Technical Report Documentation Page

1. Report No. ABC-UTC-2013-C3-FIU04	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle **NDT Methods Applicable to Health Monitoring of ABC Closure Joints**	5. Report Date March 2019 6. Performing Organization Code
7. Author(s) Armin Mehrabi https://orcid.org/0000-0003-4736-850X Saman Farhangdoust https://orcid.org/0000-0002-5061-3513	8. Performing Organization Report No. ABC-UTC-2013-C3-FIU04
9. Performing Organization Name and Address Department of Civil and Environmental Engineering Florida International University 10555 West Flagler Street, EC 3680 Miami, FL 33174	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTRT13-G-UTC41
12. Sponsoring Organization Name and Address Accelerated Bridge Construction University Transportation Center Florida International University 10555 W. Flagler Street, EC 3680 Miami, FL 33174 US Department of Transportation Office of the Assistant Secretary for Research and Technology And Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 201590	13. Type of Report and Period Covered Final Report June 2017- March 2019 14. Sponsoring Agency Code

15. Supplementary Notes

Visit www.abc-utc.fiu.edu for other ABC reports.

16. Abstract

In Accelerated Bridge Construction (ABC), prefabricated bridge deck elements are connected using "Closure Joints." Because of cast-in-place nature of closure joints that are expected to go into service and field observations, there have been some concerns about their long-term durability. This has necessitated the need for health monitoring of ABC closure joints using Non-Destructive Testing (NDT) methods. Closure joints contain unique features that sets them apart from conventional deck panels. They require a special treatment when it comes to selecting the appropriate NDT technique. However, a clear guideline for selection of the most applicable NDT method for various types of closure joints has not been developed yet. To address this, a research project was carried out at ABC-UTC at FIU. This report describes this investigation that includes review of all relevant NDT methods and efforts for categorizing closure joints based on features affecting the use of NDT. Since the applicability of NDT methods heavily depend on the type of expected anomaly to be detected and its root causes, all potential defects and damages were identified and investigated using a Damage Sequence Tree (DST). Consequently, damage etiology for closure joints were established using Fault Tree Analysis (FTA). Finally, a quantitative statistical analysis was performed to substantiate the selection of the most applicable NDT methods. The results presented in this report can readily be used by bridge owners and consultants as a practical guideline for selection of NDT methods for health monitoring of ABC bridges with closure joints. Future experimental work is planned for support in implementation and validation of the project conclusions.

17. Key Words Damage Etiology, Damage Detection, Structural Health Monitoring, Non-destructive Testing, Accelerated Bridge Construction, Closure Joints, Bridge Inspection, Concrete Deck.	18. Distribution Statement No restrictions.

19. Security Classification Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages 79	22. Price

(this page is intentionally left blank)

NDT Methods Applicable to Health Monitoring of ABC Closure Joints

Final Report

March 2019

Principal Investigator: Armin Mehrabi

Department of Civil and Environmental Engineering

Florida International University

Authors

Armin Mehrabi
Saman Farhangdoust

Sponsored by

Accelerated Bridge Construction University Transportation Center

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

A report from

Department of Civil and Environmental Engineering
Florida International University
Miami, FL

DISCLAIMER

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This project was supported by the Accelerated Bridge Construction University Transportation Center (ABC-UTC at www.abc-utc.fiu.edu) at Florida International University (FIU). The authors would like to acknowledge the ABC-UTC support.

The author would like to extend special appreciation to the ABC-UTC and the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology for funding this project.

The authors would like express their appreciation to the Research Advisory Panel members: Mr. Steve Womble of Florida DOT, D7, and Mr. Ahmad Abu-Hawash of Iowa DOT.

ABSTRACT

In Accelerated Bridge Construction (ABC), prefabricated bridge deck elements are connected using "Closure Joints." Because of cast-in-place nature of closure joints that are expected to go into service and field observations, there have been some concerns about their long-term durability. This has necessitated the need for health monitoring of ABC closure joints using Non-Destructive Testing (NDT) methods. Closure joints contain unique features that sets them apart from conventional deck panels. They require a special treatment when it comes to selecting the appropriate NDT technique. However, a clear guideline for selection of the most applicable NDT method for various types of closure joints has not been developed yet. To address this, a research project was carried out at ABC-UTC at FIU. This report describes this investigation that includes review of all relevant NDT methods and efforts for categorizing closure joints based on features affecting the use of NDT. Since the applicability of NDT methods heavily depend on the type of expected anomaly to be detected and its root causes, all potential defects and damages were identified and investigated using a Damage Sequence Tree (DST). Consequently, damage etiology for closure joints were established using Fault Tree Analysis (FTA). Finally, a quantitative statistical analysis was performed to substantiate the selection of the most applicable NDT methods. The results presented in this report can readily be used by bridge owners and consultants as a practical guideline for selection of NDT methods for health monitoring of ABC bridges with closure joints. Future experimental work is planned for support in implementation and validation of the project conclusions.

NDT METHODS APPLICABLE TO HEALTH MONITORING OF ABC CLOSURE JOINTS

1 INTRODUCTION

ABC promises to reduce on-site construction time and mobility impact in bridge construction and rehabilitation projects by the use of special design and construction methods. Generally, it comprises of precast elements of the bridge fabricated on site or away, moved to the bridge location and installed in place. Regardless of the fabrication and installation of precast-prefabricated elements, connections need to be established on site and in place. These connections, Closure Joints, are expected to provide continuity between adjoining elements for the purpose they are designed for. Therefore, normally, they contain reinforcing bars and enclosures of various shapes that in some cases create congestion within the joint. To provide shear connectivity, some of these joints are designed with cavities within the precast elements. Ultra-High Performance Concrete (UHPC), Self-Consolidating Concrete (SCC), and other high- and normal-strength, fast-setting concrete mixes are normally used to fill the closure joints. In all, the specific nature of the joint application, in-situ casting, curing, material incompatibility, cavities and steel congestion contribute to creating potential for leaving defects and anomalies in the closure joints. This, in turn, results in a higher potential for exposure and other detrimental effects with possible degradation in time, and therefore reducing the strength and serviceability of the joint and the structure. The long-term deflections and environmental loading will only exacerbate the situation. It is therefore critical to first assure the closure joint is in good health right after construction, and secondly to remain healthy in future.

Cast-in-place closure joints therefore may introduce a potential for weak link within ABC structures. The quality of the joints, expected to become serviceable quickly, depends on the concrete mix design, reinforcement and enclosure details, and is influenced by placement and curing procedure. Despite the efforts to prevent weaknesses in these critical elements, potential exists that defects or anomalies are left in the joints during construction or develop later during the life of the structure. It is therefore critical to first assure the closure joints are in good health immediately after the construction, and then to remain healthy during their service life.

2 STATEMENT OF PROBLEM

A variety of NDT methods have been utilized for evaluation of bridges including those with closure joints. However, a concerted attempt for categorization of these methods, comparison of capabilities, and a clear guideline for selection of methods most applicable to closure joints is lacking. It is also realized that a variety of closure joints have been used in ABC projects each with unique features and associated with specific types of defects and damages, requiring special treatment when it comes to inspection and non-destructive testing. To the knowledge of the authors, no investigation has been performed to methodically relate the selection and application of NDT methods to the specific type of closure joints and associate defects. The main objective of this project was therefore search, identification, and selection of practical and economical methods for field inspection and damage detection of ABC closure joints. The idea is to perform a set of NDT evaluation immediately after completion to assure the health, and periodically thereafter during the service life of the bridge for health monitoring and damage detection. The presence of defects and damages may be readily identifiable by detecting significant anomalies in the response of the joint to NDT techniques. However, the overall approach to NDT evaluation of closure joints will also include constructing a signature response record of an intact joint to specific NDT technique at completion of construction. This baseline record can then be used for comparison with future periodic (or on demand) inspections for determining the type and extent of potential damages.

3 OBJECTIVES

A variety of NDT methods have been utilized for evaluation of bridges including those with closure joints. However, a concerted attempt for categorization of these methods, comparison of capabilities, and selection of the methods most applicable to closure joints is lacking. The main objective of this project therefore is search, identification, and selection of the most practical and economical NDT methods applicable to field inspection and damage detection of ABC closure joints. The methods will be evaluated based on their applicability, effectiveness, efficiency, and ease of use. A search was carried out to identify type, composition and critical details, potential defects, failure modes and serviceability problems of the closure joints. The selected techniques therefore are to be evaluated according to their applicability to specific types of defects and anomalies. The objective of the project is to develop a practical guideline with which the bridge owners and consultants can select the NDT methods that fit best to their need in regard with specific type of closure joint and associated defects. It is attempted to organize the project results in a manner to allow future development of field procedures, evaluation guidelines, reporting methods, and appraisal of methods for ease of use and suitability for integration into states bridge inspection programs.

4 RESEARCH APPROACH AND METHODS

The overall approach of this project is organized in three basic stages; search of background information for identification of detailed problems and available NDT methods, evaluation of methods for applicability to closure joints, and finally selection of the methods most applicable to specific types of closure joints and associate defects and damages. It is realized that the usefulness of data collected, practicality of approach, ease of use and quantifiable results are defining factors for acceptance, utility, and implementation of any inspection technique. It is also believed that instead of reinventing the wheel, the adaptation, albeit with modification and customization, of existing experiences and well-served practices from other industries/applications provide the maximum returns for the bridge engineering community. Lessons learned over the past decades from the design, inspection, maintenance, and repair of ABC, and prior experiences would provide true and tried methods for minimizing experimentation with potential inspection methods. The project objectives will be met within the following approach and set of activities:

- A literature reviews to identify common types of ABC closure joints,
- Categorize the common closure joints based on their features and details impacting the selection of respective NDT method,
- Investigate the type of damages and defects associated with each group of closure joints,
- Construct an etiology to establish cause-and-effect relationships for relevant defects and damages,

- Based on available technological resources, identify and categorize candidate NDT methods,
- Select NDT methods with promise for application to closure joints,
- Associate specific defects/damages related to each type of joint with the most applicable NDT method using etiology and fault-tree analysis,
- Substantiate the selection method with quantitative statistical analysis,
- And develop a guideline for selection of NDT methods best applicable to specific type of defect/damage associated with each type of closure joint,
- Reporting and communication of results with peers and advisory panel to solicit input and guidance.

5 DEFENITIONS

5.1 ACCELERATED BRIDGE CONSTRUCTION (ABC)

Accelerated Bridge Construction (ABC) is defined as design, planning and construction methods to organize and arrange construction activities for new bridges, as well as repair, replacing, and rehabilitating of existing bridges so that onsite construction time and mobility impacts are reduced, and public and worker's safety is enhanced [1]–[3]. Among other features, the use of pre-fabricated modular bridge elements and assemblies are the most common aspect of the Accelerated Bridge Construction (ABC) [1], [4] (Fig. 1).

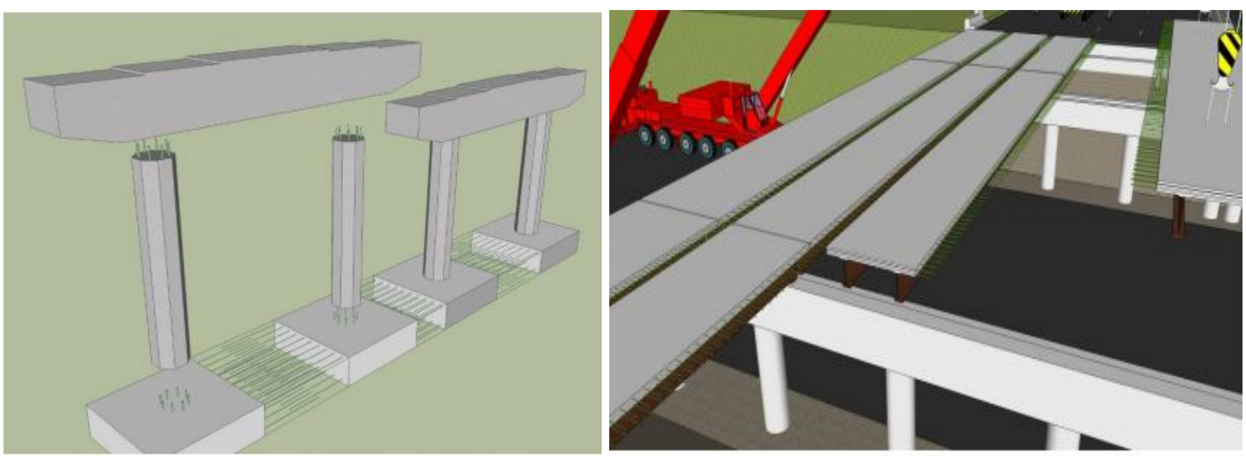


Figure 1: Some examples of Accelerated Bridge Construction [1], [5]

ABC addresses some of the major drawbacks of the conventional bridge construction methods including delays to allow concrete curing, time constraints due to sequential construction, traffic interruptions and safety issues, compromise in quality for in-situ activities, dependency on weather, etc. From a more practical standpoint, the most important of ABC potentials are:

- Reducing disruption to traffic
- Avoiding congestion
- Safer operation
- Alleviating public/workers exposure to construction activities

- Achieving higher quality control for precast elements
- Decreasing environmental impacts
- Better control over schedule

Owing to these advantages, application of ABC methods is growing across the US (Figs 2,3).

Figure 2: ABC superstructure positioning; bridges in Utah [5]

Figure 3: ABC superstructure positioning; Rhode Island (down) [5]

5.2 ABC CLOSURE JOINTS

Application of the Accelerated Bridge Construction (ABC) using prefabricated elements and assemblies necessitates the use of joints for connecting and integrating the bridge structure. Closure joints normally refer to joints for connecting the bridge deck elements to each other and to the substructure. Other joints are used for connecting superstructure to substructure as well as substructure elements to each other. Selection and design of the type of closure joints may depend on type of deck elements, need for continuity for shear and bending transfer, time constraint for the deck to become drivable, type of substructure, and the environmental condition at the bridge site, type of material available for closure joints as well as the prefabricated elements, functional requirements, etc. (Fig. 4). Moreover, establishing closure joints with the use of appropriate concrete such as Ultra-High Performance Concrete (UHPC), Self-consolidating Concrete (SCC), and other high- and normal-strength, fast-setting, early strength concrete mixes makes the closure joint less vulnerable to potential defects and discontinuities. A variety of health monitoring methods have been used for NDT evaluation of ABC closure joints. This report attempts to present the most applicable NDT methods based on the different defects for distinctive type ABC closure joints.

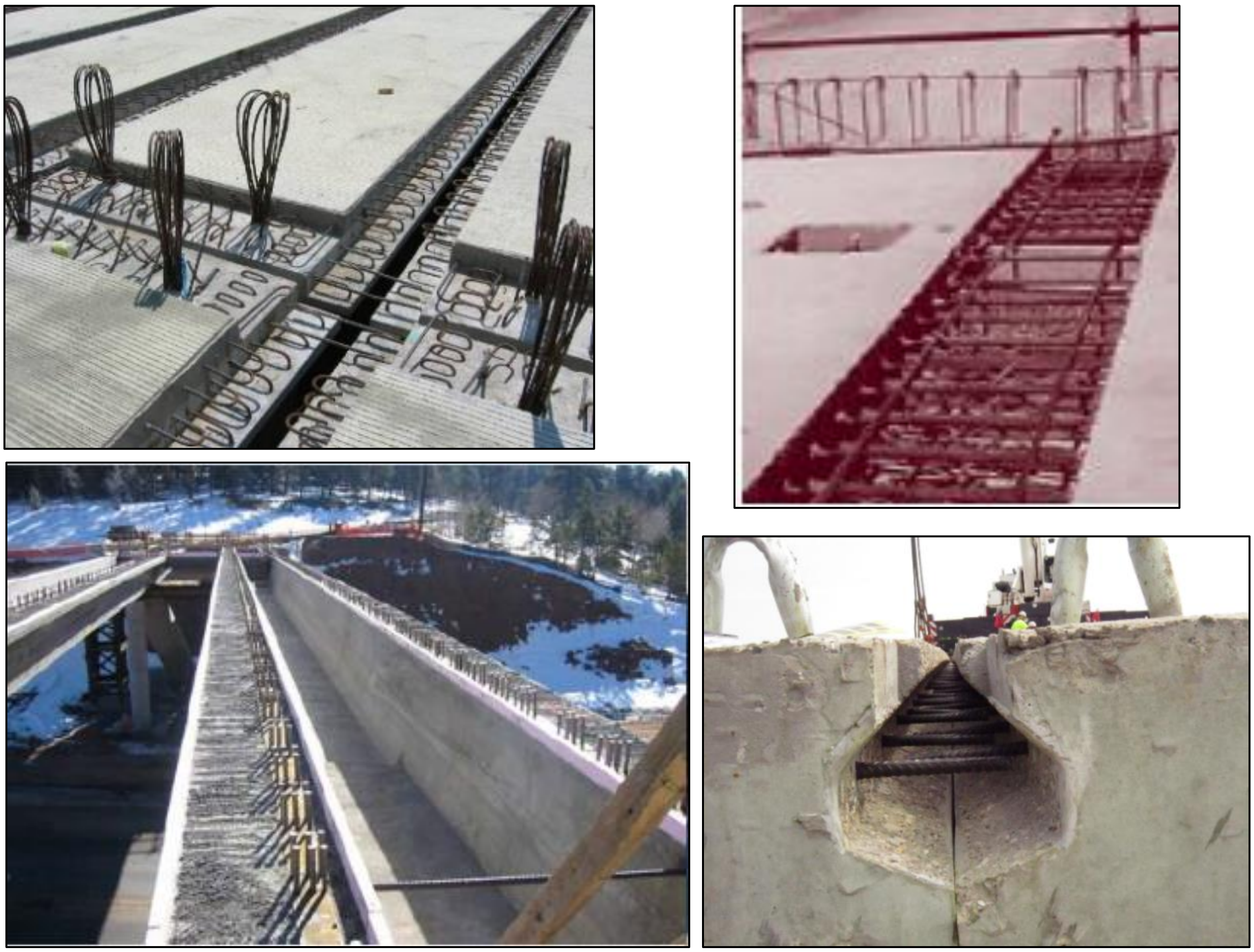


Figure 4: Examples of various types of ABC closure joints [6]–[9]

6 TYPE, POTENTIAL DEFECTS, AND SERVICEABILITY PROBLEMS OF CLOSURE JOINTS

6.1 LITERATURE SEARCH

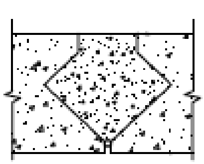
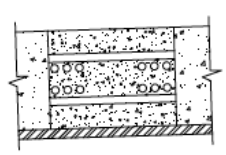
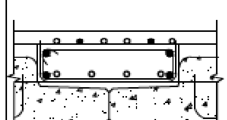
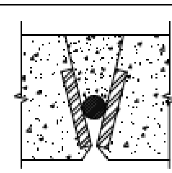
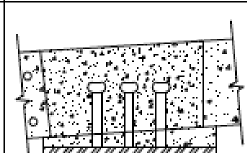
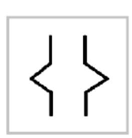
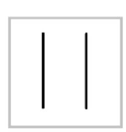
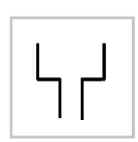
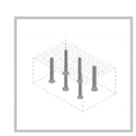
A review of available literature and data was being carried out to identify type, potential defects, failure modes and serviceability problems of the closure joints.

6.2 CATEGORIZATION OF CLOSURE JOINTS

The assessment process focused on indexing different types of closure joints and compositions, critical details, types of damage including causes and thresholds. The review in its first step examined closely the FHWA report on Connection Details for Prefabricated Bridge Elements and Systems (2009) [7]. The manual consists of a compilation of survey reports by engineers who completed projects with certain connections located on the superstructure, substructure and foundation. The primary focus was put on superstructure connections and on mostly concrete deck configurations that are used commonly for ABC. Therefore, only relevant joint types were reviewed. FRP (Fiber Reinforced Plastic), Timber (wood), and Steel of any shape are excluded. Based on consideration of the applicability of NDT methods, and types more commonly used in ABC, a series of 32 connection types were chosen for further investigation. Each closure joint type is categorized by shape, presence and type of reinforcement, distinguished for linear joint or blockouts, and is referenced by section number to the FHWA report [7].

Eventually, five types of closure joints were identified to represent dominant groups according to anticipation of type of defects that could be present for these joints and overall configuration of joints influencing the use of specific NDT methods. These five categories are shown in the Table 1. As shown in this table, for identification purposes, an equivalent symbol has been introduced for each type of closure joints.

Table 1: Grouping of closure joints

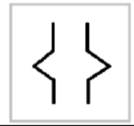
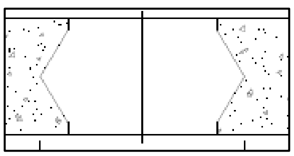
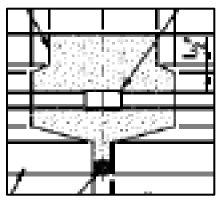
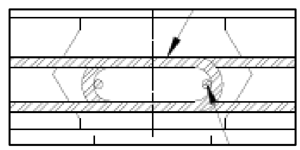
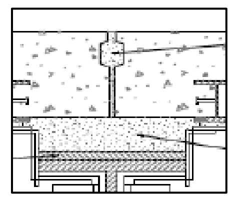
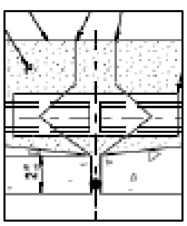
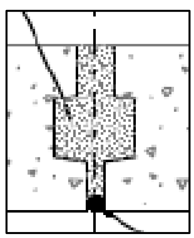
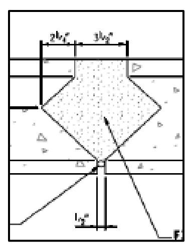
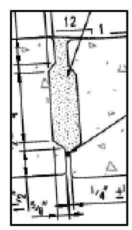
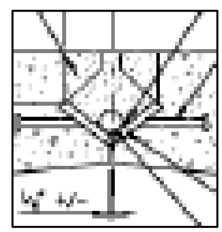
Group	Type 1	Type 2	Type 3	Type 4	Type 5
Sample					
Symbol					

The first four shapes cover "linear" joints, and the last shape covers "blockouts." Linear joints refer to longitudinal and transverse joints for connecting deck panels to each other and to the girders, and connecting deck panels to the abutment/piers. Blockouts are pocket-type joints mostly for connecting deck panels to the girders. Joints in each of these groups may have reinforcing bars and post-tensioning ducts passing through, and may have other embedded steel elements needed for installation processes. Inclusion of bars and ducts will be considered when evaluating each group for type of defects and applicability of NDT methods. Some closure joint types however could not be categorized in any of these five shapes. For those, if needed, separate reference will be made on the applicability of NDT and type of defects. The following is the description of the five types of joints representing most common types of closure joints.

6.2.1 Type 1 Closure Joint

Type 1 Joint designation refers to linear joints known also as shear-key or keyway joint, and is normally used to join full-depth precast decks, while in some cases it is also used to join precast beams [7]. In one case, this type of joint in combination with a larger grout pocket has been used for joining precast slabs on top of steel floorbeams. As seen in the cross-sections in Table 2, to provide shear transfer, this type of joint are designed in various shapes including diamond-like and rectangle. Because of their shape, there is a potential for voids, debonding, and porous grout to form in the corners. Sharp corners have also been reported to contribute to onset and propagation of cracks in the precast elements under loading [10]. This shearkey joint are used both longitudinally and transversely depending on the desired application. Early high strength and low shrinkage concrete has been used to prevent formation of pockets of air. In most cases, the joint is left plain with no steel reinformecement, however, double hoops and straight bars extending from the precast panels into the joint has also been used. In addition, steel plates anchored into the edge of prefabricated segments are sometimes used to line the bottom of the joint [7]. For the case of unreinforced joints, the application is more suited for joining precast decks joined together in the middle of the girder spacing, i.e., the bottom side of the joint is not supported/covered by the girder line. The joint is also usually post-tentioned in the longitudinal or transverse direction depending on the orientation of the joint, hence, the joint may include post-tensioing ducts [7]. It should be expected that a layer of wearing or leveling surface will be cast over the entire deck including this type of joint.

