ABC-UTC GUIDE FOR:

SELECTION OF NDT METHODS APPLICABLE TO HEALTH MONITORING OF ABC CLOSURE JOINTS

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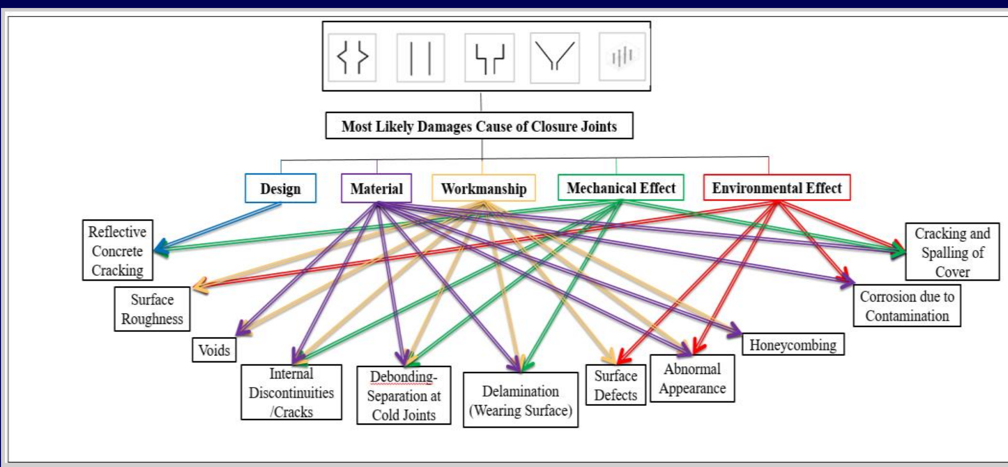

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ABSTRACT

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 guide and process presented in Section 8 of this report can be readily used by bridge owners and consultants as a practical guide for selection of NDT methods for health monitoring of ABC bridges with closure joints. The proposed guide will be validated in upcoming projects to further support their implementation.

ACKNOWLEDGMENTS

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1 INTRODUCTION

Cast-in-place closure joints therefore may introduce a potential for weak link within Accelerated Bridge Construction (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.

3 OBJECTIVES

The objective of this document is to provide for 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 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 DEFENITIONS

4.1 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) (Fig. 1) [1], [4].

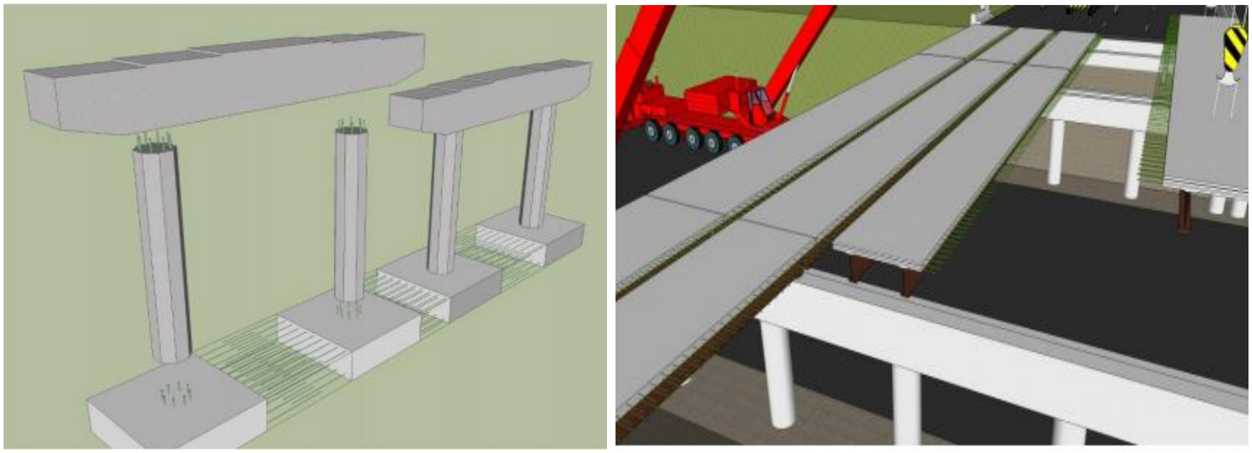


Figure 1: Some examples of Accelerated Bridge Construction [1], [4]

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 (Fig. 2).

Figure 2: ABC superstructure positioning; bridges in Utah [4]

4.2 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. 3). 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

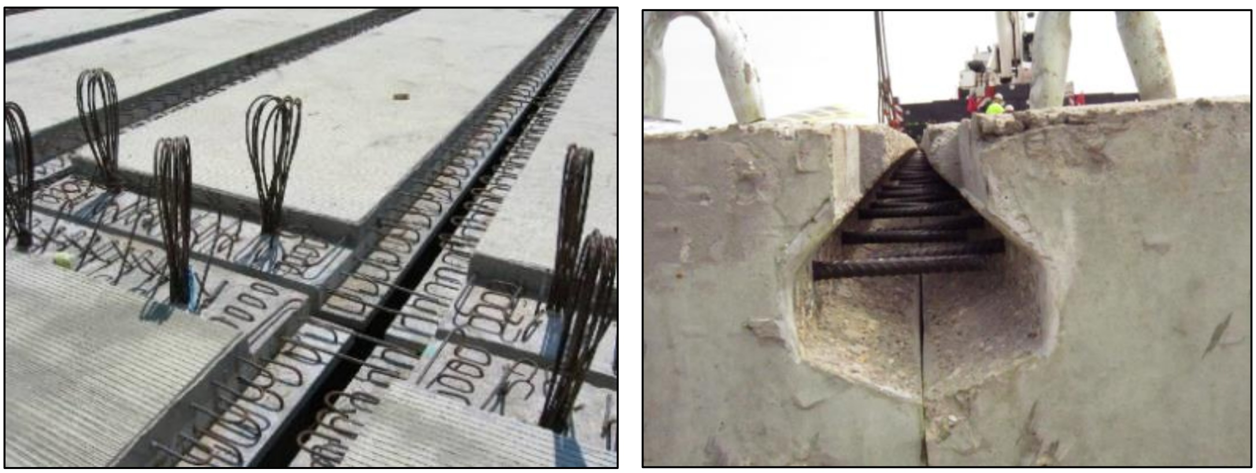


Figure 3: Examples of various types of ABC closure joints [5], [6]

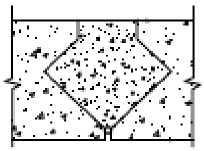
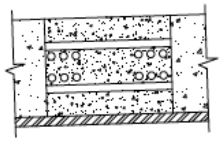
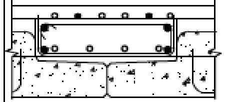
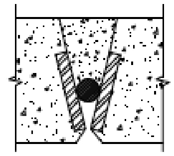
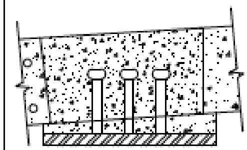
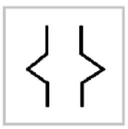
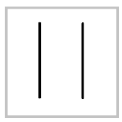
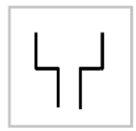
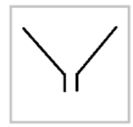
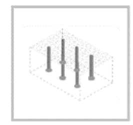
joint less vulnerable to potential defects and discontinuities. A variety of health monitoring methods have been used for NDT evaluation of ABC closure joints. This report attempts to present the most applicable NDT methods based on the different defects for distinctive type ABC closure joints.

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

5.1 CATEGORIZATION OF CLOSURE JOINTS

The primary focus of this guide is on superstructure connections and on mostly concrete deck configurations that are used commonly for ABC. FRP (Fiber Reinforced Plastic), Timber (wood), and Steel of any shape are excluded. Among the closure joints commonly used for ABC projects [7], 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 [8]. 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

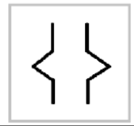
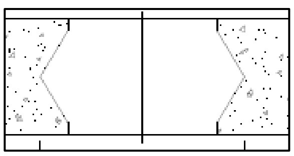
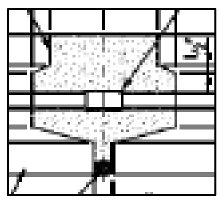
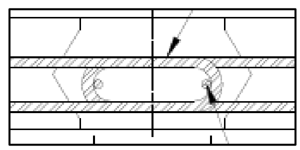
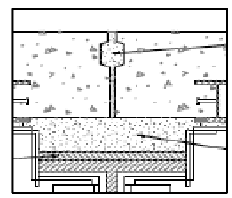
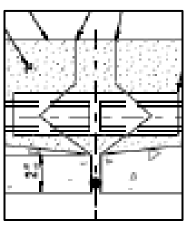
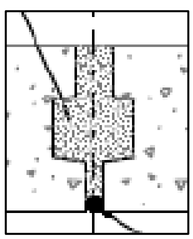
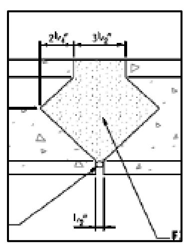
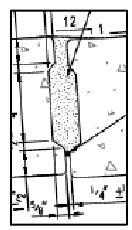
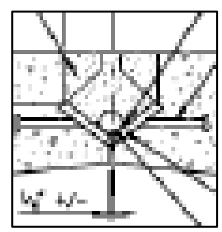
Group	Type 1	Type 2	Type 3	Type 4	Type 5
Sample					
Symbol					

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.

