1. Introduction

With the use of special planning, design, and construction methodologies, Accelerated Bridge Construction (ABC) is expected to reduce on-site construction activities and traffic interruptions during replacement of the existing bridges and new bridge construction as well as rehabilitation. It also promises cost saving during the service life cycle of the bridge. Generally, ABC uses precast elements of the bridge fabricated on site or away, moved to the bridge location and installed in place (Farhangdoust and Mehrabi 2019) (Fig. 1). The prefabricated elements are then made continuous using cast-in-place joints. Deck joints are, normally, referred to as “Closure Joints.” The quality of the joints, expected to quickly become serviceable, depends on the concrete mix design, reinforcement and enclosure details, and is influenced by placement and curing procedure. Normally, ABC joints contain reinforcing bars and enclosures of various shapes that in some cases create congestion within the joint. To provide shear connectivity, some of these joints are designed with cavities within the precast elements. Ultra-High Performance Concrete (UHPC), Self-Consolidating Concrete (SCC), and other high- and normal-strength, fast-setting concrete mixes are, normally, used to fill the closure joints. In all, because of cast-in-place nature of closure joints that are expected to go into service rapidly, there have been always concerns about potential of leaving defects in the closure joints. This, in turn, results in a higher potential for exposure and other detrimental effects with possible degradation in time, and therefore reducing the strength and serviceability of the joint and the structure. The long-term deflections and environmental loading will only exacerbate the situation. Hence, evaluation and health monitoring of the closure joints becomes inevitable. Despite the wide use of non-destructive testing (NDT) methods for bridge structures in general, a concerted attempt for categorization of these methods, comparison of capabilities, and selection of methods most applicable to closure joints is lacking. To address this, a research project was carried out as part of activities in the Accelerated Bridge Construction University Transportation Center (ABC-UTC) of Florida International University. This study included a comprehensive literature review with a focus on NDT methods applicable to health monitoring of ABC closure joints. The study focused on joint types relevant to precast concrete decks commonly used for ABC bridges, therefore, FRP (fiber reinforced plastic), timber (wood), and steel of any shape were excluded for the time being. The study resulted in categorizing the most common closure joints in five general groups based on their features affecting the application of the NDT methods. Accordingly, the most promising NDT methods were identified taking into account the distinctive defects and anomalies associated with closure joints. These methods were evaluated for their efficacy, ease of use and other characteristic influencing their use as preferred methods for each type of joint. A flowchart was introduced to assist in selection of the most applicable NDT method to each type of defect in closure joints. This paper summarizes the results of this study.

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**Scientific Paper**

**Health Monitoring of Closure Joints in Accelerated Bridge Construction: A Review of Non-Destructive Testing Application**

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**Abstract**

Accelerated Bridge Construction (ABC) uses prefabricated elements that are made continuous using cast-in-place joints. Deck joints are normally referred to as “Closure Joints.” There have been concerns about long-term durability of these joints that are expected to become rapidly serviceable. Normally, they contain reinforcing bars and enclosures of various shapes that in some cases create congestion within the joint. The specific nature of the joint application, in-situ casting, curing, material incompatibility, cold joints, cavities and steel congestion contribute to creating the potential for leaving defects and anomalies in the closure joints. This, in turn, results in a higher potential for exposure and other detrimental effects with possible degradation in time, and therefore reducing the strength and serviceability of the joint, hence creating a weak link for the structure. The long-term deflections and environmental loading will only exacerbate the situation. Hence, evaluation and health monitoring of the closure joints becomes inevitable. Despite the wide use of non-destructive testing (NDT) methods for bridge structures in general, a concerted attempt for categorization of these methods, comparison of capabilities, and selection of methods most applicable to closure joints is lacking. To address this, a research project was carried out as part of activities in the Accelerated Bridge Construction University Transportation Center (ABC-UTC) of Florida International University. This study included a comprehensive literature review with a focus on NDT methods applicable to health monitoring of ABC closure joints. The study focused on joint types relevant to precast concrete decks commonly used for ABC bridges, therefore, FRP (fiber reinforced plastic), timber (wood), and steel of any shape were excluded for the time being. The study resulted in categorizing the most common closure joints in five general groups based on their features affecting the application of the NDT methods. Accordingly, the most promising NDT methods were identified taking into account the distinctive defects and anomalies associated with closure joints. These methods were evaluated for their efficacy, ease of use and other characteristic influencing their use as preferred methods for each type of joint. A flowchart was introduced to assist in selection of the most applicable NDT method to each type of defect in closure joints. This paper summarizes the results of this study.

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construction, or develop later during the life of the structure. Concerns have been raised about long-term durability of these joints. 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. Otherwise, maintenance issues with the damaged closure joints may question the very advantage perceived for ABC projects. A variety of Non-Destructive Testing (NDT) methods have been utilized for evaluation of bridge concrete slab including those with closure joints (Lai et al. 2018; Jaber et al. 2018). However, a concerted attempt for categorization of these methods, comparison of capabilities, and selection of methods most applicable to closure joints is lacking.

The study reported in this paper was carried out with the aim of investigating and identifying the defects and problems associated with closure joints, review of available NDT methods for applicability to closure joints, and finally selection and evaluation of the most promising methods. Although most methods considered in this study are applicable to all types of deck materials, let it be with some modifications, the focus was put on joint types that are most relevant to precast concrete decks commonly used for ABC bridges. In this relation, a comprehensive search has been run to identify type, composition and crucial details, potential defects, and potential serviceability problems of the closure joints. Concurrently, NDT methods applicable to bridge evaluation were reviewed from a large pool of literature to identify those with a greater potential for use in inspection and health monitoring of ABC closure joints. Among those, a set of methods were recognized as promising, and were evaluated based on their applicability, effectiveness, efficiency, and ease of use. The selected techniques are to be also evaluated according to their applicability to specific types of defects and anomalies.

2. Definitions

Following definitions are provided to facilitate description of the activities in this paper.