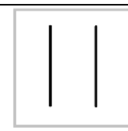
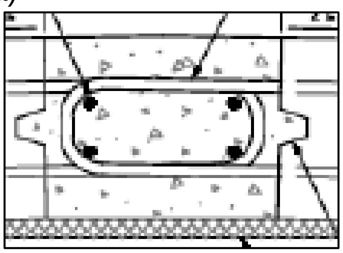
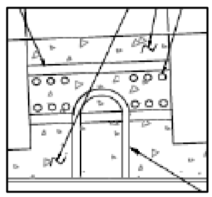
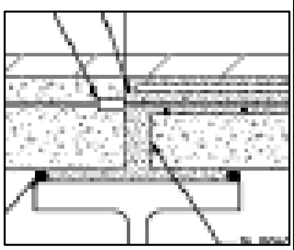
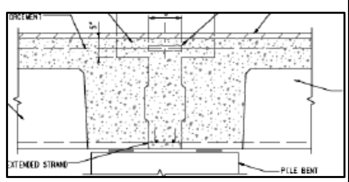
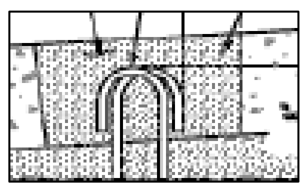
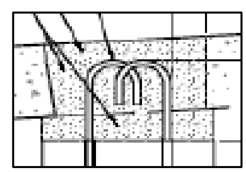
Table 2: Type 1 Joint [6]–[8], [10], [11]

<table>
<tr><td colspan="10">Symbol Representing Joint</td><td colspan="10"></td></tr>
<tr><td colspan="20">Sample Cross Section</td></tr>
<tr><td colspan="10">(a) </td><td colspan="10">(b) </td></tr>
<tr><td colspan="5"> (c)</td><td colspan="5">(d) </td><td colspan="5"> (e)</td><td colspan="5"> (f)</td></tr>
<tr><td colspan="4"> (g)</td><td colspan="4"> (h)</td><td colspan="4"> (i)</td><td colspan="4"> (j)</td><td colspan="4"> (k)</td></tr>
</table>

6.2.2 Type 2 Closure Joint

Type 2 Joint designation refers to linear joints that normally join full-depth precast decks to each other, and precast decks to precast concrete beams. This simple connection type is distinguished from other types with its straight (or near straight) sides allowing better placement of joint concrete with lower chance of formation of voids [7]. When connecting the slabs to the girder, this joint is accompanied with shear reinforcement that extends into the joint channel to transfer horizontal shear between the beams and the slab. In some cases, post-tensioning has been used in the longitudinal direction with mild steel reinforcement running in the transverse direction. This joint is usually cast with self-consolidating non-shrink grout. This joint shape has also been used as a transverse joint or link slabs to provide continuity and negative moment transfer at the piers [7]. For those joints, normally no transverse post tensioning is needed. It should be expected that a layer of wearing or leveling surface will be cast over the entire deck including this type of joint. Table 3 shows example of this type of joint.

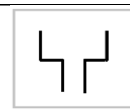
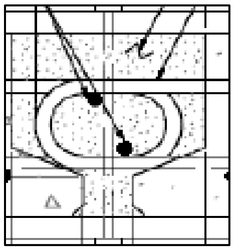
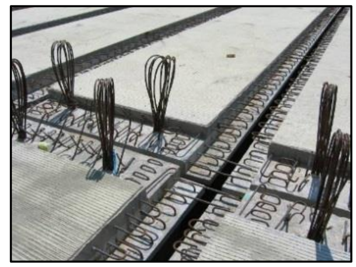
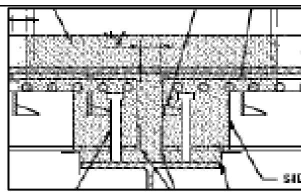
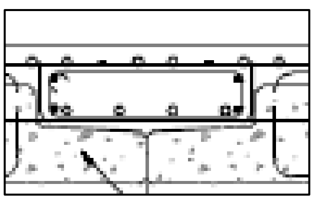
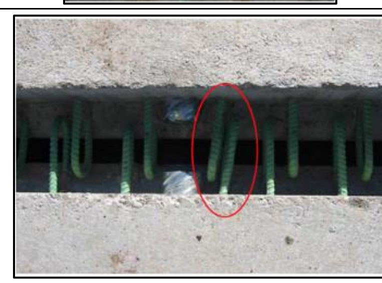
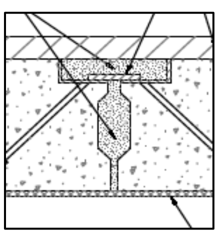
Table 3: Type 2 Joint [7], [9]

Symbol Representing Joint			
Sample Cross Section			
(a) 	(b) 	(c) 	
 (d)	(e) 	(f) 	(g) 

6.2.3 Type 3 closure Joint

Type 3 Joint designation refers to linear joints that normally joining partial depth precast deck panels, butted decked precast girders, and in some cases P/C Slab Longitudinal connections to Steel Girder Superstructure [7]. Type 3 Joint is similar to Type 2 but for partial depth. This configuration normally creates two dissimilar concrete layer in the depth, hence distinguishes this type from others for the application of NDT methods. The joint is cast in both longitudinal and transverse directions, and normally contains longitudinal and transverse reinforcement. Post-tensioning option can be used for unreinforced joints [7]. Table 4 shows examples of this type of joint.

Table 4: Type 3 Joint [7], [8], [12]

Symbol Representing Joint	
Sample Cross Section	
(a) 	(e) 
(b) 	(f) 
(c) 	(g) 
(d) 	

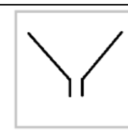
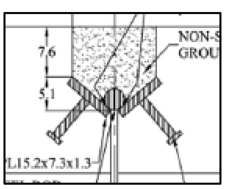
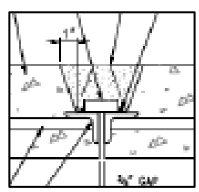
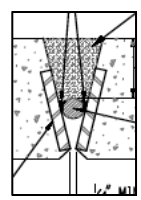
In some cases, this joint shape is used to connect precast deck slabs to Precast PT Tub Girders, where the projecting tie bars of the panels were bent and used as reinforcement in the connection. This joint shape has also been used as a transverse joint or partial-depth link slabs to provide continuity and negative moment transfer at the piers. Self-consolidating concrete is normally used to fill the joints. Leaking has been reported for this specific case [7]. In cases where the closure joint is aligned with a steel or concrete girder, shear connectors may extend partially into the joint.

A layer of bituminous (or other) overlay is expected to be cast over the entire deck covering this type of joint.

6.2.4 Type 4 closure Joint

Type 4 Joint designation refers to linear joints that normally joins two prestressed tee beams or double beam, and in some cases full or partial depth deck panels. The V shaped joint is cast in the longitudinal direction. In one of the common uses of this type of joint, a smooth lateral connector rod sits in-between two connector plates that form the shape of the joint. These connectors normally run along the entire length of the beam and are spaced at intervals equal to beam width. When connector plates are used at two sides of this joint, these plates are normally anchored in the beams using deformed bars. Non-shrink cementitious grout is normally used to fill the joint. In one application shown in Table 5, this type of joint was used to connect beams/slabs longitudinally to one another, utilizing long anchor rods, steel flanges and a centered plates [7]. It should be expected that a layer of wearing or leveling surface will be cast over the entire deck including this type of joint. Table 5 shows examples of this type of joint.

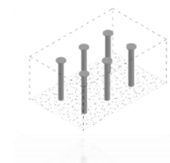
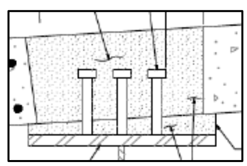
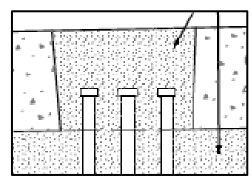
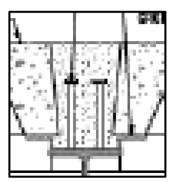
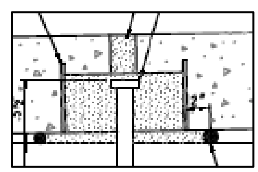
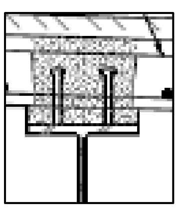
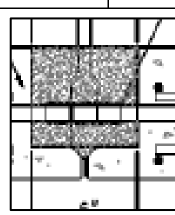
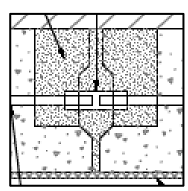
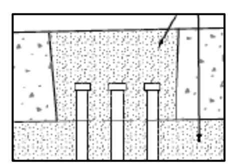
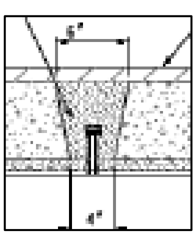
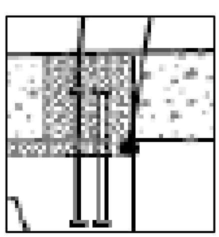
Table 5: Type 4 Joint [7], [8], [12]

Symbol Representing Joint		
Sample Cross Section		
(a) 	(b) 	(c) 
(d) 		

6.2.5 Type 5 of closure Joint

Type 5 Joint designation refers to box/recangular shaped joints that are known as blockouts. These joints are spaced throughout the decking and usually connect precast full depth decks to steel girders or concrete I-beams. Normally, some kind of shear connectors such as headed studs extend from girders below into the blockout void, and the void is cast using high-early strength concrete [7]. Steel reinforcement that crosses the joint or post tensioning normally are not included in the blockout, however, exceptions have been observed (Table 6-d). Any reinforcement in the deck needs to be adjusted to accommodate space for the blockouts. In some cases, the joint is used in conjunction with a grouted linear shear key joint (Table 6-i).

Table 6: Type 5 Joint on a bridge deck [7], [9]

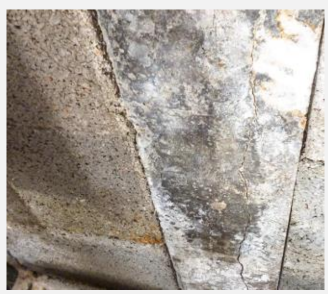
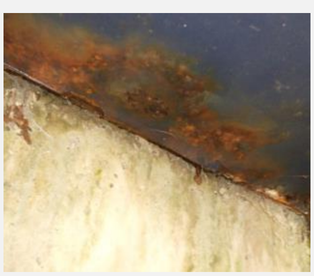
Symbol Representing Joint 			
Sample Cross Section			
(a) 	(b) 	(c) 	
(d) 	(e) 	(f) 	
(g) 	(h) 	(i) 	(j) 
(k) 	(l) 	(m) 	(n) 

High-early-strength concrete is normally used to fill the blockouts. In some cases, to prevent leaking of filler concrete from the joint, adhesive tape or foam is used to seal the bottom of the joint [7]. It should be expected that a layer of wearing or leveling surface will be cast over the entire deck including this type of joint. Table 6 shows example of this type of joint. In some cases, to prevent leaking of filler concrete from the joint, adhesive tape or foam is used to seal the bottom of the joint [7]. It should be expected that a layer of wearing or leveling surface will be cast over the entire deck including this type of joint. Table 6 shows example of this type of joint. The review continues by searching more references. The new joints will be either categorized within the above groups if applicable, or new groups will be added.

6.3 REPORTED AND PRESUMED DEFECTS AND ANOMALIES

The literature reviews also focused on the type of defect and anomalies anticipated or reported for each closure joint type. Defect is interpreted as an anomaly that would affect the structural performance or serviceability of the closure joints within the bridge structure. Defects and anomalies in closure joints are generally expected to follow those observed for concrete deck construction. Accordingly, unless a specific case is reported for closure joints that is different from those observed for bridge deck, defects and anomalies reported for bridge decks, with adaptation to the closure joints wherever possible, will be considered in this study. This can include lack of the cohesion or continuity in concrete or similar material in the closure joint such as cracking, separation and delamination, voids and/or honeycombing filled with air or water, corrosion and loss of cross-section of reinforcing bars within the joints and their vicinity, leakage of surface water through joints, roughness, and abnormal appearance. The type of defect, certainly, plays a significant role in selection of the most applicable NDT method for analyzing and health monitoring of the ABC closure joints. Examples of defects and anomalies expected in general for bridge superstructure are shown in Table 7. This survey subscribes to the view that different types of defects and anomalies in concrete or steel section of the closure joint can be associated with the type of joints and a potential cause. This study will also attempt to describe an etiology for the expected defects. Literature with a focus on defects and damages to ABC closure joints are very limited. Following summarizes results from some of the few investigations performed in this regard.

Table 7: Examples of defects and anomalies in bridge superstructure [13]–[21]

Crack [13]	**Delamination** [14]	**Internal Discontinuities** [14]
		
Surface Discontinuities [15]	**Corrosion of Reinforcing Bars** [16]	**Spalls** [16]
		
Honeycombing [14]	**Abnormal Appearance** [17]	**Leakage Through the Joints** [19]
		
Corrosion of Embedded Steel Plates or Connectors [18]	**Wearing and abrasion** [20]	**Loss of Cross-section or Breakage of Reinforcing Bars** [21]
		

ABC closure joints may contain different types of defects and anomalies. The type of defects and their causes are major factors when choosing the most applicable NDT techniques for nondestructive evaluation of the ABC closure joints. Literature with a focus on defects and damages related to ABC closure joints are very limited, however, much can be learned from defects associated with concrete deck in general. A review of literature in this subject has recognized following defects and damages that may apply to closure joints:

- Delamination (wearing surface),
- Reflective concrete cracking,
- Internal cracks/discontinuities,
- Debonding-separation at cold joints,
- Delamination of concrete cover
- Cracking/spalling of concrete cover
- Internal voids
- Honeycombing
- Concrete segregation
- Surface roughness
- Surface defects
- Abnormal appearance
- Exposure of reinforcing bars and steel embedment
- Leakage through joints and cracks
- Corrosion of embedded steel plates or connectors (due to exposure or material contamination)
- Corrosion of reinforcing bars (due to exposure or material contamination)
- Cross-section loss or breakage of reinforcing bars, couplers, and other steel embedment

These damages are, directly or indirectly, a result of factors such as material defects, design flaws, improper workmanship, and mechanical and environmental effects. These damages in turn may result in initiation of sequential damages within the closure joints at various stages. For example, shrinkage caused by the use of excessive water in the concrete mix can result in cracking at joint interfaces, which in turn would allow leakage of water through cracks and consequently cause corrosion of embedded steel. Corrosion of steel follows with volume increase, therefore if left unchecked can in time cause cracking and spalling of concrete. Spalling of concrete exposes the steel and makes it more vulnerable to corrosive environment.

Workmanship issues are commonly mentioned as potential cause for typical anomalies in ABC deck joints. As an example, honeycombing and voids are two typical defects in concrete structures which can be caused by improper mix design, and substandard concrete mixing, placing and curing process. One of the most detailed investigation on the evaluation of performance of ABC closure joints has been performed by Utah Department of Transportation (UDOT). In their investigations, shrinkage cracks in blockouts have been reported after construction pointing to selection of an improper concrete mix as the major cause [22]. Their report also mentioned bleeding of the excess water in concrete that contributed to increase in shrinkage (Figure 5). In another case, shrinkage crack in several blockouts were observed and selection of wrong construction materials was blamed as the major cause of the defect. Such causes are considered as mix design and workmanship issues in the etiology of defects in bridge closure joints summarized later in the Damage Sequence Tree (DST). Welded tie connections have been reported by the Utah department of transportation [25] to have performed the worst among others. Leakage and efflorescence was observed for this type of connection (Figure 5).

Figure 5: Typical joint leakage at deck panels (I-84 WB over Weber Canyon with welded-tie connections from 2009 inspection) [25]

Other investigations have been conducted for evaluation of different types of cracks in closure joints. Reflective cracking is a type of crack that initiate from sharp corners and cold joints inside the deck, because of stress concentration and/or shrinkage, and finds its way to the surface through wearing surface or other upper layers. Longitudinal cracking along linear joints is another type of damage which in turn causes leakage issues for closure joints (Fig. 6).

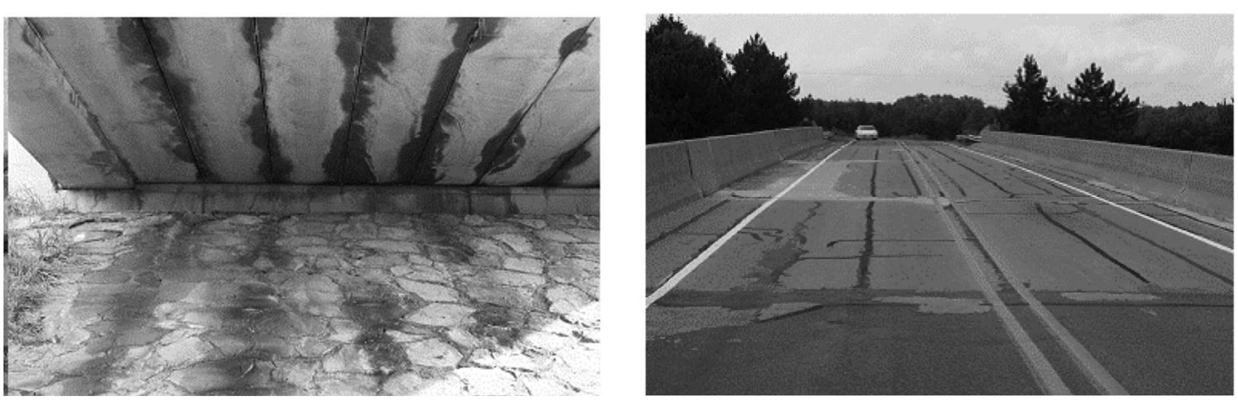


Figure 6: Longitude deck cracking of ABC closure joint [23]

Leakage through joints and cracks itself becomes a cause for corrosion of reinforcement within the closure joints. One of the first sources pertinent to damages in closure joints for side-by-side box-beam bridge superstructure is the work by Attanayake and Aktan [23]. They concluded that longitudinal reflective cracking is prevalent among all side-by-side box-beam bridges, regardless of the age of the bridge constructions. For this type of bridges, cracks appear along the beam-shear key interface within two to three days after grouting the joints. These cracks were somehow closed after post-tensioning but were still visible. Additionally, they noted that at about 15 days after deck placement, and often before the deck is subjected to live load, reflective cracks appeared in the deck. The cause of cracking was inferred to be environmental and intrinsic loading such as temperature variation and drying shrinkage. The cracking at joints resulted in leakage of water and corresponding damages shown in Figure 7 [23]. It is realized that ABC superstructures, regardless of the type of closure joints, are prone to surface discontinuities and corrosion of the embedded reinforcement.

Figure 7: Shrinkage crack in the blockout type of ABC closure joint [22]

It is realized that some of the typical surface discontinuities and corrosion of the embedded reinforcement are common among all ABC superstructures regardless of the type of closure joints. On the other hand, each of five groups of closure joints could be more vulnerable to one or more of distinctive defects. As an illustration:

- In Type 1 closure joint that is a linear joint with diamond-shaped cross-section, reflective cracking and void in the cavity at the acute corners can be expected.
- Type 2 closure joint connecting full-depth precast deck panels to each other, has more potential for cracking and debonding at cold joint and leakage through the joints.
- Debonding and delamination at the cold joint area, as well as cracking and reflective cracking can be expected in Type 3 closure joint in which two dissimilar concrete layers form the deck thickness.
- V-shaped Type 4 closure joint designed for connecting two pre-stressed tee beams or double beam using connector plates at the joint, can be vulnerable to corrosion of embedded steel.

6.4 ETIOLOGY OF DEFECTS/DAMAGES

In this section, it is attempted to construct rational relationships between observed or presumed defects in the five groups of ABC closure joints and their causes that will be analyzed as defect etiology. A reliable etiology which takes into account the specific characteristics of closure joint types, is believed to be essential for effective and accurate ABC superstructure health monitoring. Evaluation of causes and etiology of defects in specific cases for bridge superstructure has been carried out by others. For example, Brown et al. [24] introduced a cause-effect relationship for cracking in bridge decks. According to observations from bridge inspections, most of the defects and damages/defects mentioned above can be caused by one or more of the issues with; Design, Material, Workmanship, Shrinkage, Mechanical and Environmental conditions.

6.4.1 Workmanship

Observations from several investigations [26] reveal that workmanship perhaps plays the most significant role in many defects reported for closure joints. Workmanship errors can affect all aspects of closure joints including forming, concrete mixing, casting, curing, pumping, steel fabrication and installation. Error in material selection and procurement can also become a factor in development of defects. Excessive shrinkage has been considered as a result of material and/or workmanship issues. Shrinkage is the change in volume of concrete because of changes in moisture content (drying) or chemical changes. Shrinkage of restrained concrete normally results in cracking. This has significant role in closure joint durability. Shrinkage is a likely cause for various types of cracks, delamination and separation in ABC closure joints [24], [27], [28]

6.4.2 Design Issues

One significant parameter in occurrence of defects in deck joints is improper design and detailing. A design intended to provide for certain function for the joint may cause complications in implementation or performance of the joint for other aspects. Some design features in certain joint configuration has shown to result in initiation and progress of specific type of damages. For example, shear-key, diamond-shape joints may be susceptible to voids being left at their internal acute corners or develop reflective cracking initiated from the corners. The joints with sharp corners lead to stress concentration which makes the joints more vulnerable in some defects [29].

6.4.3 Material Deficiency

Deficient and substandard material used for constructing ABC closure joint can cause some typical defects such as; delamination, void, and cracks. As an example, the type of aggregates can cause internal crack or debonding. Also, chemical contaminants such as chloride or sulfate in cement material can be the cause of accelerated corrosion of embedded reinforcement and degradation of concrete. Another important parameter is the concrete mix design. Improper mix design can lead to segregation, bleeding, and high porosity [27, 30].

6.4.4 Mechanical Effects

Mechanical parameters such as live load effects can be another cause for damages during the service life of ABC closure joints. Abrasion and similar mechanical effects can also cause damages to the closure joints. Mechanical effects should therefore be considered when the etiology of defects is evaluated [31].

6.4.5 Environment Effects

Another set of important parameters causing defects, particularly in terms of surface defects, are environmental effects. Moisture, temperature variation, freeze and thaw, precipitation, exposure to salt and seawater, carbonation, and other environment factors can have detrimental effects on ABC closure joints [32].

6.5 DAMAGE SEQUENCE

Table 8, attempts to make the connection between various common defects of ABC closure joints and their main causes as the defect etiology. Taking into account characteristics of the five categories of ABC closure joints discussed earlier, the main causes of damages and defects can be viewed as a reliable etiology for use in health monitoring of closure joints. Evaluation of distinctive ABC closure joints is performed in relation with different types of defect/anomaly as well as their causes.

6.5.1 Root Causes and Fault Tree Analysis

A Damage Sequence Tree (DST) covering potential closure joint defects and damages at various levels was developed in this study and is illustrated by Figure 8. As it is shown in this figure, DST attempts to make the connection between various recognized defects of ABC closure joints and their main causes as the basis for a better understanding of approach to bridge defect etiology. Following the path in the etiology of several types of damages in bridge decks and closure joints, in many cases, leads to procession of damages from smaller scope to larger, and more importantly from one to another type and level of damages. Therefore, a root cause may be a direct culprit for one type of damage which if unattended can result in occurrence of another type of damage (Figure 8). As a practical approach, DST can facilitate investigating the root cause of defects in closure joints for structural health monitoring of bridges. This forms the basis for the new approach introduced in this report for health monitoring of ABC closure joints that combines a deep knowledge of features and vulnerabilities of the closure joints with the capabilities and potentials of various NDT methods for detection of potential defects and damages.

Figure 9 illustrates the relationships between common defects anticipated for ABC closure joints and the most likely causes including issues with design and detailing, material, mechanical effects, workmanship, and environmental effects. Potential causes, including root causes, for damages and defects in ABC closure joints are illustrated in detail in Figure 10. The information in this figure along with cause-and-effect relationships shown in Figure 9 will allow an effective Fault Tree Analysis (FTA). FTA can assist in application of proper NDT method and health monitoring of closure joints. It is essential that the evaluation of distinctive ABC closure joints is performed in relation with different types of defect/anomaly as well as their causes. For example, sign of water leakage or efflorescence on the underside of the deck can be traced on the FTA to cracking, and therefore, will lead to the use of NDT method(s) capable of detecting cracks. The presence of cracks in turn may point on the FTA to a cause or source that would indicate potential for other type of damage associated with the same source, and prompt the application of a specific NDT method.