5.1.1 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 [9]. 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 [5, 7, 9, 10, and 11]

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

5.1.2 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],[12]

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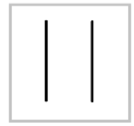
<tr><td colspan="4">Symbol Representing Joint</td><td colspan="3"></td></tr>
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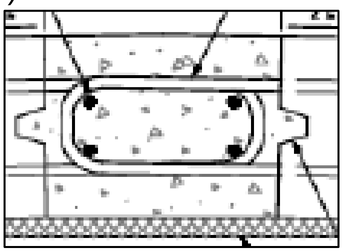
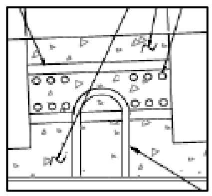
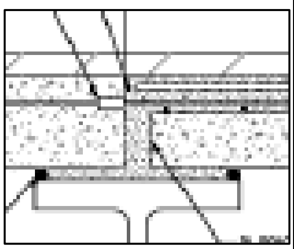
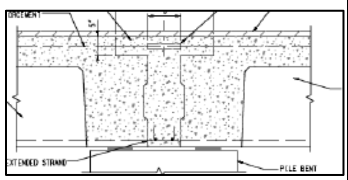
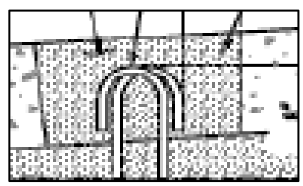
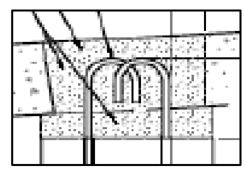
<tr><td colspan="2">(a) </td><td colspan="2">(b) </td><td colspan="3">(c) </td></tr>
<tr><td> (d)</td><td colspan="2">(e) </td><td colspan="2">(f) </td><td colspan="2">(g) </td></tr>
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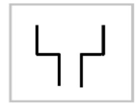
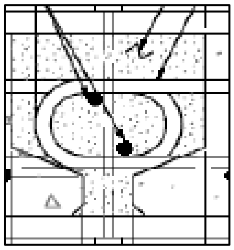
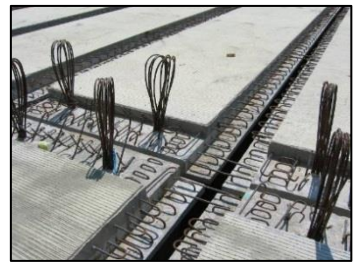
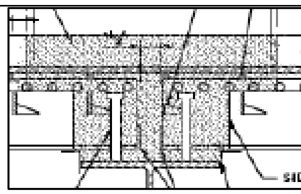
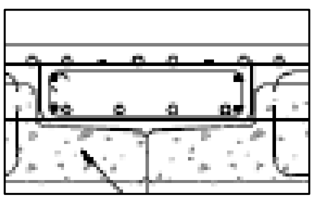
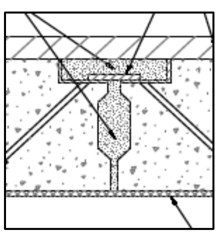
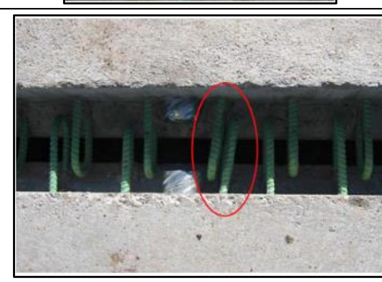
5.1.3 Type 3 closure Joint

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 [6, 7, 10]

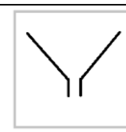
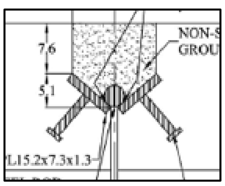
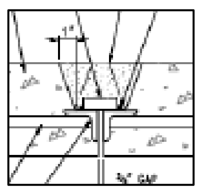
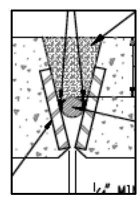
<table>
<tr><td colspan="2">Symbol Representing Joint</td><td colspan="2"></td></tr>
<tr><td colspan="4">Sample Cross Section</td></tr>
<tr><td>(a)</td><td></td><td rowspan="2">(e)</td><td rowspan="2"></td></tr>
<tr><td>(b)</td><td></td></tr>
<tr><td>(c)</td><td></td><td>(f)</td><td></td></tr>
<tr><td>(d)</td><td></td><td>(g)</td><td></td></tr>
</table>

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.

5.1.4 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.

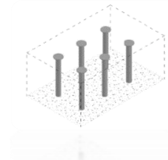
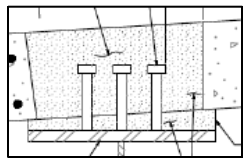
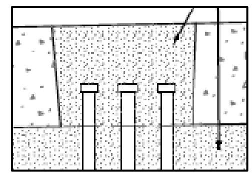
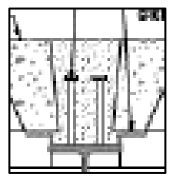
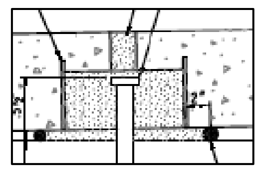
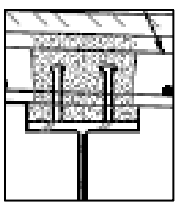
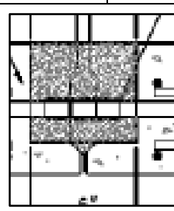
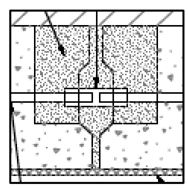
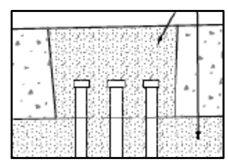
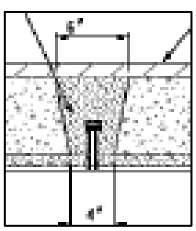
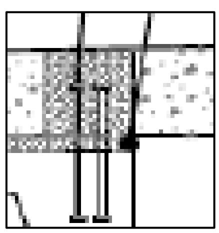
Table 5: Type 4 Joint [6, 7, 10]

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

5.1.5 Type 5 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], [12]

<table>
<tr><td colspan="4">Symbol Representing Joint </td></tr>
<tr><td colspan="4">Sample Cross Section</td></tr>
<tr><td>(a) </td><td>(b) </td><td colspan="2">(c) </td></tr>
<tr><td>(d) </td><td>(e) </td><td colspan="2">(f) </td></tr>
<tr><td>(g) </td><td>(h) </td><td>(i) </td><td>(j) </td></tr>
<tr><td>(k) </td><td>(l) </td><td>(m) </td><td>(n) </td></tr>
</table>

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.

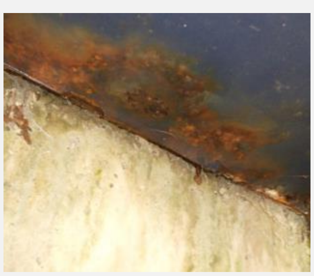
5.2 REPORTED AND PRESUMED DEFECTS AND ANOMALIES

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 [13]. Examples of defects and anomalies expected in general for bridge superstructure are shown in Table 7. This document therefore includes development of an etiology for the expected defects. This approach here 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.

ABC closure joints may contain different types of defects and anomalies [14]. 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 [8]:

- 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 (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

Table 7: Examples of defects and anomalies in bridge superstructure [15–23]

Crack [22]	**Delamination** [15]	**Internal Discontinuities** [15]
		
Surface Discontinuities [23]	**Corrosion of Reinforcing Bars** [16]	**Spalls** [16]
		
Honeycombing [17]	**Abnormal Appearance** [16]	**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]
		

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 4). 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 (Figure 5). 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 [24] to have performed the worst among others. Leakage and efflorescence was observed for this type of connection (Figure 4).

Figure 4: Typical joint leakage at deck panels (I-84 WB over Weber Canyon with welded-tie connections from 2009 inspection) [24]

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 (Figure 6).

Figure 5: Shrinkage crack in the blockout type of ABC closure joint [22]

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

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.

5.3 ETIOLOGY OF DEFECTS/DAMAGES

A rational relationship between observed or presumed defects in the five groups of ABC closure joints and their causes is introduced here 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. 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.

5.3.1 Workmanship

Observations from several investigations 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. Excessive shrinkage has been considered as a result of material and/or workmanship issues. Shrinkage is a likely cause for various types of cracks, delamination and separation in ABC closure joints [25-28]

5.3.2 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].

5.3.3 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].

5.3.4 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].

5.3.5 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].

5.4 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 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.

