View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Directory of Open Access Journals

ISSN 1392-3730/eISSN 1822-3605
2015 Volume 21(5): 654–665
doi:10.3846/13923730.2014.890665

BRIDGE INSPECTION PRACTICES USING NON-DESTRUCTIVE TESTING METHODS

Sangwook LEE, Nikolas KALOS

Department of Construction Engineering and Engineering Technology, Texas Tech University,
2500 Broadway Lubbock, TX 79406, USA

Received 09 Nov 2012; accepted 20 Dec 2012

Abstract. Non-Destructive Testing (NDT) methods have been developed and employed as a means of rapid and effective structural inspection. Despite the various kinds of NDT methods developed for bridge inspection, not much study has been performed on their usage and effectiveness at a practical level. This paper presents an evaluation of NDT methods to identify how they are implemented in state agencies in the U.S. The findings and analysis presented herein were based on the results obtained from a survey questionnaire, targeted at Departments of Transportation (DOTs) in all U.S. states and territories. The survey questionnaire was initiated to clarify multiple issues regarding NDT implementation, such as identifying the types of inspection that involve NDT methods, bridge components that are most likely to be inspected with NDT, effective methods of inspecting concrete or steel structures, and so on. A total of 40 state agencies participated in the survey processing, and the major findings obtained from the states are illustrated and explained in detail in this paper. In addition, bridge defects that are hard to detect in the course of inspection and current research efforts to develop novel NDT methods were investigated.

Keywords: non-destructive testing, non-destructive evaluation, bridge management, bridge inspection.

Introduction

According to the data from the Bureau of Transportation Statistics, there are more than 600,000 highway bridges in the U.S., among which around 25% are rated as either structurally deficient, functionally obsolete, or both (Bureau of Transportation Statistics 2009). The number of structurally deficient or functionally obsolete bridges by state can be found in Minchin *et al.* (2006). As existing infrastructure systems are aged and deteriorated rapidly, more and more investment funding becomes necessary to eliminate deficiencies. However, the amount of funding available is typically limited and much less than the amount required for correcting deficiencies. Some critical defects in a bridge can be missed under this limited funding situation and increased inspection loads, and may eventually lead to catastrophic bridge collapses such as the Silver Bridge collapse in Point Pleasant, West Virginia in which 46 people were killed (LeRose 2001). Accurate assessment of bridge condition has become a daunting challenge to keep bridges at the acceptable level. As a result, bridge management standards, methods, and strategies have been developed continuously to meet this challenge. Recently, a joint ad-hoc group of the American Society of Civil Engineers/Structures Engineering Institute and American Association of State Highway and Transportation Officials (ASCE/SEI – AASHTO) was formed to identify needs and issues associated with ensuring the safety of highway bridges across the U.S. and to examine how current bridge inspection practices could be improved in the future. They addressed ten major challenges, including bridge inspection policy and consistency of inspection ratings (ASCE/SEI-AASHTO 2009). It should be noted that one of the challenges was the development of effective NDT methods and their guidelines for the appropriate application of the methods.

Over the last several decades, non-destructive testing (NDT) methods have been developed and employed as a means of rapid and effective structure inspections. The implementation of NDT methods has drastically impacted the time required to detect, analyze, and diagnose a host of structural problems such as cracks, voids, fatigue, delamination, corrosion, and loss of cross section. In general, NDT technologies are distinguished from one another based on the type of material they are designed to inspect or the type of structural defect they are designed to detect. The two most common categories of materials NDT methods are designed for are concrete and steel. While some NDT methods are simple, many are very complicated and require significant operator training. Also, some bridge inspections are inherently

Corresponding author: Sangwook Lee
E-mail: *sang.lee@ttu.edu*

Copyright © 2015 Vilnius Gediminas Technical University (VGTU) Press
www.tandfonline.com/tcem

Taylor & Francis
Taylor & Francis Group

dangerous to inspectors, such as underwater inspections (Stromberg 2010).

While research on the application of specific NDT methods can be easily found from multiple sources, a study on NDT usage by state DOTs for their bridge management programs has not been performed actively in the literature. Rens *et al.* (1997) presented a detailed review of major NDT methods and their application areas for civil engineering structures. The methods they reviewed are acoustic emission, thermal methods, ultrasound, magnetic methods, and vibration analysis. They also presented some tables on the use of NDT obtained from a short survey to transportation agencies, focused on types of methods and application areas. A more comprehensive study on bridge inspections and NDT usage was performed by Rolander *et al.* (2001). They revealed that the most frequently used non-destructive evaluation technique was visual inspection, which was applied by most states participating in the survey. Also, they found that five techniques were commonly used for bridge inspections: ultrasonic testing, magnetic particle testing, penetrant testing, radiographic testing, and ultrasonic testing. From the literature review, it was clear that there is a need to make a further study on the NDT usage in state agencies since previous studies failed to deliver in-depth knowledge on the use or effectiveness and did not properly reflect currently available NDT methods such as smart concrete.

The main objective of this paper is to clarify how, when, and where state DOTs utilize NDT methods specifically for highway bridge inspections. This was accomplished by developing and distributing a survey questionnaire to as many U.S. state DOTs as possible. The questionnaire was launched to accomplish several objectives: (1) to identify the circumstances that DOTs use contractors for NDT and general inspection work, (2) to determine the types of inspections that involve NDT methods and bridge components that are most likely to be inspected with NDT, (3) to gauge the effectiveness and ease of NDT methods for both concrete and steel structural systems, (4) to determine bridge defects that are hard to detect with current NDT methods, and (5) to report current research efforts to develop novel NDT methods.