Table 8: Defect Etiology to ABC Closure Joints

<table>
<tr><th colspan="4">Damage Types</th><th colspan="5">Most Likely Root Causes</th></tr>
<tr><th>Subsequent Damages</th><th>Secondary Damages</th><th colspan="2">Primary Damage</th><th>Design</th><th>Material</th><th>Workmanship</th><th>Mechanical Effect</th><th>Environmental Effect</th></tr>
<tr><td rowspan="2">Corrosion of Reinforcing Bars</td><td rowspan="5">Leakage through joints and cracks</td><td colspan="2">Delamination
(wearing surface)</td><td></td><td>*</td><td>*</td><td>*</td><td></td></tr>
<tr><td colspan="2">Reflective Concrete Cracking</td><td>*</td><td>*</td><td></td><td>*</td><td></td></tr>
<tr><td rowspan="2">Corrosion of Embedded Steel Plates or Connectors</td><td colspan="2">Internal Discontinuities/
Cracks</td><td></td><td>*</td><td>*</td><td>*</td><td></td></tr>
<tr><td colspan="2">Debonding
Separation at Cold Joints</td><td></td><td>*</td><td>*</td><td>*</td><td></td></tr>
<tr><td>Loss of
Cross-section or Breakage of Reinforcing Bars/Couplers</td><td>Cracking/ Spalling of Cover</td><td>Corrosion of Bars</td><td>*</td><td>*</td><td></td><td></td><td>*</td></tr>
<tr><td colspan="4">Voids</td><td></td><td>*</td><td>*</td><td></td><td></td></tr>
<tr><td colspan="4">Honeycombing</td><td></td><td>*</td><td>*</td><td></td><td></td></tr>
<tr><td colspan="4">Surface Roughness Created by the Joint</td><td></td><td></td><td>*</td><td>*</td><td>*</td></tr>
<tr><td colspan="4">Surface Defects</td><td></td><td></td><td>*</td><td></td><td>*</td></tr>
<tr><td colspan="4">Abnormal Appearance</td><td></td><td>*</td><td>*</td><td></td><td>*</td></tr>
</table>

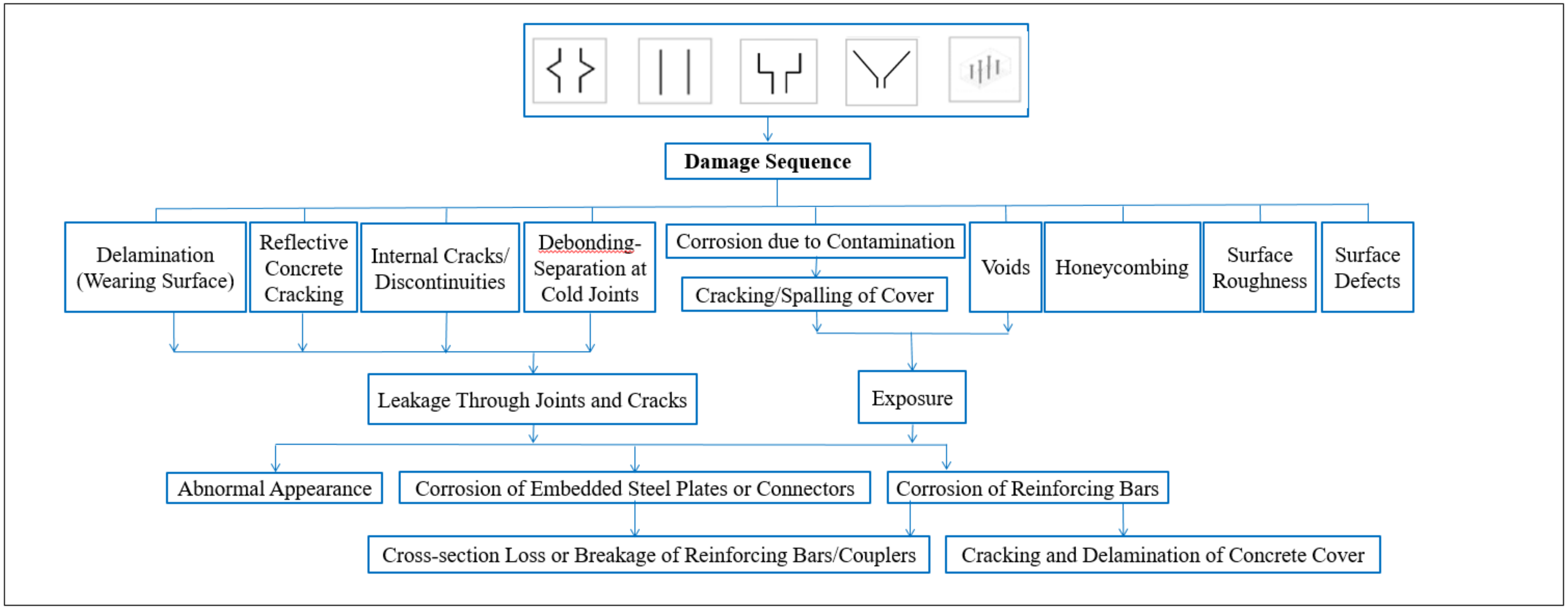


Figure 6: Damage Sequence Tree (DST) for ABC closure joints.

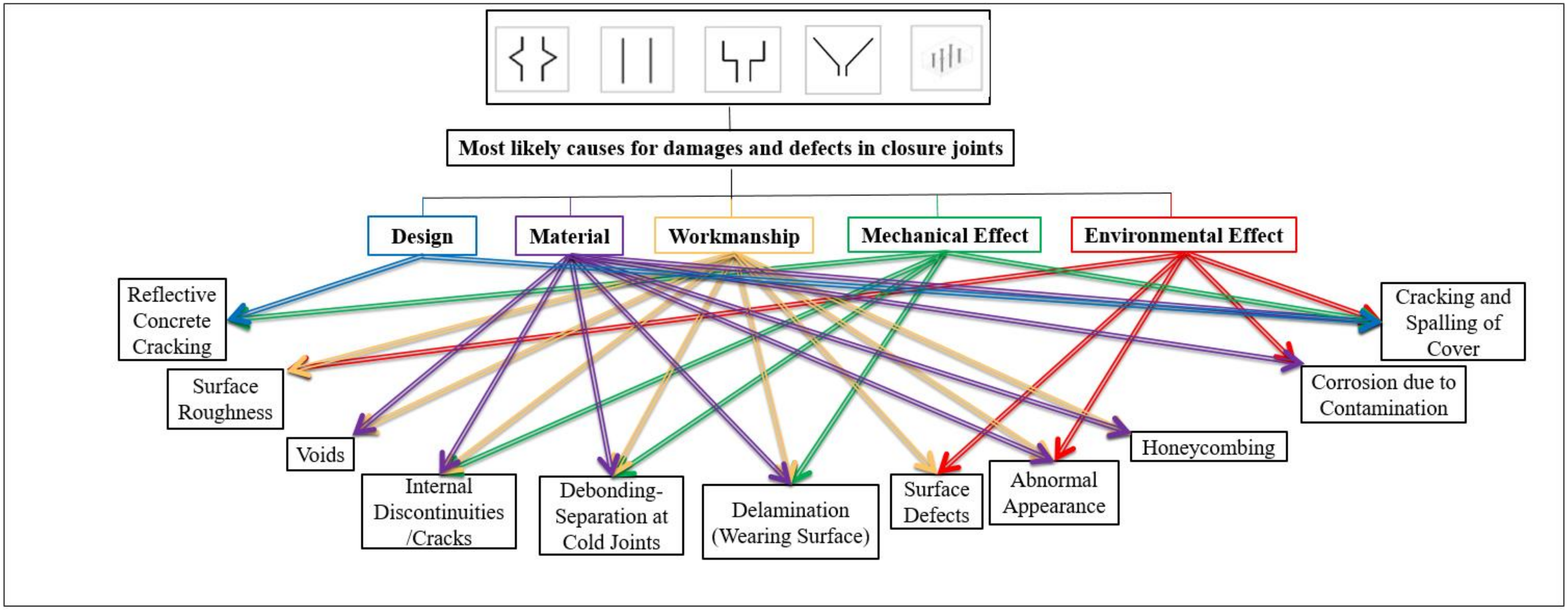


Figure 7: The most likely causes for damages and defects in ABC closure joints.

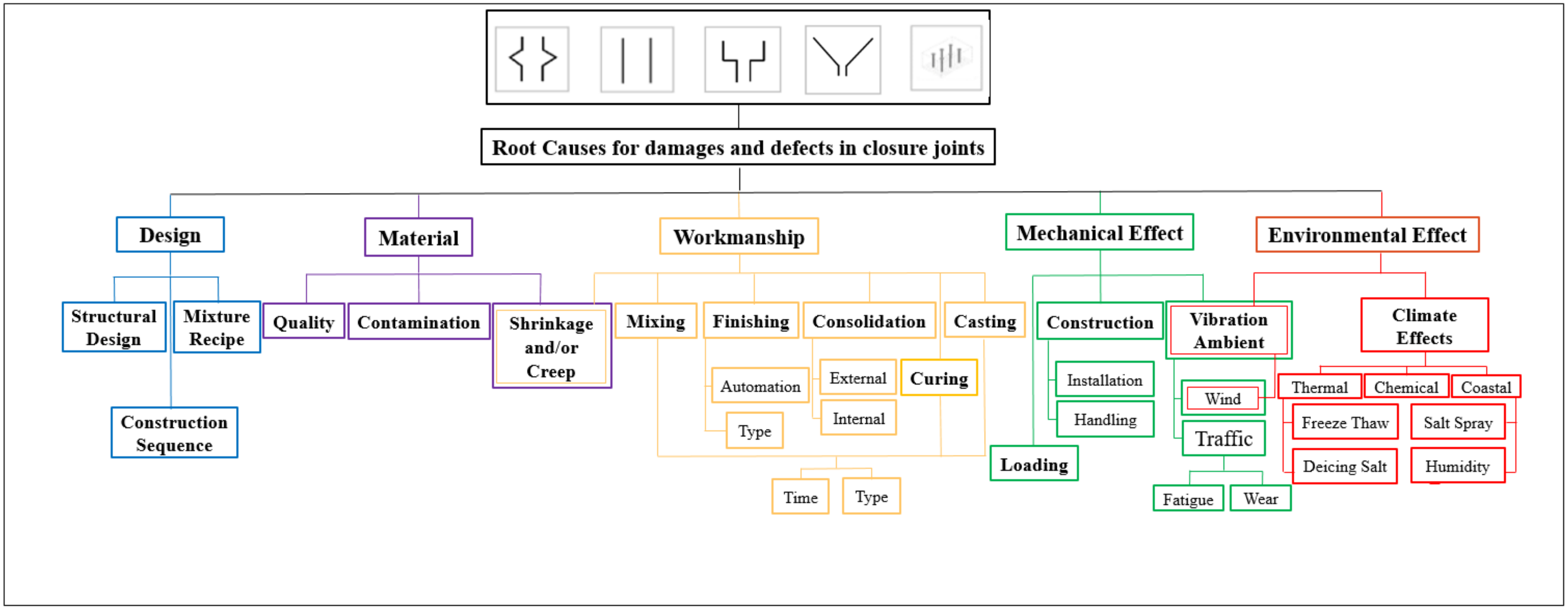


Figure 8: Root causes for damages and defects in ABC closure joints.

7 IDENTIFICATION, EVALAUTION, AND SELECTION OF NDT METHODS

7.1 CURRENT INSPECTION/NDT PRACTICES

It is intended to identify and combine the best practices from various applications of NDT to ABC including but not limited to those that are currently being used. The goal is to create standardized methods and techniques that would be similar or useable for inclusion within the customary bridge inspection practices.

7.1.1 Literature Review

Condition assessment of components of bridges built using Accelerated Bridge Construction (ABC) method, particularly closure joint and bridge deck, requires means and methods for detecting and characterizing different deteriorations and defects in the form of voids, cracks, delamination, leakage, corrosion and other damages. The uses of Non-destructive Testing (NDT) methods are preferable since they do not require changing or damaging the structure in the course of the inspection.

There is a variety of nondestructive inspection methods that can be used to evaluate and examine the integrity of ABC components, however, to select the most effective methods, there are some basic question that need to be answered:

- ✓ Which of the NDT technologies are the most reliable and repeatable?
- ✓ Which one will provide better accuracy and easier interpretation?
- ✓ Is there an ideal method for a certain type of closure joint?
- ✓ What are the advantages and limitations for utilizing one or the other NDT techniques?
- ✓ Or, do more reliable inspection methods also cost more?

To address these, a comprehensive literature review was conducted focusing on NDT methods for field inspection and damage detection. The evaluation of methods for applicability to closure joints, and consequently, the selection of the most effective methods in accordance with the objectives of ABC closure joints were emphasized. Eighteen NDT methods in three distinctive groups considering to the potential in evaluating the ABC closure joints have been identified that include:

1. NDT Methods potentially applicable to ABC closure Joints
    - Impact Echo Testing (IE)
    - Microwave Testing (MW) – Ground Penetrating Radar (GPR)
    - Sonic Pulse Velocity Testing (SPV)
    - Ultrasonic Testing (UT)
    - Phased Array Ultrasonic Testing (PAU)
    - Infrared Thermography Testing (IR)
    - Acoustic Emission Testing (AE)
    - Impulse Response Testing (IRT)
    - Laser Testing Method (LT)
    - Radiographic Testing (RT)

- Magnetic Flux Leakage Testing (MFL)
- Visual Testing (VT)
- Global Structural Response Testing (GSR)
- Chemical and Electrical Testing (CET)

2. Other Common NDT Methods
    - Penetrant Testing (PT)
    - Eddy Currant Testing (ET)
    - Magnetic Particle Testing (MT)

3. Complementary to NDT Methods
    - Testing under Service Load (SL)
    - Automated Testing Platforms (ATP)

Among a number of factors and conditions identified as defect, perhaps a discontinuity, its type and location could be of focus. Discontinuity is interpreted as a lack of the cohesion or continuity in a material [33]. Most of damage types anticipated for closure joints, and for concrete decks in general, involve some type of discontinuity. They are either a direct result of a discontinuity, intentionally or unintentionally left in the concrete, or they cause a discontinuity themselves. For example, leakage through closure joints and subsequent corrosion of embedded steel could be a result of cold joint between prefabricated elements and closure filler that its condition could have been degraded because of workmanship issues, material deficiency, or structural response. On the other hand, corrosion of steel reinforcement may cause cracks and spalling after corrosion is progressed in the steel reinforcement. Discontinuities are, fundamentally, classified as surface, subsurface, and internal discontinuities [34]. The type of discontinuities certainly plays an important role in selection of the most applicable NDT method for analyzing and health monitoring of the ABC closure joints (Fig.11).

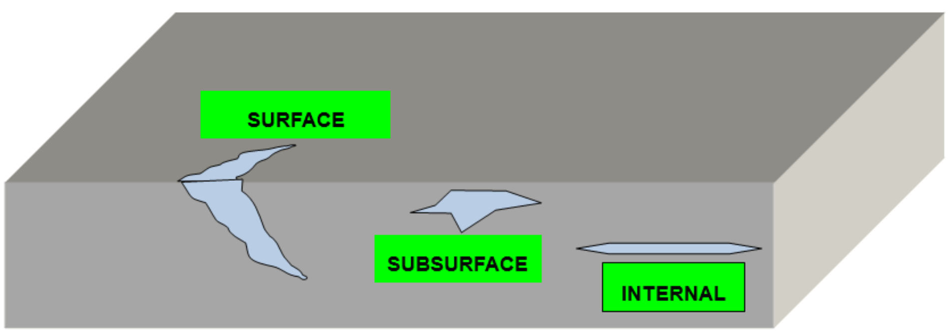


Figure 9: Three different types of discontinuities [35]

These methods are being thoroughly reviewed in relation to their applicability to ABC closure joints inspections [33], [34], [36]–[42]. Considering the type of closure joints and anomaly or defect type, different aspects of inspection sufficiency and efficacy criteria that will be taken into account for the evaluation and the comparison of various nondestructive testing methods are listed below:

- ✓ Accuracy
- ✓ Level of repeatability of measurement results
- ✓ Speed of data collecting
- ✓ Ease of use
- ✓ Speed of analyzing
- ✓ Cost
- ✓ Level of required knowledge and skill for utilizing each method
- ✓ Safety of use for operator and public

After these evaluations, the applicability or versatility of each method for inspection of various types of closure joints and types of defects will be discussed in later sections.

7.1.2 NDT Methods potentially applicable to ABC Closure Joints

Based on their background application to bridge decks, following methods have been identified to have potential for health monitoring of closure joints.

7.1.2.1 Impact Echo Testing (IE)

Impact Echo Testing (IE) uses mechanical wave type and has deep penetrating ability into the concrete, and has a great potential for detecting discontinuity and delamination in concrete of ABC closure joints [34], [37], [42]. IE was experimentally studied by Gucunski et al. [39] for estimating the bridge deck defects. They pointed out that IE is the most reliable method for detection of delamination, and that the interpretation of results can be automated and directly presented for effective data collection. Based on their work, IE shows promising for evaluation of cracks, voids, delamination and discontinuities. Other advantage of IE is that it is capable of determining deck and slab thickness [34], [37]. Hurlebaus et al. [42] investigated the accuracy of this NDT methods in defect evaluation and detection. IE has shown moderate accuracy for void detection in tendon ducts, and requires a multiple impact points for high accuracy [38], [42]. A schematic of the IE method is illustrated in Fig.12 [34].

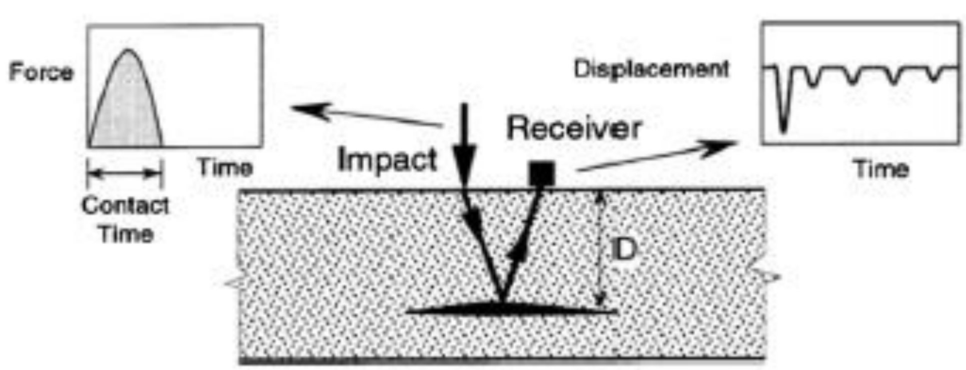


Figure 10: A scheme of an IE method set-up [34]

As shown in Fig. 12, for IE, the surface of element is impacted by a steel ball or small impulse hammer [43]. The energy of reflected wave is recorded using an accelerometer receiver which is mounted on the surface near the impact location [42]. In IE method, evaluation process is associated with a relatively sparse grid, and lane closure. This method also has some limitations for crack detection for elements in which there is a gap between the overlay and deck [39]. The ability of IE for void detection in reinforced-concrete is somehow limited because of the interfering effect of steel embedment in distribution and reflection of the waves [42]. Fig. 13 shows IE being used for void detection for the concrete in a bridge structure [44]. For crack detection, IE has high level of accuracy, repeatability of measurements, and speed of data collecting and analyzing. However, the cost of testing and the ease of use rate is graded in moderate level by Gucunski et al. [39].

Figure 11: Void detection at bridge concrete by using IE method [44]

7.1.2.2 Microwave Testing (MW)

Microwave Testing is a single side scanning technique which is used to detect the internal discontinuities, voids, and cracks within materials. MW method is sensitive to dielectric variation. It can be divided in two main technique of Ground Penetrating Radar (GPR) and Surface Penetrating Radar (SPR) [45]. The dominant methodology in this method is that the microwave energy travels at different velocity through different materials. As it shown in Fig. 14, in Microwave Testing, radar antenna will detect any internal anomaly in the depth of the elements by sending and receiving the electromagnetic signals. In this technique, considering the wave velocity, the system can, readily, determine the characteristics of each defect based on the depth and time by the signal reflection [45]. In the last decade, software developments have helped mechanical and civil engineers to improve outputs of their non-destructive evaluation, and plot high quality and more accurate defect model for elements. Two dimensional image by stacking the single scanned signals next to each other (Fig. 15), and three dimensional images by combination of multiple scans of the elements in different directions (Fig. 16) are two possible outputs for the result of Microwave Testing method [45].

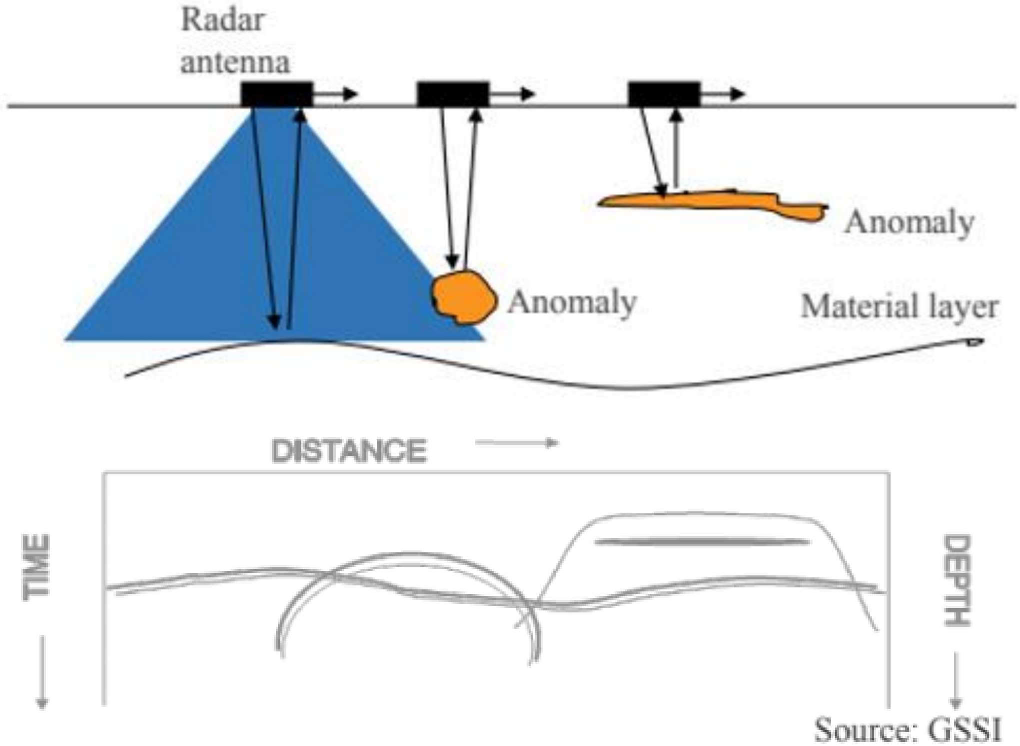


Figure 12: Void and crack detection by using MW method [45]

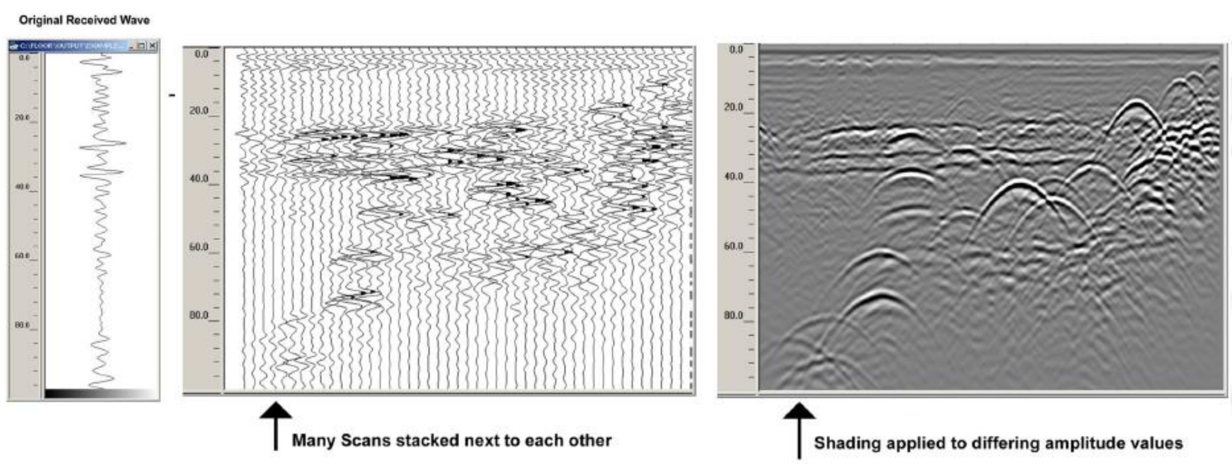


Figure 13: 2D Image output of MW method [45]

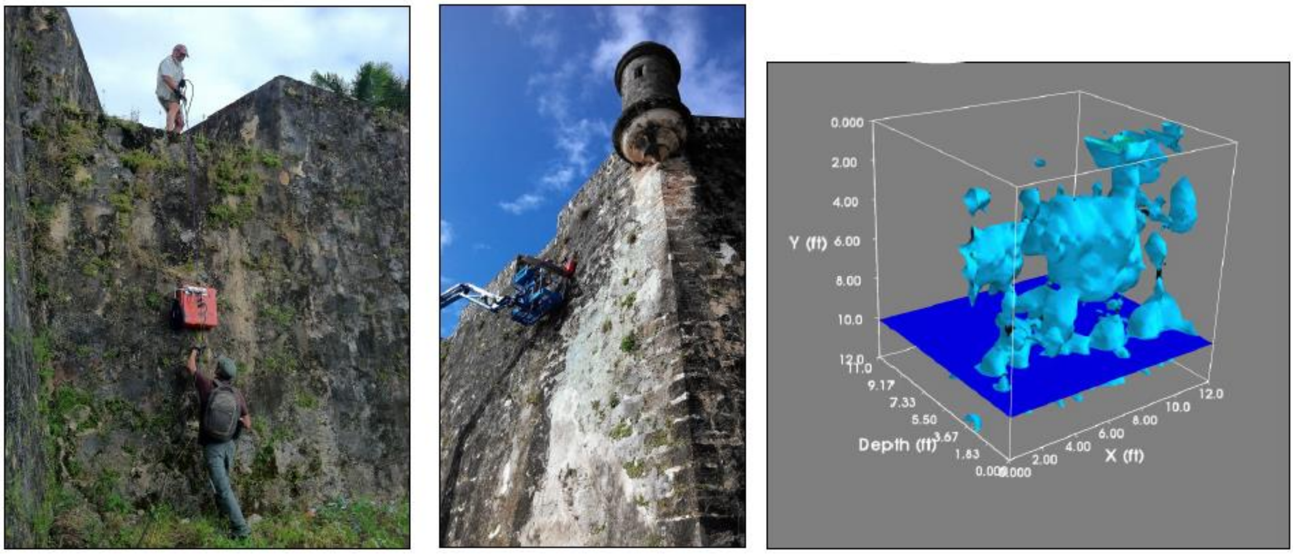


Figure 14: A sample of 3D Image result of MW method [45]

7.1.2.2.1 Ground Penetrating Radar Testing (GPR)

As it was mentioned earlier, Ground Penetrating Radar Testing (GPR) or Impulse Radar Testing (IRT) is one of the most applicable methods among Microwave Testing (MW) methods. The most common use for GPR is for locating reinforcing bars and other inclusions in reinforced concrete structures, and it is often used in combination with other NDT methods. However, GPR is also applicable to bridge decks and other bridge elements for detecting damage, delamination, cracks and voids by exploring the propagation model of electromagnetic waves which are sent through the deck via antenna, and received from internal reflectors (Fig. 17) [34], [37], [38], [42], [46], [47]. In other words, internal defects are identified with moderate accuracy by analyzing and interpretation of the reflected pulses [42]. GPR was employed by Huston at el. [48] for monitoring concrete bridge deck, and introduced as a reliable NDT method which is applicable with and without asphalt overlays owing to its relative insensitivity to ambient conditions. Various types of damages to the asphalt layer used as wearing surface for concrete bridge decks such as rutting and fracture has been, experimentally and theoretically, studied by researchers. Based on concrete cover, the effective depth of GPR is varied. For instance, penetrating depth will be around 24 in. for high frequency in the range of ~ 500 – 3000 MHz [42]. Higher cost of this method as compared to other methods is one of the drawbacks of this method [34]. Different aspects of using GPR technique is experimentally analyzed by Gucunski et al.[39] in detection of delamination. They considered GPR as a good method for its speed of data collecting and analyzing. They also placed GPR technique in the group of low level for its accuracy and the ease of use rate. The repeatability of measurements with GPR testing is graded moderate for this method. It is important to mention that GPR is preferred method for detection of presence and location of steel reinforcement and embedment. For this, several other NDT methods rely on GPR for locating reinforcing bars. This makes GPR a candidate for NDT methods applicable to closure joints.