2.1 Accelerated bridge construction (ABC)

Accelerated Bridge Construction (ABC) is defined as design, planning and construction methods for construction of new bridges and for repairs, rehabilitations, and replacement of existing bridges in terms of reducing the traffic impact, onsite construction time, and construction cost, as well as increasing the quality and safety (Farhangdoust and Mehrabi 2019). 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, and dependency on weather. Owing to these advantages, application of ABC methods has been growing rapidly across the US. 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, and better control over cost as well as schedule are all the most important of ABC potentials. Five technologies have been utilized for ABC projects including: prefabricating bridge elements and systems (PBES), structural placement methods, fast track contracting, foundation and wall elements, and rapid embankment construction. Among these, the use of pre-fabricated modular bridge elements and assemblies is the most common feature of the ABC (FHWA 2018, 2011). Based on the ABC applications, the PBES is divided into four major groups of girders, decks, modular superstructure elements and systems, and substructure elements (MDOT 2013). Apart from the structural merits of ABC implementations, as it said earlier, it also has a considerable impact on roadway safety compared to on-site bridge construction. The effect of work zone presence on crash severity using sophisticated machine learning techniques has been recently investigated by Mokhtarimousavi et al. (2019). In their study, different contributing factors that affect injury severity due to work zone presence have been identified and statistically analyzed.

Fig. 1 Prefabricated deck panels being installed by ABC method (MnDOT 2013).
2.2 Closure joints for accelerated bridge construction

Application of the ABC using prefabricated elements and assemblies necessitates the use of joints for connecting and integrating the bridge structure. Different types of ABC connections and evaluation of the available connections have been experimentally and analytically studied by the Nevada Department of Transport (NDOT 2017). Closure joints, normally, refer to joints for connecting the bridge deck elements to each other and to the substructure (Fig. 2). Other joints are used for connecting superstructure to substructure and 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, environmental conditions at the bridge site, type of available material, and functional requirements. Development of new details and investigation on the performance of the existing joints have been the subject of several research investigations (Ma et al. 2012). Moreover, the use of appropriate concrete such as UHPC, SCC, and other high- and normal-strength, fast-setting, early strength concrete mixes has been considered to make the closure joints less vulnerable to potential defects and discontinuities. As an example, UHPC has gained national attention for its use in accelerated bridge construction applications by several departments of transportation (DOTs) and the Federal Highway Administration (FHWA) (Aaleti et al. 2019). UHPC improves the performance of the connections, enhances the capacity of the ABC joints, and increases the durability of the bridge structures (Wang et al. 2019).

3. Research approach and methods

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

4. Types, potential defects, and serviceability problems of ABC closure joints

A review of available literature and data has been carried out to identify type, potential defects, and serviceability problems of the ABC closure joints.

4.1 Categorization of closure joints

The assessment process focuses on indexing different types of closure joints, compositions, critical details, and type of damage including causes and thresholds. The review in its first step examined closely the FHWA report on connection details for prefabricated bridge elements and systems (FHWA 2009). The manual consists of a compilation of survey reports by engineers who completed projects with certain connections located on the superstructure, substructure, and foundation. In this study, the primary focus was put in this study on superstructure connections and on mostly concrete deck configurations that are, commonly, used more for ABC projects. Therefore, only relevant joint types were reviewed. FRP (Fiber Reinforced Plastic), timber (wood), and steel of any shape were excluded for the time being from the scope of this study.

Based on consideration of the applicability of NDT
methods, and types of joints more commonly used in ABC, a series of 32 joint types were chosen for further investigation. Each closure joint type was categorized by shape, presence and type of reinforcement, and distinguished as linear joint or blockouts. Eventually, five types of closure joints were identified to represent dominant groups according to anticipation of type of defects that could be present for these joints, and overall configuration of joints influencing the use of specific NDT methods. These five categories are shown in the Table 1. For identification purposes, an equivalent symbol has been introduced for each type of closure joints. 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 or decking beams to each other and to the girders, and connecting deck panels to the abutment/piers. Blockouts are pocket-type joints for connecting mostly 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. Normally, a layer of bituminous (or other) overlay is expected to be cast over the entire deck covering this type of joint. Some closure joint types however could not be categorized in any of these five shapes. For those, if needed, each case will be, separately, addressed in regards with 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.

(1) Type 1 closure joint
Type 1 Joint designation refers to linear joints known also as shearkey 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 (Porter et al. 2011). As seen in the cross-sections for this type in Table 1, to provide shear transfer, this type of joint are designed in various shapes including diamond-like and rectangle (Wipf 2009). 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 (NCHRP 2011). Shearkey joints are used both longitudinally and transversely depending on the desired application. Early high strength and low shrinkage concrete have been used to prevent formation of pockets of air. In most cases, the joint is left plain with no steel reinforcement, however, double hoops and straight reinforcing 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. For the case of unreinforced joints, the application is more suited for connecting 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-tensioned in the longitudinal or transverse direction depending on the orientation of the joint, hence, the joint may include post-tensioning ducts (FHWA 2009).

(2) Type 2 closure joint
Type 2 Joint designation refers to linear joints that, normally, connect 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. 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 steel reinforcement running in the transverse direction. This joint is usually cast with self-consolidating non-shrink grout. This type has also been used as a transverse joint or link slabs to provide continuity and negative moment transfer at the piers (FHWA 2009). For those joints, normally, no transverse post tensioning is needed.

(3) Type 3 closure joint
Type 3 Joint designation refers to linear joints that normally connect partial depth precast deck panels, butted decked precast girders, and in some cases precast slab longitudinal connection to steel girders (FHWA 2009). Type 3 Joint is similar to Type 2 but for partial depth deck slabs. This configuration normally creates two dissimilar concrete layer in the depth, hence distinguishes this type from others for the application of NDT methods. This type of joint can be cast in both longitudinal and transverse directions, and normally contains longitudinal and transverse reinforcement. Post-tensioning option can be used for unreinforced joints (FHWA 2009). Table 1 shows an example of this type of joint.