5.4.1 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 7. 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 7). 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 8 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 9. The information in this figure along with cause-and-effect relationships shown in Figure 8 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 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 [13]

<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>
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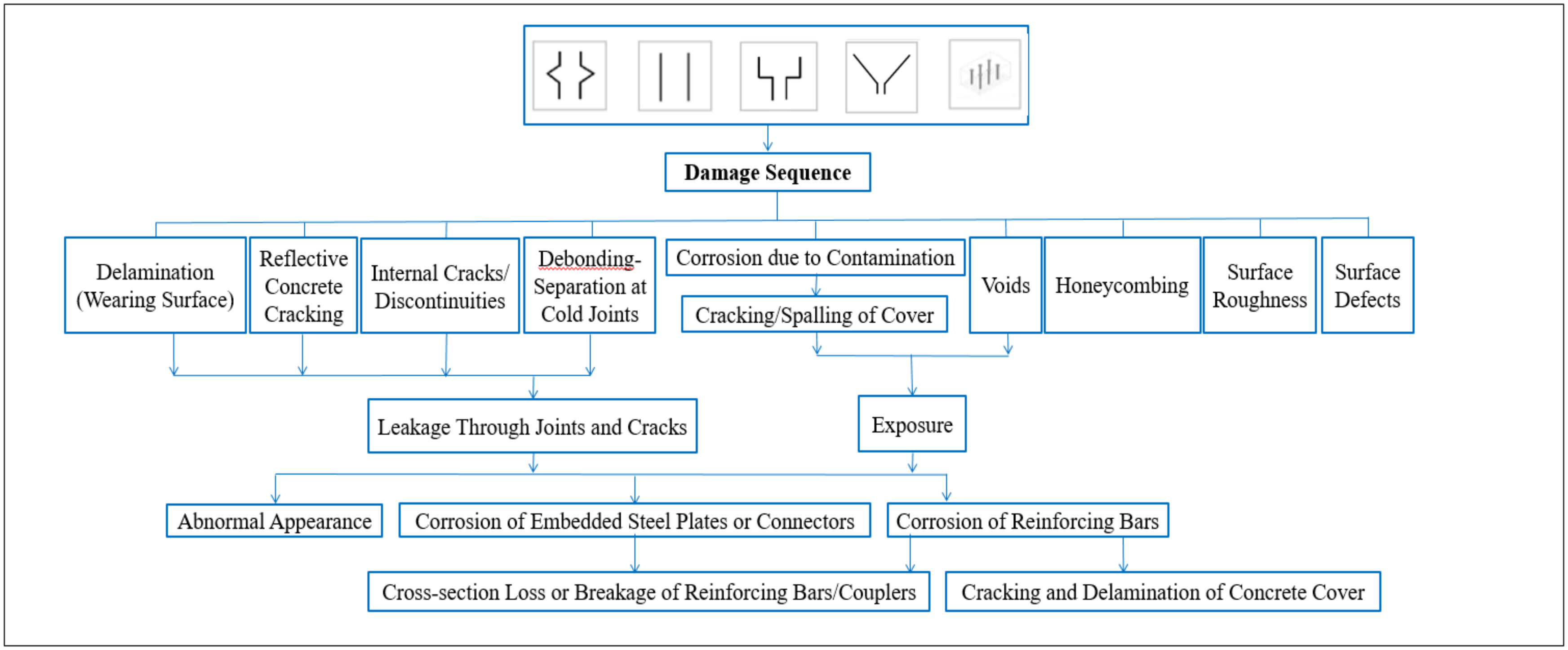


Figure 7: Damage Sequence Tree (DST) for ABC closure joints [8]

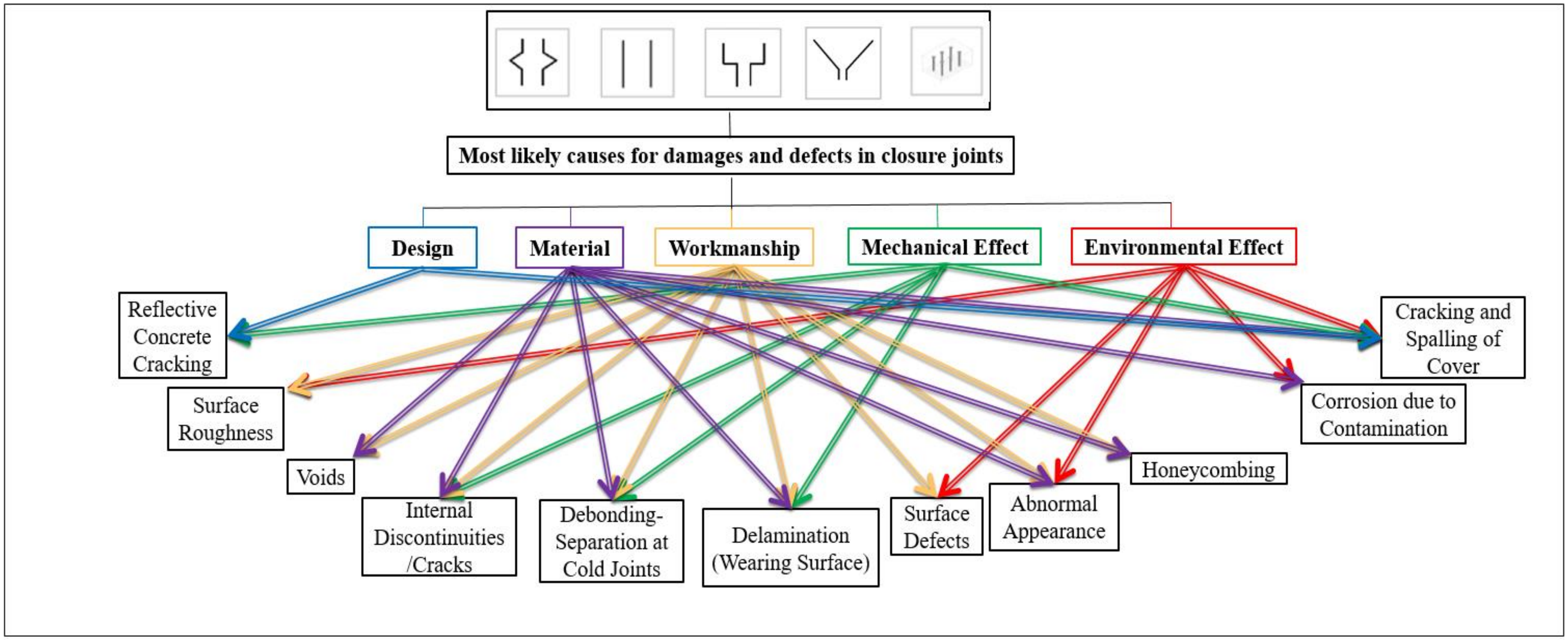


Figure 8: The most likely causes for damages and defects in ABC closure joints.

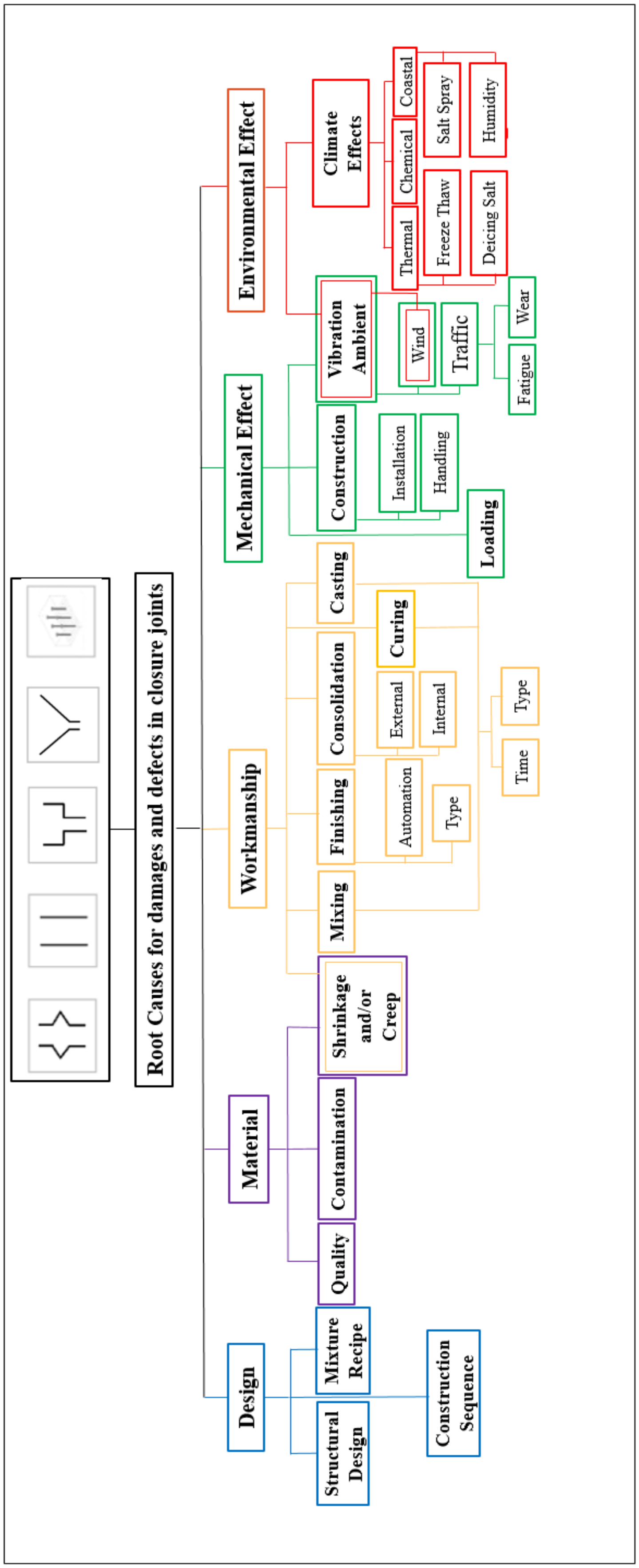


Figure 9: Root causes for damages and defects in ABC closure joints.