Figure 15: An example of GRP Testing [47]

7.1.2.3 Pulse Velocity Testing (PVT)

Arrival time, amplitude and frequency are the three important parameters of different types of velocity testing methods [49], [50], particularly in Pulse Velocity Testing (PVT). PVT techniques are, generally, used for evaluating existing element by transmission approach which is divided into two main propagation techniques [45]:

- Ultrasonic Testing (UT) method with high frequency stress waves is transmitted through in the elements.
- Sonic Pulse Velocity Testing (SPV) method with low frequency or mechanical pulse method.

For example, in the SPV, an operator can generate low frequency sonic wave propagation through the element by using a mechanical hammer, and analyze the response on the opposite side of the case study by sensors. As it is shown in the Fig. 18, density variation in the tested element will cause different velocity of the wave propagation, and therefore signaling difference in results. This is the main theory for investigation the discontinuities and other distinctive defects in the element [45].

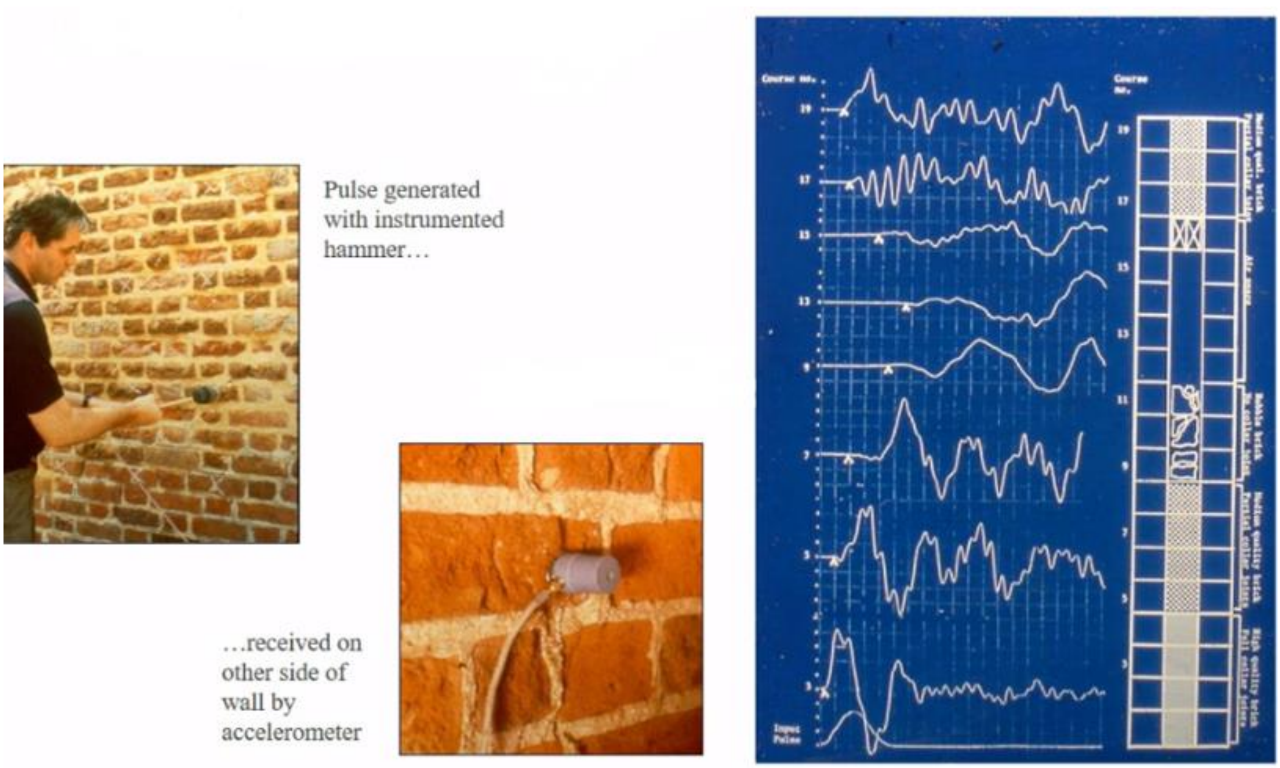


Figure 16: Set-up of a Sonic Pulse Velocity Testing (SPV) method [45]

7.1.2.3.1 Ultrasonic Testing (UT):

Ultrasonic Testing (UT) is one of the most commonly techniques among other PVT testing methods which evaluates various types of internal cracks and voids in the concrete by utilizing the sound waves at frequencies above the audible range [37], [51]. In UT method which is one of the most applicable tests for the detection of internal defects, the structural elements are tested by using high frequency sound waves, typically above 2 MHz, in which Ultrasonic Testing monitor displays the reflection of the sound wave indicating the exact distance of any sub-surface or internal defect from the surface (Fig.19) [52], [53]. Although UT method has the ability to specify depth and location of the defects, it is less effective for inspection evaluation in very thin elements, brittle materials and for complex geometry's components [38]. The application of UT may be limited for surfaces with considerable roughness. This method also has some limitations for coarse-grained type of materials. It should be mentioned that for UT evaluation, the operator needs to be experienced and adept for testing and analyzing the results, and extensive training is required for this type of nondestructive testing. UT is limited to test on smooth concrete surface [42], and very applicable to defect evaluation in different types of materials. Portability and high safety are other merits of UT method [35]. UT is a relatively quick nondestructive evaluation test and its cost is moderate [40]. UT is experimentally analyzed by Gucunski et al. [39] who evaluated the method to have good accuracy in crack detection.

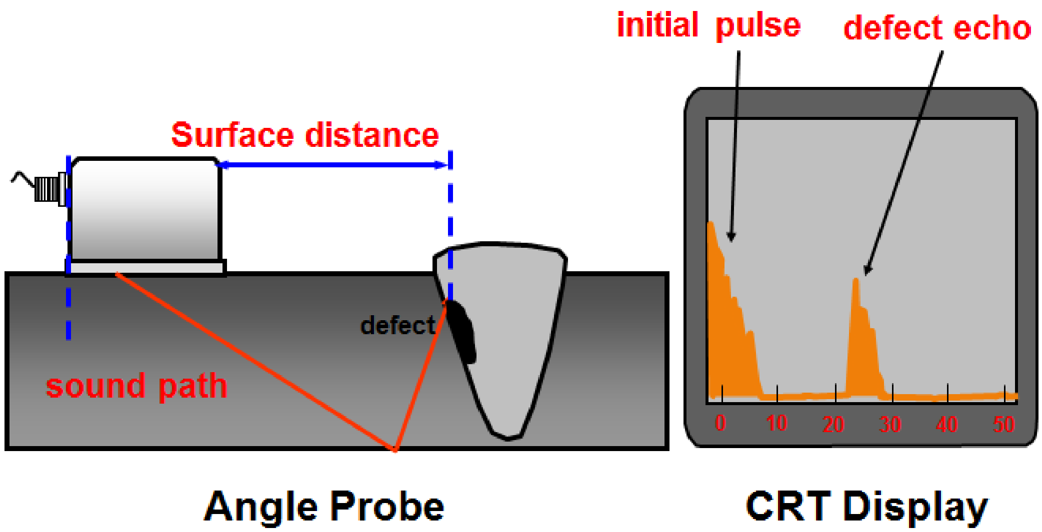


Figure 17: The defects are read from the screen [52]

7.1.2.3.2 Phased Array Ultrasonic Testing (PAU)

Phased Array Ultrasonic Testing (PAU), uses an array of probes each of which is individually controlled by computer program. According to the controlled excitation, a concentrated ultrasonic beam of various angels and focal length using a single array of transducers is generated by the software. Two or three dimensional presentation can be produced for displaying the exact location and size of each potential defects such as manufacturing flaws (like lack of root penetration and lack of root fusion), service flaws (like fatigue cracking and stress cross ion cracking), parent material flaws (like inclusions), or erosion [35]. Although this method has been evolved from UT testing and uses UT principles, because of its unique features and potential for adopting for the case of closure joints, the method is discussed separately in this section. The ability of flaw visualization and portability are two excellent features of this nondestructive evaluation system [35]. PAU technique, usually, generates frequencies between 750 kHz to 100 MHz which is used for nondestructive evaluation in industrial applications. An array of elements (sensors) within a distinctive relatively large transducer can be utilized for making spatial diversity in PAU systems [54]. A linear array of elements (sensors) is used by a PAU set-up for coverage on the emitted wave. This system with almost small wavelengths is not appropriate for depth penetration in elements with the elastic heterogeneity of concrete. Apart from that, although this set-up can be applicable for laboratory environment, it does not seem practical for the required productivity for concrete pavement evaluation because of portability issues reported for this device. Such disadvantages can be addressed by using multiple-angles and portable transmission devices such as Impact Echo Testing (IE) [54]. Nevertheless, due to high potential for applicability to the case of closure joints, the research team will follow and investigate the progress in improvements for the use of this method, and consider its future adoption. Piping inspection has been reported as a specific application of Phased Array Ultrasonic Testing usage [35]. Based on an extensive slab data inventory, a quantitative numerical analysis for damage evaluation in concrete has been studied by Freeseman and Khazanovich [55]. As another application of PAU, the localization of multi-defect has been experimentally carried out by Senyurek at el. (Fig. 20) [56].

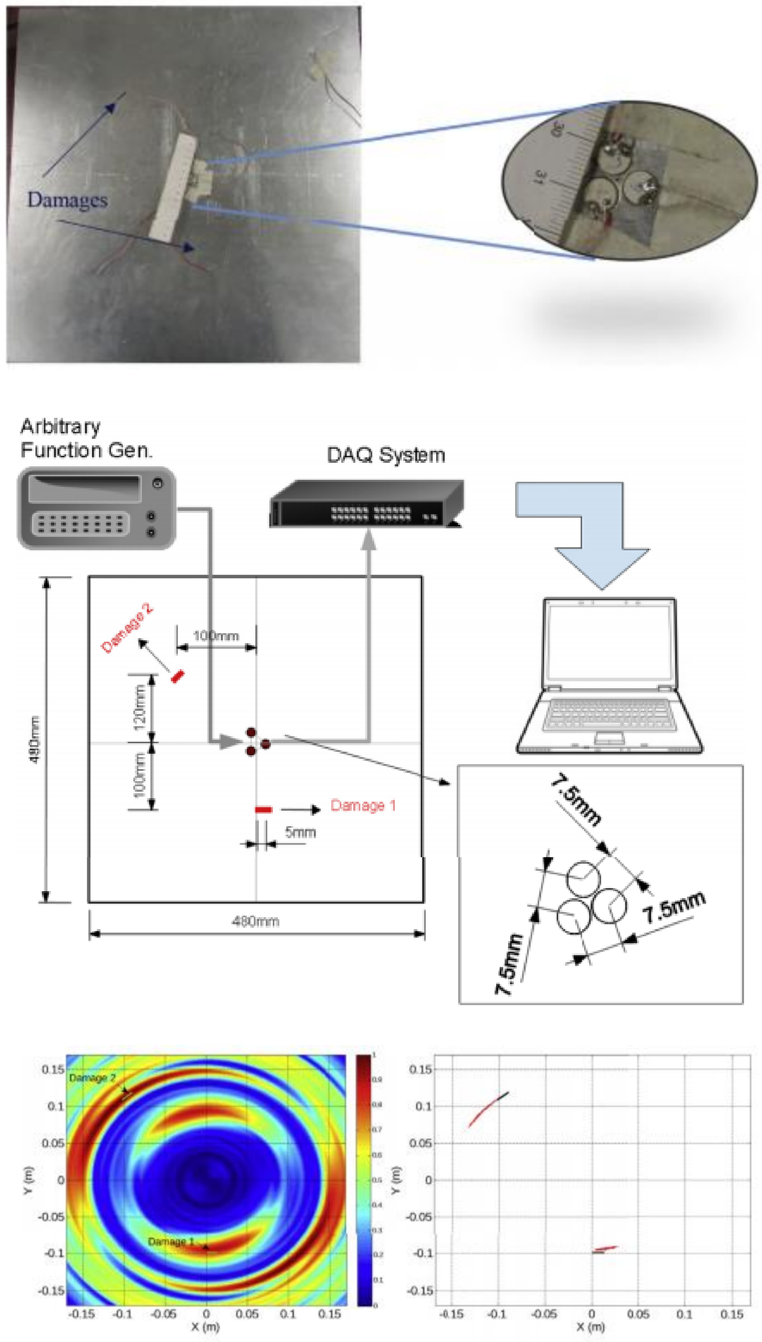


Figure 18: A sample of localization of multiple defects using PAU [54]

7.1.2.4 Infrared Thermography Testing (IR)

Infrared thermography testing (IR) has been used widely for detection of material variation based on variation of temperature (Fig. 21). It was discussed by Seshu and Murthy [37] as a structural damage detection method including cracks, delamination, and voids. In this method an infrared camera is used for detection that measures the emitted infrared radiation from a structural member [38].

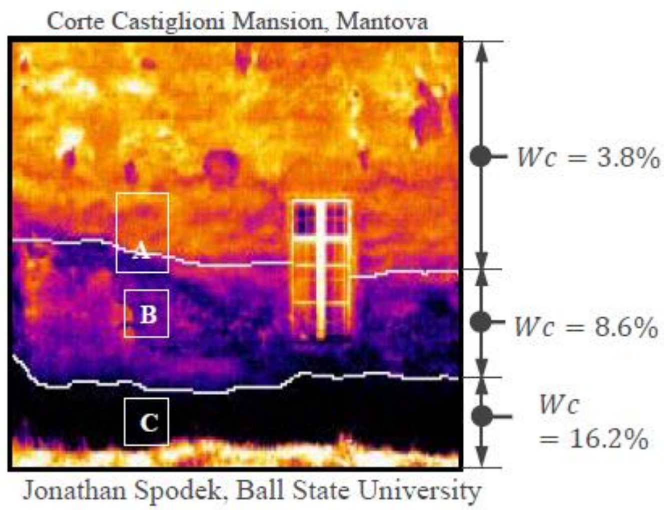


Figure 19: Infrared thermography testing sample [45]

This method is based on emissivity of individual elements within the structural elements each of which absorbs or releases heat of emitted infrared radiation by distinctive rate due to the different rate of emissivity [42]. Ahmad et al. [57], [58] experimentally evaluated the validation of IR performance as a temperature monitoring method by combining two techniques; embedded temperature sensors and IR (Fig. 22).

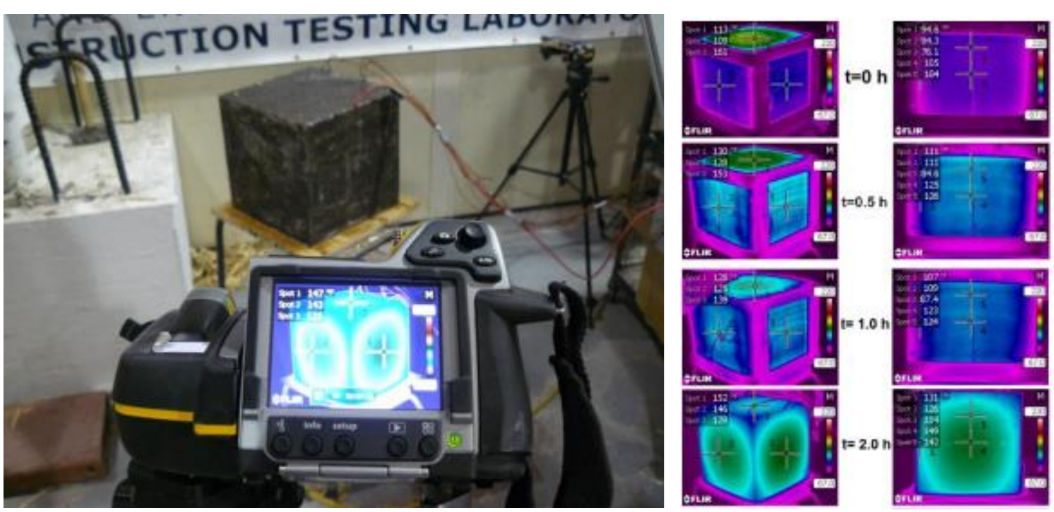


Figure 20: Surface examination of the specimen by Infrared thermography testing [57]

IR method is categorized into the two classes of passive and active thermography by Lee et al. [38]. In the former type, the Infrared Thermography testing is performed without any external cooling or heating source. However, for the active IR method, the heating or cooling source is needed to induce temperature differences [59]. Bridge deck with or without overlays can be tested with this method. One of the drawbacks in the use of IR method is its high sensitivity to contaminants on the bridge deck [38], [51], [60]. Hurlebaus et al. [42] stated that IR is applicable only to non-metal elements, and any uneven heating could have negative effect on the results in testing by this method. However, IR has several advantages in relation with cost, ease of use and interpretation of results. These advantages are significantly pronounced if the ambient heat or cold can be used for testing. Testing immediately after sunrise, right after sunset, or wetting of the surfaces can produce effective results with minimal efforts. Nondestructive evaluation of the health monitoring of cable-stayed bridges using Infrared thermography testing by Mehrabi (Fig. 23) [61].

Figure 21: Figure 23: Infrared Thermal Imaging; Use of IRT camera (left) and a thermal image (right) [61]

7.1.2.5 Acoustic Emission Testing (AE)

The primary basis for Acoustic Emission testing lies in the propagation of acoustic waves originated within a structure from external or internal sources. In general, onset of cracks, delamination, and similar anomalies releases stress and generates an elastic wave which goes from the sound source through the element. This wave is sensed by acoustic sensors attached to the element surface [51]. These events can be generated by applying a localized external force either as sudden mechanical load or a rapid temperature or pressure change to the element being investigated (Fig. 24) [34], [38], [62], [63]. The events can also be generated because of material deterioration such as cross-section loss in reinforcing bars and pre-stressing strands leading to fracture of steel or cracking of the concrete. The method is capable of sensing the waves in a large area just by one sensor depending on the sensitivity of the sensor and extent of damages. However, for detecting the location of damage, more than one sensor is required. It can also be used as a continuous monitoring system for recording events within a specified timeframe [38], [64]. AE method is sensitive to external noise, and less effective for particular types of loading [38]. The bridge evaluation application of Acoustic Emission testing is studied by Carter and Holford [65], Rehman at el [34], and Holford and Lark [66]. Severity assessment, source location and identification are the main aspects of damage for which AE is used as an applicable nondestructive testing method [67]. Apparently, this method is not applicable for detection of damages prior to installation of the sensor, unless the activity at the damage creates sound waves.

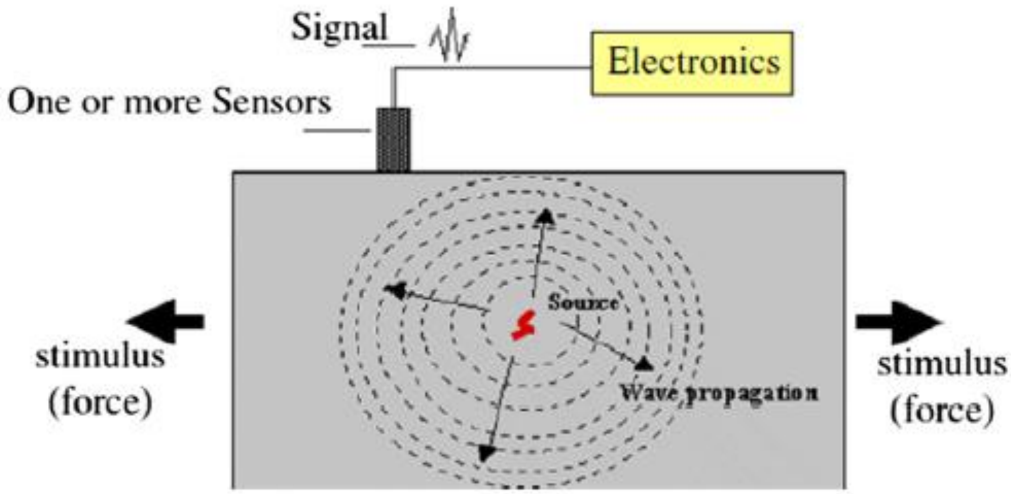


Figure 22: Acoustic Emission Testing (AE) method principle [34]

7.1.2.6 Impulse Response Testing (IRT)

Impulses Response Testing (IRT) uses a stress wave method for determining sonic mobility of a structural element. Deep foundation evaluation is one of the most important utilization of IRT [34], [68]. Compressive stress waves are propagating after striking the concrete surface with a hammer. The frequency of this waves ranges between 0 to 3000 Hz depending on hammer material [69]. As a result, returning signals are collected by data acquisition system, and recorded data is interpreted for defects detection in concrete structure of ABC [34]. Gucunski et al. [39] studied the application of Impulse Response testing method. They evaluated this inspection technique from different aspects for detection of delamination. Impulse Response testing is graded by low degree for its accuracy, high degree for its repeatability of measurements, moderate degree for its speed of data collecting and analyzing. Moreover, what makes this method so applicable is its ease of use [39]. Despite its simplicity, this technique has a wide range usage in inspection and exploring the defects of distinctive parts of concrete structures, and a good potential for use in closure joints. Recently, various IRT applications have been introduced for the subgrade voids detection such as the experimental set-up of Slab Impulse Response Test shown in Fig. 25 [70]. As it shown in Fig. 26, some investigations on ABC closure joints has been carried out by ABC – UTC using IRT for detecting the honeycombs, voids, and cracks [71], [72].

