NDT METHODS APPLICABLE TO HEALTH MONITORING OF ABC CLOSURE JOINTS

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1 INTRODUCTION

ABC comprises of precast elements of the bridge fabricated on site or away, moved to the bridge location and installed in place. Regardless of the fabrication and installation of precast-prefabricated elements, connections need to be established on site and in place. These connections, Closure Joints, are expected to provide continuity between adjoining elements for the purpose they are designed for. In all, the specific nature of the joint application, in-situ casting, curing, material incompatibility, cavities and steel congestion contribute to a higher potential for exposure and other detrimental effects with possible degradation in time, and therefore reducing the strength and serviceability of the joint and the structure. The long-term deflections and environmental loading will only exacerbate the situation. It is therefore critical to first assure the closure joint is in good health right after construction completes, and secondly to remain healthy in future.

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 selection of methods most applicable to closure joints is lacking. The main objective of this project is search, identification, and potential development of practical and economical methods for field inspection and damage detection of ABC closure joints, immediately after completion and periodically thereafter during its service life. The presence of defect may be readily identifiable by detecting significant anomalies in the response of the joint to NDT techniques. However, the overall approach to NDT evaluation of closure joints will also include constructing a signature response record of an intact joint to specific NDT technique at completion of construction. This base record will be used for comparison with future periodic (or on demand) inspections for determining the type and extent of potential damages. In conjunction with review of various NDT methods, it is the intent of this project to evaluate the promising NDT techniques, as much as the scope of project allows, and identify how best these techniques could be used to provide suitable practical methods for inspection, therefore health monitoring of the ABC structure. It is attempted to organize the project results in a manner to allow, in a separate follow-up project, development of field procedures, evaluation guidelines, and reporting methods and appraisal of methods for ease of use and suitability for integration into states bridge inspection programs.

3 RESEARCH APPROACH AND METHODS

The overall approach of this project is organized in three basic stages; search of background information for identification of detailed problems and available NDT methods, evaluation of methods for applicability to closure joints, and finally selection of the best methods and verification and necessary adaptation/modification in accordance with the objectives of this project. It is realized that the usefulness of data collected, practicality of approach, ease of use and quantifiable results are defining factors for acceptance, utility, and implementation of any inspection technique. It is also believed that instead of reinventing the wheel, the adaptation, albeit with modification and customization, of existing experiences and well-served practices from other industries/applications provide the maximum returns for the bridge engineering community. Lessons 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. The project objectives will be met within the following approach and set of activities:

- A complete technological review to identify ABC closure joint problems and causes.
- In parallel to the published literature and technology practices, information may be collected, via surveys, from practices and experiences of owners and inspectors.
- Based on technological resources, candidate NDT methods will be categorized and NDT practices with promise for application to closure joints will be selected.
- The second stage will deal with verification of selected methods and their application on available specimens, and adaptation or modifications of methods if necessary.
- An outline of inspection procedure/protocol associated with selected methods will be developed.
- Reporting and communication of results with peers and advisory panel will be carried out in timely manner and at necessary juncture during the project.

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) [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 cost and schedule

Owing to these advantages, application of ABC methods is growing across the US (Fig. 1).

Figure 1: ABC superstructure positioning [5]

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.