The paper begins with a detailed look at the survey questionnaire methodology and design, followed by an analysis and discussion of the survey results. Lastly, this paper concludes with the authors' findings.

1. Survey questionnaire

1.1. Survey methodology

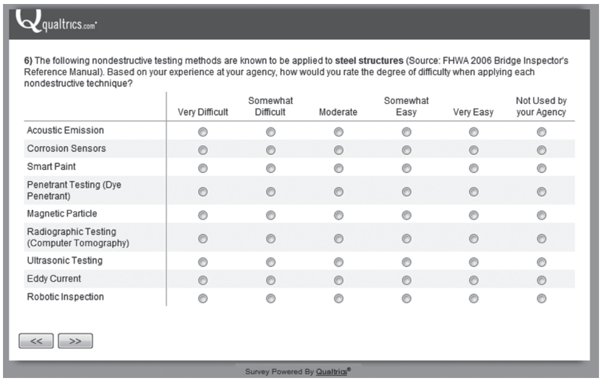
The objective of the survey questionnaire was to investigate how NDT technologies are being utilized in U.S. bridge inspection programs. The survey seeks to ascertain the most commonly used NDT technologies for concrete and steel structures, the most common types of inspections in which NDT is considered, the technologies that provide accurate measurements, and the level at which outside contractors are used for NDT. All 52 states and territories of the U.S. were initially targeted for survey distribution. The survey considered NDT methods in two categories – methods for inspecting concrete and methods for inspecting steel. The technologies covered were chosen based on those covered in the Bridge Inspector's Reference Manual published by the Federal Highway Administration in 2006 (Ryan 2006). The 2006 FHWA manual was chosen for several reasons: (1) It provides a comprehensive guide for all state agencies for conducting bridge inspections, (2) Many state DOTs widely use this document as a primary reference, and (3) It is the most recent publication of its type.

From the reference manual, sixteen NDT methods were chosen for concrete structure inspection. These are: Acoustic emission, electrical method, delamination detection machinery, ground penetrating radar, electromagnetic methods, pulse velocity, impact-echo testing, infrared thermography, ultrasonic testing, laser ultrasonic testing, magnetic method, neutron probe, nuclear method, pachometer, smart concrete, and rebound and penetration.

Nine NDT methods were chosen for steel structure inspection. These are: Acoustic emission, corrosion sensors, smart paint, penetrant testing, magnetic particle, radiographic testing, ultrasonic testing, eddy current, and robotic inspection.

1.2. Survey questionnaire design

The survey questionnaire was created using an online service to minimize the time required to take the survey, and for ease of distribution of the questionnaire. The questionnaire was designed to seek statistics on level of usage, perceived ease of use, perceived difficulty of operation, division of in house versus contractor work, and the most common applications of NDT technologies from each state's department of transportation. Additionally, respondents were asked if there was any novel NDT research being conducted by their department. Figure 1 shows a screenshot of the survey questionnaire. Typically, bridge inspection personnel's schedules are pretty tight, splitting their time between their regional office and the



6) The following nondestructive testing methods are known to be applied to **steel structures** (Source: FHWA 2006 Bridge Inspector's Reference Manual). Based on your experience at your agency, how would you rate the degree of difficulty when applying each nondestructive technique?

	Very Difficult	Somewhat Difficult	Moderate	Somewhat Easy	Very Easy	Not Used by your Agency
Acoustic Emission	○	○	○	○	○	○
Corrosion Sensors	○	○	○	○	○	○
Smart Paint	○	○	○	○	○	○
Penetrant Testing (Dye Penetrant)	○	○	○	○	○	○
Magnetic Particle	○	○	○	○	○	○
Radiographic Testing (Computer Tomography)	○	○	○	○	○	○
Ultrasonic Testing	○	○	○	○	○	○
Eddy Current	○	○	○	○	○	○
Robotic Inspection	○	○	○	○	○	○

Fig. 1. Survey questionnaire sample

field. Thus, it was critical to keep the questionnaire as brief as possible to ensure responses in a timely manner and so the questionnaire was designed to be taken in under an hour.

Further, the amount of writing required to answer the questionnaire was kept as minimal as possible. Additionally, answer choice appearance logic was used to minimize the potential for a respondent to make a mistake by removing choices in later questions if the respondent selected "No experience" for a particular NDT technology. The questionnaire consisted of six major categories described in detail below. Despite its common use by bridge inspection units, the questionnaire did not consider visual inspections. Visual inspections are applied by most states currently and are well documented by previous studies.