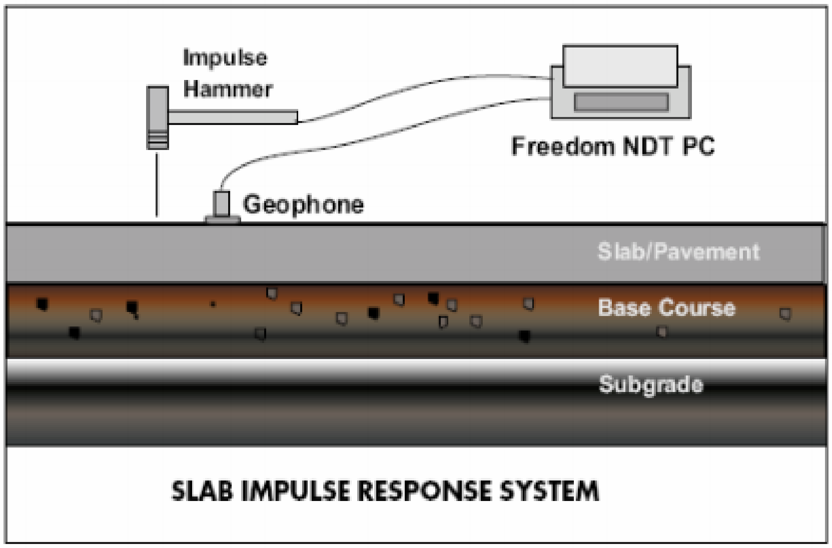


Figure 23: A principle of Impulse Response Testing (IRT) set-up for slab evaluation [70]

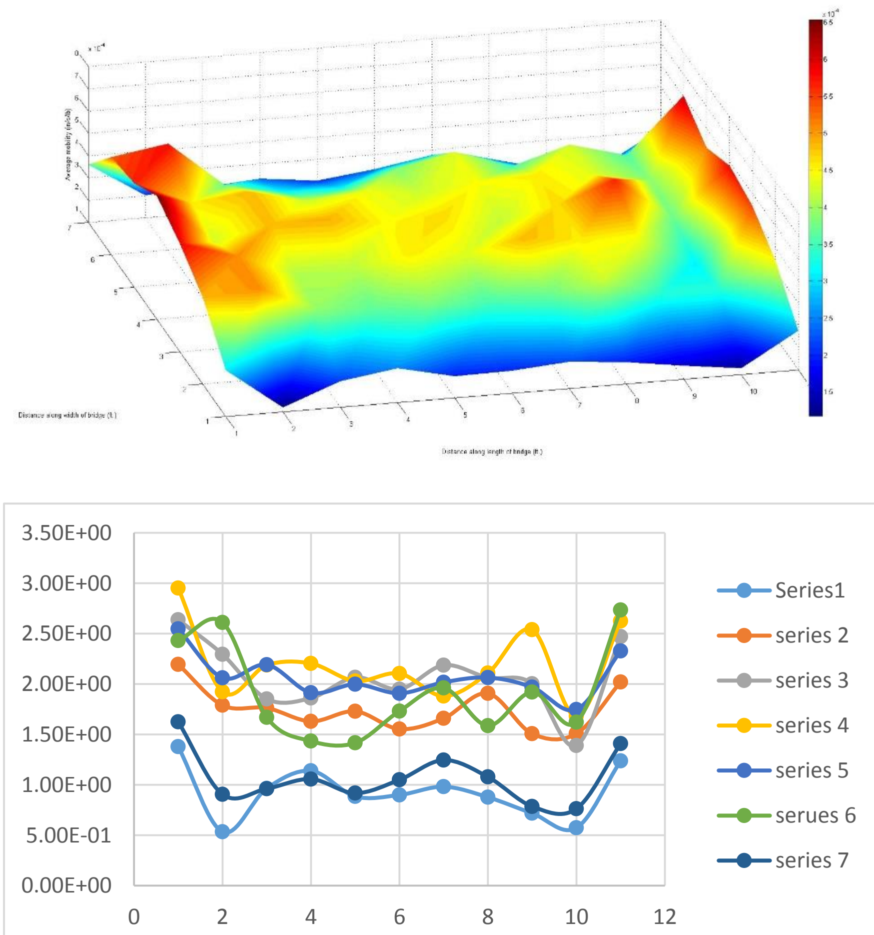


Figure 24: IRT on laboratory constructed test specimens [71]

7.1.2.7 Laser Testing (LT)

Laser Testing is another NDT method used for detection of defects in structural elements. In general, Laser Ultrasonic Testing (LT) method uses a Lamb wave initiation by a pulsed laser which generates a laser impact on the element [38] (Fig. 27).

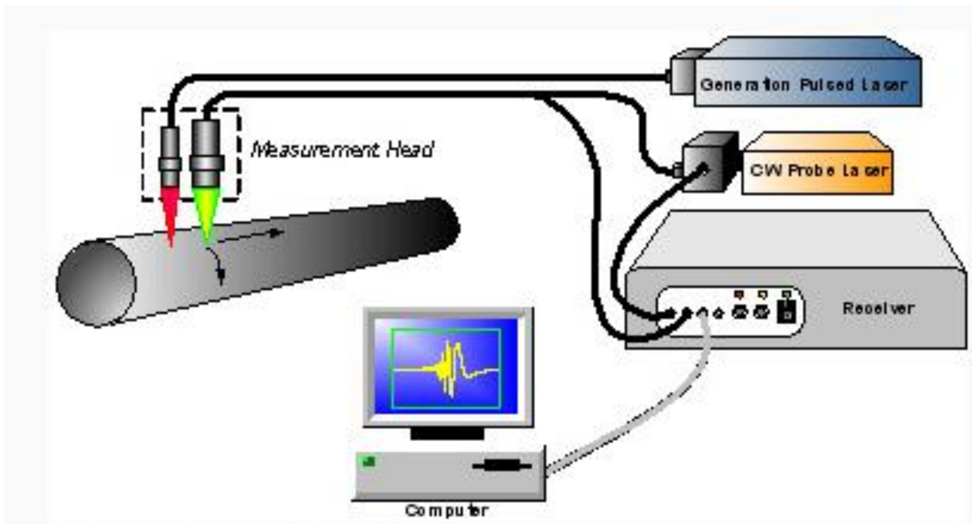


Figure 25: Principle of Laser Ultrasonic Testing (LT) [73]

This method is in its experimental stage and is considered a new technology requiring more study [38]. In Laser Testing method, if the impact locates a flaw area, which is the cause of producing a standing Lamb wave, the defect will be recognized by a photorefractive interferometer [74]. In particular, Laser Testing method is comprised of three main techniques; Profilometry, Shearography, and Holography all of which use laser for inspection [63]. These three techniques have almost the same methodology but different processing. When using any of these methods the surface defects can be detected in the elements subjected to stress developed by heat, pressure, or mechanical load [63]. This method can detect cracks, splits, delamination, and voids by scanning across the surface of the elements, and comparing the test outputs with an undamaged reference element [63]. This method seems to have a potential for use in testing closure joints, and will be investigated further in future.

7.1.2.8 Radiographic Testing (RT)

Radiographic testing (RT) is another NDT method for detecting voids and defects in concrete [37]. In RT, the element is subjected to radiation. Based on the material density, the radiation is transmitted at various rates. These variations in transmission can be detected by photographic films or fluorescent screens (Fig.28) [73]. RT method can have application in a variety of closure joints components and material types. This method is very effective for detecting the internal defects, and specifying an accurate image of the defects or discontinuities. Little surface preparation is required for the use of this method. This test is considered as a low speed test with high sensitivity, but it requires expensive and bulky equipment (x-ray). Inspection by RT methods also needs an experienced, skillful, and well trained operator for application of the method and analyzing the results. Radiography testing has some limitations in detecting small discontinuities, and the element thickness in comparison with UT [33]–[36], [39]–[41]. Safety considerations often precludes the use of this method for structural damage detection.

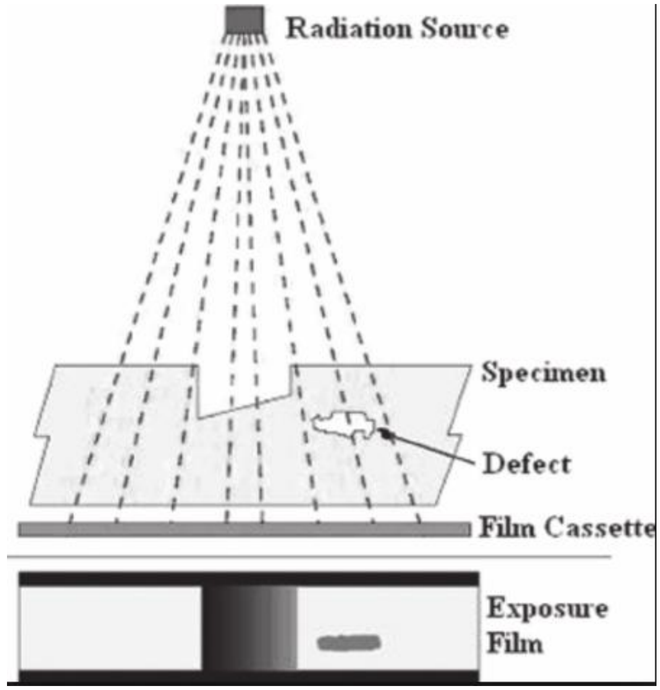


Figure 26: The defects are read from the screen [73]

7.1.2.9 Magnetic Flux Leakage Testing (MFL)

Magnetic Flux Leakage testing method involves magnetizing the steel within the structure by a strong magnet to detect defects such as corrosion, loss of cross section, breaks, and pitting on steel elements [75]. The magnet source can be a permanent or electrically activated magnet. This method works on the principle that when defect is present in the steel element, the magnetic field in the material "leaks" from its flux path. At this stage, any change in magnetic field (the leakage) can be sensed by magnetic detector which is placed between the poles of the magnet (Fig. 29) [42], [76].

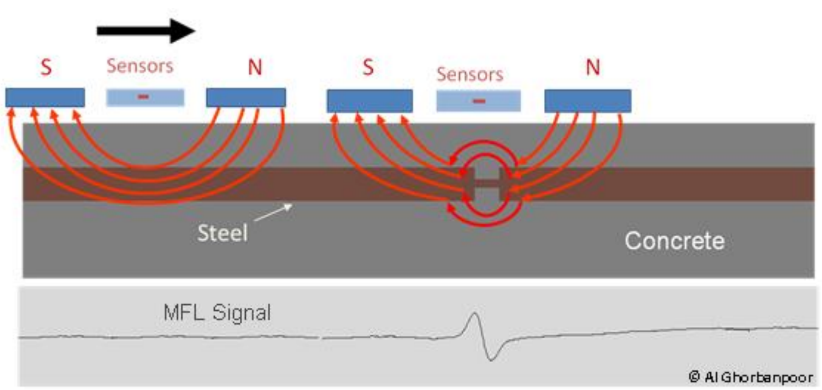


Figure 27: Schematic layout of Magnetic Flux Leakage testing method [77]

The Magnetic Flux Leakage testing is used for near surface detection of defects of the reinforcing steel and rebar damage covered by concrete. It should be mentioned that this method is less effective for the steel elements that are covered by thicker concrete layer [78], [79]. The Magnetic Flux Leakage testing method is more effective for cases in which the rebar location is known. Otherwise, inspector first needs to use another method, like ground penetrating radar, to locate the reinforcement [38].

MFL technique is not often used as an independent method because of its size limitations. MFL has been used successfully for detection of steel defects in stay cables and post-tensioning tendons [61], [80]. This method may be applicable to damage detection in tendons with both non-metal and metal ducts [42]. Like Radiography, the Magnetic Flux Leakage Testing requires extensive experience and training, and carries some safety concerns for its operation. Based on the condition, one or more magnetic sensors may be used in MFL testing. This type of nondestructive testing can be utilized by moving the set-up manually or mounted on a trolley or moving vehicle traveling the surface of the bridge element (Fig. 30) [77].

Figure 28: The Magnetic Flux Leakage testing for Bridge inspection [77]

7.1.2.10 Visual Inspection (VT):

Visual Inspection (VT) is perhaps the fastest, most economical, and practical method intended for detection of seepage, cracking, spalling, exposed reinforcement, beam delamination, and concrete deterioration (Fig. 31). These defects normally serve as a precursor for more detailed investigation [34], [37], [40], [81], however, visual inspection has potential to miss some of the defects, especially internal defects that are hidden from naked eye, and therefore may introduce low accuracy.

Figure 29: Widen cracks observed by Visual Testing (VT) method [82]

This method is applicable to both metal and non-metal elements, but cannot offer any quantitative information about internal defect [34], [42]. Visual inspection however can be improved by the use of fiberscope, borescopes, portable microscope and handheld magnifier [83] for locations with difficult access.

7.1.2.11 Global Structural Response Testing (GSR)

Damage detection based on Global Structural Response could be also categorized among applicable methods in ABC nondestructive evaluation. Vibration Techniques are used to evaluate the condition of the elements by considering the mechanical properties reflected in their dynamic behavior. Changes in modal frequencies and modal shapes are among structural response parameters that can be affected by defects in the structure. Accelerometers, displacement, and velocity are the three main sensors for monitoring the vibration characteristics of a structure [63]. In general, civil engineering structures can be exposed to varying environmental conditions, and undergo changes in stiffness, material properties and boundary conditions over time, therefore experience damage from various sources. These damages have potential to alter the stiffness of the structure locally and affect its global behavior subsequently. Extensive research has been performed on health monitoring and damage detection of structures based on their global response, the most prominent of which perhaps relates to vibration-based modal analysis techniques. These techniques have shown some success in applications such as machinery trouble-shooting and aerospace structural components. These methods also have applications in civil engineering structures. On the other hand, modal parameters may not be sufficiently sensitive for identifying many types of structural damage and their locations unless the level of damage is significant [84], [85]. Vibration tests normally require greater data acquisition and processing efforts when compared to static measurements. Researchers at the Naval Research Laboratory developed a methodology to relate the output of a finite number of sensors to strain-induced structural damage in composite structures using dissipated energy density [86]. Their method requires a knowledge of the exact loading configuration and does not directly identify location of damage or its intensity. Another method used by Banan et al. [85], [87] and Sanayei et al. [88]–[91] is parameter estimation and model updating using experimental static measurements. These methods normally require a relatively large number of different loading conditions to provide for accurate and reliable damage detection. In these methods, displacements or strains of structure under several known static load cases are measured selectively. A finite element model of the structure is constructed, and measured and analytical finite element responses are compared and the model stiffness is updated until the difference between the measured and analytical responses is minimized. This method has a better application for structures with distinct elements such as trusses. A method for identifying the properties of a truss using the measured strains of the truss members under predefined static loads is proposed by Liu and Chian [92]. Similarly, Mehrabi et al. [93] developed a new concept, Precursor Transformation Method (PTM), for damage detection and long-term health monitoring of structures with emphasis on cable-supported bridge application. The method is based on determining the causes (precursors) of change in the measured state of the structure under non-variable loading conditions (e.g. dead loads in bridges). The applicability of damage detection methods based on global response may have limited application to ABC closure joints. Only significant damages that have potential to alter stiffness of the structure would be able to be detected with this method. Recently, several investigations have focused on the use of GSR by either contact or non-contact techniques, consequently, a large number of articles have so far been published on this aspect of health monitoring, especially for aerospace composite structures. Monitoring the effects of applied load on structures by using Surface Response to Excitation Method (SuRE) has been experimentally studied by Tashakori at el. [94] with contact (Piezoelectric sensors) and non-contact (Laser Vibrometer) approaches (Fig. 32).

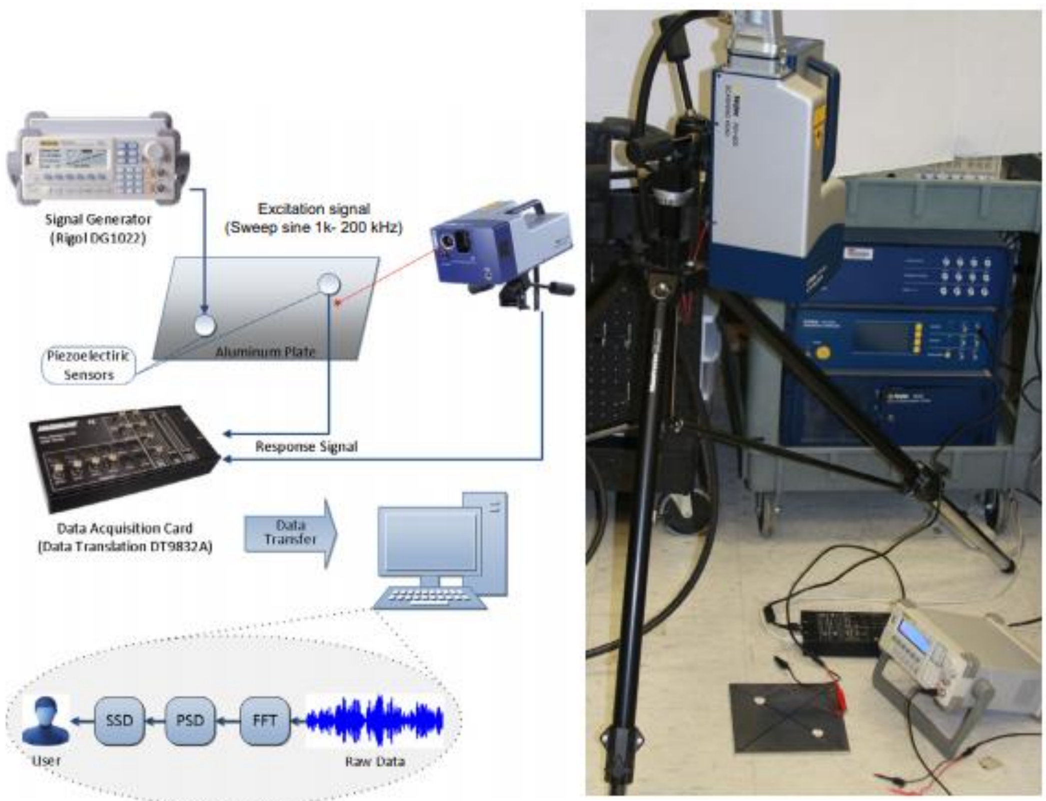


Figure 30: A schematic of Surface Response to Excitation Method [94]

7.1.2.12 Chemical and Electrical Testing (CET)

The main application of CET to ABC health monitoring would be for detecting corrosion or potential of corrosion in reinforcing concrete elements are:

- Electrical Capacitance Tomography
- Electrical Resistivity Tomography
- Half-cell Potential
- Chloride Measurements
- Carbonation Measurements

Electrical Capacitance Tomography has been introduced in the late 1980's as a new internal examination method for measuring the spiral dielectric permittivity distribution by an external capacitance modules as inter-electrode capacitance measurements [95]–[99]. Low cost, speed and safety are some of its merits [96] (Fig. 33).

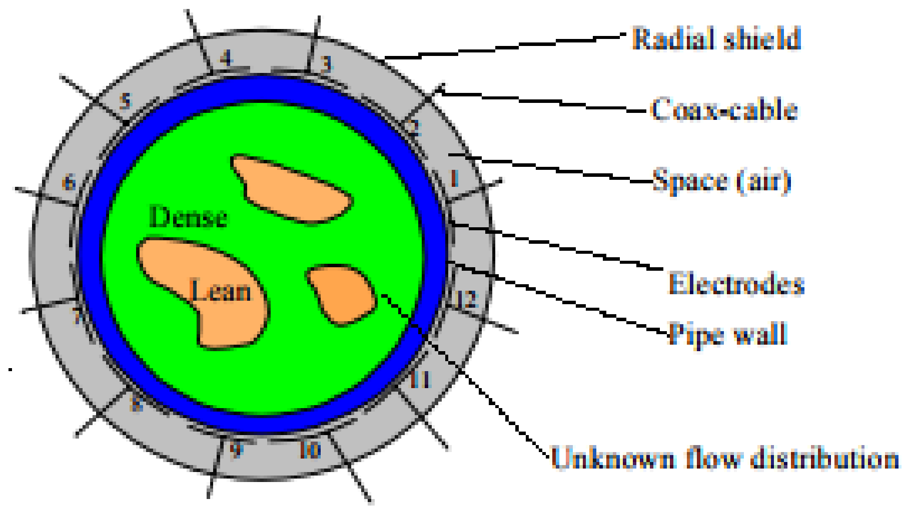


Figure 31: A cross-section model of Electrical Capacitance Tomography system [93]

Electrical Resistivity Imaging or Electrical Resistivity Tomography as a geophysical method can be used for recording the subsurface image by either some electrical resistivity set-up from the surface or electrodes from some boreholes of the structure [98], [99] (Fig. 34).

Half-cell Potential measurement method works based on chemical reactions within Helmholtz Double layer which is result of a natural separation of conductive electrodes surrounding a conductive electrolyte. The potential difference between electrodes and electrolyte is utilized for Half-cell Potential technique as a chemical method in health monitoring of the structures. As it shown in Fig. 35, Half-cell Potential method was used for estimation and determination of the corrosion activity of the reinforcing steel in concrete elements [100]. Although Half-cell Potential method is inexpensive as well as very simple to perform both for the test and analysis the data, it has some limitations such as: difficulty in performing when concrete is contaminated, and inability for quantitative measure for corrosion [101].

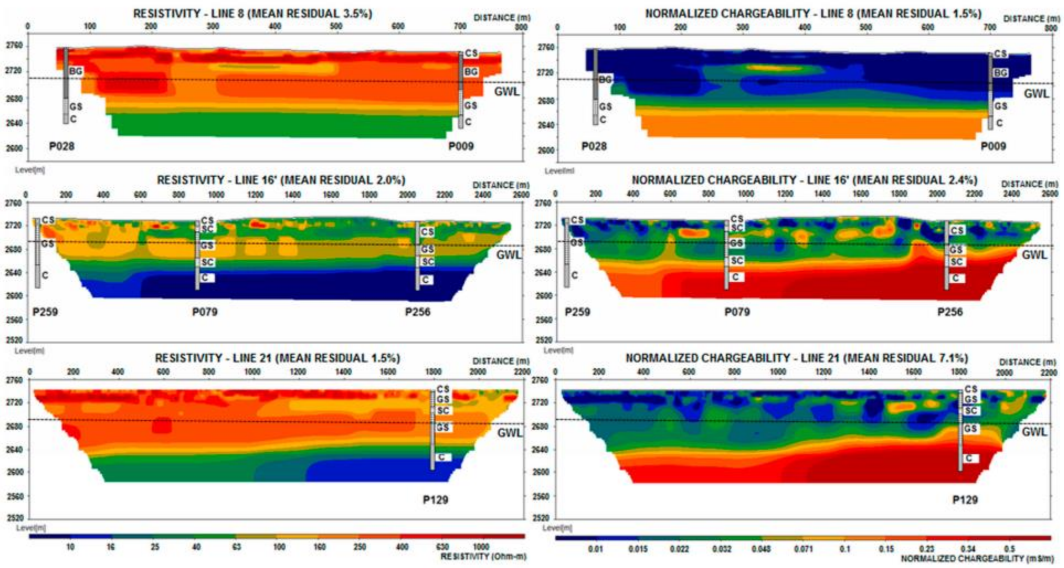


Figure 32: Some sample of Electrical Resistivity Tomography analysis [98]

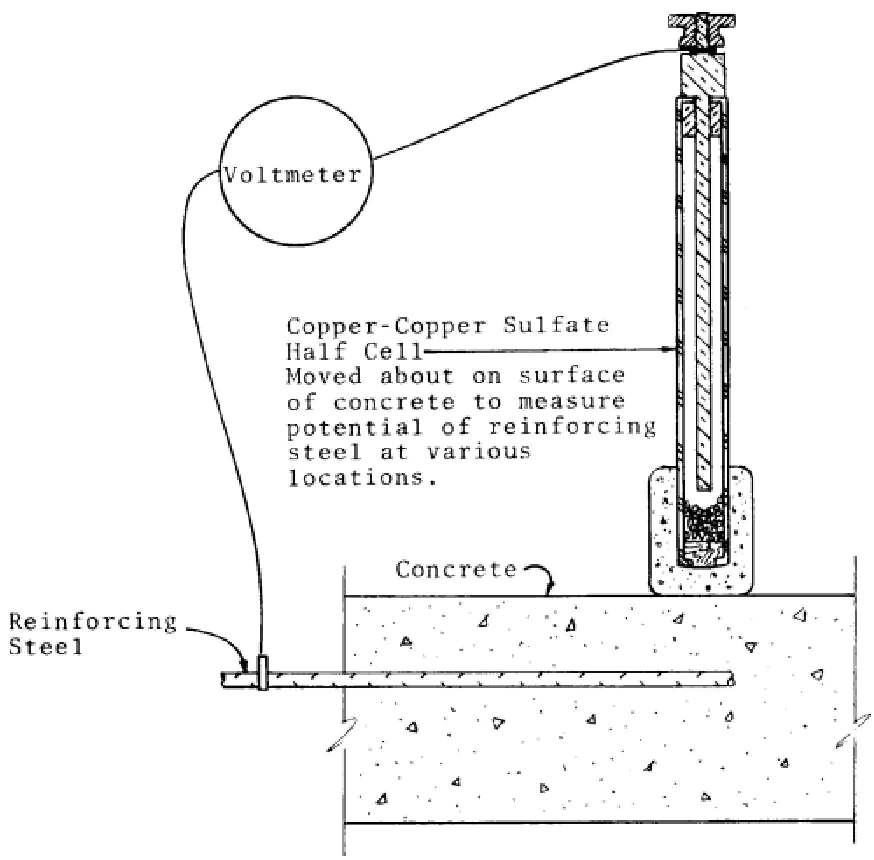


Figure 33: An example of Half Cell Potential test of uncoated reinforcing steel in concrete [100]

7.1.3 Other Common NDT Methods:

Penetrant Testing (PT), Eddy current testing (ET), and Magnetic Particle Testing (MT) have a better applicability to Metallic elements. Hence, although these common types of nondestructive testing methods may not be directly applicable to closure joints considered in this study, they are reviewed here for completeness in covering the NDT techniques.

7.1.3.1 Penetrant Testing (PT):

Penetrant testing also known as Dye Penetrant Inspection (DPI), Penetrant Flaw Detection (PFD), and Liquid Penetrant Inspection (LPI). This surface testing method is very applicable for all types of material except for porous materials such as unglazed ceramic, wood, pottery, and cloth. The PT can detect surface breaking defects because penetrant must be able to enter the discontinuities or defects to form indication. In this test, the case study needs pre- and post-cleaning. In this test, penetrating fluid applied to the element (Fig. 36), and drawn into the surface discontinuities and defects by capillary actions. The use of penetrants for detection of defects on concrete is questionable because of its porosity, however, there may be some application on detecting surface cracks at closure joints.