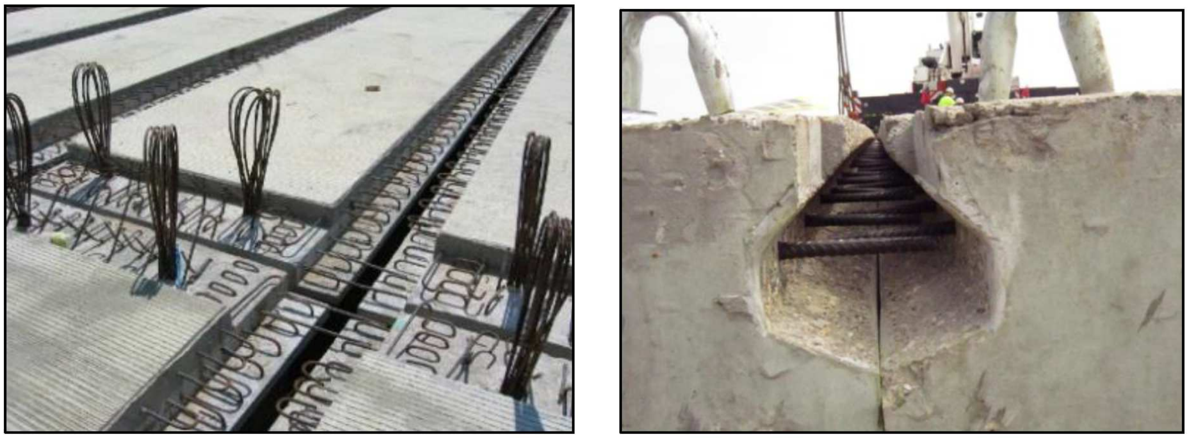


Figure 2: Examples of various types of ABC closure joints [6]–[9]

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 (Fig. 2).

5 DESCRIPTION OF RESEARCH PROJECT TASKS

The following is a description of tasks carried out to date.

5.1 TASK 1 – TYPE, POTENTIAL DEFECTS, AND SERVICEABILITY PROBLEMS OF CLOSURE JOINTS

5.1.1 Literature Search

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

5.1.2 Categorization of Closure Joints

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.

5.1.2.1 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 (Fig.3).

5.1.2.2 Type 2 Closure Joint

Type 2 Joint designation refers to linear joints that normally join full-depth precast decks to each other, and precast decks to precast concrete beams (Fig. 4).