6 IDENTIFICATION, EVALAUTION, AND SELECTION OF NDT METHODS

6.1 AVAILABLE 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.

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?

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 (not necessarily applicable to closure joints)
   - 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.10).

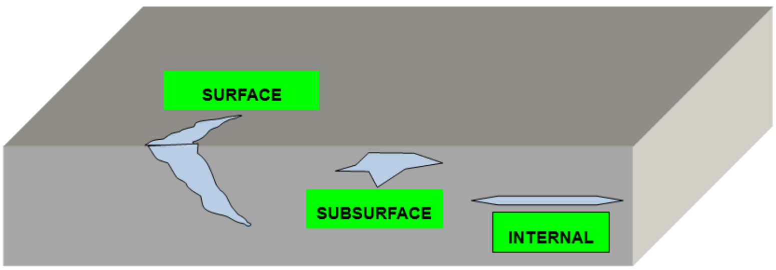


Figure 10: Three different types of discontinuities [35]

These methods were thoroughly reviewed in relation to their applicability to ABC closure joints inspections [33], [34], [36]–[42]. Description and evaluation of all the methods listed above can be found in Report [43].

6.1.1 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. Ground Penetrating Radar Testing (GPR),
3. Ultrasonic Testing (UT), including Phased Array Ultrasonic Testing (PAU)
4. Infrared Thermography Testing (IR),
5. Impulse Response Testing (IRT),
6. Radiographic Testing (RT),
7. Magnetic Flux Leakage Testing (MFL)

Following describes the selected NDT methods identified as promising.

6.1.1.1 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. [16] 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.11 [34].

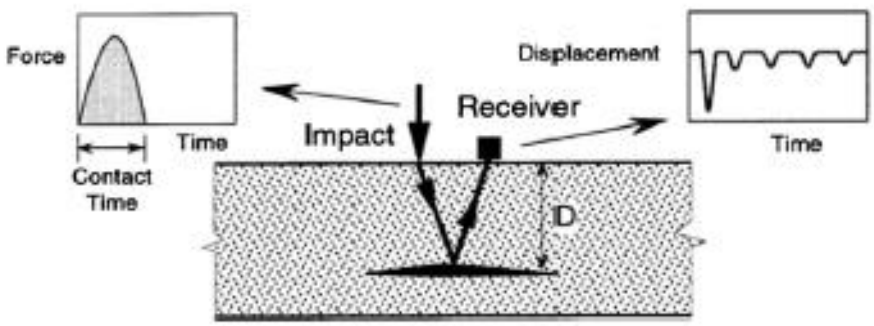


Figure 11: A scheme of an IE method set-up [34]

As shown in Fig. 12, for IE, the surface of element is impacted by a steel ball or small impulse hammer [34]. 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 [16]. 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]. IE has been 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. [16].

Figure 12: Void detection at bridge concrete by using IE method [44]

6.1.1.2 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. 13) [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.[16] 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.

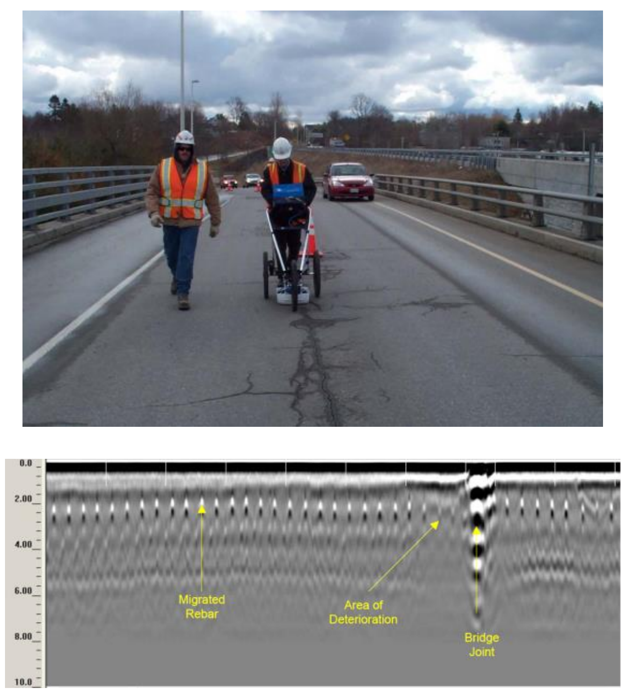


Figure 13: An example of GPR Testing [47]

6.1.1.3 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] (Fig. 14). 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.15) [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. [16] who evaluated the method to have good accuracy in crack detection.

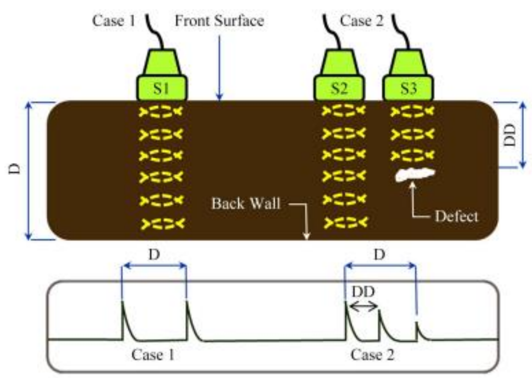


Figure 14: The defects are read from the screen [52]

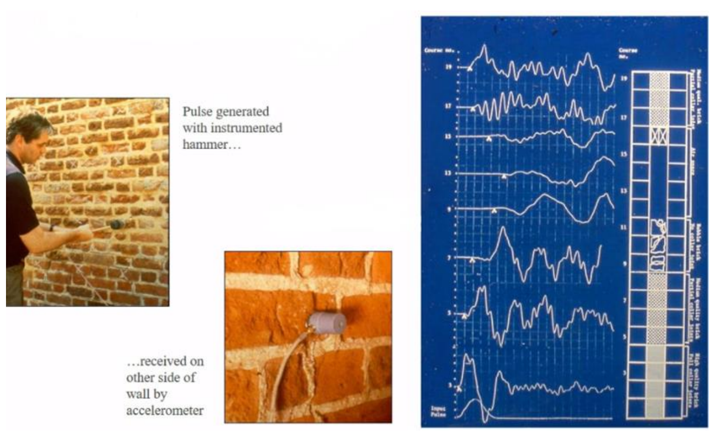


Figure 15: Set-up of a Sonic Pulse Velocity Testing (SPV) method [45]

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. 16) [56].

6.1.1.1 Infrared Thermography Testing (IR)

Infrared thermography testing (IR) has been used widely for detection of material variation based on variation of temperature (Fig. 17). 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]. 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. 18). 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. 19) [61].