(4) Type 4 closure joint
Type 4 Joint designation refers to linear joints that normally joins two prestressed tee beams or double beams, 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 (normally welded to) 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.
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, shear connectors such as headed studs extend from girders below into the blockout void, and the void is cast using high-early strength concrete (FHWA 2009). Blockouts, normally, do not include steel reinforcement that crosses the joint or post tensioning, however, exceptions have been observed (Table 1). 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. 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 (FHWA 2009).

5. Reported and expected defects and anomalies

The literature search also focused on the type of defect and anomalies anticipated or reported for each closure joint type. Defect is interpreted as an anomaly that would affect the structural performance or serviceability of the closure joints within the bridge structure. Defects and anomalies in closure joints are, generally, expected to follow those observed for concrete deck construction. Very few investigations have been conducted with a focus on defects in closure joints. Attanayake and Aktan (2015) reported that despite efforts to improve the design of closure joints, reflective longitudinal cracking persists in ABC bridges. Reflective cracking is a crack that initiates from sharp corners, cold joints, and around inclusions such as rebar inside the deck because of stress concentration and/or shrinkage, and finds its way to the surface through wearing surface or other upper layers. This defect, subsequently, results in other issues such as exposure of reinforcing bars due to leakage of surface water through cracks. Accordingly, in addition to specific cases reported for closure joints, i.e., reflective cracking, other defects and anomalies reported for bridge decks will be considered in this paper with adaptation to the closure joints wherever possible.

The commonly reported defects are comprised of 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 and cracks, and roughness. Examples of defects expected for bridge superstructure in general are shown in Table 2. The type of defect, certainly, plays a significant role in selection of the most applicable NDT method for evaluation and health monitoring of the ABC closure joints. Therefore, evaluation of NDT methods is to be performed in relation with the type of closure joints and expected defects/anomalies. Defective closure joints may include various levels of damages, one caused by another. For example, mixing issues may cause excessive shrinkage that in turn would be a cause for cracking, and cracking may lead to water leakage and consequently corrosion of reinforcing bars. A knowledge of interrelation between various damages and their sequence will be able to guide the selection of an appropriate NDT method. The sequence of the damages constructed for closure joints is shown by Fig. 3.

6. Current inspection/NDT practices

It is intended to identify and combine the best practices from various applications of NDT to ABC including those that are currently being used. The goal eventually is to create standardized methods and techniques that would be similar or useable for inclusion within the customary bridge inspection practices. For health monitoring of structures in general, the use of NDT methods is preferable since they do not require changing or damaging the structure in the course of the inspection. There is a variety of nondestructive inspection methods that can be used to evaluate and examine the integrity of
ABC components, however, to select the most effective methods, there are some basic questions that need to be answered:

1. Which of the NDT technologies are the most reliable and repeatable?
2. Which one will provide better accuracy and easier interpretation?
3. Which one is the most practical method for a certain type of closure joint?
4. What are the advantages and limitations for utilizing one or the other NDT technique?
5. Are more reliable inspection methods also costlier?

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

1. NDT Methods potentially applicable to ABC closure Joints:

| Crack | Delamination | Internal Discontinuities | Honeycombing |
|-------|--------------|--------------------------|--------------|
| (URS 2014) | (NEODEX 2019) | (NEODEX 2019) | (Daily Civil 2017) |
| Surface Discontinuities | Abnormal Appearance | Spalls | Wearing and Abrasion |
| (Carden 2010) | (Gucunski et al. 2010) | (Gucunski et al. 2010) | (Record 2012) |
| Corrosion of Embedded Steel Plates or Connectors | Corrosion of Reinforcing Bars | Leakage Through the Joints | Loss of Cross-section or Breakage of Reinforcing Bars |
| (ARUP 2010) | (Gucunski et al. 2010) | (India Cements 2019) | (Krieger 2017) |

Table 2 Some examples of defects and anomalies for bridge structures.

![Damage Sequence](Image)

Fig. 3 Sequence of damages for deck 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 (LM)
Radiographic Testing (RT)
Magnetic Flux Leakage Testing (MFL)
Visual Testing (VT)
Global Structural Response Testing (GSR)
Chemical and Electrical Testing (CET)

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

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

Most of damage types anticipated for closure joints, and for concrete decks in general, involve some type of discontinuity. Discontinuity is interpreted as a lack of the cohesion or continuity in a material (Farhangdoust et al. 2018). Discontinuities left, intentionally (cold joints) or unintentionally (defective material or workmanship), in concrete in addition to introducing more discontinuities. For example, leakage through closure joints and subsequent corrosion of embedded steel could be a result of cold joint between prefabricated elements and/or closure filler that has 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 (Rehman et al. 2016) (Fig. 4). 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. Considering the type of closure joints and anomaly or defect type, different aspects of inspection sufficiency and efficacy criteria considered for the evaluation and the comparison of various nondestructive testing methods are: Accuracy, level of repeatability of measurement results, speed of data collecting, ease of use, speed of analyzing, cost, level of required knowledge and skill for utilizing each method, and safety of use for operator and public.

6.1 Health monitoring and non-destructive testing methods potentially applicable to ABC closure Joints
Based on their background application to bridge decks, following methods have been identified to have potential for health monitoring of closure joints.

