack depth and deterioration. Further, new bridges constructed in NJ are to be investigated with various techniques. For example, curing will be monitored after 1 or 2 days of casting the deck, the concrete modulus will be investigated, any cracks that are developed will be characterized, and investigation will be performed to identify the consequences of crack propagation.

Q. David Juntunen: The damage evaluation worksheet shown by Dr. Ahlborn, which involves different elements and their condition, is of interest in bridge preservation and maintenance. In bridge preservation, for a given condition state of the bridge, the corrective action is decided based on a similar worksheet that MDOT developed. Can the worksheet that Dr. Ahlborn's team developed be shared with MDOT?

A. Tess Ahlborn: The worksheet is the part of RITA project deliverable. The final report is published and available on the RITA website. The worksheet is public information and is available to MDOT. The worksheet needs to be reassessed for use in bridge preservation, because it is about health indicators. Based on the type of defect and its extent, the health indicators may change and affect the condition states. This will be a next step for advancing that worksheet.

Q. David Juntunen: Regarding the database that Ali Maher and his team is working on, AASHTO in parallel is updating the national bridge elements and defining the condition states as good, fair, or severe. Is there any coordination between what Ali Maher's team is doing and AASHTO?

A. Ali Maher: The Rutgers team regularly briefs various AASHTO committees. The way that FHWA LTBPP set up the project is that in the long-term (i.e., 20 years) process of data collection, there is the expectation to identify relationships for the performance indicators. However, there are also short-term objectives for the FHWA LTBPP to address. From the AASHTO standpoint, the message is quite different where short-term results need to be produced by testing etc., through complementing projects for providing data in updating the national bridge elements and their condition states.

Q. David Juntunen: This is in Regard to the animation that Nenad Gucunski showed, which presented the future delamination growth in a component with time. Here in Michigan, MDOT tries to preserve the bridges as long as economically feasible. For bridge deck rehabilitation, first the quantity of bridge deck that is delaminated and spalled is calculated. Then an appropriate rehabilitation procedure is performed to stop the deterioration. MDOT is interested in knowing if there is possibility to identify the time duration from delamination to spall (using the animation showed in the presentation) so that corrective actions could be scheduled proactively.

A. Nenad Gucunski: The animation presented utilized data from GPR. The research team needs to obtain more data through LTBPP; then the deterioration curves could be developed that can better predict the time of progression from one stage of deterioration to the next. Also, the bridge assessment project that is being developed under FHWA funding identifies the delaminated or any other deteriorated areas in the bridge deck. It then transfers respective coordinates to another robot that Rutgers is currently developing. This robot is expected to take action to stop the deterioration, similar to welding a crack to stop its propagation.

A. Ali Maher: This is a fundamental question that constantly drives the LTBPP, and it is among the primary questions that were obtained from discussions with several stakeholders. There are around 1000 bridges distributed around the US under periodic monitoring among which Michigan bridges would be prominently represented. Ultimately, those bridges will be

instrumented, and we could obtain more data points to develop the deterioration curves for Michigan bridges. However, this process will take time as these come under the long-term objectives of the LTBPP. Clearly, it is challenging to manage the long-term objectives with the intermittent short-term expectation of the LTBPP.

APPENDIX C: WORKSHOP PARTICIPANTS

Table B-1. List of Attendees (Non-Destructive Testing of Highway Bridge Assets- March 28, 2013- Lansing)

Last Name	First Name	Account Name	E-mail
Adefeso	Olukayode	MDOT – Metro Region	adefesoo@michigan.gov
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