1) *Who inspects highway bridges?* This category investigated what percentage of bridge inspection work was done in-house or contracted out to a third-party.
2) *In which types of inspection is NDT being considered?* The respondent was asked to rate each category based on how often an NDT technology was considered for that category. The categories of inspections are as follows:
   - Initial Inspection: This is the first inspection performed to a new bridge or when there is a major change in the configuration or geometry of a bridge.
   - Routine Inspection: A regularly scheduled inspection consisting of observations and/or measurements needed to determine the physical and functional condition of the bridge.
   - Damage Inspection: An unscheduled inspection to assess structural damages resulting from environmental factors or human actions.
   - In-depth Inspection: A close-up inspection of one or more members above or below the water level to identify any deficiencies not readily detectable using routine inspection procedures.
   - Fracture-Critical Inspection: A regularly scheduled inspection to examine the fracture-critical members or components of a bridge.
   - Underwater Inspection: This inspection involves sounding to locate the channel bottom, probing to locate the deterioration of substructure and undermining, diving to visually inspect and measure bridge components, or some combination thereof.
   - Special Inspection: An inspection scheduled at the discretion of the bridge owner or the responsible agency. It is used to monitor a particular known or suspected deficiency such as foundation settlement or scour.
3) *To which bridge components is NDT commonly applied?* The respondent was asked to rate a list of bridge components based on how often an NDT technology was considered for that component. A wide range of bridge components were investigated, including: decks, beams and girders, truss members, cables, rivets bolts and welding, pins and hangars, bearings, paint, abutments, retaining walls, piers and bents, pile bents, dolphins and fenders, footings and foundations, and culverts as bridges.
4) *What types of NDT methods are used for concrete structures, and how effective are those methods?* The respondent was asked to rate a list of applicable NDT methods for concrete structures for effectiveness on a five degree scale ranging from very effective to not effective. Additionally, respondents were asked to rate the difficulty of application of NDT methods for concrete structures, on a five degree scale ranging from very difficult to very easy.
5) *What types of NDT methods are used for steel structures, and how effective are those methods?* The respondent was asked to rate a list of applicable NDT methods for steel structures for effectiveness on the same scale as concrete methods. Additionally, respondents were asked to rate the difficulty of application of NDT methods for steel structures on the same scale as concrete methods.
6) The final category asked the respondents if they were aware of any bridge defects that to their knowledge cannot be detected by an existing NDT method mentioned previously in the questionnaire. The respondent was also asked if their state agency was conducting any novel NDT research.

1.3. Process of survey questionnaire

The questionnaire was targeted at bridge inspection unit managers or a similar high level position within a state's bridge inspection program. The respondents were contacted by looking up their contact information in their respective state agency's online directory. However, not all states list their bridge inspection unit's contact information on their website, or only list staff phone numbers. This created some difficulty locating the proper staff to send the survey to. In cases where the bridge unit's contact information was not listed, the main agency office had to be contacted and the bridge unit was tracked down by transfer after transfer.

Survey distribution began on February 14th, 2012. Since each agency's target contact had to be found, the surveys were distributed to one respondent at a time. The target response rate for the survey was at least 60% of the states in the U.S. The distribution period was initially set from mid-February to mid-April, but was extended to May 1st to increase the number of responses. During this time period, the survey was constantly monitored to check for errors and to quickly process newly completed questionnaires. Of the 52 states and territories, a total of 40 responded, equivalent to a 76% response rate (refer to Fig. 2).

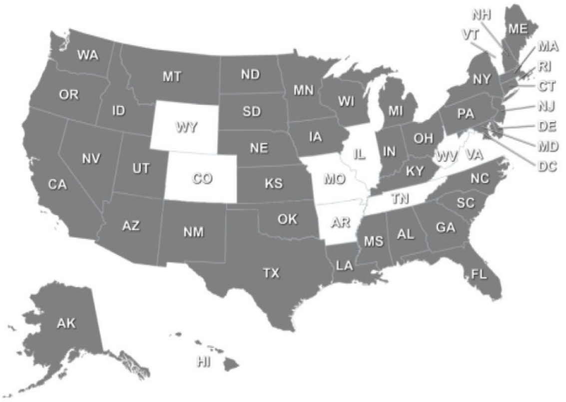


Fig. 2. Map of states surveyed

2. Analysis and results of survey questionnaire

The analysis and results of the survey questionnaire are presented below. The reader should note that the findings on the ease of use and the level of effectiveness of a NDT method are from the point of view of state agencies, and do not necessarily represent the true ease of use and level of effectiveness of a particular NDT method.

2.1 Allocation of state bridge inspection labor

The analysis of collected responses showed that state agencies conduct 74% of the total bridge inspection workload on average, while outside contractors are responsible for 26%.

Six states, Connecticut, Florida, Nevada, New Jersey, South Dakota, and Texas, are exceptions, contracting greater than 60% of bridge inspection work to third parties. Alaska, Arizona, Hawaii, Minnesota, New York, North Dakota, Washington, and Wisconsin perform 100% of their general inspection work in house. California, Georgia, Idaho, Iowa, Kansas, Louisiana, Maine, Mississippi, and Ohio contract out less than 2% of their bridge inspection work.

2.2. Application of NDT methods by inspection types

Each respondent was asked to rate each inspection type on a five degree scale: very often considered, often considered, sometimes considered, rarely considered, and not considered. The complete description of these inspection types is presented in Section 1.2. Table 1 shows the survey responses by percentage. The data shows that while there is some variability among the states surveyed, NDT methods are considered for every type of inspection. However, in the initial inspection category, 48% of states did not consider NDT methods for this inspection type. Also, 43% of states rarely or never use NDT methods for routine inspections. NDT usage in underwater inspections also appears to be very minimal.

Divers are required to inspect any underwater structural element, such as foundation footings, and typically employ sonar based equipment to create images of damaged areas. However, these sonar techniques only detect visible surface flaws, and their performance can be greatly affected by in-situ water conditions (Stromberg 2010). Because divers and expensive equipment are required, it is reasonable for many states to contract underwater inspections to third party specialists.

Responses for damage and special inspections indicated that NDT methods are frequently used in these cases, with “Not considered” response percentages of 5% and 0%, respectively.