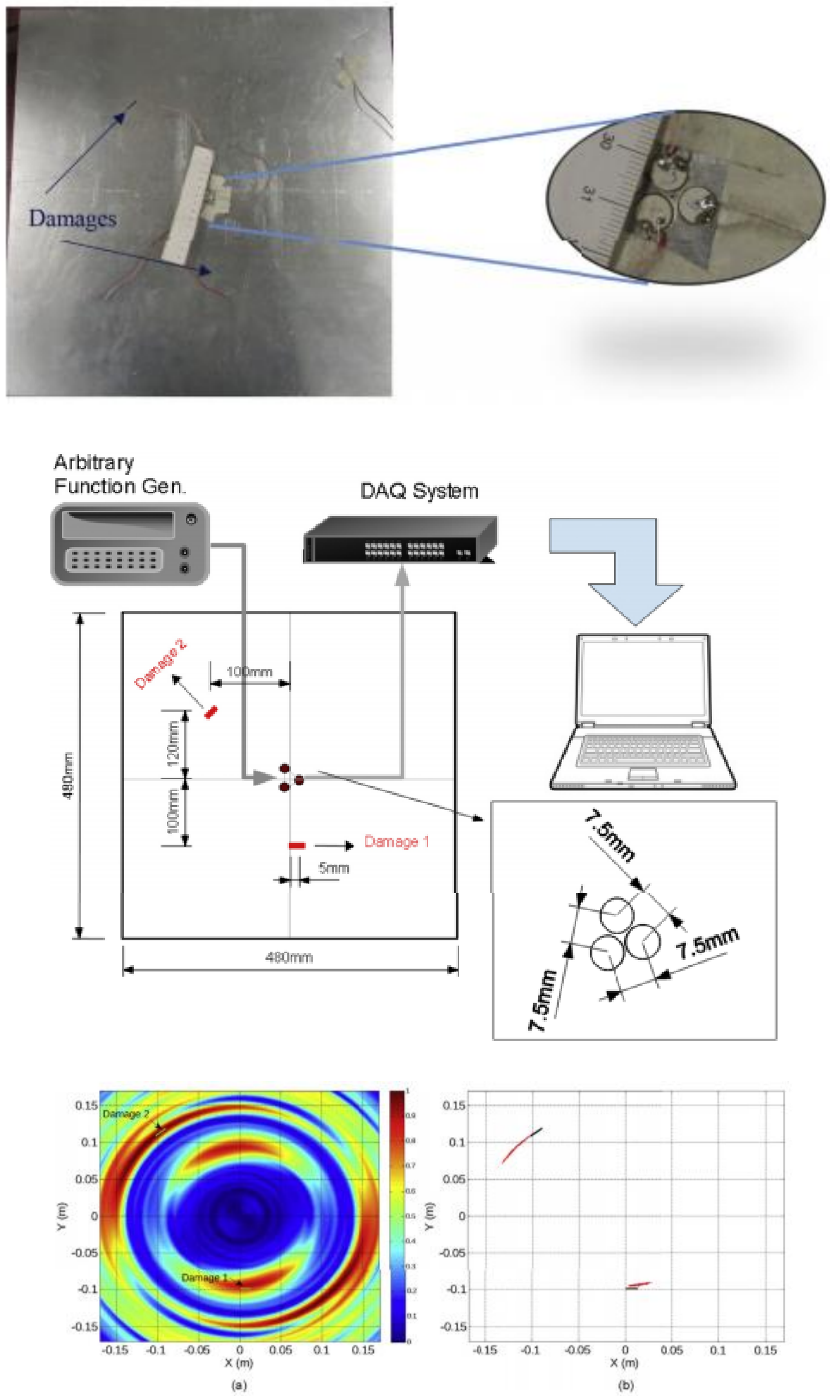


Figure 16: A sample of localization of multiple defects using PAU [56]

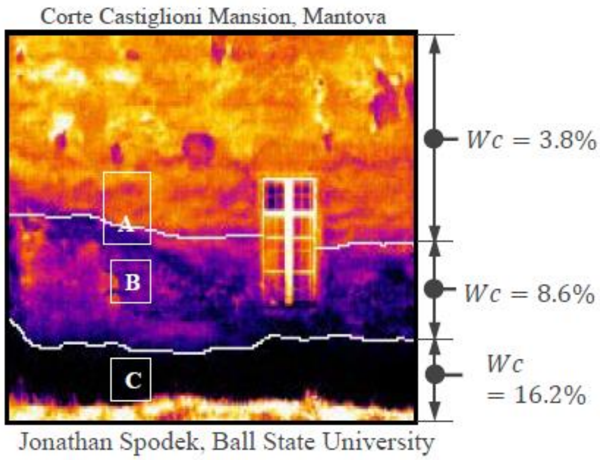


Figure 17: Infrared thermography testing sample [45]

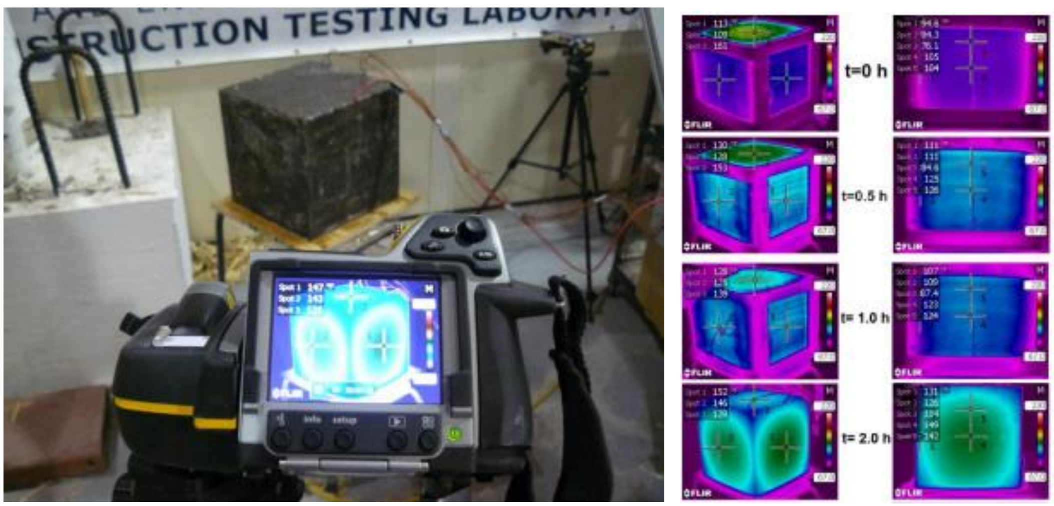


Figure 18: Surface examination of the specimen by Infrared thermography testing [57]

Figure 19: Infrared Thermal Imaging; Use of IRT camera (left) and a thermal image (right) [61]

6.1.1.2 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], [62]. 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 [63]. 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. [16] 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 [16]. 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. 20 [64]. As it shown in Fig. 21, some investigations on ABC closure joints has been carried out by ABC – UTC using IRT for detecting the honeycombs, voids, and cracks [65-66].

6.1.1.1 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.22) [67]. 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], [40]–[41]. Safety considerations often precludes the use of this method for structural damage detection.

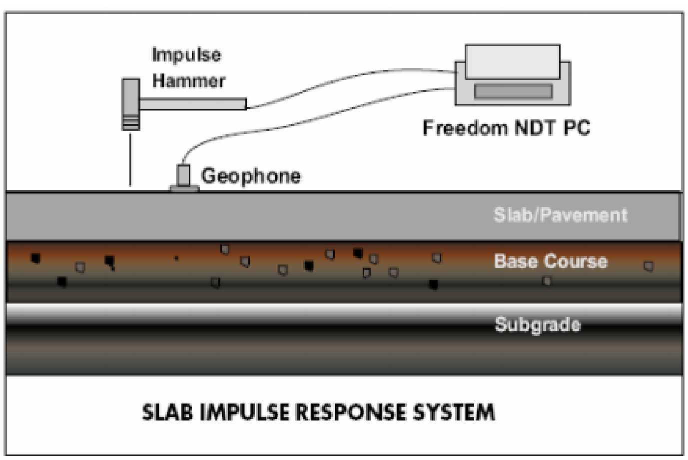


Figure 20: A principle of Impulse Response Testing (IRT) set-up for slab evaluation [64]

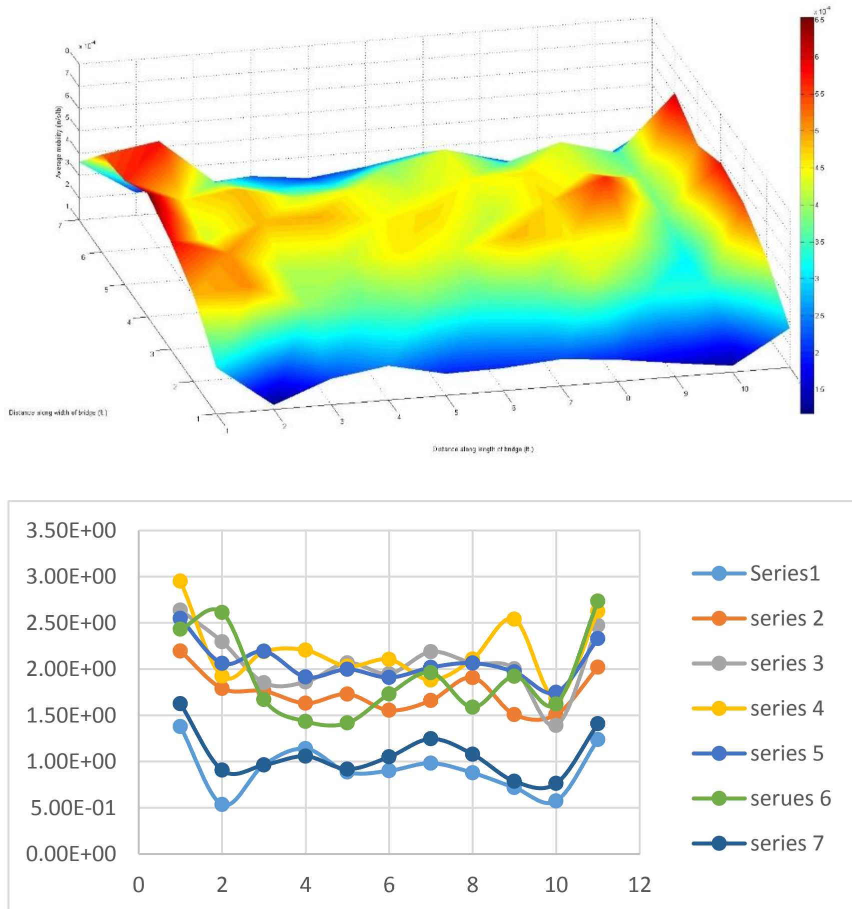


Figure 21: IRT on laboratory constructed test specimens [65]