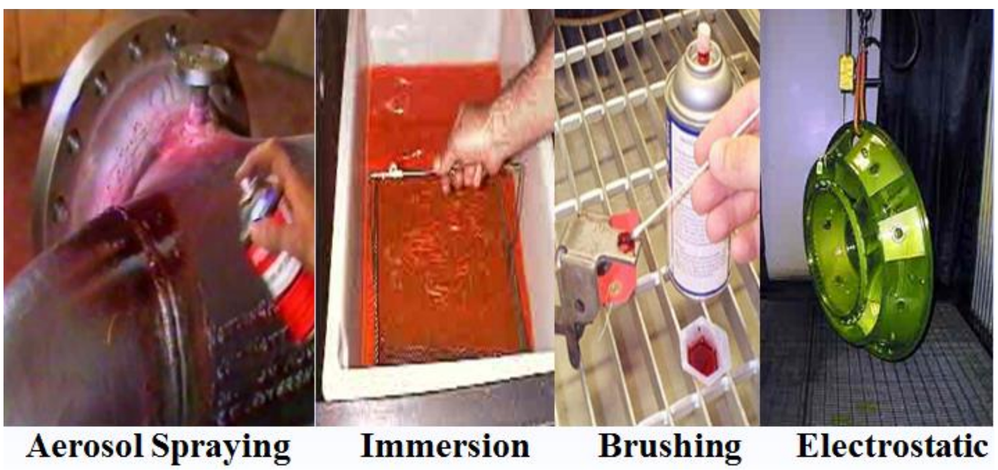


Figure 34: Different types of penetrating fluid used for Nondestructive evaluation [35]

After removing the excess amount of the penetrant, the inspection will be done by the developer forms indication of the defect (Fig.37) [102]. No shape and size limitation for elements, easy use and interpret, low cost equipment, possibility of testing a large number of cases study at the same time, easy to use for testing and analyzing, and high Sensitivity are some of more important advantages of using PT [35]. Temperature dependent, test contamination, compatibility of chemicals, pre- and post-cleaning and preparing of the element surface, high possibility for damaging the element, and disability of exanimating the sub-surface and internal discontinuities as well as testing porous (absorbing) material are all other drawbacks of utilizing of PT [35].

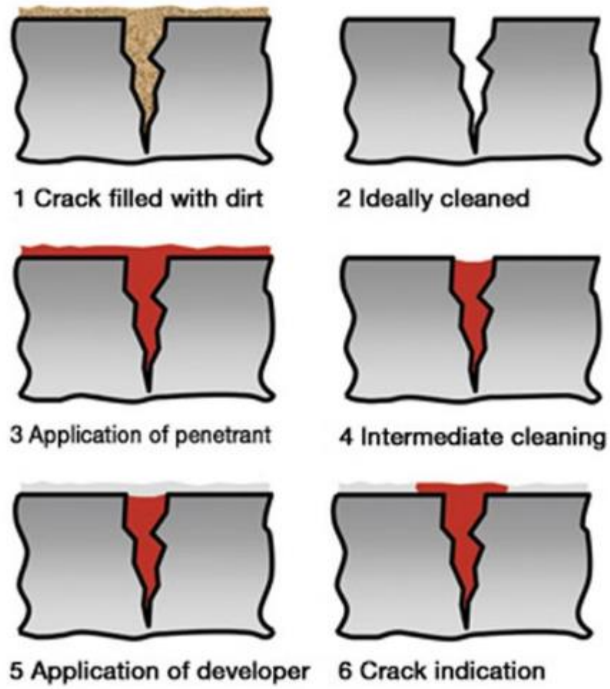


Figure 35: Penetrant Testing (PT) principle [102]

7.1.3.2 Eddy Current Testing (ET):

Eddy current testing (ET) is one of the most practical and common NDT methods for defects inspection of conducting components like steel and aluminum. In this method, an alternating current, by passing through a coil, makes an alternating field. This field generates the eddy currents in the conductors (Fig. 38) [103].

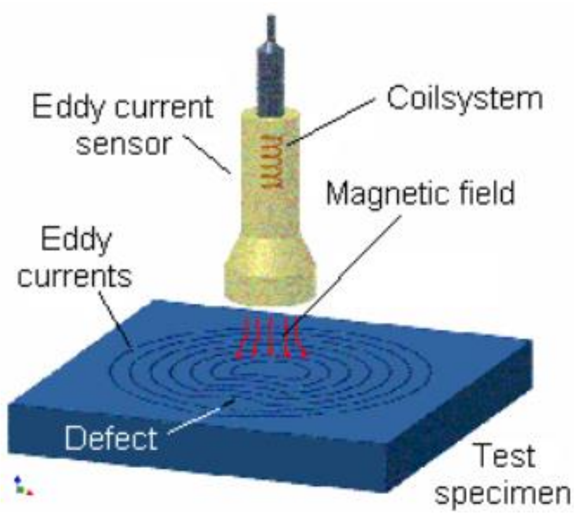


Figure 36: The scheme of the ET method mechanism [103]

In this test, defects will interrupt the eddy current, and the interruption in the coil current is displayed on the set (Fig. 39) [104]. The size of the current as affected by different factors such as flaws, permeability, standoff distance, electrical conductivity, specimen dimensions and so on.

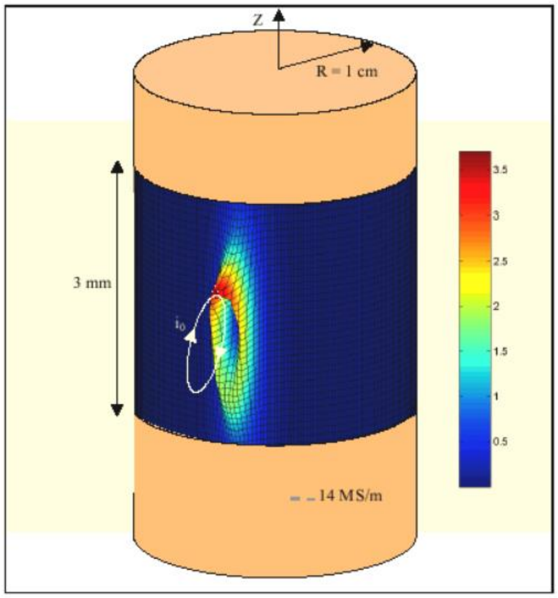


Figure 37: An example of ET distribution on a cylinder [104]

Suitable sensitivity to surface defects, ability to detect defects through several layers, high precise conductivity measurements, automated measuring, ability to detect defects through surface coatings, easy use and portability, and little pre-cleaning surface required could be the most important merits of using ET. On the other hand, inability in recognizing and analyzing the internal defects, application limited to conducting elements, high susceptibility to permeability changes, inability to detect defects parallel to surface, inability in using for large areas and complex geometry's, high expensive equipment are all the advantages of application of ET [35].

7.1.3.3 Magnetic Particle Testing (MT):

Magnetic Particle Testing (MT) method is used for detection the surface and sub-surface defects in ferromagnetic materials. In this test, magnetic field magnetizes the element defects, and discontinuities disrupt the magnetic flux (straight line of magnetic force which is existing in magnetic circuit). The sub-surface and surface defects are revealed by applying the ferromagnetic particles like iron powders (Fig. 40) [105].

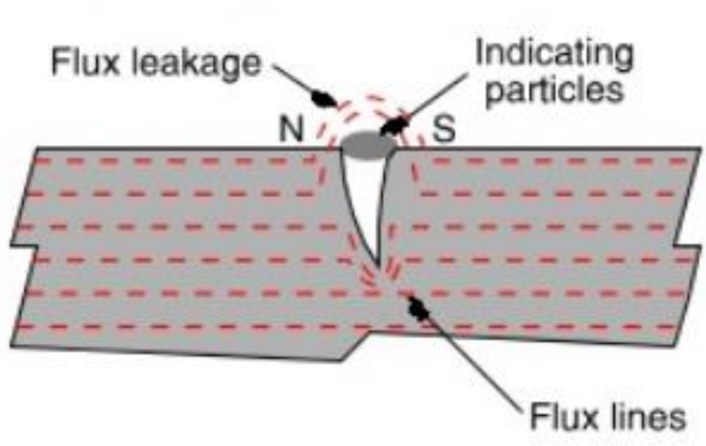


Figure 38: An example of MT principle [105]

Any Defect makes the flux leakage by attracting ferromagnetic particles due to the change of permeability, and shows up as either a dark indication in the fluorescent particles or under Fluorescent lamp as a yellow or green indication (Fig. 41) [35].

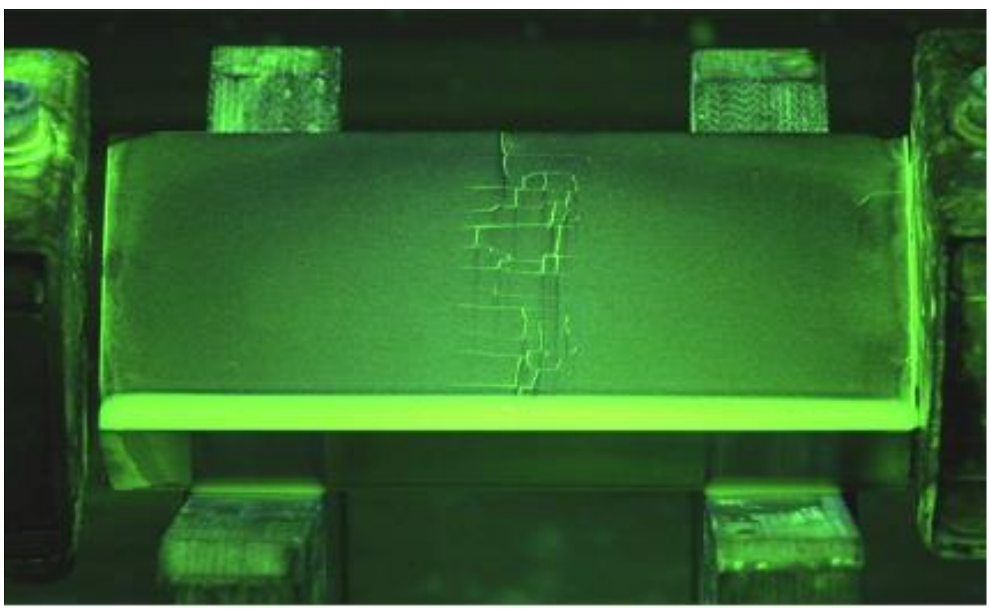


Figure 39: A MT testing sample [106]

Recognizing the sub-surface and surface discontinuities, high speed test (in comparison with PT), Needlessness of the surface cleaning and preparing (in comparison with PT), ability to test the elements which have a very thin coating, low cost equipment, easy to use for testing and analysing the element, and high sensitivity of testing are some of important advantages for MT evaluation. However, material type limitation (useful just for ferromagnetic materials), shape and size limitation, requiring two directions of measuring, inaccuracy for the element with coating, demagnetization needed after the test, inability to detect internal defects are some of the disadvantages of MT [35].

7.1.4 Complementary to NDT Methods

In recent years, to improve precision, effectiveness, safety, and efficiency, various means have been implemented. Combining several methods in one platform and automation are among means for enhancing the use of NDT in bridge structures.

7.1.4.1 Testing under Service Load (SL)

The extent and severity of defects and damages in the closure joints may not be at a level readily detectable by the NDT methods discussed here. To improve the effectiveness of the NDT methods in detection of damages, loads can be introduced in the structure in a manner to emphasize the defect. For example, loading applied on the deck in between girders can pronounce the crack at the closure joint and precast deck elements for longitudinal joints along and on top of main girders. Depending on the type of the joint to be investigated and the NDT method used for damage detection, loading patterns can be designed to improve the effectiveness of the damage detection methods.

7.1.4.2 Automated Testing Platforms (ATP)

Robots and Unmanned Aerial Vehicles (UAV) or drones have been used in recent years for many applications in construction, including visual and non-destructive testing [107]. As it shown in Fig. 42, robots of various types and sophistication carry combination of NDT methods for bridge superstructure.

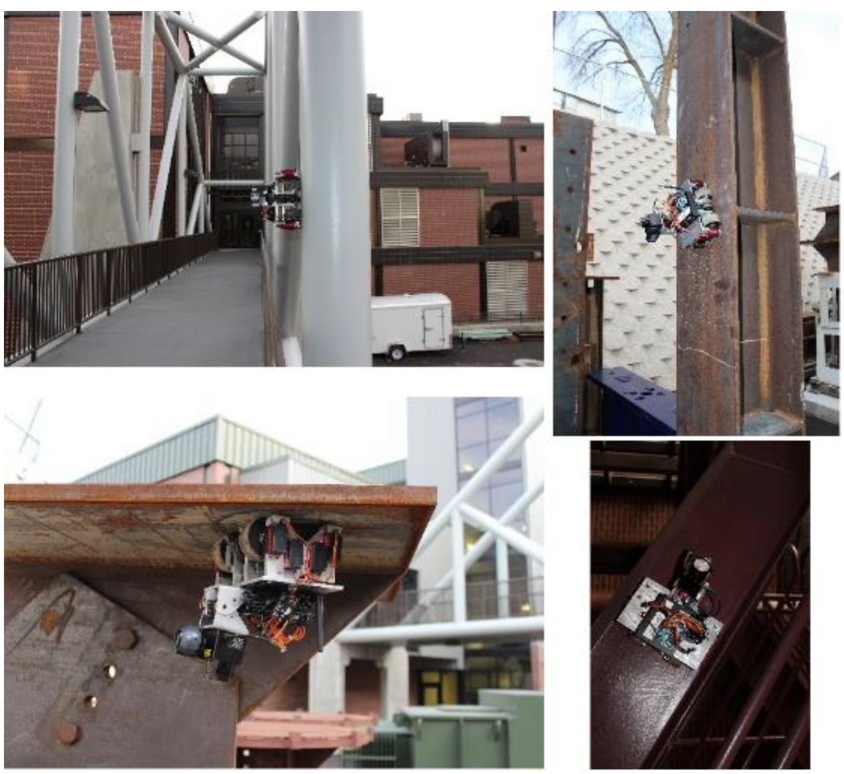


Figure 40: Some robots who collaborate with operator for bridge inspection [107]

High demand for automation of inspection have increasingly led researchers to study the potential of the robotic systems for bridge non-destructive examination. According to conditions and environment, robotic and automated methods may consist of multi-NDT techniques: GPR, LT, IRT, RT, etc. Ghasemi et al. [108] have performed a pilot project for condition assessment of concrete bridge decks using Robotics in which Global Positioning System, Ground Penetrating Radar, Impact Echo, Electrical Resistivity, Ultrasonic Surface Waves, and High-resolution Imaging are used in a complex inspection set up as shown in Fig. 43.

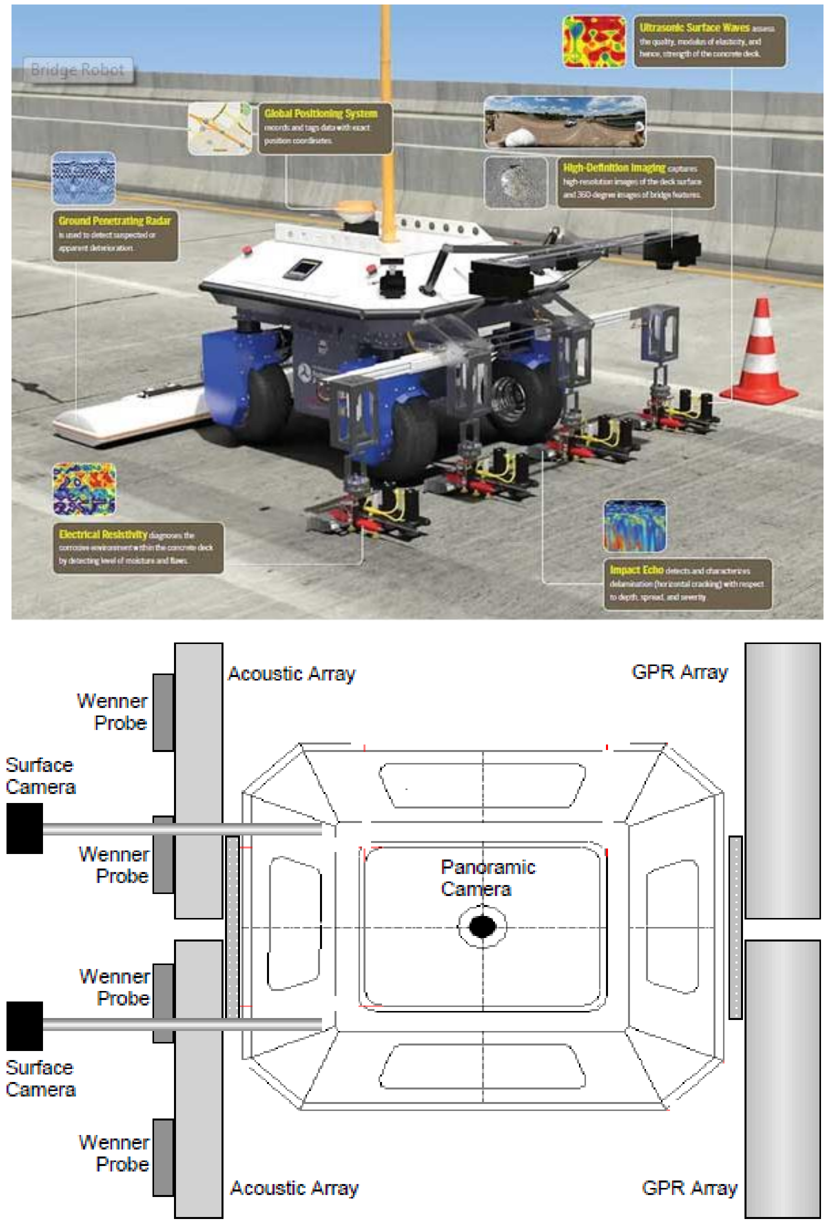


Figure 41: Multitask robot for NDT inspection on the bridge concrete deck [108], [109]

There have also been investigations on the effectiveness and application of robots and drones to inspection and damage detection. As it shown in the Fig. 44, Minnesota Department of

Transportation has performed one such demonstration project to investigate effectiveness and application of drones to bridge inspection. This investigation along with others have demonstrated the great potential for drones in inspection of hard to reach locations on bridges, but at the same time pointed to some technological limitation of existing UAVs and robot-assisted bridge inspection preventing in some cases their full implementation [110-115].

Figure 42: Drone used for bridge inspection by Minnesota Department of Transportation [110]

7.1.5 Promising Methods

Taking into account characteristics of the non-destructive methods discussed above, following methods can be viewed as promising for use in health monitoring of closure joints:

1. Impact Echo Testing (IE)
2. Microwave Testing (MW) – Ground Penetrating Radar (GPR)
3. Ultrasonic Testing (UT)
4. Phased Array Ultrasonic Testing (PAUT)
5. Infrared Thermography Testing (IR)
6. Impulse Response Testing (IRT)
7. Laser Testing (LM)
8. Radiographic Testing (RT)
9. Magnetic Flux Leakage Testing (MFL)

A comprehensive tabulated format is used for Table 9 shows the comparison and rating of the selected promising methods for ABC closure joints based on the characteristics, features, and attributes. These results are preliminary, and some rating relies on authors' experiences with these or similar methods. These ratings will be revisited as more information becomes available.

Following capabilities and attributes have been considered for rating of the applicability of the methods to closure joints:

- Test Speed: The speed of coverage and data collecting in using the NDT test.
- Surface Scanning: This indicator measures the test ability in detecting surface defects
- Internal Detection: This index shows the test ability in examining the internal defects.
- Accuracy: Considers the precision of the method.
- Analyzing Speed: This indicator is related to the speed of data analysis collected by the NDT method.
- Cost: Shows the cost of associated with the usage of the method, equipment and tools.
- Ease of Use: Indicates user friendliness, regardless of required skill for the ND technique.
- Safety: This indicator shows the safety of use of the NDT method for operators and public.
- Skill: This index considers the level of training and skill requirement for utilizing each method.
- Repeatability: Indicates the level of repeatability of measurement results.

Table 9: Comparison and preliminary rating of NDT methods for ABC closure joints – Good=G, Fair=F, Poor=P [116-117]

Capability / Type — NDT Method	Test Speed	Sub-surface Scanning	Internal Detection	Accuracy	Analyzing Speed	Cost	Ease of Use	Safety	Skill	Repeatability
IE	F	F	G	G	F	G	G	G	F	G
GPR	G	G	G	F	F	G	G	G	G	F
UT	F	G	G	G	F	F	G	G	F	G
PAUT	F	G	G	G	F	F	F	G	F	G
IR	G	G	F	F	G	G	G	G	F	F
IRT	G	G	F	F	G	G	G	G	G	F
LM	F	G	F	F	F	P	P	F	P	F
RT	P	G	G	G	G	P	P	P	P	G
MFL	F	G	F	F	F	P	P	P	P	F

7.2 SELECTION OF APPLICABLE METHODS

The ability or versatility of each NDT method for inspection of various groups of closure joints and distinctive types of defects is an important target of this study. In this section, based on the defect etiology, nondestructive testing methods will be analyzed according to the rating of their capabilities reflected in Table 9. These NDT techniques will also be evaluated according to their applicability to specific types of defects and anomalies. Moreover, the ability or versatility of each method for inspection of various groups of closure joints and distinctive types of defects is an important target of this study.

7.2.1 Grouping of Various Defects

Although the focus of this study is on NDT methods that would be employed to detect damages that are not visible, it is realized that for visible damages and defects, visual inspection always offers the fastest, most economic and accurate method of detection. Hence, among potential defects for closure joints described earlier in this report, visible defects such as abnormal appearance including signs of leakage and efflorescence, surface defects, surface roughness, surface cracks, spalling of concrete cover, and exposure of reinforcing bars and embedment can be best detected using visual inspection. The potential defects that are not visible therefore can be listed as;

- Delamination of wearing surface
- Delamination of concrete cover (before cracking and spalling becomes visible)
- Reflective cracks (for the extent of cracking inside the joint)
- Voids (internal)
- Honeycombing (internal)
- Debonding at cold joints (for the extent inside the joint)
- Concrete material segregation
- Corrosion of reinforcing bars
- Corrosion of embedded steel

According to the bridge damage etiology approach, the following defect types are recognized as the most common defects that may occur in deck closure joints.

1. Delamination
2. Cracks (discontinuities of various orientations including debonding)
3. Voids (including internal honeycombing and segregation as variation in density)
4. Corrosion of embedded steel (including reinforcing bars, connectors, plates, and couplers)

Collectively, these four types of defects/damages represent, by type or feature, all damages and defects associated with closure joints.

7.2.2 Quantitative Comparison among the Most Promising NDT Methods

To substantiate the basic conclusions of the above analyses with quantitative measures, a statistical analysis of the applicability of NDT methods to specific types of defects and damages was performed. A total of 50 literature sources were reviewed and evaluated for this purpose. The defects considered for this evaluation are as described above as delamination, cracks (includes debonding), voids, and corrosion of embedded steel. The criteria or measure considered for this evaluation is the number of citations of a specific method deemed applicable to a specific defect. In other words, to derive a quantitative measure for comparison among various NDT methods and their applicability to each defect type, results of the literature search were analyzed to find the number of sources who identified a method as applicable to a defect type. Information for each defect type is summarized in Table 10. In this table, the first column lists the four groups of expected defects for closure joints. The second column of this table lists NDT methods recognized as promising for closure joints. Subsequently, the sources/references which have identified each NDT method for applicability to certain type of defect are listed in the third column in a row corresponding to the NDT method and the row corresponding to the type of defect. N and M in the fourth and fifth columns of the table refer to the total number of sources (for each NDT method applicable to the type of defect) and percentage of number of sources in comparison with the total sources cited, respectively. The results are also illustrated in Figures 45-48 for clarity. The charts show clearly the NDT method(s) that is most appropriate for each damage type in closure joints denoted by the higher percentage(s). Each chart shows the results for one of the four common types or groups of damages or defects. The charts in these Figures can be used as selection guide and allow bridge owners/operators to select the most applicable NDT method for detecting each type of specific damages. The results presented here attempt to establish clear relationship between the expected damages in each of the five distinctive types of closure joints and appropriate NDT methods. Along with future development of field procedures and reporting methods, selection and decision making aids developed in this study can be integrated into states and national bridge health monitoring programs.

Table 10: Statistical analysis of applicability of NDT methods to defects in ABC closure joints [118].