2.3. Allocation of state bridge inspection labor when NDT is required

Respondents were asked to describe the allocation of labor when NDT methods are required. They were asked to assign a percentage to either in house or contract work based on inspection type. The categories of inspection types were the same as in Section 2.2. Table 2 shows the survey responses.

The values show the average percentage of the typical division of labor for each inspection type. “Not considered” responses were not included in the calculation of the average. Most state agencies contract out underwater inspections due to the high degree of difficulty and extra training required.

2.4. Application of NDT methods on bridge components

Each respondent was asked to rate each bridge component’s frequency of consideration on a five degree scale: very often considered, often considered, sometimes considered, rarely considered, and not considered. Three different categories of bridge components were considered,

Table 1. NDT usage by inspection type

Inspection type	Very often considered (%)	Often considered (%)	Sometimes considered (%)	Rarely considered (%)	Not considered (%)
Initial	10	5	–	37	48
Routine	12	12	33	23	20
Damage	20	37	38	–	5
In-depth	32	17	30	13	8
Fracture-critical	22	32	33	5	8
Underwater	7	8	35	30	20
Special	25	35	30	10	–

Table 2. Allocation of inspection labor when NDT is required

Inspection type	State agency (%)	Outside contractor (%)
Initial	87.7	12.3
Routine	75.7	24.3
Damage	78.4	21.6
In-depth	73.4	26.6
Fracture-critical	71.5	28.5
Underwater	18.4	81.6
Special	67.4	32.6

bridge decks, superstructure components, and substructure components. The bridge components considered are: decks, beams and girders, truss members, cables, rivets bolts and welding, pins and hangars, bearings, paint, abutments, retaining walls, piers and bents, pile bents, dolphins and fenders, footings and foundations, and culverts as bridges. Tables 3 and 4 present the survey results by percentage for each component of the three categories.

The data collected from this question indicate that NDT methods are frequently used to inspect components of bridge superstructure, and seldom used to inspect substructure components. However, there are exceptions in the superstructure, such as bearings and paint. Bearings transfer load to the foundations, dampen vibrations throughout the bridge, and are located in between pier and foundation footings.

Bearings are composed of smaller elements such as bolts, pins, and welds and thus many inspections of bearings would fall under other categories.

Paint on structural members is primarily used to increase corrosion resistance, and typically a simple visual inspection is all that is required to determine its condition.

Similarly, many substructure components, such as retaining walls, dolphins, and culverts as bridges, do not require extensive inspection, either due to their function as non-load bearing structures or their size. Table 5 provides an overall look at the level of preference for NDT methods for bridge components.

Each component was assigned a score from –2 to +2, described by Eqn (1), based on the number of responses corresponding to the frequency of consideration scale mentioned above. Based on this scoring system, pins, hangars, rivets, bolts, welding, beams, girders, and decks are the most commonly inspected components using NDT methods. All substructure components received negative preference scores, indicating that they are rarely inspected using NDT.

$$P_s = 2s_1 + 1s_2 + 0s_3 - 1s_4 - 2s_5, \quad (1)$$

where: P_s is the NDT Preference Score; s_1 – number of very often considered responses; s_2 – number of often considered responses; s_3 – number of sometimes considered responses; s_4 – number of rarely considered responses; and s_5 – number of not considered responses.

Table 3. NDT usage for bridge deck and superstructure components

Bridge component		Very often considered (%)	Often considered (%)	Sometimes considered (%)	Rarely considered (%)	Not considered (%)
Superstructure	Deck	17	18	35	15	15
	Beams and girders	10	17	60	10	3
	Truss members	17	25	50	8	–
	Cables	12	22	33	13	20
	Rivets, bolts, and welding	20	37	33	10	–
	Pins and hangars	50	32	18	–	–
	Bearings	–	–	22	55	23
	Paint	–	10	20	37	33

Table 4. NDT usage for bridge substructure components

Bridge component	Very often considered (%)	Often considered (%)	Sometimes considered (%)	Rarely considered (%)	Not considered (%)
Abutments	–	–	20	35	45
Retaining walls	–	–	12	35	53
Piers and bents	–	–	37	35	28
Pile bents	–	–	31	33	36
Dolphins and fenders	–	–	10	45	45
Footings and foundations	–	–	25	37	38
Culverts as bridges	–	–	7	45	48

2.5. Degree of difficulty for application of NDT methods to concrete structures

Each respondent was asked to rank how difficult each NDT method is to use on a five degree scale: very difficult, somewhat difficult, moderate, somewhat easy, and very easy. The NDT methods were chosen based on the FHWA 2006 Bridge Inspector's Reference Manual, which is a comprehensive manual on programs, procedures, and techniques for inspecting and evaluating a variety of in-service highway bridges. Table 6 shows the survey responses for the difficulty of application for concrete NDT inspection methods.

Table 5. NDT preference score for bridge components

Bridge component		NDT preference score (Ps)
Decks		3
Superstructure	Beams and girders	9
	Truss members	21
	Cables	–2
	Rivets, bolts, and welding	27
	Pins and hangers	53
	Bearings	–40
	Paint	–41
Substructure	Abutments	–50
	Retaining walls	–56
	Piers and bents	–36
	Pile bents	–41
	Dolphins and fenders	–54
	Footings and foundations	–45
	Culverts as bridges	–56

The results in Table 6 illustrate which NDT methods are the easiest for an operator to use in the field for a concrete structure and the exposure level of each NDT method.