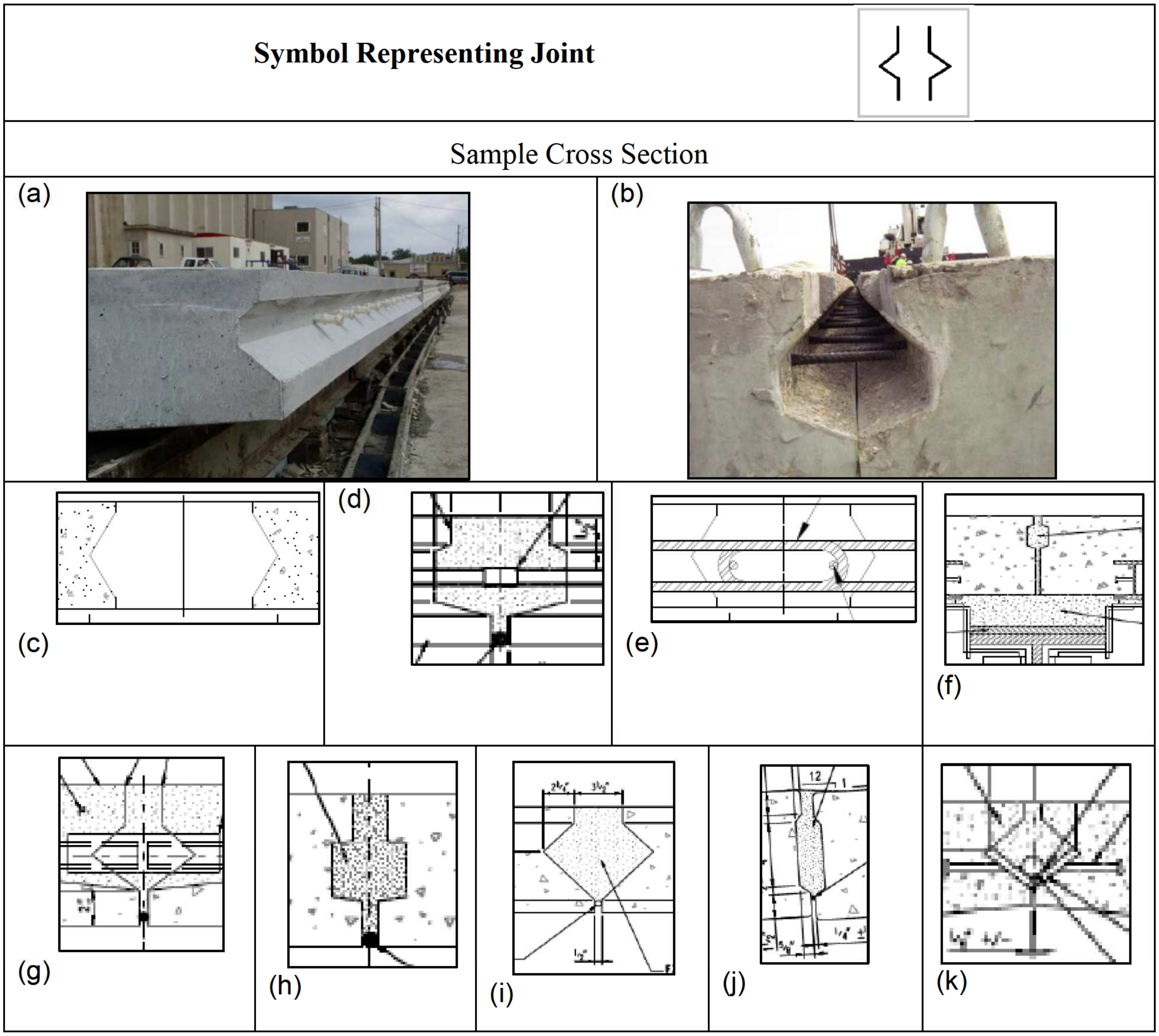


Figure 3: Type 1 Joint [6]–[8], [10], [11]

Symbol Representing Joint	‖
Sample Cross Section	

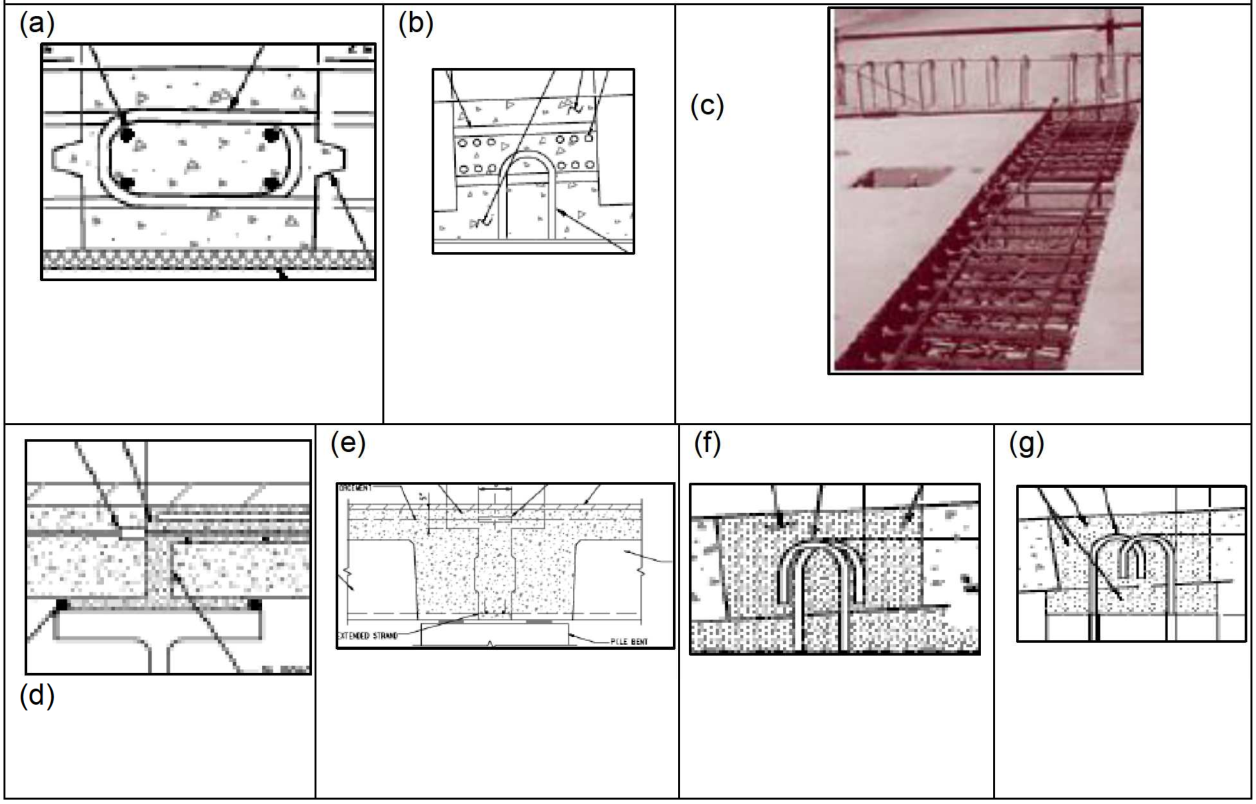
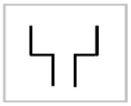