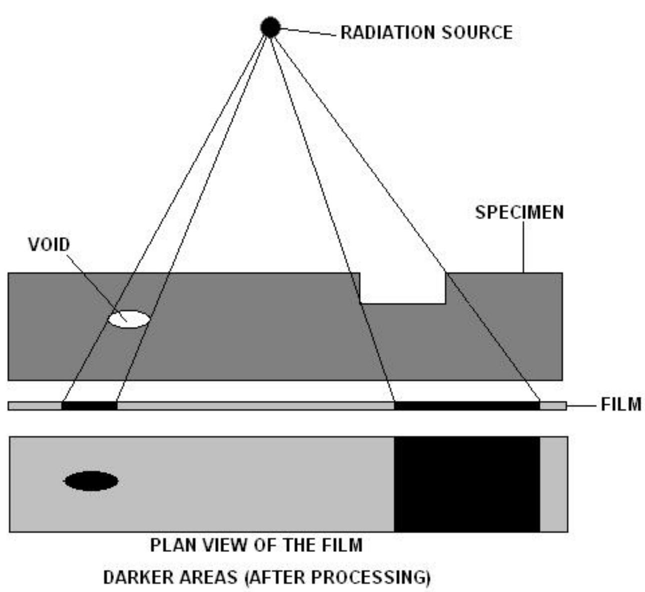


Figure 22: The defects are read from the screen (Courtesy of Bernoullies, 2011)

6.1.1.2 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 [68]. 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 placed between the poles of the magnet (Fig. 23) [42], [69].

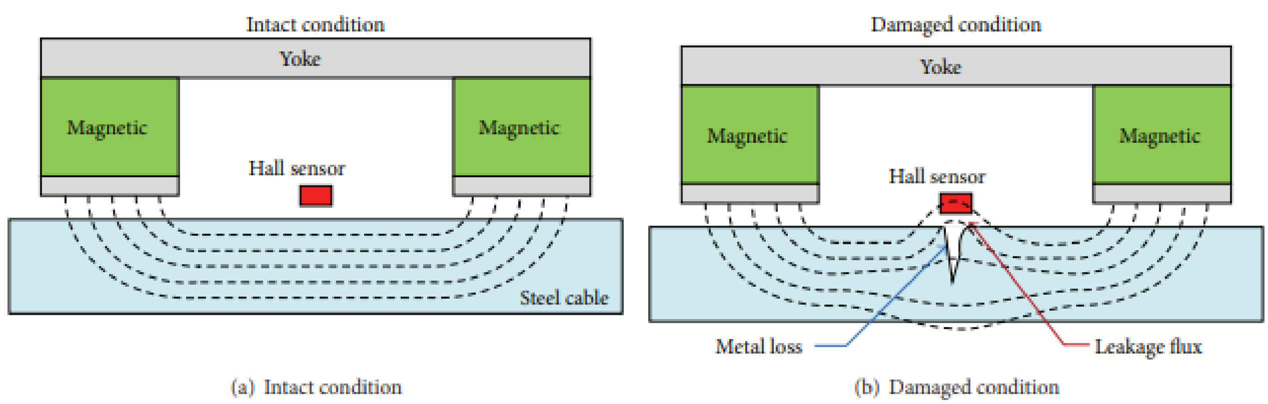


Figure 23: Schematic layout of Magnetic Flux Leakage testing method [70]

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 [71], [72]. 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]. 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. 24) [70].

Figure 24: The Magnetic Flux Leakage testing for Bridge inspection (Courtesy of Ali Ghorbanpoor)

6.2 EVALUATION OF PROMOSING NDT METHODS

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.

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 are analyzed according to the rating of their capabilities reflected in Table 9. These NDT techniques are also 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.

Table 9: Comparison and preliminary rating of NDT methods for ABC closure joints – Good=G, Fair=F, Poor=P [13]

	IE	GPR	UT	IR	IRT	RT	MFL
Test Speed	**F**	**G**	**F**	**G**	**F**	**P**	**F**
Internal Detection	**G**	**G**	**G**	**P**	**F**	**G**	**F**
Analyzing Speed	**F**	**F**	**F**	**G**	**F**	**G**	**F**
Cost	**G**	**G**	**F**	**G**	**G**	**P**	**P**
Accuracy	**G**	**F**	**G**	**F**	**F**	**G**	**F**
Ease of Use	**G**	**G**	**G**	**G**	**G**	**P**	**P**
Safety for Public and Operator	**G**	**G**	**G**	**G**	**G**	**P**	**F**
Required Operator Skill	**G**	**G**	**G**	**G**	**G**	**P**	**P**
Repeatability	**G**	**F**	**G**	**F**	**F**	**G**	**F**

6.3 SELECTION OF APPLICABLE METHODS

6.3.1 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. Potential defects that are not visible 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.

6.3.2 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 tabulated in the Report [43]. The summary of results is illustrated in Figures 25-28 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.

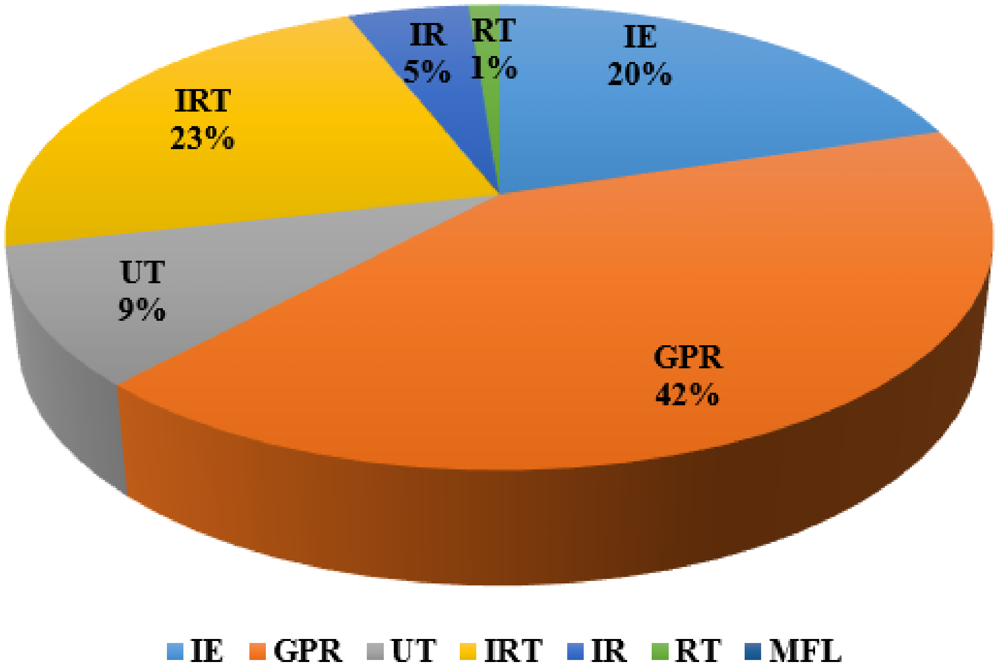


Figure 25: Statistical representation of NDT methods most applicable to detect delamination

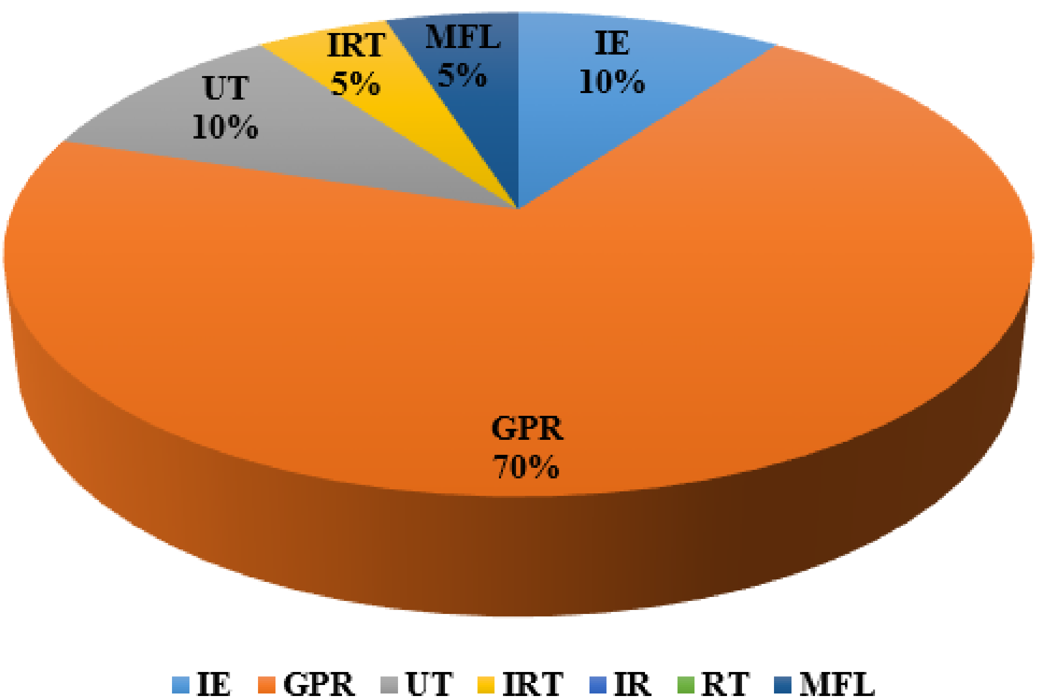


Figure 26: Statistical representation of NDT methods most applicable to detect corrosion