Surprisingly, every NDT method received a large number of "no experience" responses, indicating that state agencies use only a few NDT methods, and that there is a large degree of variability between agencies as to what NDT methods they use to inspect concrete structures. Additionally, the results show which technologies state agencies have almost no experience using. By taking the number of responses received for a concrete NDT method and dividing by the number of "no experience" responses received for that method, an exposure percentage can be calculated. A lower value for the exposure percentage indicates that the NDT method has been used rarely by state agencies.

The following methods received the lowest exposure percentages for concrete methods: laser ultrasonic testing (10%), neutron probe (5%), nuclear method (5%), and smart concrete (10%).

These technologies require very expensive and complicated equipment and extensive training to be used properly.

Table 6. Concrete NDT methods: degree of difficult

NDT method	Very difficult (%)	Somewhat difficult (%)	Moderate (%)	Somewhat easy (%)	Very easy (%)	No experience (%)	Exposure percentage (%)
Acoustic emission	10	20	17	3	–	50	50.0
Electrical (half-cell) method	7	10	25	17	8	33	67.5
Delamination detection machinery	–	12	12	15	13	48	52.5
Ground penetrating radar	7	25	37	5	3	23	77.5
Electromagnetic methods (HERMES)	2	10	10	8	–	70	30.0
Pulse velocity	2	10	10	8	–	70	30.0
Impact echo testing	10	20	12	13	–	45	55.5
Infrared thermography	–	7	18	5	15	55	45.0
Ultrasonic testing	–	27	25	12	3	33	67.5
Laser ultrasonic testing	–	7	–	3	–	90	10.0
Magnetic method	–	2	12	15	13	58	42.5
Neutron probe	–	–	5	–	–	95	5.0
Nuclear methods	5	–	–	–	–	95	5.0
Pachometer	–	5	25	22	20	28	72.5
Rebound and penetration	–	–	–	15	25	60	40.0
Smart concrete	–	–	2	5	3	90	10.0

Due to these constraints, it follows that these methods are more than likely to be operated by contractors when used for structural inspection. A notable exception is smart concrete. This method is relatively new, which might be why very few agencies have experience with it. Table 7 illustrates the difficulty of each NDT method for concrete inspection. A point system (Eqn (2)) was used to give each method a score, with a higher score meaning greater difficulty. "No experience" responses were not considered in the calculation of the score:

$$D_f = [5d_1 + 4d_2 + 3d_3 + 2d_4 + 1d_5]/N, \qquad (2)$$

where: D_f – Degree of Difficulty score; d_1 – number of very difficult responses; d_2 – number of somewhat difficult responses; d_3 – number of moderate responses; d_4 – number of somewhat easy responses; d_5 – number of very easy responses; and N – total number of responses.

A score for a NDT method between 0 and 2 can be considered easy to use, between 2 and 4 moderately difficult to use, and greater than 4 difficult to use. The magnetic method, rebound and penetration, and pachometer are the least difficult methods. Medium difficulty methods include electrical methods, delamination detection machinery, ground penetrating radar, and ultrasonic testing.

The most difficult methods to use are the nuclear method and acoustic emission. This distribution is likely due to a mix of several factors; the required number of steps for a method, the level of understanding required to properly apply the method, the amount of time required for setup, or simply the current design of a method.

Table 7. Concrete NDT methods: difficulty score

NDT method	Degree of difficulty (Df)	Standard deviation
Acoustic emission	3.75	0.85
Electrical (half-cell) method	2.89	1.15
Delamination detection machinery	2.48	1.12
Ground penetrating radar	3.39	0.88
Electromagnetic methods (HERMES)	3.25	0.97
Pulse velocity	2.67	1.15
Impact echo testing	3.50	1.06
Infrared thermography	2.39	1.14
Ultrasonic testing	3.15	0.86
Laser ultrasonic testing	3.50	1.00
Magnetic method	2.12	0.93
Neutron probe	3.00	0.00
Nuclear method	5.00	0.00
Pachometer	2.21	0.94
Rebound and penetration	1.38	0.50
Smart concrete	2.00	0.82

2.6. Degree of difficulty for application of NDT methods to steel structures

Each respondent was asked to rank each NDT method for steel structures by using a five degree scale: very difficult, somewhat difficult, moderate, somewhat easy, very easy, and no experience. These technologies were also selected in accordance with the FHWA 2006 Bridge Inspector's Manual. Table 8 shows the survey responses for the difficulty of application for steel NDT inspection methods.

Table 8 was generated in the same way as in Section 2.5. The degree of difficulty was calculated using Eqn (2). A similar exposure percentage as calculated in Section 2.5 can be calculated for steel NDT methods and are denoted next to the following methods in parentheses. From Table 8, it is clear that almost every state agency has experience with penetrant testing (100%), magnetic particle (95%), and ultrasonic testing (95%) indicating that these methods are very popular for steel inspection.

From Table 9, the easiest technologies for application to a steel structure are penetrant testing, the magnetic particle method, and smart paint. Because penetrant testing is simply based on visual examination of how the dye penetrates a member, it is very easy to use. Similarly, the magnetic particle method is very visual, only requiring that the ferrous dust be observed to detect flaws. Medium difficulty methods are ultrasonic testing and the eddy current method. The most difficult methods are acoustic emission and radiographic testing.

State agencies had little to no experience with corrosion sensors (25%), smart paint (10%), and robotic inspection (5%). Corrosion sensors must be installed during the construction of reinforced beams. Corrosion sensors were also developed within the last decade, which is a reasonable explanation for why most states do not have experience using them.