(1) Impact echo testing (IE)
Impact Echo Testing (IE) uses mechanical wave type, has deep penetrating ability into the concrete, and has a great potential for detecting discontinuity and delamination in concrete for ABC closure joints (NCHRP 2016). IE was, experimentally, studied by Gucunski et al. (2010) 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. Accordingly, IE shows promising for evaluation of large delamination and cracks, voids, and discontinuities. They also noted that 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 for this technique was rated as moderate. Other advantage of IE is that it is capable of determining deck and slab thickness (Seshu and Murthy 2013). The accuracy of this NDT method in defect evaluation and detection has been investigated (NCHRP 2016). IE has shown moderate accuracy for void detection in tendon ducts, and requires a multiple impact points for higher accuracy (Lee et al. 2014). A schematic of the IE method is illustrated in Fig. 5. As shown in Fig. 5, for IE, the surface of element is impacted by a steel ball or small impulse hammer (Liu and Yeh 2011). The energy of reflected wave is recorded using an accelerometer (receiver) which is mounted on the surface near the impact location (NCHRP 2016). In IE method, evaluation process is associated with a relatively sparse grid, and normally requires a lane closure. This method also has some limitations for crack detection for elements in which there is a gap between the overlay and deck (Gucunski et al. 2010). 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 (NCHRP 2016). Figure 6 shows IE being used for void detection for the concrete in a bridge structure (Grosse et al. 2013).

(2) Microwave testing (MW)
Microwave Testing is a single side scanning technique that is used to detect the internal discontinuities, voids, and cracks within materials. MW method is sensitive to dielectric variation (Grosse et al. 2013). It can be di-
vided in two main technique of Ground Penetrating Radar (GPR) and Surface Penetrating Radar (SPR) (Schuller 2017). The dominant methodology in this method is that the electromagnetic microwave energy travels at different velocity through different materials. As it shown in Fig. 7, in Microwave Testing, radar antenna will detect any internal anomaly in the depth of the elements by sending and receiving the electromagnetic signals. In this technique, considering the wave velocity, the system can determine the characteristics of each defect based on the depth and time of the signal reflection (Schuller 2017). In the last decade, software developments have helped mechanical and civil engineers to improve outputs of their non-destructive evaluation, and plot high quality and more accurate defect model for elements. Two-dimensional image by stacking the single scanned signals next to each other, and three dimensional images by combination of multiple scans of the elements in different directions are two possible outputs for the result of Microwave Testing method (Schuller 2017).

**Ground penetrating radar testing (GPR)**

As it was mentioned earlier, Ground Penetrating Radar Testing or Impulse Radar Testing is one of the most applicable methods among MW methods (Fig. 8). The most common use for GPR is 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. 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 (Abudayyeh et al. 2007; TRB 2013). In other words, internal defects are identified with moderate accuracy.

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**Fig. 5** The principle of IE for bridge deck inspection with different kinds of internal defects (Gucunski et al. 2011).

**Fig. 6** Void detection in concrete using IE method (Liu and Yeh 2011).

**Fig. 7** Void and crack detection using MW method (Schuller 2017).
by analyzing and interpretation of the reflected pulses (NCHRP 2016). GPR was employed by Huston et al. (2000) 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. However, the application of GPR for multilayer deck, e.g., concrete deck and asphalt overlay, is an active and developing area of research. Based on concrete cover, the effective depth of GPR is varied. For instance, penetrating depth will be around 24 in. (60 cm) for high frequency in the range of around 500 – 3000 MHz (NCHRP 2016). Performing GPR in a mobile or automated platform makes this method more cost effective (Rehman et al. 2016). Different aspects of using GPR technique is, experimentally, analyzed by Guenucki et al. (2010) 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.

(3) Sonic pulse velocity testing (SPV)

Sonic Pulse Velocity Testing (SPV) method uses low frequency or mechanical pulse method. For example, in the SPV, an operator can generate low frequency sonic wave propagation through the element by using a mechanical hammer, and analyze the response on the opposite side of the case study by sensors. Arrival time, amplitude and frequency are the three important parameters of different types of velocity testing methods (Farhangdoust et al. 2011). As it is shown in the Fig. 9, density variation in the tested element will cause different velocity of the wave propagation, and therefore signaling difference in results. This is the basis for investigation of the discontinuities and other distinctive defects in an element (Schuller 2017).

(4) Ultrasonic testing (UT)

Ultrasonic Testing (UT) is one of the most common techniques which evaluates various types of internal cracks and voids and delamination in the concrete by utilizing the sound waves at frequencies above the audible range (Hellier 2001; Shokouhi et al. 2013). In UT method, the structural elements are tested by sound waves in which UT monitor displays the reflection of the sound wave indicating the exact distance of any subsurface or internal defect from the surface (Fig. 10) (Tashakori et al. 2018; Kumar and Mahto 2013). Although UT method has the ability to specify depth and location of the defects (Farhangdoust et al. 2019), it is less effective for inspection of very thin elements, brittle materials and for complex geometry's components (Lee et al. 2014). UT is very applicable to defect evaluation in different types of materials, but this method has some limitations for coarse-grained type of materials. Concrete aggregate size and variation affect the complexity of the damage level, therefore its evaluation (Ongpeng et al. 2016a, 2016b, 2018a, 2018b).

Fig. 8 An example of GPR test using Conquest-100 equipment.

Fig. 9 Set-up of a Sonic Pulse Velocity Testing for masonry application (Schuller 2017).

Fig. 10 UT testing se-tup (Mohamed and Rens 2001).
UT is limited to test on smooth concrete surface (NCHRP 2016). Presence of air gaps in the contact type ultrasonic test may cause wave scattering. Therefore, this type of UT system uses transducers with gel-couplant applied on the material to strengthen the in-situ bonding (Ongpeng et al. 2018a, 2018b). Air-coupled ultrasonic test without the use of couplant enables fast scanning of large structures (Zhu and Popovics 2005). Ongpeng et al. (2018a, 2018b) showed that the sensitivity of the noncontact ultrasonic test is higher for a concrete structure made by a higher water-cement ratio, whereas for the contact ultrasonic test, a lower water-cement ratio concrete structure provides a good sensitivity.