			N	M
Delamination	IE	[126][127][129][130][140][141][143][144][145][148][153][155][156][161][162][120][168]	17	34%
	GPR	[125][124][126][127][129][131][132][133][134][135][138][140][143][145][146][148][150][151][152][153][155][156][157][159][160][161][162][163][164][165][123][122][120][119][166]	35	70%
	UT	[140][148][155][158][161][164][120][168]	8	16%
	IR	[126][127][128][129][130][148][133][141][142][151][153][154][159][160][161][163][165][122][167]	19	38%
	IRT	[140][148][151][121]	4	8%
	RT	[132]	1	2%
	MFL	---	0	0%
Corrosion	IE	[126][156]	2	4%
	GPR	[124] [126][127][162][131][134][137][138][144][145][148][155][120][119]	14	28%
	UT	[147][156]	2	4%
	IR	[127]	1	2%
	IRT	---	0	0%
	RT	---	0	0%
	MFL	[128]	1	2%
Crack	IE	[127][129][147][148][155][161]	6	12%
	GPR	[134][135][152][155][119]	5	10%
	UT	[126][128][132][136][139][140][148][153][155][158][160][161][164][123][120]	15	30%
	IR	[128][129][147][148][161][165][120][167]	8	16%
	IRT	[147][148][151]	3	6%
	RT	[126][147]	2	4%
	MFL	[149]	1	2%
Void	IE	[126][128][129][147][148][153][161][162][120]	9	18%
	GPR	[126][128][129][132][136][146][148][150][153][160][165][123][120][119]	14	28%
	UT	[126][139][140][153][161][123][120]	7	14%
	IR	[126][129][142][147][148][151][160][120]	8	16%
	IRT	[147][148][151][121]	4	8%
	RT	[126][132][147][153]	4	8%
	MFL	---	0	0%

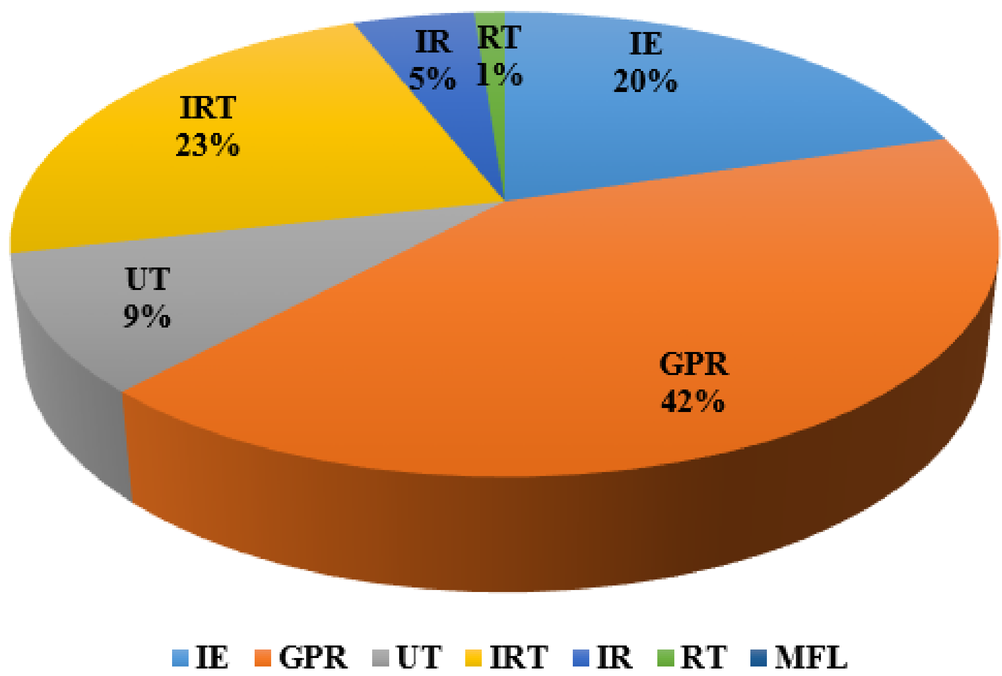


Figure 43: Statistical representation of NDT methods most applicable to detect delamination

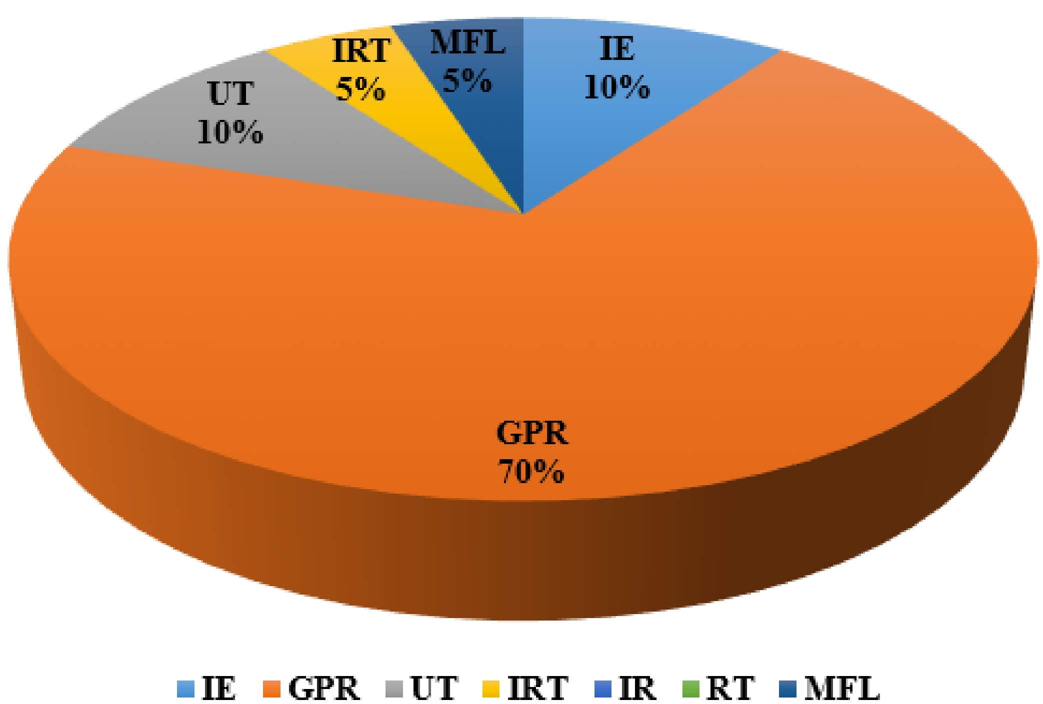


Figure 44: Statistical representation of NDT methods most applicable to detect corrosion

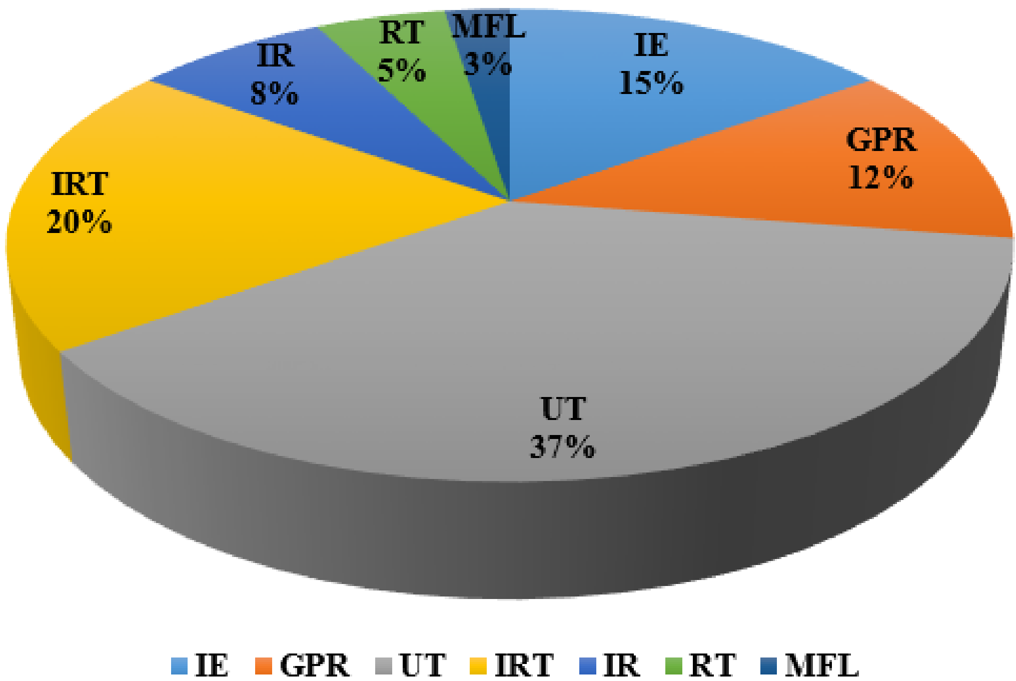


Figure 45: Statistical representation of NDT methods most applicable to detect cracks

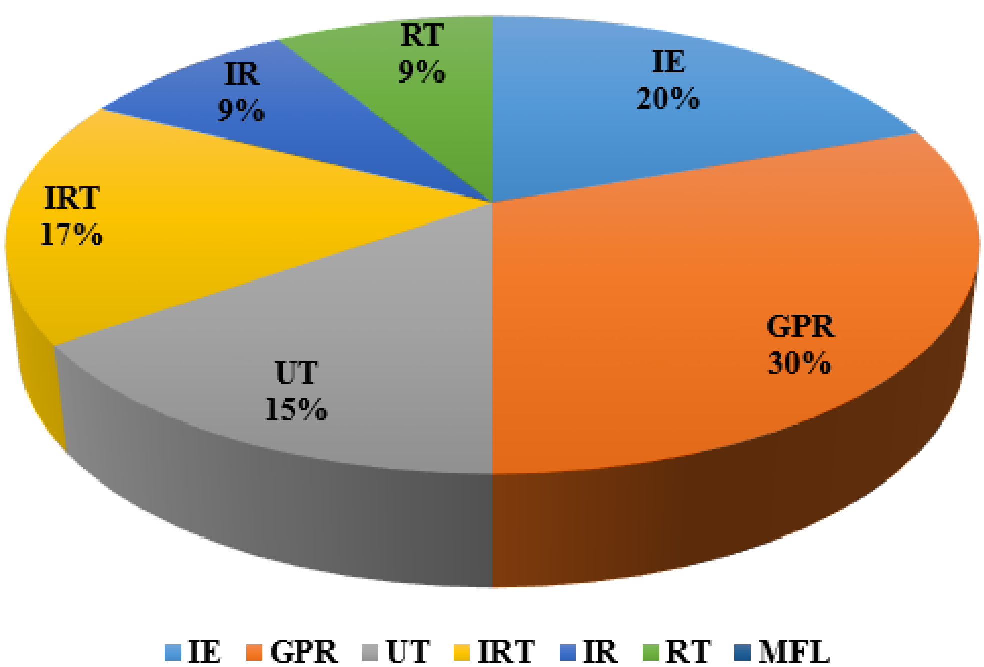


Figure 46: Statistical representation of NDT methods most applicable to detect voids

8 SUMMARY AND CONCLUSIONS

In Accelerated Bridge Construction (ABC), prefabricated bridge deck elements are connected to each other using "Closure Joints." Because of cast-in-place nature of closure joints that are expected to go into service rapidly and problems observed for some types of closure joints, there have been some concerns about their long-term durability. The closure joints have presented themselves as the weak link in bridges built using high quality manufactured prefabricated elements and systems. Therefore, for the health monitoring of ABC bridges, it has become important to first assure that the closure joints are free of defects immediately after construction, and that any damages can be detected during their service life to allow timely remediation. Otherwise, susceptibility of closure joint details to damage may question the entire notion of benefits from ABC.

Non-destructive Testing (NDT) methods offer valuable means for monitoring the health of closure joints. In this report, a detailed investigation was presented on the evaluation of NDT methods that are applicable to specific defects related to various types of closure joints in ABC. For this purpose, closure joint in bridge decks were categorized according to their composition and distinctive details, and potential damages and serviceability problems of the closure joints were identified. Five groups of ABC closure joints were recognized that are common for ABC deck structures, each group containing specific shared details which may affect their sensitivity to specific damages and applicability of the NDT techniques. Evaluation of the performance of the closure joints and general observations from bridge inspections pointed to a series of damages and their sequence expected for closure joints using a practical Damage Sequence Tree (DST). Taking into account the specific characteristics of closure joint types and aided by the DST, the most likely causes for defects and damages were identified. It was attempted to construct rational relationships between observed or presumed defects in the five types of ABC closure joints and their causes in the form of damage etiology.

The process has determined that most of defects related to the ABC closure joints can be caused by one or more of issues related to material, design, workmanship, mechanical and environmental factors. These factors were incorporated in a Fault Tree Analysis (FTA) which is believed to be instrumental for effective and accurate selection of NDT methods for health monitoring of ABC bridges. As part of this study, a comprehensive literature search was performed to first identify the most promising NDT techniques and their respective capabilities for application to ABC closure joints. The results were then analyzed through DST and FTA to construct a guide framework capable of practical identification of the NDT methods that are most appropriate for detection of specific defects associated with each type of closure joints.

To substantiate the basic conclusions of these analyses with quantitative measures, a statistical analysis of the applicability of NDT methods to specific types of defects and damages was performed. More than 50 papers and information sources were reviewed to obtain the information necessary for this analysis, mainly in the form of number of citations for each method as being effective or applied for certain defect and damage type. The procedure and framework presented in this report can be effectively and readily used by the bridge owners/operators and/or consultants as a guideline for connecting the capabilities of NDT methods to potential defects expected for closure joints, and selecting the most appropriate method that best serves the purpose of the bridge health monitoring. The results of the study reported here have been organized so that its outcomes would allow future development of field procedures, reporting techniques, and suitability for integration into bridge health monitoring programs. Laboratory and field verification are being considered as future research to demonstrate the utility of the guideline developed as part of this study. Future experimental work is planned for support in implementation and validation of the project conclusions.

9 REFERENCES

[1] Culmo, M. P., Sadasivam, S., Gransberg, D., Boyle, H., Deslis, A., Duguay, W., Rose, D., Mizioch, C. and Mallela, J., 2011, ‘Contracting and Construction of ABC Projects with Prefabricated Bridge Elements and Systems,’ Federal Highway Administration, Washington, D.C., Rep. FHWA-HIF-17-020.

[2] Mashal, M., White, S. and Palermo, A., 2012, ‘Concepts and Developments for Accelerated Bridge Construction and Dissipative Controlled Rocking,’ 15 WCEE LISBOA.

[3] Bowers, R., Klaiber, F. W., Kevern, S., Landau, C., Kieffer, R. and Nelson, J. S., 2007, ‘Construction and Testing of an Accelerated Bridge Construction Project in Boone County,’ Proceedings of the 2007 Mid-Continent Transportation Research Symposium.

[4] Jahromi, A. J., Dickinson, M., Valikhani, A. and Azizinamini, A., 2017, ‘Toward Development of Best Practices for Closure Joints in ABC Projects,’.

[5] Culmo, M. P., 2011, ‘Accelerated Bridge Construction - Experience in Design, Fabrication and Erection of Prefabricated Bridge Elements and Systems,’ Federal Highway Administration, McLean, VA, Rep. FHWA-HIF-12-013.

[6] Adjacent precast box beam bridges,’ The Construction Specifier CSI, Available: https://www.constructionspecifier.com/adjacent-precast-box-beam-bridges/4/. [Accessed: 1-Jan-2018].

[7] Culmo, M. P., 2009, ‘Connection Details for Prefabricated Bridge Elements and Systems,’ Federal Highway Administration, Rep. FHWA-IF-09-010.

[8] Porter, S. D., Julander, J. L., Halling, M. W. and Barr, P. J., 2012, ‘Shear Testing of Precast Bridge Deck Panel Transverse Connections.’ Journal of Performance of Constructed Facilities, 26(4), 462-468.

[9] Russell, H., Ralls, M., Tang, B., Bhide, S., Brecto, B., Calvert, E., Capers, H., Dorgan, D., Matsumoto, E., Napier, C., and Nickas, W., 2005, ‘Prefabricated Bridge Elements and Systems in Japan and Europe,’ Federal Highway Administration, Rep. FHWA-P.

[10] French, C., Shield, C., Ma, Z. J, Klaseus, D., Smith, M., Eriksson, W., Zhu, P., Lewis, S. and Chapman, C. E., 2011, ‘Summary of Cast-In-Place Concrete Connections for Precast Deck Systems,’ National Academy of Sciences.

[11] Wipf, T., 2009, “Iowa’s Perspective on ABC,” FHWA ABC workshop International Bridge conference.

[12] Marin III, D., 2008, ‘Accelerated Bridge Construction,’ Iowa DOT ABC Workshop Bridge Devision Texas DOT.

[13] Megrio, 2014, ‘Cracked Bridge in Rio de Janeiro Brazil,’ CNN, 09-Apr-2014. [Online]. Available: http://ireport.cnn.com/docs/DOC-1118550. [Accessed: 08-Feb-2018].

[14] ‘Concrete Internal Defect Location,’ NeoDex, [Online]. Available: http://neodexndt.com/en/concrete-internal-defect-location-2/. [Accessed: 08-Feb-2018].

[15] Carden, D., 2010, ‘Valpo prof tries to crack case of MLK bridge defects,’ The Times nwi.com, 05-Jul-2010. [Online]. http://www.nwitimes.com/news/state-and-regional/indiana/valpo-prof-tries-to-crack-case-of-mlk-bridge-defects/article_287deb0b-07a2-54c4-a079-79e4b1e6d61f.html. [Accessed: 08-Feb-2018].

[16] Gucunski, N., Imani, A., Romero, F., Nazarian, S., Yuan, D., Wiggenhauser, H., Shokouhi, P., Taffe, A. and Kutrubes, D., 2013, Nondestructive Testing to Identify Concrete Bridge Deck Deterioration, Transportation Research Board, Washington, D.C.

[17] Rogerson, R., Ed., ‘HAC concrete,’ Sandberg. [Online]. Available:

https://www.sandberg.co.uk/investigation-inspection/inspection/hac-concrete.html. [Accessed: 02-Feb-2018].

[18] 2010, 'Structure: 22269 Tees Quay Millennium FB,' Bridge Inspections 09-10/Structure: Tees Quay Millennium FB , [Online]. Available: https://www.whatdotheyknow.com/request/106745/response/262543/attach/4/22269%20Tees%20Quay%20Millenium%20FB%20Defects%20Summary.pdf. [Accessed: 08-Feb-2018].

[19] 2016, 'Aging Structures,' Infratech360 Advanced Civil Technologies, [Online]. Available: https://www.infratech360.com/single-post/2013/07/24/aging-structures. [Accessed: 08-Feb-2018].

[20] Record T., 2012,cSpokane Street Viaduct updates: Truck trouble; ramp updates; old bridge deck, up close,' West Seattle Blog, [Online]. Available: http://westseattleblog.com/2012/04/spokane-street-viaduct-updates-truck-trouble-ramp-updates-old-bridge-deck-up-close/. [Accessed: 08-Feb-2018].

[21] Krieger, L. M., 2017, 'Big Sur bridge set to open Sept. 30, connecting broken link along Highway 1,' The Mercury News, [Online]. Available: https://www.mercurynews.com/2017/03/28/big-sur-bridge-set-to-open-jan-1-connecting-broken-link-along-highway-1/. [Accessed: 08-Feb-2018].

[22] URS, 2014, 'Lessons Learned After Construction: Bridge County Road Over I-80,' Salt Lake City, Utah, Project No. IBHF-80-4(90)160.

[23] Attanayake. U., and Aktan, H., 2015, 'First-generation ABC system, evolving design, and half a century of performance: Michigan side-by-side box-beam bridges,' *J. Perform. Constr. Facil.*, vol. 29, no. 3, pp. 1–14.

[24] Brown, M., Sellers, G., Folliard, K., and Fowler, D., 2001, 'Restrained shrinkage cracking of concrete bridge decks : state-of-the-art review,'Austin, TX, Rep. FHWA/TX-0-4098-1.

[25] Utah Department of Transportation (UDOT), 'Performance of Accelerated Bridge Construction Projects in Utah: As of May 2009 (Lessons Learned Report),' 2009

[26] E. & D. MD, 2004, 'Prefabricated Bridge Replacement Report: i-215 East 3760 S. & 3900 S.,' Salt Lake City, Utah, Project No. IBHF-215-9(110)2.

[27] French, C., Le, Q. T. C., Eppers, L. J., and Hajjar, J. F., 1999, 'Transverse Cracking in Concrete Bridge Decks,' St. Paul, MN, Rep. MN/RC -1999-05.

[28] Nair, H., Ozyildirim, C., and Sprinkel, M. M., 2016, 'Evaluation of Bridge Deck with Shrinkage- Compensating Concrete,' Richmond, VA, Rep. FHWA/VTRC 16-R15.

[29] T. R. Synthesis, 2011, 'Bridge Deck Cracking,' Rep. TRS1105.

[30] Rettner, D. L., Fiegen, M. S., Snyder, M. B., and MacDonald, K. A., 2014, 'Analysis of Bridge Deck Cracking Data a Review of Mechanisms, Analysis of MnDOT Bridge Construction Data, and Recommendation for Treatment and Prevention,' St. Paul, MN, Rep.MN/RC 2014-09.

[31] Mishalani, R. G., Shafieezadeh, A., & Li, Z. (2018). Updating Bridge Deck Condition Transition Probabilities as New Inspection Data Are Collected: Methodology and Empirical Evaluation. Transportation Research Record, 0361198118796003.

[32] Hopper, T., Manafpour, A., 2015, 'Bridge Deck Cracking: Effects on In-Service Performance, Prevention, and Remediation,' Harrisburg, PA, Rep. FHWA-PA-2015-006-120103.

[33] 2012, 'Non-destructive Testing,' DNV CLASSIFICATION NOTES.

[34] Rehman, S. K . U., Ibrahim, Z., Memon, S. A., and Jameel, M., 2016 'Nondestructive

test methods for concrete bridges: A review,' Construction and Building Materials, 107, pp 58-86.
[35] 'NDT Appreciation,' TWI Training and Examinations. [Online]. Available: http://www.twitraining.com/home. [Accessed: 20-Feb-2018].
[36] 2016, 'Personnel qualification and certification in nondestructive testing', American Society for Nondestructive Testing, Rep. SNT-TC-1A.
[37] D., R. S. and N.R, D. M, 2013, 'Non Destructive Testing of Bridge Pier - A Case Study,' Procedia Engineering, 54, pp 564-572.
[38] Lee, S., Kalos, N., and Shin, D. H., 2014, 'Non-Destructive Testing Methods in the U.S. for Bridge Inspection and Maintenance,' KSCE Journal of Civil Engineering, 18(5), pp 1322-1331.
[39] Gucunski, N., Nazarian, S., Wiggenhauser, H. and Kutrubes, D., 2010, 'Nondestructive Testing to Identify Concrete Bridge Deck Deterioration,' SHRP 2–FEHRL Workshop, TRA 2010 Brussels, Belgium.
[40] Mccann, D. and Forde, M., 2001, 'Review of NDT methods in the assessment of concrete and masonry structures,' NDT & E International, 34(2), pp 71-84.
[41] 1999, Non-destructive Testing: A Guidebook for Industrial Management and Quality Control Personnel, 5th ed., vol. 31. Vienna: International Atomic Energy Agency, Austria.
[42] Hurlebaus, S., Hueste, M., Karthik, M. and Terzioglu, T., 2016, 'Condition Assessment Of Bridge Post-Tensioning And Stay Cable Systems Using NDE Methods,' Transportation Research Board of The National Academies, College Station, TX.
[43] Liu, P.-L. and Yeh, P.-L., 2011 'Spectral tomography of concrete structures based on impact echo depth spectra,' NDT & E International,. 44(8), pp 692-702.
[44] Grosse, C. U., Reinhardt, H., Krüger, M. and Beutel, R., 2013, 'Application of Impact-Echo Techniques for Crack Detection and Crack Parameter Estimation in Concrete,' ICF11, Italy.
[45] Schuller, M., 2017, 'Nondestructive Evaluation and Testing of Masonry,' The Masonry Society, The American Institute of Architects Continuing Education Systems Course.
[46] Yehia, S., Abudayyeh, O., Nabulsi, S. and Abdelqader, I., 2007, 'Detection of Common Defects in Concrete Bridge Decks Using Nondestructive Evaluation Techniques,' Journal of Bridge Engineering, 12(2), pp 215-225.
[47] Gucunski, N., Iman, A., Romero, F., Nazarian, S., Yuan, D., Wiggenhauser, H., Shokouhi, P., Taffe, A. and D. Kutrubes, 2013, 'Nondestructive Testing to Identify Concrete Bridge Deck Deterioration,' Transportation Research Board of the National Academie.
[48] Huston, D., Hu, J. Q., Maser, K., Weedon, W. and Adam C., 2000 'GIMA ground penetrating radar system for monitoring concrete bridge decks,' Journal of Applied Geophysics, 43(2-4), pp 139-146.
[49] Farhangdoust, S., Farahbakhsh, M., Najafpoor, A., 2012, 'Designing and Manufacturing a Device to Generate a Frequency Balance in Acoustic Testing', International Conference on Mechanical Engineering and Advanced Technology – ICMEAT, Isfahan, Iran.
[50] Farhangdoust, S., Kianifar, A., Najafpoor, A., 2011, 'Designing and Manufacturing All-way Acoustic Generator for Testing the Frequency of Sound Transmission Loss (STL)', 1st International Conference on Acoustics and Vibration – ISAV, Tehran, Iran.
[51] Hellier, C. J., 2001, Handbook of nondestructive evaluation, New York: McGraw-Hill, Columbus, OH.
[52] Kumar, S. and Mahto, D., 2013, 'Recent Trends in Industrial and Other Engineering Applications of Non Destructive Testing: A Review,' International Journal of Scientific &