Table 8. Steel NDT methods: degree of difficulty

NDT method	Degree of difficulty (Df)	Standard deviation
Acoustic emission	4.07	0.73
Corrosion sensors	3.20	0.92
Smart paint	2.00	0.00
Penetrant testing (dye penetrant)	1.80	0.82
Magnetic particle	2.08	0.88
Radiographic testing (computer tomography)	4.31	0.48
Ultrasonic testing	3.11	0.86
Eddy current	2.68	0.75
Robotic inspection	4.00	1.41

Table 9. Steel NDT methods: difficulty score

NDT method	Very difficult (%)	Somewhat difficult (%)	Moderate (%)	Somewhat easy (%)	Very easy (%)	No experience (%)	Exposure percentage (%)
Acoustic emission	10	17	8	–	–	65	35.0
Corrosion sensors	–	10	12	–	3	75	25.0
Smart paint	–	–	–	10	–	90	10.0
Penetrant testing (dye penetrant)	–	5	10	45	40	–	100.0
Magnetic particle	–	2	33	30	30	5	95.0
Radiographic testing (computer tomography)	12	28	–	–	–	60	40.0
Ultrasonic testing	–	35	40	15	5	5	95.0
Eddy current	–	7	17	23		53	47.5
Robotic inspection	2	–	3	–	–	95	5.0

While smart paint was reported to be easy to use, there were very few state agencies that had experience with it, primarily because of how young the technology is.

2.7. Effectiveness of NDT methods applied to concrete structures

Each respondent was asked to rank the effectiveness of defect detection of each NDT method on a five degree scale: very effective, somewhat effective, moderate, less effective, not effective, and no experience. The respondents were asked to evaluate the same NDT methods listed in Section 2.5 based on the five degree scale.

Table 11 illustrates the effectiveness of each NDT method for concrete inspection, and was generated similarly with the previous tables.

A point system (Eqn (3)) was used to give each method a score, with a higher score being more effective. "No experience" responses were not considered in the calculation of the score.

$$E_f = \frac{\left[5e_1 + 4e_2 + 3e_3 + 2e_4 + 1e_5\right]}{N}, \qquad (3)$$

where: E_f – degree of effectiveness; e_1 – number of very effective responses; e_2 – number of somewhat effective responses; e_3 – number of moderate responses; e_4 – number of less effective responses; e_5 – number of not effective responses; and N – total number of responses.

An NDT method with a value for E_f between 0 and 2 can be considered not effective, between 2 and 4 moderately effective, and greater than 4 very effective.

The results displayed in Table 10 show a high degree of variability in the perceived effectiveness of each NDT method, with many of the methods displaying a high standard deviation. Comparing these findings with those found in Section 2.5, no one NDT method is a "silver bullet" when inspecting concrete.

Table 10. Concrete NDT methods: effectiveness score

NDT method	Degree of effectiveness (Ef)	Standard dev iation
Acoustic emission	2.85	1.14
Electrical method (half-cell)	3.11	1.01
Delamination detection machinery	3.71	1.01
Ground penetrating radar	3.29	1.01
Electromagnetic methods (HERMES)	2.33	0.78
Pulse velocity	2.42	0.67
Impact echo testing	3.18	1.01
Infrared thermography	3.11	0.96
Ultrasonic testing	3.04	1.32
Laser ultrasonic testing	2.00	0.82
Magnetic method	2.59	1.23
Neutron probe	4.00	0.00
Nuclear method	2.50	0.71
Pachometer	3.45	0.91
Rebound and penetration	3.19	0.83
Smart concrete	3.00	0.00

Generally, most of the methods were reported to be somewhat difficult to use and somewhat effective. There was very little variability for the degree of effectiveness for each technology, with scores ranging from 2 to 4. Thus, it is reasonable to assume that most concrete NDT methods have some problem inspecting a particular structural element due to its size, shape, or condition. The neutron probe method received the highest effectiveness score. However, only a few state agencies reported having experience with this method.

Table 11. Concrete NDT methods: degree of effectiveness

NDT method	Very effective	Somewhat effective	Moderate	Less effective	Not effective	No experience
Acoustic emission	–	17	18	5	10	50
Electrical (half-cell) method	–	30	22	7	8	33
Delamination detection machinery	12	20	12	8	–	48
Ground penetrating radar	7	27	25	15	3	23
Electromagnetic methods (HERMES)	–	–	15	10	5	70
Pulse velocity	–	–	15	12	3	70
Impact echo testing	5	12	30	3	5	45
Infrared thermography	–	20	12	10	3	55
Ultrasonic testing	10	17	15	15	10	33
Laser ultrasonic testing	–	–	2	5	3	90
Magnetic method	2	7	13	10	10	58
Neutron probe	–	5	–	–	–	95
Nuclear methods	–	–	2	3	–	95
Pachometer	2	45	7	18	–	28
Rebound and penetration	–	15	20	2	3	60
Smart concrete	–	–	10	–	–	90

Table 12. Steel NDT methods: degree of effectiveness

NDT method	Degree of effectiveness (Ef)	Standard deviation
Acoustic emission	3.57	0.94
Corrosion sensors	2.30	0.67
Smart paint	3.00	1.15
Penetrant testing (dye penetrant)	4.13	0.88
Magnetic particle	4.13	0.81
Radiographic testing (computer tomography)	4.25	0.68
Ultrasonic testing	4.34	0.78
Eddy current	3.68	1.25
Robotic inspection	4.00	1.41

2.8. Effectiveness of NDT methods applied to steel structures

Each respondent was asked to rank the effectiveness of defect detection of each NDT method on a five degree scale: very effective, somewhat effective, moderate, less effective, and not effective.