Zamen and Niri (2019) investigated nonlinear behavior of ultrasound wave in phase-space domain and compared it with results in frequency domain. The depth to which damage can be detected by the use of UT depends on the level of the frequency. Normally higher frequencies correspond to longer distance for detection. For example, Ongpeng et al. (2016a, 2016b) showed that 100 kHz and 200 kHz are effective frequencies of the transmitting transducer and the receiving transducer, respectively, for detection of internal defects within plain concrete cubes of 150 mm thickness. UT is a relatively quick nondestructive evaluation test and its cost is moderate (McCann and Forde 2001). Portability and high safety are other merits of UT method. UT is experimentally analyzed by Gucunski et al. (2010) who evaluated the method to have good accuracy in crack detection. 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 (Hasanian and Lissenden 2018).

(5) Phased array ultrasonic testing (PAU)
Phased Array Ultrasonic Testing (PAU), uses an array of probes each of which is individually controlled by computer program (Taheri et al. 2019). 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, service, and parent material flaws, or erosion. Although this method has been evolved from UT testing and uses its 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 method. An array of elements (sensors) within a distinctive relatively large transducer can be utilized for making spatial diversity in PAU systems (Hoegh 2013). 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. Hoegh (2013) raised some questions about portability of the PAU system used in the laboratory set-up. Despite some disadvantages, 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 will consider its future adoption. Piping inspection has been reported as another specific application of Phased Array Ultrasonic Testing usage. Based on experimental evaluation of concrete slab specimens, a quantitative numerical analysis for damage evaluation in concrete using ultrasonic linear array technology has been studied by Freeseman and Khazanovich (2016) (Fig. 11).

(6) Infrared thermography testing (IR)
Infrared thermography testing (IR) 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 (Fig. 12). It was discussed by Seshu and Murthy (2013) 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. IR method is categorized into two classes of passive and active thermography by Lee et al. (2014). 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 (IDOT 2010). 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 (Stimolo 2003). It has been 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 (NCHRP 2016). 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. Mehrabi (2006) used the IR method for nondestructive evaluation of stay cables in cable-stayed bridges using ambient heat source (Fig. 13).

(7) Acoustic emission testing (AE)

The primary basis for Acoustic Emission testing lies in the propagation of acoustic waves originated within a structure from external or internal sources. In general, onset of cracks, delamination, and similar anomalies releases stress and generates an elastic wave that goes from the sound source through the element. This wave is sensed by acoustic sensors attached to the element surface (Tashakori et al. 2019). These events can be generated by applying a localized external force either as sudden mechanical load or as a rapid temperature or pressure change to the element being investigated (Fig. 14). The events can also be generated because of material deterioration such as cross-section loss in reinforcing bars and pre-stressing strands leading to fracture of steel or cracking of the concrete. The method is capable of sensing the waves in a large area just by one sensor depending on the sensitivity of the sensor and extent of damages. However, for detecting the location of damage, more than one sensor is required. It can also be used as a continuous monitoring system for recording events within a specified timeframe (Lee et al. 2014; Chotickai 2001). AE method is sensitive to external noise, and less effective for particular types of loading (Lee et al. 2014).

The bridge evaluation application of Acoustic Emission testing is studied by Holford and Lark (2005). Severity assessment, source location and identification are the main aspects of damage for which AE is used as an applicable nondestructive testing method (Holford et al. 2001). Apparently, this method is not applicable for detection of damages prior to installation of the sensor, unless the activity at the damage creates sound waves. Therefore, it is categorized mostly as a structural health monitoring (SHM) method.

To classify active cracks and estimate the scale of fracture or the degree of damage in the structure, the acquired AE data needs to be appropriately interpreted (JCMS 2003). Correlation-based, time-based, and External parameter-based AE parametric methods have been used as practical indicators for AE data interpretation. To correlate the cracking behavior with AE parameters, two fracture modes of cracking need to be

![Fig. 13 Infrared Thermal Imaging; Use of IR camera (left) and a thermal image (right) (Mehrabi 2006).](image)

![Fig. 14 Schematic of Acoustic Emission Testing (AE) method (Rehman et al. 2016).](image)
considered. Mode I is the tensile type of fracture, and Mode II is the shear type of fracture (Ohtsu 1995). In order to analyze the modes, the factors of RA and Fa (the averaged frequency) have been defined by Ohtsu et al. (2007) as below.

\[
RA = \frac{\text{the rise time}}{\text{the maximum amplitude}} \\
Fa = \frac{\text{AE ringdown-count}}{\text{the duration time}}
\]

As it is shown in Fig. 15, the rise time is as the duration between the arrival time and the time where the maximum amplitude is recorded (Grosse and Ohtsu 2008). By means of two indices of RA and Fa, cracks could be classified into tensile and shear cracks as referenced in Fig. 16.

(8) Impulse response testing (IRT)
Impulse Response Testing (IRT) uses a stress wave method for determining sonic mobility of a structural element. Deep foundation evaluation is one of the original applications and important utilization of IRT (Davis 2003). 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 (ACI 1998). As a result, returning signals are collected by data acquisition system, and recorded data is interpreted for detection of defects in concrete structure. Gucunski et al. (2010) studied the application of Impulse Response testing method, and evaluated this technique for detection of delamination.

Impulse Response testing is graded low for its accuracy, high for its repeatability of measurements, and moderate for its speed of data collecting and analyzing. Moreover, what makes this method attractive is its ease of use. Despite its simplicity, this technique has a wide range of usage in inspection 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. As it is shown in Fig. 17, some investigations on ABC closure joints has been carried out by Accelerated Bridge Construction University Transportation Center (ABC – UTC) at Florida International University (FIU) using IRT for detecting the honeycombs, voids, and cracks (Farhangdoust and Mehrabi 2019).

(9) Laser testing method (LM)
Laser Testing Method is another NDT method used for detection of defects in structural elements. In general, Laser Ultrasonic Testing method uses a Lamb wave initiation by a pulsed laser which generates a laser im-

![Fig. 15 Some of typical AE parameters (Grosse and Ohtsu 2008).](image1)

![Fig. 16 Crack classification using a combination of Fa and RA values (Ohtsu et al. 2007).](image2)

![Fig. 17 IRT test and results for a laboratory test specimen.](image3)
impact on the element (Lee et al. 2014) (Fig. 18). This method is in its experimental stage and information on its applicability is very limited. In Laser Testing method, a defect can be detected by the presence of a standing Lamb wave produced by the impact and recorded by a photorefractive interferometer. It should be noted that this method is applicable to thin structures and may not be readily practical for the case of deck closure joints, however, it was discussed here for completeness.