Engineering Research, 4(9), pp 183-195.
[53] Mohamed, O. and Rens, K. L., 2001, ‘Ultrasonic testing of properties of 50-year-old concrete,’ Materials Evaluation, 59(12), pp 1426-1430.
[54] Hoegh, K. E., 2013, ‘Ultrasonic linear array evaluation of concrete pavements,’ Dissertation, University of Minnesota, MN.
[55] Freeseman, K. and Khazanovich, L., 2016, ‘Quantitative Signal Analysis of Concrete Pavements Using Ultrasonic Linear Array Technology,’ The American Society for Non-Destructive Testing Digital Library.
[56] Senyurek, V. Y., Baghalian, A., Tashakori, S., Mcdaniel, D. and Tansel, I. N., 2018, ‘Localization of multiple defects using the compact phased array (CPA) method,’ Journal of Sound and Vibration, vol. 413, pp. 383–394.
[57] Ahmad, I., Suksawang, N., Sobhan, K., Corven, J. A., Sayyafi, E. A., Pant, S. and Martinez, F. 2016, ‘Develop Epoxy Grout Pourback Guidance and Test Methods to Eliminate Thermal/Shrinkage Cracking at Post-Tensioning Anchorages: Phase II,’ Research Center, Florida Department of Transportation, Rep. BDV29-977-13.
[58] Ahmad, I., Suksawang, N., Sobhan, K., Corven, J., Vallier, R., Sayyafi, E. and Pant, S, 2018, “Developing Guidelines for Epoxy Grout Pourback Systems for Controlling Thermal/Shrinkage Cracking at Post-Tensioning Anchorages: Full-scale Testing and Numerical Analysis, Transport Reserch Board, 97th Annual Meeting (No. 18-01740).
[59] Breen, R., Brown, T. M., Collins, T. J., Dillworth, B., Garlich, M., Kaderbek, S., O’Toole, M. A., Stromberg, D. and Triandafilou, N., 2010 ‘Indiana bridge inspection manual,’ Indianapolis, IN.
[60] Stimolo, M., 2003, ‘Passive Infrared Thermography as Inspection and Observation Tool in Bridge and Road Construction,’ Non-Destructive Testing in Civil Engineering 2003 BAM, Available: http://www.ndt.net/article/ndtce03/papers/v083/v083.htm [Accessed: 2018-02-08].
[61] Mehrabi, A. B., 2006, ‘In-Service Evaluation of Cable-Stayed Bridges, Overview of Available Methods and Findings,’ Journal of Bridge Engineering.
[62] Parmar, D. S. and Sharp, S. R., 2009 ‘Acoustic Emission for Non-Destructive Testing of Bridges and other Transportation Infrastructure,’ Beyond the Crossroads: A National Conference on Transportation Infrastructure & Regulatory Policy.
[63] ‘About ASNT,’ Introduction to Nondestructive Testing. [Online]. Available: https://www.asnt.org/MinorSiteSections/AboutASNT/Intro-to-NDT. [Accessed: 03-Jan-2018].
[64] Chotickai, P., 2001, ‘Acoustic emission monitoring of prestressed bridge girders with premature concrete deterioration,’ Thesis, University of Texas, Austin, TX.
[65] Carter, D. and Holford, K., 1998, ‘Strategic considerations for the AE monitoring of bridges: a discussion and case study,’ Insight, 40(2), pp 112-116.
[66] Holford, K. and Lark, R., 2005, ‘Acoustic Emission Testing of Bridges: Inspection and Monitoring Techniques for Bridges and Structures,’ Woodhead Publishing Ltd.
[67] Holford, K., Davies, A., Pullin, R. and Carter, D., 2001, ‘Damage Location in Steel Bridges by Acoustic Emission,’ Journal of Intelligent Materials Systems and Structures, 12(8), pp 567-576.
[68] Davis, A. G., 2003, ‘The nondestructive impulse response test in North America: 1985–2001,’ NDT & E International, 36(4), pp 185-193.
[69] 1998, ‘Nondestructive Test Methods for Evaluation of Concrete in Structures ACI,’

American Concrete Institute, Farmington Hills, Michigan, Rep. ACI 228.2R-98.
[70] 'System Reference Manual 2008 Slab Impulse Response,' 2008, Slab Impulse Response (SIR).
[71] Jaberi, A., 2016, 'Development of Manual for Enhanced Service Life of ABC Projects,' ABC-UTC, Department of Civil and Environmental Engineering, Florida International University, Miami, FL.
[72] Jahromi, A. J., Dickinson, M., Valikhani, A. and Azizinamini, A., 2017, 'Assessing Structural Integrity of Closure Pours in ABC Projects,'.
[73] Taskin, M., Elazig, U. C., Turkmen, M. and Elazig, 2011, 'X-Ray Tests of AISI 430 and 304 Stainless Steels and AISI 1010 Low Carbon Steel Welded by CO2 Laser beam welding,' Radiography, 53(11-12), pp 741-747.
[74] Kotyaev, O., Shimada, Y., and Hashimoto, K., 2006, 'Laser-based nondestructive detection of inner flaws in concrete with the use of lamb waves,' European Conference for Non Destructive Testing, pp 26-29.
[75] Azizinamini, A., 2017, 'Non-destructive Testing (NDT) of a Segmental Concrete Bridge Scheduled for Demolition, with a Focus on Condition Assessment and Corrosion Detection of Internal Tendons,' FDOT Research Project, Department of Civil and Environment.
[76] Shi, Y., Zhang, C., Li, R., Cai, M. and Jia, G., 2015, 'Theory and Application of Magnetic Flux Leakage Pipeline Detection,' Sensors, vol. 15(12), pp 31036-31055.
[77] 'Magnetic Flux Leakage (MFL),' NDE Technology. [Online]. Available: https://fhwaapps.fhwa.dot.gov/ndep/DisplayTechnology.aspx?tech_id=19. [Accessed: 08-Jan-2018].
[78] Makar, J. and Desnoyers, R., 2001, 'Magnetic field techniques for the inspection of steel under concrete cover,' NDT & E International, 34(7), pp 445-456.
[79] Ryan, T., Hartle, R., Mann, E., and Danovich, L., 2006, "Bridge Inspector's Reference Manual", U.S. Department of Transportation, Rep. FHWA NHI 03-001.
[80] Mehrabi, A. B., 2016, 'Performance of Cable-Stayed Bridges: Evaluation Methods, Observations, and a Rehabilitation Case,' Journal of Performance of Constructed Facilities, 30(1).
[81] Alani, A. M., Aboutalebi, M. and Kilic G., 2014, 'Integrated health assessment strategy using NDT for reinforced concrete bridges,' NDT & E International, 61, pp 80-94.
[82] Kilic, G., 2012, 'Application of advanced non-destructive testing methods on bridge health assessment and analysis,' Degree of Doctor of Philosophy, thesis, University of Greenwich, London, UK.
[83] 1998, 'Nondestructive Test Methods for Evaluation of Concrete in Structures ACI,' American Concrete Institute Report, Farmington Hills, Michigan, Rep. ACI 228.2R-98.
[84] Liang, Z., Lee, G.C. and Kong, F., 1997, 'On Detection of Damage Location of Bridges,' Proceedings of the 15th International Modal Analysis Conference, Orlando, FL, 1, pp 308-312.
[85] Banan, M. R., Banan M. R. and Hjelmstad,K. D., 1994, 'Parameter Estimation of Structures from Static Response. I. Computational Aspects,' Journal of Structural Engineering, 120(11), pp 3243-3258.
[86] Mast, P.W., Michopoulos, J.G., Badaliance, R. and Chaskelis, H., 1994, 'Dissipated Energy as the Means for Health Monitoring of Smart Structure,' Proceedings of Smart Structures and Material, SPIE, Orlando, FL, pp 199-207.
[87] Banan, M. R., Banan, M. R. and Hjelmstad, K. D., 1994, 'Parameter Estimation of

Structures from Static Response. II. Numerical Simulation Studies,' Journal of Structural Engineering, 120(11), pp 3259-3283.

[88] Sanayei, M., Imbaro, G.R., McClain, A.S. and Brown, L.C., 1997, 'Structural Modal Updating Using Experimental Static Measurements,' Journal of Structural Engineering, ASCE, 123(6), pp 792-798.

[89] Sanayei, M. and Saletnik, M.J., 1996a, 'Parameter Estimation of Structures from Static Strain Measurements. I: Formulation,' Journal of Structural Engineering, ASCE, 122(5), pp 555-562.

[90] Sanayei, M. and Saletnik, M.J., 1996b, 'Parameter Estimation of Structures from Static Strain Measurements. II: Error Sensitivity Analysis,' Journal of Structural Engineering, ASCE, 122(5), pp 563-572.

[91] Sanayei, M., O. and Onipede, 1991, 'Damage Assessment of Structures Using Static Test Data,' AIAA Journal, 29(7), pp 1174-1179.

[92] Liu, P. and Chian, C., 1997, 'Parametric Identification of Truss Structures Using Static Strains,' Journal of Structural Engineering, ASCE, 123(7), pp 927-933.

[93] Mehrabi, A. B., Tabatabai, H. and Lotfi, H. R., 1998, 'Damage Detection in Structures Using Precursor transformation method for,' Journal of Intelligent Material Systems and Structures, 9(10), pp 808-817.

[94] Tashakori, S., Baghalian, A., Unal, M., Fekrmandi, H., Şenyürek, V. y, Mcdaniel, D. and Tansel, I. N., 2016, 'Contact and non-contact approaches in load monitoring applications using surface response to excitation method,' Measurement, 89, pp 197-203.

[95] Soleimani, M. and Lionheart, W. R. B., 2005, 'Nonlinear image reconstruction in electrical capacitance tomography using experimental data,' Measurement Science and Technology, 16(10), pp 1987-1996.

[96] Abraham, B. B. and Anitha, G., 2012, 'Designing of Lab View Based Electrical Capacitance Tomography System for the Imaging of Bone Using NI ELVIS and NI USB DAQ 6009,' Bonfring International Journal of Power Systems and Integrated Circuits, 2(2), pp 01.

[97] Sun, T. D., Muddeb, R., Schoutena, J. C., Scarletta, B. and Van Den Bleek C. M., 1999, 'Performance of neural network in image reconstruction and interpretation for electrical capacitance tomography,' 1st World Congress on Industrial Process Tomography.

[98] Beck, M.S., et. al., 1986, 'Image for measurements of two phase flow', Proc. Flow Visualisation IV, Paris, France, pp 585-588.

[99] Huang, S.M., Plaskowsk, A. B., Xie C. G., M. and Beck, M. S., 1989, 'Tomographic imaging of two-flow component flow using capacitance sensor', J. Phys. E:Sci. Instrum., 22, pp 173-177.

[100] 1999, 'Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete,' ASTM International: Designation: C 876 – 91 (Reapproved 1999)."

[101] Ahmed, S., 'CORROSION POTENTIAL MAPPING.'

[102] 'Liquid Penetrant Testing', INTREX. Company, Available: http://www.intrexkw.com/Home/OurServices/Non-Destructive-Testing/Dye-Penetration-Testing. [Accessed: 10-Nov-2017].

[103] Gbenga E., 2016, 'Using Non-Destructive Testing for the Manufacturing of Composites for Effective Cost Saving: A Case Study of a Commercial Prepreg CFC,' International Journal of Materials Engineering, pp 28-38.

[104] Pichenot, G. and Sollier T., 2003, 'Eddy Current Modelling for Nondestructive Testing,' 8th ECNDT, 8(6).

[105] Willcox, M. and Downes, G., 2003, 'A Brief Description of NDT Techniques,' Insight NDT.
[106] 'Magnetic Particle Inspection,' Inspection Services. [Online]. Available: http://ccindt.com/magnetic-particle-inspection.php. [Accessed: 19-Jan-2018].
[107] Ghantous, J., 'Project 1. Human-robot collaboration for bridge inspection,' Advanced Robotics and Automation (ARA) Laboratory. [Online]. Available: https://ara.cse.unr.edu/?page_id=183. [Accessed: 09-Jan-2018].
[108] Ghasemi, H., Ibrahim, F. I. S., Gucunski, N. and Maher A., 'Robotic System for Condition Assessment of Concrete Bridge Decks,' U.S. Department of Transportation/Federal Highway Administration. [Online]. Available: https://www.fhwa.dot.gov/publications/research/infrastructure/structures/ltbp/13035/index.cfm. [Accessed: 09-Jan-2018].
[109] Gucunski, Kee, N., S.-H., La, H., Basily, B., Maher, A. and Ghasemi, H., 2015, 'Implementation of a Fully Autonomous Platform for Assessment of Concrete Bridge Decks RABIT,' Structures Congress 2015.
[110] Zink, J. and Lovelace, B., 2015, 'Unmanned Aerial Vehicle Bridge Inspection Demonstration Project,' Minnesota Department of Transportation, St. Paul, Minnesota, Rep. MN/RC 2015-40.
[111] Zink, J., 'Will drones transform bridge inspection?,' Roads & Bridges, 06-Sep-2016. [Online]. Available: https://www.roadsbridges.com/will-drones-transform-bridge-inspection. [Accessed: 03-Feb-2018].
[112] Metni, N. and Hamel, T., 2007, 'A UAV for bridge inspection: Visual servoing control law with orientation limits,' Automation in Construction, 17(1), pp 3-10.
[113] Murphy, R. R., Steimle, E., Hall, M., Lindemuth, M., Trejo, D., Hurlebaus, S., Medina-Cetina, Z. and Slocum, D., 2011,'Robot-Assisted Bridge Inspection,' J Intell Robot Syst , 64, pp 77–95.
[114] Sutter, B., Lelevé, A., Pham, M. T., Gouin, O., Jupille, N., Kuhn, M., ... & Rémy, P. (2018). A semi-autonomous mobile robot for bridge inspection. Automation in Construction, 91, 111-119.
[115] Peel, H., Luo, S., Cohn, A. G., & Fuentes, R. (2018). Localisation of a mobile robot for bridge bearing inspection. Automation in Construction, 94, 244-256.
[116] S. Farhangdoust and A. B. Mehrabi, NDT Inspection of Critical ABC Details to Assure Life Cycle Performance and Avoid Future Unforeseen Excessive Repairs," ASCE Structures Congress 2019, 2019 April Orlando, Florida, United States.
[117] S. Farhangdoust, A.B. Mehrabi, S.F. Al Mosawi, "NDT Methods Applicable to Health Monitoring of ABC Closure Joints," 27th Research Symposium - The American Society for Non-destructive Testing (ASNT), Orlando, Fl, 26-29 March, 2018.
[118] S. Farhangdoust, A.B. Mehrabi, "Developing Defect Etiology to Facilitate NDE of Full-Depth Precast Concrete Deck Panels in Accelerated Bridge Construction," ASNT Research Symposium 2019 - The American Society for Non-destructive Testing (ASNT), Garden Grove, CA, 1 - 4 April 2019, 2018.
[119] Sun, H., Pashoutani, S., & Zhu, J. (2018). Nondestructive Evaluation of Concrete Bridge Decks with Automated Acoustic Scanning System and Ground Penetrating Radar. Sensors, 18(6), 1955.
[120] Lin, S., Meng, D., Choi, H., Shams, S., & Azari, H. (2018). Laboratory assessment of nine methods for nondestructive evaluation of concrete bridge decks with overlays. Construction

and Building Materials, 188, 966-982.
[121] Davis, A. G. (2003). The nondestructive impulse response test in North America: 1985–2001. NDT & E International, 36(4), 185-193.
[122] Washer, G., Fenwick, R., Bolleni, N., & Harper, J. (2009). Effects of environmental variables on infrared imaging of subsurface features of concrete bridges. Transportation Research Record, 2108(1), 107-114.
[123] Maierhofer, C. (2003). Nondestructive evaluation of concrete infrastructure with ground penetrating radar. Journal of Materials in Civil Engineering, 15(3), 287-297.
[124] Tarussov, A., Vandry, M., & De La Haza, A. (2013). Condition assessment of concrete structures using a new analysis method: Ground-penetrating radar computer-assisted visual interpretation. Construction and Building Materials, 38, 1246-1254.
[125] Huston, D., Hu, J. Q., Maser, K., Weedon, W., & Adam, C. (2000). GIMA ground penetrating radar system for monitoring concrete bridge decks. Journal of Applied Geophysics, 43(2-4), 139-146.
[126] "Guidebook on non-destructive testing of concrete structures." Training Course Series. International Atomic Energy Agency. Vienna, 2002.
[127] Scott, M., Rezaizadeh, A., Delahaza, A., Santos, C. G., Moore, M., Graybeal, B., & Washer, G. (2003). A comparison of nondestructive evaluation methods for bridge deck assessment. NDT & E International, 36(4), 245-255.
[128] Chase, S. B., & Washer, G. (1997). Nondestructive evaluation for bridge management in the next century. Public Roads, 61(1).
[129] Yehia, S., Abudayyeh, O., Nabulsi, S., & Abdelqader, I. (2007). Detection of common defects in concrete bridge decks using nondestructive evaluation techniques. Journal of Bridge Engineering, 12(2), 215-225.
[130] Oh, T., Kee, S. H., Arndt, R. W., Popovics, J. S., & Zhu, J. (2012). Comparison of NDT methods for assessment of a concrete bridge deck. Journal of Engineering Mechanics, 139(3), 305-314.
[131] Sbartaï, Z. M., Laurens, S., Balayssac, J. P., Arliguie, G., & Ballivy, G. (2006). Ability of the direct wave of radar ground-coupled antenna for NDT of concrete structures. NDT & e International, 39(5), 400-407.
[132] Büyüköztürk, O. (1998). Imaging of concrete structures. Ndt & E International, 31(4), 233-243.
[133] Rhazi, J. (2000). NDT in civil engineering: the case of concrete bridge decks. CSNDT JOURNAL, 21(5), 18-25.
[134] Barnes, C. L., Trottier, J. F., & Forgeron, D. (2008). Improved concrete bridge deck evaluation using GPR by accounting for signal depth–amplitude effects. NDT & E International, 41(6), 427-433.
[135] Alani, A. M., Aboutalebi, M., & Kilic, G. (2014). Integrated health assessment strategy using NDT for reinforced concrete bridges. NDT & E International, 61, 80-94.
[136] Kohl, C., & Streicher, D. (2006). Results of reconstructed and fused NDT-data measured in the laboratory and on-site at bridges. Cement and Concrete Composites, 28(4), 402-413.
[137] Rhazi, J., Dous, O., & Laurens, S. (2007, December). A new application of the GPR technique to reinforced concrete bridge decks. In Proceeding of the 4th Middle East NDT conference and Exhibition, Manama, Kingdom of Bahrain (pp. 2-5).
[138] Rhazi, J., Dous, O., Ballivy, G., Laurens, S., & Balayssac, J. P. (2003, September). Non destructive health evaluation of concrete bridge decks by GPR and half cell potential

techniques. In International Symposium on Non-Destructive Testing in Civil Engineering.
[139] Maierhofer, C., Zacher, G., Kohl, C., & Wöstmann, J. (2008). Evaluation of radar and complementary echo methods for NDT of concrete elements. Journal of Nondestructive Evaluation, 27(1-3), 47.
[140] Lim, M. K., & Cao, H. (2013). Combining multiple NDT methods to improve testing effectiveness. Construction and Building Materials, 38, 1310-1315.
[141] Krause, M., Mielentz, F., Milman, B., Müller, W., Schmitz, V., & Wiggenhauser, H. (2001). Ultrasonic imaging of concrete members using an array system. NDT & E International, 34(6), 403-408.
[142] Abdel-Qader, I., Yohali, S., Abudayyeh, O., & Yehia, S. (2008). Segmentation of thermal images for non-destructive evaluation of bridge decks. Ndt & E International, 41(5), 395-405.
[143] Gucunski, N., Romero, F., Kruschwitz, S., Feldmann, R., Abu-Hawash, A., & Dunn, M. (2010). Multiple complementary nondestructive evaluation technologies for condition assessment of concrete bridge decks. Transportation Research Record: Journal of the Transportation Research Board, (2201), 34-44.
[144] Arndt, R., & Jalinoos, F. (2009). NDE for corrosion detection in reinforced concrete structures–a benchmark approach. Proceedings of the Non-Destructive Testing In Civil Engineering (NDTCE'09), Nantes, France, 30.
[145] Gucunski, N., Romero, F., Kruschwitz, S., Feldmann, R., & Parvardeh, H. (2011). Comprehensive bridge deck deterioration mapping of nine bridges by nondestructive evaluation technologies (No. Project SPR-NDEB (90)--8H-00). Iowa. Dept. of Transportation.
[146] Bungey, J. H. (2004). Sub-surface radar testing of concrete: a review. Construction and Building materials, 18(1), 1-8.
[147] Akhtar, S. (2013). Review of nondestructive testing methods for condition monitoring of concrete structures. Journal of construction engineering, 2013.
[148] Rehman, S. K. U., Ibrahim, Z., Memon, S. A., & Jameel, M. (2016). Nondestructive test methods for concrete bridges: A review. Construction and Building Materials, 107, 58-86.
[149] Krause, H-J., W. Wolf, W. Glaas, E. Zimmermann, M. I. Faley, G. Sawade, R. Mattheus, G. Neudert, U. Gampe, and J. Krieger. (2002). SQUID array for magnetic inspection of prestressed concrete bridges. Physica C: Superconductivity, 368(1-4), 91-95.
[150] Belli, K., Wadia- Fascetti, S., & Rappaport, C. (2008). Model based evaluation of bridge decks using ground penetrating radar. Computer- Aided Civil and Infrastructure Engineering, 23(1), 3-16.
[151] Bungey, J. H., & Grantham, M. G. (2014). Testing of concrete in structures. Crc Press.
[152] Alani, A. M., Aboutalebi, M., & Kilic, G. (2013). Applications of ground penetrating radar (GPR) in bridge deck monitoring and assessment. Journal of Applied Geophysics, 97, 45-54.
[153] Zhu, J. (2008). Non-contact NDT of concrete structures using air coupled sensors. Newmark Structural Engineering Laboratory. University of Illinois at Urbana-Champaign.
[154] Omar, T., & Nehdi, M. L. (2017). Remote sensing of concrete bridge decks using unmanned aerial vehicle infrared thermography. Automation in Construction, 83, 360-371.
[155] Gucunski, N., Kee, S. H., La, H., Basily, B., Maher, A., & Ghasemi, H. (2015, April). Implementation of a fully autonomous platform for assessment of concrete bridge decks RABIT. In Structures Congress 2015 (pp. 367-378).

[156] Gucunski, N., Kee, S., La, H., Basily, B., & Maher, A. (2015). Delamination and concrete quality assessment of concrete bridge decks using a fully autonomous RABIT platform. Structural Monitoring and Maintenance, 2(1), 19-34.
[157] Van der Wielen, A., Courard, L., & Nguyen, F. (2010, June). Nondestructive detection of delaminations in concrete bridge decks. In Ground Penetrating Radar (GPR), 2010 13th International Conference on (pp. 1-5). IEEE.
[158] Shokouhi, P., Wolf, J., & Wiggenhauser, H. (2013). Detection of delamination in concrete bridge decks by joint amplitude and phase analysis of ultrasonic array measurements. Journal of Bridge Engineering, 19(3), 04013005.
[159] Washer, G. A. (1998). Developments for the non-destructive evaluation of highway bridges in the USA. NDT & E International, 31(4), 245-249.
[160] Hearn, G., & Shim, H. S. (1998). Integration of bridge management systems and nondestructive evaluations. Journal of Infrastructure Systems, 4(2), 49-55.
[161] Rens, K. L., Nogueira, C. L., & Transue, D. J. (2005). Bridge management and nondestructive evaluation. Journal of performance of constructed facilities, 19(1), 3-16.
[162] Huston, D., Cui, J., Burns, D., & Hurley, D. (2011). Concrete bridge deck condition assessment with automated multisensor techniques. Structure and Infrastructure Engineering, 7(7-8), 613-623.
[163] Maser, K. R., & Roddis, W. K. (1990). Principles of thermography and radar for bridge deck assessment. Journal of transportation engineering, 116(5), 583-601.
[164] Toutanji, H. (2000). Ultrasonic wave velocity signal interpretation of simulated concrete bridge decks. Materials and Structures, 33(3), 207.
[165] Vaghefi, K., Oats, R.C., Harris, D.K., Ahlborn, T.T.M., Brooks, C.N., Endsley, K.A., Roussi, C., Shuchman, R., Burns, J.W. and Dobson, R. (2011). Evaluation of commercially available remote sensors for highway bridge condition assessment. Journal of Bridge Engineering, 17(6), 886-895.
[166] Xu, Y., & Turkan, Y. (2019). Bridge Inspection Using Bridge Information Modeling (BrIM) and Unmanned Aerial System (UAS). In Advances in Informatics and Computing in Civil and Construction Engineering (pp. 617-624). Springer, Cham.
[167] Chen, S., Laefer, D. F., Mangina, E., Zolanvari, S. I., & Byrne, J. (2019). UAV Bridge Inspection through Evaluated 3D Reconstructions. Journal of Bridge Engineering, 24(4), 05019001.
[168] Bogue, R. (2018). Applications of robotics in test and inspection. Industrial Robot: An International Journal, 45(2), 169-174.