Figure 4: Type 2 Joint [7], [9]

5.1.2.3 Type 3 closure Joint

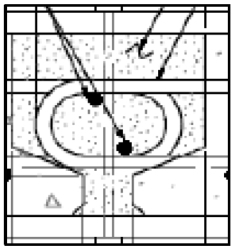
Type 3 Joint designation refers to linear joints that normally joining partial depth precast deck panels, butted decked precast girders, and in some cases P/C Slab Longitudinal connections to Steel Girder Superstructure [7] (Fig. 5).

Symbol Representing Joint



Sample Cross Section

(a)



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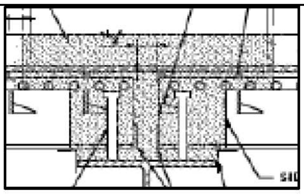

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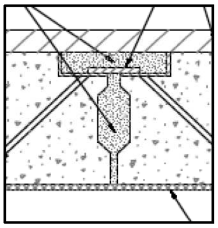

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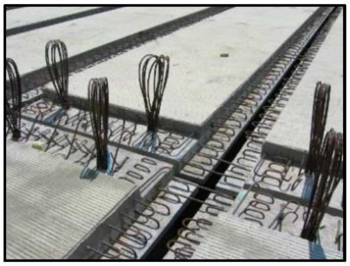


(f)

(g)

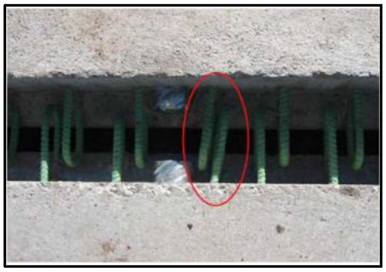


Figure 5: Type 3 Joint [7], [8], [12]

5.1.2.4 Type 4 closure Joint

Type 4 Joint designation refers to linear joints that normally joins two prestressed tee beams or double beam, and in some cases full or partial depth deck panels. The V shaped joint is cast in the longitudinal direction (Fig. 6).

5.1.2.5 Type 5 of closure Joint

Type 5 Joint designation refers to box/recangular shaped joints that are known as blockouts. These joints are spaced throughout the decking and usually connect precast full depth decks to steel girders or concrete I-beams (Fig. 7).

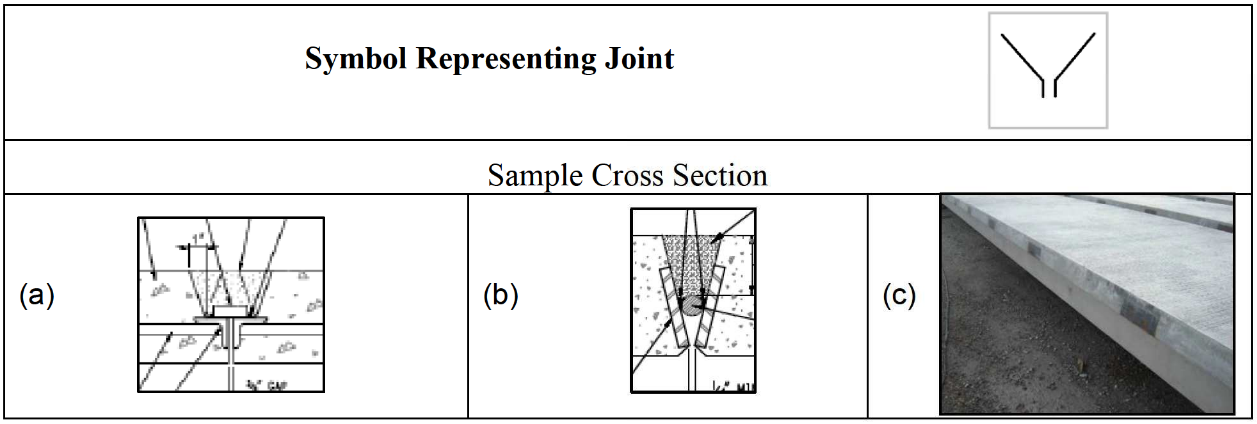


Figure 6: Type 4 Joint [7], [8], [12]