(10) Radiographic testing (RT)
Radiographic testing (RT) is another NDT method for detecting voids and defects in concrete (Seshu and Murthy 2013). In RT, the element is subjected to X-Ray 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. 19) (Taskin et al. 2011). RT method can have application in a variety of 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), also requiring access to both sides of the element. 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 (McCann and Forde 2001). Safety considerations often preclude the use of RT for structural damage detection.

(11) Magnetic flux leakage testing (MFL)
Magnetic Flux Leakage testing method involves magnetizing the steel within the structure by a strong external magnet to detect defects such as corrosion, loss of cross section, breaks, and pitting on steel elements (NCHRP 2016). The magnet source can be a permanent or electrically activated magnet. This method works on the principle that when defect is present in the steel element, the magnetic field in the material “leaks” from its flux path. At this stage, any change in magnetic field (the leakage) can be sensed by magnetic detector which is placed between the poles of the magnet (Fig. 20) (Shi et al. 2015). 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 (Makar and Desnoyers 2001; FHWA 2006). 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 (Lee et al. 2014). MFL technique is not often used
as an independent method because of its size limitations. MFL has been used successfully in limited cases for detection of steel defects in stay cables and post-tensioning tendons (Mehrabi 2014). This method may be applicable to damage detection in tendons with both non-metal and metal ducts (NCHRP 2016). 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.

(12) Visual testing (VT): Visual Testing (VT) is perhaps the fastest, most economical, and practical method intended for detection of seepage, cracking, spalling, exposed reinforcement, delamination, and concrete deterioration (Fig. 21). These defects normally serve as a precursor for more detailed investigation (McCann and Forde 2001; Alani et al. 2014), however, visual inspection has potential to miss some of the defects, especially internal defects that are hidden from naked eye, and therefore may introduce low accuracy. This method is applicable to both metal and non-metal elements, but cannot offer any quantitative information about internal defect (NCHRP 2016). Visual inspection however can be improved by the use of fiberscope, borescopes, portable microscope and handheld magnifier for locations with difficult access.

(13) Global structural response testing (GSR): Damage detection based on Global Structural Response could be also categorized among applicable methods in ABC health monitoring. Vibration techniques are used to evaluate the condition of the element by considering their dynamic behavior (Hosseinkhani et al. 2018). Changes in modal frequencies and modal shapes are among structural response parameters that can be affected by defects in the structure (Farhangdoust et al. 2017). Accelerometers, displacement and velocity sensors are the three types of sensors for monitoring the vibration characteristics of a structure. Extensive research has been performed on health monitoring and damage detection of structures based on their global response, the most prominent of which perhaps relates to vibration-based modal analysis techniques. These techniques have shown some success in applications such as machinery trouble-shooting and aerospace structural components. These methods also have applications in civil engineering structures. On the other hand, modal parameters may not be sufficiently sensitive for identifying many types of structural damage and their locations unless the level of damage is significant (Liang et al. 1997; Banan et al. 1994).

Vibration tests normally require greater data acquisition and processing efforts when compared to static measurements. Researchers at the Naval Research Laboratory developed a methodology to relate the output of a finite number of sensors to strain-induced structural damage in composite structures using dissipated energy density (Mast et al. 1994). Their method requires a knowledge of the exact loading configuration and does not directly identify location of damage or its intensity. Another method used by Banan et al. (1994) and Sanayein and Saletnik (1996) is parameter estimation and model updating using experimental static measurements. These methods normally require a relatively large number of different loading conditions to provide for accurate and reliable damage detection. In these methods, displacements or strains of structure under several known static load cases are measured selectively. A variety of sensors has been used for structural response measurement including fiber optics and other sensor types. A finite element model of the structure is constructed, and measured and analytical finite element responses are compared and the model stiffness is updated until the difference between the measured and analytical responses is minimized. This method has a better application for structures with distinct elements such as trusses. A method for identifying the properties of a truss using the measured strains of the truss members under predefined static loads is proposed by Liu and Chian (1997). Similarly, Mehrabi et al. (1998) developed a new concept, Precursor Transformation Method (PTM), for damage detection and long-term health monitoring of structures with emphasis on cable-supported bridge application. The method is based on determining the causes (precursors) of change in the measured state of the structure under non-variable loading conditions (e.g. dead loads in bridges) (Mehrabi and Farhangdoust 2018). The applicability of damage detection methods based on global response may have limited application to ABC closure joints. Only significant damages that have potential to alter stiffness of the structure would be able to be detected with this method.

(14) Chemical and electrical testing (CET): The main application of CET to ABC health monitoring would be for detecting corrosion or potential of corrosion in reinforcing concrete elements as well as void and inclusions of considerable sizes. These methods include:

1. Chloride Measurements
2. Carbonation Measurements
3. Electrical Capacitance Tomography
4. Electrical Resistivity Tomography
5. Half-cell Potential

In marine exposure conditions as well as when deicing salt is used for bridges, measurement of chloride in concrete is a means for predicting or detecting corrosion activity for steel reinforcement. Corrosion of reinforcing steel in turn is a cause for cracking and spalling of concrete cover, consequently, the degradation of reinforced concrete structures (Kalogeropoulos 2012; Dérobert et al. 2017). Chloride Measurement is performed directly through chemical testing or use of sensors/indicators, or indirectly through measurement of electrical resistivity of concrete. It can also be measured by the use of GPR as a part of non-destructive testing (Kalogeropoulos 2012).

Carbonation from external or internal sources can affect reinforced concrete bridges significantly as they age. Carbonation is a chemical reaction due to the formation of calcium carbonate which tends to reduce the strength of concrete as well as reduce protective ability of concrete for its reinforcement (Breccolotti et al. 2013). Measuring carbonation depth in concrete is a means for monitoring concrete health and its corrosion protection capacity.