The respondents were asked to evaluate the same NDT methods listed in Section 2.6. Table 12 presents the survey responses for the effectiveness level of steel NDT inspection methods. Table 13 was generated similarly to Table 10. Penetrant testing, ultrasonic testing, radiographic testing, and magnetic particle are very effective NDT methods for inspecting steel members. Comparing this data with the data from Section 2.6, penetrant testing and the magnetic particle methods are all around great candidate methods for inspecting steel structures. Acoustic emission and eddy current fall into the medium effectiveness category. Interestingly, acoustic emission was reported to have an effectiveness score of 2.85 in the Section 2.7 data when inspecting concrete.

The higher score for steel is probably attributable to steel's higher acoustical propagation properties versus reinforced concrete. Again, state agencies had very little experience with corrosion sensors, smart paint, and robotic inspection. Steel NDT methods seem to be rated as much more effective on average versus their concrete counterparts.

2.9. Efficiency of NDT methods: concrete

Based on Tables 7 and 11, an efficiency ratio can be calculated (Eqn (4)) for each concrete NDT method to illustrate which technologies are the "best":

$$Efficiency\ Ratio = \frac{E_f}{D_f}. \tag{4}$$

A high efficiency ratio indicates that the NDT method is more effective and less difficult, while a low efficiency ratio indicates the method is less effective and more difficult. The minimum and maximum possible values for the efficiency ratio are 0.2 and 5, respectively. The technologies were ranked from high to low. This study calculated efficiency ratio values from only two factors, the degree of difficulty and the degree of effectiveness of each technology.

Other factors, such as cost of equipment or required number of personnel, were not considered in this study.

Table 13. Steel NDT methods: effectiveness score

NDT method	Very effective (%)	Somewhat effective (%)	Moderate (%)	Less effective (%)	Not effective (%)	No experience (%)
Acoustic emission	5	15	10	5	–	65
Corrosion sensors	–	–	10	12	3	75
Smart paint	–	5	–	5	–	90
Penetrant testing (dye penetrant)	40	37	18	5	–	–
Magnetic particle	35	40	18	6	–	1
Radiographic testing (computer tomography)	15	20	5	–	–	60
Ultrasonic testing	45	42	3	5	–	5
Eddy current	15	12	15	–	5	53
Robotic inspection	2	–	3	–	–	95

Table 14. Efficiency ratio of concrete NDT methods

NDT method	Efficiency Ratio
Rebound and penetration	2.32
Pachometer	1.56
Delamination detection machinery	1.50
Smart concrete	1.50
Neutron probe	1.33
Infrared thermography	1.30
Magnetic method	1.22
Electrical method (half-cell)	1.08
Ground penetrating radar	0.97
Ultrasonic testing	0.96
Pulse velocity	0.91
Impact echo testing	0.91
Acoustic emission	0.76
Electromagnetic methods (HERMES)	0.72
Laser ultrasonic testing	0.57
Nuclear method	0.50

As such, the following findings for the best technology only reflect their efficiency and difficulty levels.

The results of this analysis are displayed in Table 14. By a wide margin, rebound and penetration has the highest efficiency ratio of all the concrete NDT methods. Fifty percent of concrete NDT methods had an efficiency ratio less than 1, indicating that many NDT methods still require improvements in either their accuracy or ease of use. This is especially true for laser ultrasonic testing and the nuclear method, which had the lowest ratios.

2.10. Efficiency of NDT methods: steel

Steel NDT methods were ranked in the same way as in Section 2.8, based on Tables 9 and 13, and Eqn (4). The results of this analysis are displayed in Table 15.

Table 15. Efficiency ratio of steel NDT methods

NDT method	Efficiency Ratio
Penetrant testing (dye penetrant)	2.29
Magnetic particle	1.99
Smart paint	1.50
Ultrasonic testing	1.40
Eddy current	1.37
Robotic inspection	1.00
Radiographic testing (computer tomography)	0.99
Acoustic emission	0.88
Corrosion sensors	0.72

Overall, steel NDT methods received high efficiency ratios compared with the efficiency ratios calculated for concrete NDT methods. Penetrant testing received the highest efficiency ratio of any NDT method, concrete or steel, with a value of 2.29

While most steel NDT methods received an efficiency ratio greater than one, acoustic emission and corrosion sensors appear to require improvements to become competitive with the rest of the group.

2.11. Current issues with NDT methods

Respondents were able to respond to this question with a text box. Only seven state DOTs surveyed answered this question. The purpose of this question was to gain practical knowledge from respondents about any current problems with NDT methods or evaluations:

- Alaska DOT – “Below ground pile length and condition”.
- Pennsylvania DOT – “The degree of corrosion of prestressing strand in precast bridge beams. There does not seem to be a technique that can quantify the area of prestressing steel in which corrosion is taking place but the strands are not visible”.

- Florida DOT – “Our major issue, where a better non-destructive testing method is desirable, is detecting the condition of post tensioning strands and the grout inside post tensioning ducts”.
- Ohio DOT – “Section loss in prestressing strands within concrete / Condition of transverse tie rod that distributes load through neighboring prestressed box beams”.
- Kentucky DOT – “Location and size of rebar in an old concrete bridge deck slab that is 10 inches or more thick”.
- New Mexico DOT – “Bridge decks with overlays”.