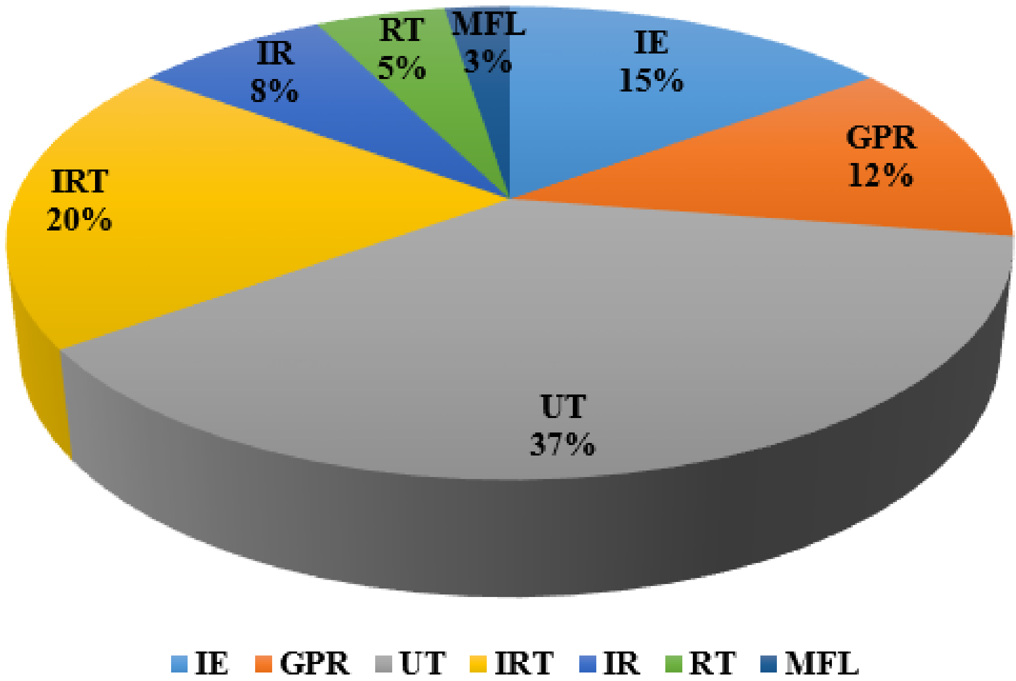


Figure 27: Statistical representation of NDT methods most applicable to detect cracks

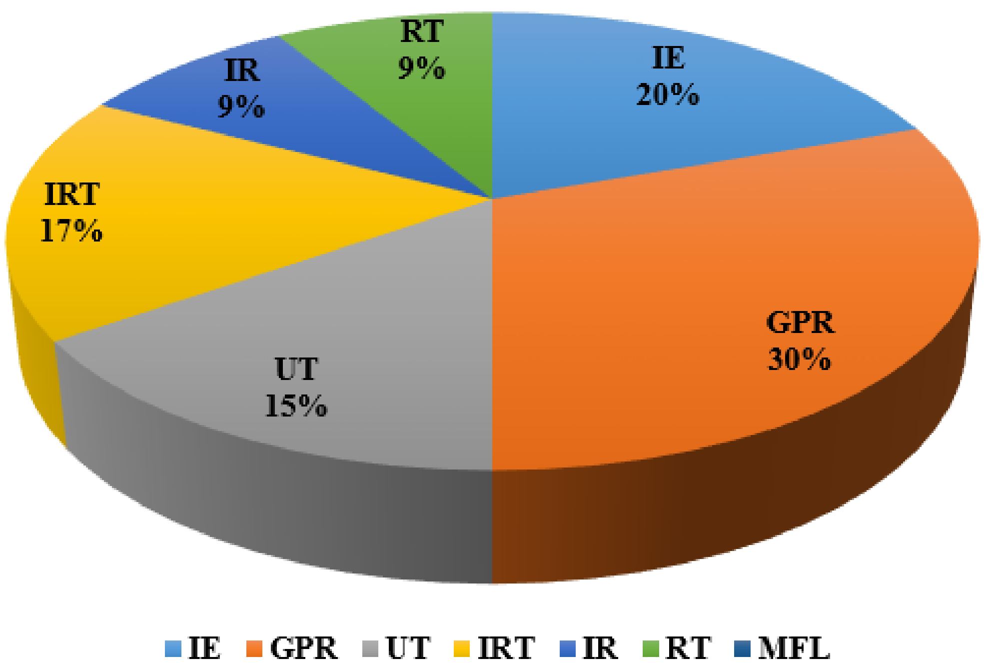


Figure 28: Statistical representation of NDT methods most applicable to detect voids

7 SUMMARY AND CONCLUSIONS

Because of cast-in-place nature of closure joints in ABC projects 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. It is however essential to select NDT methods that are most applicable to detecting various defects and damages associated with various types of joints that are accurate, effective, and economic.

According to a comprehensive investigation, 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. Rational relationships between observed or presumed defects in the five types of ABC closure joints were constructed, and their causes in the form of damage etiology.

The investigation also identified the most promising NDT techniques and their respective capabilities for application to ABC closure joints, and evaluated them through DST and FTA. 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 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.

The procedure and framework developed here will be used in the next section to construct the framework of a “Guide for Identification of NDT Methods Applicable to ABC Closure Joints.” The Guide can be effectively and readily used by the bridge owners/operators and/or consultants 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. Although focus was on closure joints, but the process and guide is applicable to a variety of ABC joints. The proposed guide will be validated in upcoming projects to further support their implementation.

8 ABC-UTC GUIDE FOR SELECTION OF NDT METHODS APPLICABLE TO HEALTH MONITORING OF ABC CLOSURE JOINTS

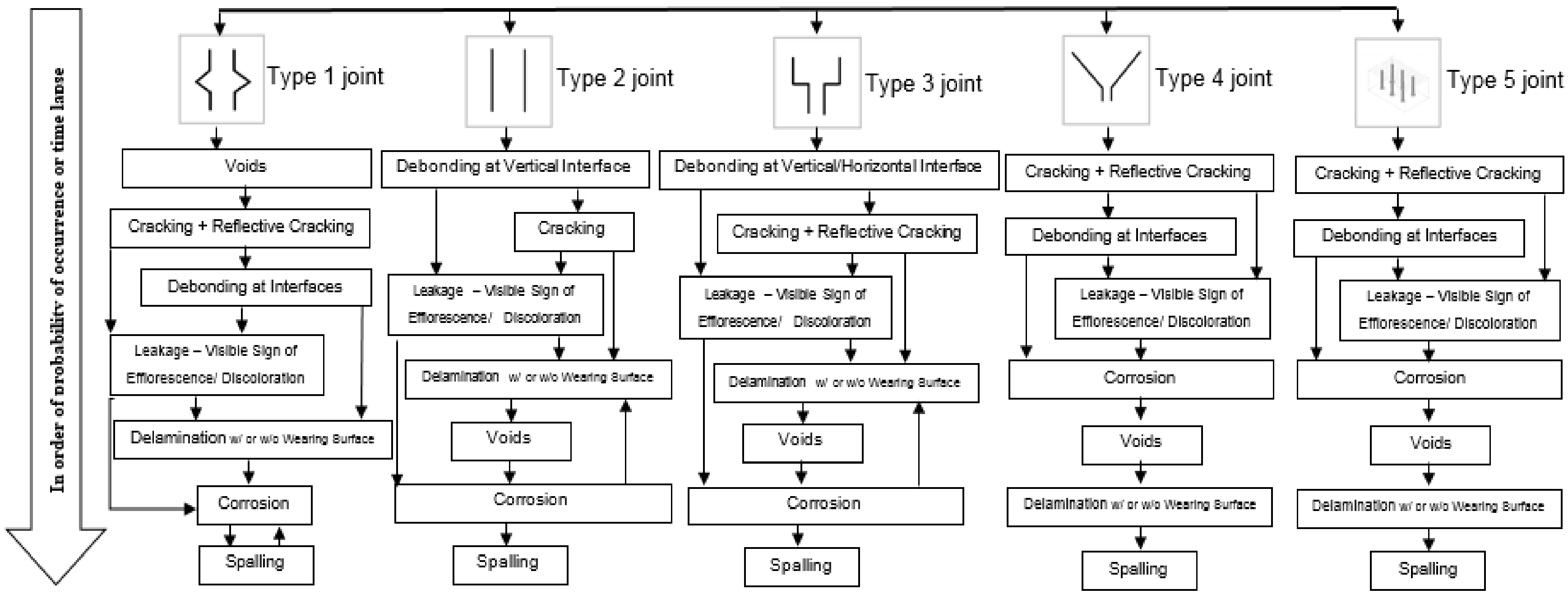
The following procedure can be used to identify the NDT method(s) most applicable to each type of closure joint and defects/damages associated with that type.