Electrical Capacitance Tomography has been introduced in the late 1980’s as a new internal examination method for measuring the spiral dielectric permittivity distribution by an external capacitance module as inter-electrode capacitance measurements (Sun et al. 1999; Huang et al. 1989). Low cost, speed and safety are some of its merits (Abraham and Anitha 2012) (Fig. 22).

Electrical Resistivity Imaging or Electrical Resistivity Tomography as a geophysical method used for recording the subsurface image by either some electrical resistivity set-up from the surface or electrodes from some boreholes of the structure (Beck 1986) (Fig. 23).

Half-cell Potential method (shown in Fig 24) is used for estimation and determination of the corrosion activity of the reinforcing steel in concrete elements based on potential difference (or voltage) against a reference elec-
trode. Although Half-cell Potential method is inexpensive as well as very simple to perform both for the test and analysis of the data, it has some limitations such as: difficulty in performing when concrete is contaminated, and inability for quantitative measure for corrosion (Rehman et al. 2016).

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

(1) Penetrant testing (PT)
Penetrant testing also known as Dye Penetrant Inspection (DPI), Penetrant Flaw Detection (PFD), and Liquid Penetrant Inspection (LPI), are applicable to all types of material except for porous materials such as unglazed ceramic, wood, pottery, and cloth. The PT can detect surface breaking defects because penetrant is able to enter the discontinuities or defects to form indication. Application of this test needs pre- and post-cleaning. In this test, penetrating fluid is applied to the element, and drawn into the surface discontinuities and defects by capillary actions. The excess penetrant is then removed from the surface and the specimen is inspected for traces of remaining dye as indication of cracks. The use of penetrants for detection of defects on concrete is questionable because of its porosity, however, there may be some application on detecting surface cracks at closure joints. No shape and size limitation for elements to be tested, ease of use and interpretation, low cost equipment, and high sensitivity are some of advantages of using PT. Temperature dependency, sensitivity to contamination, chemical compatibility issue, pre- and post-cleaning requirement and preparation of the surface, and inability of examining the sub-surface and internal discontinuities as well as inability to test porous (absorbing) material are drawbacks of utilizing of PT.

(2) Eddy current testing (ET)
Eddy current testing (ET) is one of the most practical and common NDT methods for inspection of conductive materials like steel and aluminum. In this method, an alternating current, by passing through a coil, makes an alternating electromagnetic field. This field generates the eddy currents in the conductors (Fig. 25) (Gbenga 2016). In this test, defects will interrupt the eddy current, and the interruption in the coil current is displayed on the (Pichenot and Sollier 2003). The size of the current is affected by different factors such as flaws, permeability, standoff distance, electrical conductivity, specimen dimensions, etc. Suitable sensitivity to surface defects, ability to detect defects through several layers, high precise conductivity measurements, automated measuring, ability to detect defects through surface coatings, easy use and portability, and little pre-cleaning surface requirement are advantages of using ET. On the other hand, inability to recognize internal defects, application being limited to conductive elements, high susceptibility to permeability changes, inability to detect defects parallel to surface, inability in using for large areas and complex geometry, expensive equipment are disadvantages of application of ET (Farhangdoust et al. 2018).

(3) Magnetic particle testing (MT)
Magnetic Particle Testing (MT) method is used for detection of surface and sub-surface defects in ferromagnetic materials. In this test, magnetic field magnetizes the element defects, and discontinuities disrupt the magnetic flux. The sub-surface and surface defects are revealed by applying the ferromagnetic particles like iron powder (Fig. 26) (Willcox and Downes 2003). Any Defect makes the flux leakage by attracting ferromagnetic particles due to the change of permeability, and shows as a dark indication. Recognizing the sub-surface and surface discontinuities, high speed of test (in comparison with PT), no need for surface cleaning and preparation (in comparison with PT), ability to test the elements with a thin coating, low cost equipment, ease
of use for testing and analysing, and high sensitivity are some of advantages of MT method (Liu and Chian 1997). However, limitation in material type, shape and size limitation, requiring two directions for measurement, inaccuracy for the elements with coating, demagnetization needed after the test, inability to detect internal defects are some of the disadvantages of MT.

6.3 Complementary to NDT methods

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

(1) Testing under service load (SL)

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

(2) Automated testing platforms (ATP)

Robots and Unmanned Aerial Vehicles (UAV) or drones have been used in recent years for many applications in construction, including visual and non-destructive testing (Agrawal 2018; Jo et al. 2018). As shown in Fig. 27, robots of various types and sophistication carry combination of NDT methods for bridge superstructure (Gibb et al. 2018). High demand for automation of inspection has increasingly led researchers to study the potential of the robotic systems for bridge non-destructive examination. According to conditions and environment, robotic and automated methods may consist of multi-NDT techniques. FHWA (2008) have performed a pilot project for condition assessment of concrete bridge decks using Robotics in which Global Positioning System, Ground Penetrating Radar, Impact Echo, Electrical Resistivity, Ultrasonic Surface Waves, and High-resolution Imaging are used in a complex inspection setup as shown in Fig. 28. There have also been investigations on the effectiveness and application of robots and drones to inspection and damage detection. As it shown in the Fig. 29, Minnesota Department of Transportation has performed one such demonstration project to investigate effectiveness and application of drones to bridge inspection. This investigation along with others have demonstrated the great potential for drones in inspection of hard to reach locations on bridges, but at the same time pointed to some technological limitation of existing UAVs and robot-assisted bridge inspection preventing in some cases their full implementation (MnDOT 2015).