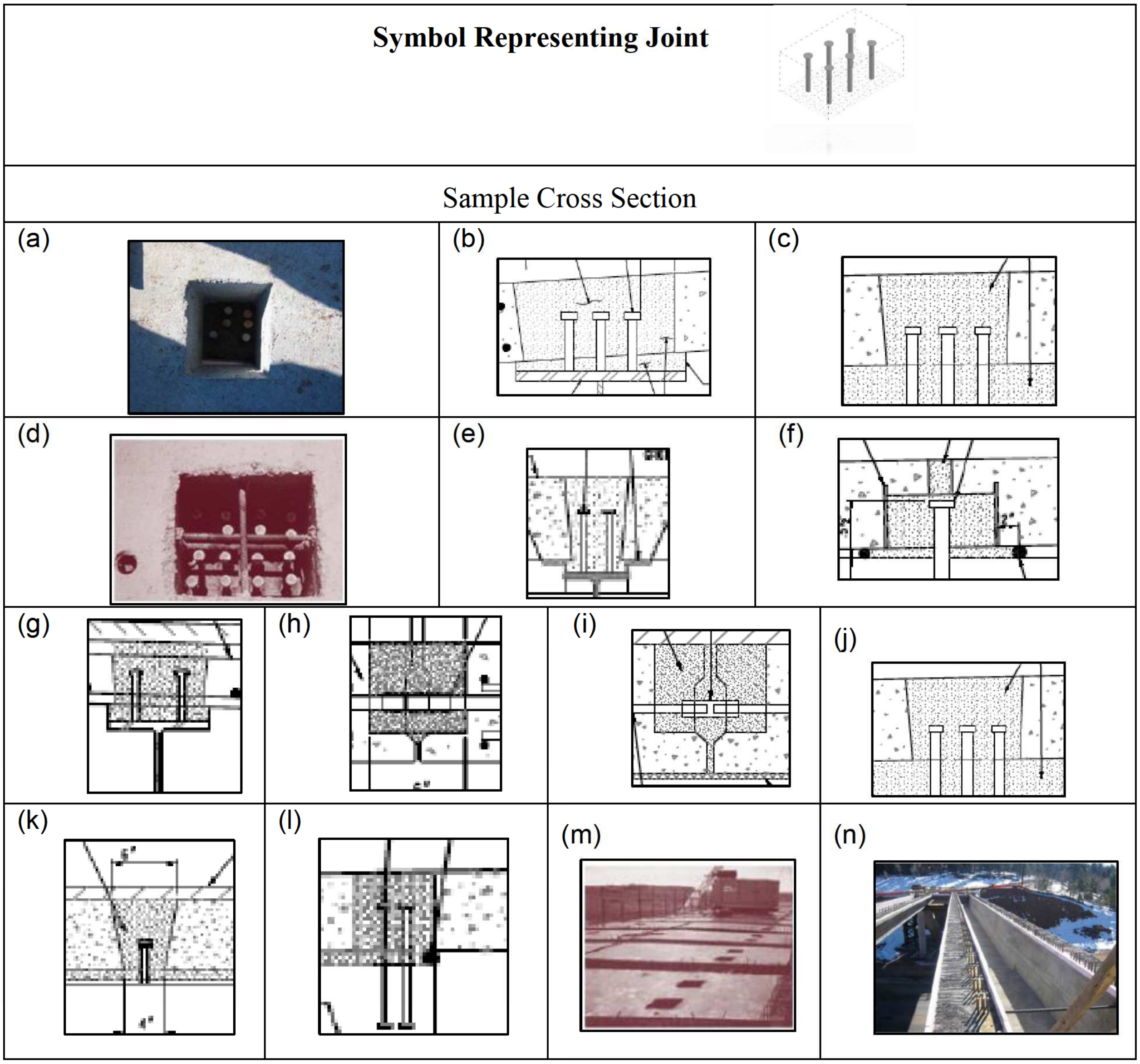


Figure 7: Type 5 Joint on a bridge deck [7], [9]