2.12. Novel NDT methods under progress

Respondents were provided with a text box to submit an answer to this question. Only two of the states surveyed provided a response. The purpose of this question was to investigate the level of research activity taking place in state agencies across the U.S.

- North Dakota DOT – “We are in a pool funded study to research non visual methods of underwater bridge inspection. While the study has been underway for a while, it has just been revitalized and is currently ongoing”.
- Florida DOT – “FDOT has a current research project doing a literature search on NDT methods for post tensioning. This should assist an NCHRP project that is just getting started”.

Conclusions

The main contribution of this paper is an in-depth study on the usage of NDT methods in the U.S. at a practical level. The authors attempted to elucidate the way the NDT methods are utilized for the purpose of bridge inspections and evaluate them principally based on their difficulty of usage and effectiveness. While there are some exceptions, state agencies contract out 25% of general inspection work on average. Sixteen of the states surveyed perform more than 98% of their general inspection work in house.

While NDT methods are used for every inspection type, state agencies rarely use NDT methods when performing initial, routine, and underwater inspections. However, NDT methods are commonly used by state agencies when performing damage and special inspections. It was found that NDT methods are used more frequently by state agencies to inspect bridge superstructure components by state agencies, and seldom used to inspect bridge substructure components. The more complex and expensive a NDT method is, the less likely a state agency is to have experience with it.

In conclusion, major findings from this study can be described as follows.

- *Exposure:* It was surprising that only a few NDT methods are utilized in the field while a variety of methods have been studied and developed by researchers. Only four methods out of 16 showed higher than 60% exposure rate in concrete, and three out of nine indicated higher than 60% in steel. The only method with 100% exposure is penetrant testing.
- *Difficulty:* It was found that state agencies consider most NDT methods difficult to use. This may be one of major reasons why NDT is not used actively. Also, there is no difference between concrete and steel in this trend. The only NDT method with a difficulty score less than two in concrete is rebound and penetration. Penetrant testing is the only method scoring less than two in steel.
- *Effectiveness:* It was found that the effectiveness of steel NDT methods is higher than that of concrete NDT methods. Only one method in concrete, neutron probe, showed an effectiveness score higher than four, but it has very limited exposure. In comparison, five methods in steel showed effectiveness scores higher than four. This may be attributable to the inherent properties of steel.

For all practical purposes, it should be careful when a bridge engineer determines any particular NDT method since there is no single method to diagnose all diseases. Firstly, he/she should identify the bridge defect in question and define the purpose for the use of NDT methods, e.g. assessing location or degree of defects. Then, the engineer can select an appropriate technique after investigating the principles, advantages, and limitations of each NDT method. There are several useful references for this purpose, e.g. Bridge Inspector’s Reference Manual in 2006. Training and education are also critical for the development of qualified bridge inspectors. Most states require inspectors to attend regular training courses and value a certification from the American Society for Nondestructive Testing (ASNT).

References

ASCE/SEI-AASHTO. 2009. White paper on bridge inspection and rating – ad-hoc group on bridge inspection, rating, rehabilitation, and replacement, *Journal of Bridge Engineering* 14(1): 1–5. http://dx.doi.org/10.1061/(ASCE)1084-0702(2009)14:1(1)

Bureau of Transportation Statistics. 2009. *Condition of U.S. highway bridges: 1990–2009* [online] [cited 2 October 2011]. Available from internet: http://www.bts.gov/current_topics/national_and_state_bridge_data/html/bridges_us.html

LeRose, C. 2001. *The collapse of the Silver Bridge*. [online] West Virginia Historical Society Quarterly [cited 15 September 2012]. Available from internet: http://www.wvculture.org/history/wvhs1504.html

Minchin, R. E.; Zayed, T.; Boyd, A. J.; Mendoza, M. 2006. Best practices of bridge system management – a synthesis, *Journal of Management in Engineering* 22(4): 186–195. http://dx.doi.org/10.1061/(ASCE)0742-597X(2006)22:4(186)

Rens, K. L.; Wipf, T. J.; Klaiber, W. 1997. Review of nondestructive evaluation techniques of civil infrastructure, *Journal of Performance Constructed Facilities* 11(4): 152–160. http://dx.doi.org/10.1061/(ASCE)0887-3828(1997)11:4(152)

Rolander, D. D.; Phares, B. M.; Graybeal, B. A.; Moore, M. E.; Washer, G. A. 2001. Highway bridge inspection, *Transportation Research Record* 1749: 73–81. http://dx.doi.org/10.3141/1749-12

Ryan, T. W; Hartle, R. A.; Mann, E.; Danovich, L. 2006. *Bridge inspector's reference manual*. Publication FHWA NHI 03-001. FHWA, U.S. Department of Transportation.

Stromberg, D. 2010. New advances in underwater inspection technologies for railway bridges over water, Presented at the American Railway Engineering and Maintenance-of-Way Association Conference, 29 August 2010, Orlando, Florida.

Sangwook LEE. Assistant Professor in the Department of Construction Engineering and Engineering Technology at Texas Tech University. PhD in the Department of Civil Engineering at Purdue University in 2005. Research interests: bridge management and inspection, application of emerging technologies, risk management, and green construction.

Nikolas KALOS. Graduate Student in the Department of Civil Engineering at Texas Tech University. Research interests: non-destructive evaluation, bridge inspection practices, and bridge maintenance.