7. Promising methods

Taking into account characteristics of the non-destructive methods discussed above, following methods can be viewed as promising with respect to their applicability to health monitoring of ABC closure joints:

1. Impact Echo Testing (IE)
2. Microwave Testing (MW) – Ground Penetrating Radar (GPR)
3. Ultrasonic Testing (UT)
4. Phased Array Ultrasonic Testing (PAU)
5. Infrared Thermography Testing (IR)
6. Impulse Response Testing (IRT)
Table 3 Comparison and preliminary rating of NDT methods for ABC closure joints: Good = G, Fair = F, Poor = P.

| Capability Type | Test Speed | Subsurface Scanning | Internal Detection | Accuracy | Analyzing Speed | Cost | Ease of Use | Safety | Skill | Repeatability |
|-----------------|------------|---------------------|--------------------|----------|-----------------|------|-------------|--------|-------|---------------|
| IE              | F          | F                   | G                  | G        | F               | G    | G           | F      | G     |               |
| GPR             | G          | G                   | G                  | F        | F               | G    | G           | G      | G     | F             |
| UT              | F          | G                   | G                  | F        | F               | G    | G           | G      | F     |               |
| PAU             | F          | G                   | G                  | F        | F               | G    | F           | G      | G     |               |
| IR              | G          | G                   | F                  | F        | G               | G    | G           | G      | F     | F             |
| IRT             | G          | G                   | F                  | G        | G               | G    | G           | G      | F     | G             |
| LM              | F          | G                   | F                  | F        | P               | P    | F           | P      | F     | F             |
| RT              | P          | G                   | G                  | G        | P               | P    | P           | P      | P     | G             |
| MFL             | F          | G                   | F                  | F        | P               | P    | P           | P      | P     | F             |

7. Laser Testing (LM)
8. Radiographic Testing (RT)
9. Magnetic Flux Leakage Testing (MFL)

Table 3 shows the comparison and rating of the selected promising methods for ABC closure joints based on the characteristics, features, and attributes. The rating is qualitative and comparative among techniques considered in this paper. Following capabilities and attributes have been considered for rating of the applicability of the methods to ABC closure joints:

7. Test Speed: The speed of coverage and data collecting in using the NDT test,
8. Sub-surface Scanning: This indicator measures the test ability in detecting sub-surface defects,
9. Internal Detection: This index shows the test ability in examining the internal defects,
10. Accuracy: Considers the precision of the method,
11. Analyzing Speed: This indicator is related to the

Fig. 28 Multitask robot for NDT inspection on the concrete bridge deck (FHWA 2008; Gucunski et al. 2015).

Fig. 29 Drone used for bridge inspection by Minnesota Department of Transportation (MnDOT 2015).
7.1 NDT methods most applicable to specific type of defect

Based on the rating results for the promising methods presented in Table 3, Farhangdoust and Mehrabi (2019) selected six highly rated methods (GPR, IRT, IE, IR, PAU, and MMFX) and Visual Inspection (VT) as the most applicable methods to ABC closure joints. They also categorized potential defects anticipated for ABC concrete deck closure joints in four main groups collectively representing all damages and defects associated with closure joints.

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

To provide a quantitative measure for application of NDT methods to specific type of defect, a statistical analysis was performed (ABC-UTC 2019). The results are summarized in a flowchart shown in Fig. 30. The flowchart illustrates the four main types of defects for both cases of closure joints with and without wearing surface. Each defect type is then associated with one or more NDT methods that are deemed to be the most applicable to that defect. In the case of multiple NDT methods associated with each defect, the methods are listed in the order of priority, with the most applicable on top.

8. Conclusion

Accelerated Bridge Construction (ABC) uses precast elements of the bridge fabricated on site or away, moved to the bridge location and installed in place. The prefabricated elements are then made continuous using cast-in-place joints. Deck joints are, normally, referred to as
“Closure Joints.” In all, the specific nature of the joint application, in-situ casting, curing, material incompatibility, cold joints, cavities and steel congestion contribute to creating potential for leaving defects and anomalies in the closure joints, therefore, may introduce a potential for weak link within ABC structures. Concerns have been raised about long-term durability of these joints. 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. To address these concerns, a research project was carried out as part of activities in the Accelerated Bridge Construction University Transportation Center (ABC-UTC) of Florida International University. In the first part of this study, type, composition and critical details, potential defects, and potential serviceability problems of the closure joints were determined. Accordingly, five groups of closure joints were recognized that are most commonly used for ABC deck structures, each group containing certain shared details that may influence their sensitivity to specific defects and applicability of the NDT methods. Investigations on performance of closure joints, as well as general observations from bridge inspections, have pointed to a series of defects/anomalies expected for closure joints. These include 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 and cracks, roughness, and abnormal appearance. The type of defect, certainly, plays a significant role in selection of the most applicable NDT method for evaluation and health monitoring of the ABC closure joints. Subsequently, NDT methods applicable to bridge evaluation were reviewed to identify those with the best potential for the use in inspection and health monitoring of ABC closure joints. Among those, a set of methods were recognized as promising, and were evaluated based on criteria including test speed, data analyzing speed, ability for surface scanning and internal damage detection, cost, ease of use, safety, required operator skill, and repeatability of results. Based on this evaluation and results shown in Table 3, top five ranked NDT methods were identified as Impulse Response, Impact Echo, Ground Penetrating Radar, Ultrasonic, and Thermal Imaging methods. Most of defects associated with the closure joints can be caused by one or more of issues such as material, design, fabrication, installation, and environmental factors. A knowledge of the cause of defects will facilitate an effective and accurate health monitoring of ABC closure joints with specific characteristics. Therefore, establishing relationships between observed or presumed defects in closure joints and the main causes in the form of defect etiology is also an important factor and need to be studied further. It was inferred from analyzing the cause-and-effect relationships that the cause and sequence of damages and defects can help in selection of an appropriate NDT method for each type of closure joint and associated potential damages. This study was organized so that its results, including Table 3 for rating of NDT methods and flowchart in Fig. 30 for selection of most applicable methods for each defect type, facilitate future development of field procedures, evaluation guidelines, reporting methods, and suitability for integration into bridge inspection programs.

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