8.1 PROCEDURE FOR SELECTION OF THE MOST APPLICABLE NDT METHOD

Guide/Procedure	Commentary
Step 1: Identify details and configuration of the closure joint.	Obtain and review design drawings and prior inspection reports to identify the joint features.
Step 2: Determine the type of closure joint using Tables 1 through 6.	
Step 3: If the type of defect or damage is known, move to Step 5. Otherwise, go to Step 4.	Type of defects/damages might be known from previous inspections or visual observations.
Step 4: Use Flowchart 1 to determine the potential defects/damages in order of priority. Start from most likely defect/damage type and go through the following steps.	
Step 5: Use Flowchart 2 to determine which NDT method is most applicable to the type of defect/damage. Select the NDT method identified for inspection of the closure joint.	Table 9 can be used to evaluate the selected method in more detail according with respect to criteria used for rating of each method and modify selection per project constraint.
Step 6: Go to Step 4 and identify the next likely type of defect/damage, and proceed to Step 5 to identify the NDT method applicable to that type.	Attempt should be made to specify one or two methods with versatility for detection of more than one type of damage/defect. Use Charts in Figures 25 to 28 or Table 9 for this purpose.
Step 7: Prepare a plan for NDT and evaluation including test protocol, procedures, and scope.	

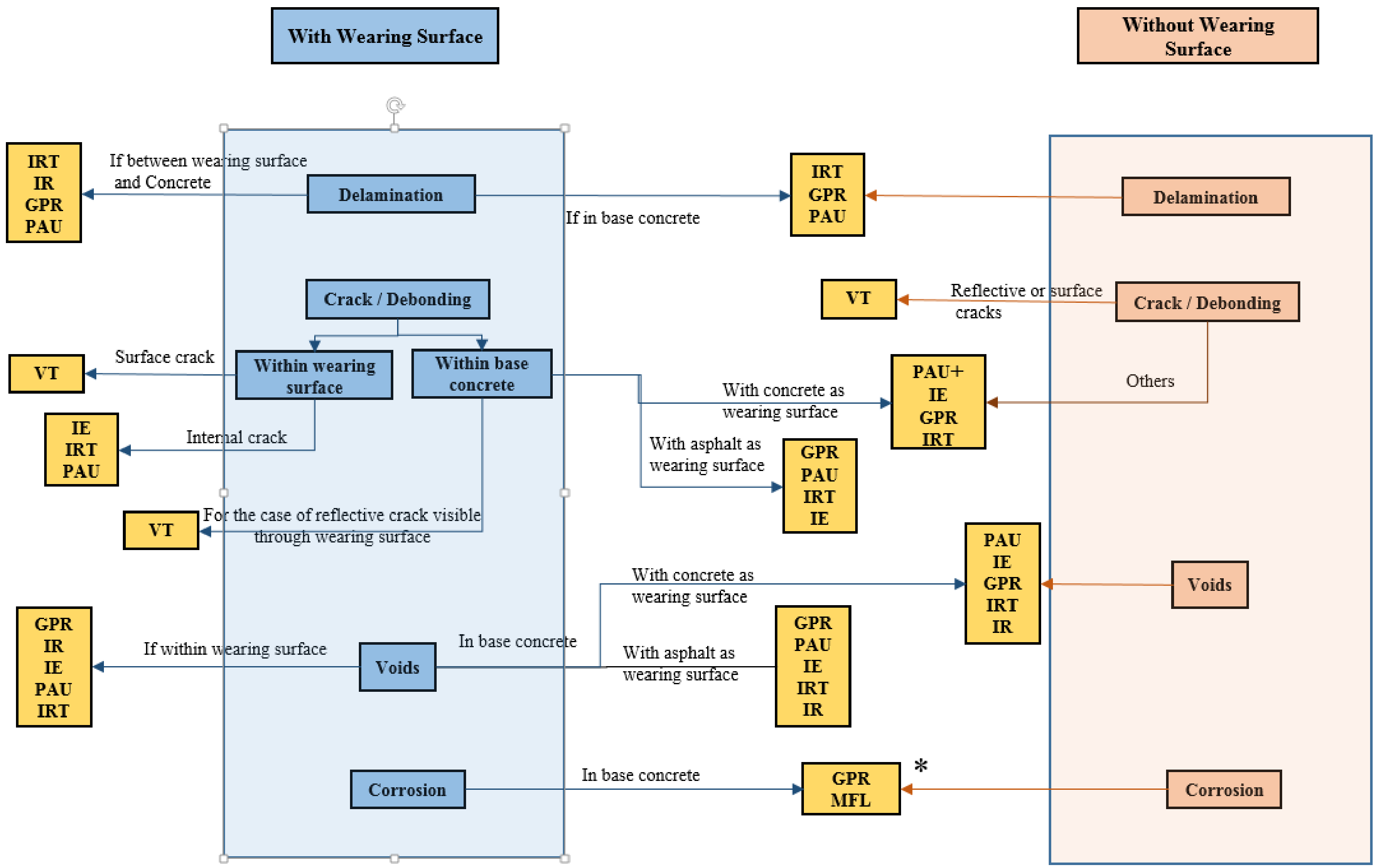
Flowchart 1 – Defects Associated with types of closure joints

For description and details of Joint Types refer to Table 1 and Section 5.1



- If post-tensioning normal to closure line is applied, debonding may be prevented at vertical surface
- Abnormal appearance will be delectable visibly

Flowchart 2 – NDT Methods Suitable for each type of Defect in order of Priority



NDT methods are listed in order of priority top being most applicable

VT denotes visual inspection

+ Effective for vertical cracks

* Methods other than electro-chemical

Abnormal appearance including honeycombing will be detected by visual inspection

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] 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.

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

[6] Marin III, D., 2008, 'Accelerated Bridge Construction,' Iowa DOT ABC Workshop Bridge Devision Texas DOT.

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

[8] S. Farhangdoust, A.B. Mehrabi, "Evaluation of Nondestructive Evaluation Methods for Applicability to Precast Concrete Deck Panels," ASNT Research Symposium 2019 - The American Society for Non-destructive Testing (ASNT), Garden Grove, CA, 1 - 4 April 2019.

[9] 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.

[10] 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.

[11] Wipf, T., 2009, "Iowa's Perspective on ABC," FHWA ABC workshop International Bridge conference.

[12] 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.

[13] 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, 24-27 April, Orlando, Florida, United States.

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

[15] 'Concrete Internal Defect Location,' NeoDex, [Online]. Available: http://neodexndt.com/en/concrete-internal-defect-location-2/. [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] [17] Honey Combing In Concrete.Causes of Honey Combing. Available: https://ceg708.blogspot.com/2017/12/honey-combing-in-concretecauses-of.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] Utah Department of Transportation (UDOT), 'Performance of Accelerated Bridge Construction Projects in Utah: As of May 2009 (Lessons Learned Report),' 2009

[25] 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.

[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] Moustafa, A., Niri, E. D., Farhidzadeh, A., & Salamone, S. (2014). Corrosion monitoring of post- tensioned concrete structures using fractal analysis of guided ultrasonic waves. Structural Control and Health Monitoring, 21(3), 438-448.
[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] Mehrabi, A. B. and Farhangdoust, S., 2019, 'NDT Methods Applicable to Health Monitoring of ABC Closure Joints,' Accelerated Bridge Construction University Transportation Center, Florida Initernational University.
[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] Parrillo, R., Roberts, R., & Haggan, A. (2006, September). Bridge deck condition assessment using ground penetrating radar. In ECNDT Conference Proceeding, Berlin, Germany (pp. 25-29).
[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., Younesian, D., & Esmailzadeh, E. (2017, August). Interaction of higher modes in nonlinear free vibration of stiffened rectangular plates. In ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. V008T12A043-V008T12A043). American Society of Mechanical Engineers.
[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] Alobaidi, W. M., Alkuam, E. A., Al-Rizzo, H. M., and Sandgren, E. (2015). Applications of Ultrasonic Techniques in Oil and Gas Pipeline Industries: A Review. American Journal of Operations Research. 5(274-287).

[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] Davis, A. G., 2003, 'The nondestructive impulse response test in North America: 1985–2001,' NDT & E International, 36(4), pp 185-193.

[63] 1998, 'Nondestructive Test Methods for Evaluation of Concrete in Structures ACI,' American Concrete Institute, Farmington Hills, Michigan, Rep. ACI 228.2R-98.

[64] 'System Reference Manual 2008 Slab Impulse Response,' 2008, Slab Impulse Response (SIR).

[65] 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.

[66] Jahromi, A. J., Dickinson, M., Valikhani, A. and Azizinamini, A., 2017, 'Assessing Structural Integrity of Closure Pours in ABC Projects,'.

[67] 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.

[68] 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.

[69] 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.

[70] Park, S., Kim, J., Lee, C., and Lee, J. (2014). Magnetic Flux Leakage Sensing-Based Steel Cable NDE Technique. Shock and Vibration.

[71] 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.

[72] 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.

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