5.1.3 Reported and presumed defects and Anomalies

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, are considered in this study. These include cracking, separation, delamination, voids, honeycombing, corrosion of reinforcing bars, leakage of surface water through joints and cracks, roughness, and abnormal appearance. These defects are shown in table below:

Table 2: Examples of defects and anomalies for bridge superstructures [15-23]

Crack [15]	Delamination [16]	Internal Discontinuities [16]	Honeycombing [16]
			
Surface Discontinuities [17]	Corrosion of Reinforcing Bars [18]	Spalls [18]	Wearing and abrasion [22]
			
Corrosion of Embedded Steel Plates or Connectors [20]	Abnormal Appearance [19]	Leakage Through the Joints [21]	Loss of Cross-section or Breakage of Reinforcing Bars [23]
			

5.1.4 Defects Etiology

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. The relationships among the causes and effects were explored and an etiology was constructed for observed or expected defects in closure joints.

5.2 TASK 2 – CURRENT INSPECTION/NDT PRACTICES

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

5.2.1 Literature Review on Current NDT Practices

It is intended to identify and combine the best practices from various applications of NDT to ABC including but not limited to those that are currently being used. The goal 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 question that need to be answered: Which of the NDT technologies are the most reliable and repeatable? Which one will provide better accuracy and easier interpretation? Is there an ideal method for a certain type of closure joint? What are the advantages and limitations for utilizing one or the other NDT techniques? Or, do more reliable inspection methods also cost more? To address these, a comprehensive study has been conducted 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 are emphasized. Eighteen NDT methods in three distinctive groups have been identified considering the potential in evaluating the ABC closure joints and include:

1. NDT Methods potentially applicable to ABC closure Joints
    - Impact Echo Testing (IET)
    - Microwave Testing (MT)- Ground Penetrating Radar (GPR)
    - Pulse Velocity Testing (PVT) – Ultrasonic Testing (UT)
    - Phased Array Ultrasonic Testing (PAU)
    - Infrared Thermography Testing (ITT)
    - Acoustic Emission Testing (AE)
    - Impulse Response Testing (IRT)
    - Laser Testing (LT)

   - Radiographic Testing (RT)
   - Magnetic Flux Leakage Testing (MFL)
   - Visual Inspection (VI)
   - Global Structural Response Testing (GSR)
   - Chemical and Electrical Testing (CET)
2. Other Common NDT Methods
   - Penetrant Testing (PT)
   - Eddy Currant Testing (ET)
   - Magnetic Particle Testing (MPT)
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. Most of damage types anticipated for closure joints, and for concrete decks in general, involve some type of discontinuity. Discontinuities left intentionally (cold joints) or unintentionally (defective material or workmanship) in concrete beside introducing an issue by themselves, can cause onset and progress of other defects which in turn can introduce 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. NDT methods are being thoroughly reviewed in relation to their applicability to ABC closure joints inspections [24-26]. Inspection sufficiency and efficacy criteria for the evaluation and comparison of various nondestructive testing methods include: 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. After these evaluations, the applicability or versatility of each method for inspection of various types of closure joints and types of defects will be assessed.

5.2.1.1 NDT Methods Potentially Applicable to ABC Closure Joints

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

5.2.1.1.1 Impact Echo Testing (IET)

Impact Echo Testing (IET) uses mechanical wave type and has deep penetrating ability into the concrete, and a great potential for detecting discontinuity and delamination in concrete of closure joints [24]. IET was studied by Gucunski et al. [25] for estimating the bridge deck defects. They pointed out that IET 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. IET has shown moderate accuracy for void detection in tendon ducts, and requires a multiple impact points for high accuracy.

5.2.1.1.2 *Ground Penetrating Radar Testing (GPR)*

Ground Penetrating Radar Testing (GPR) is one of the most common NDT 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 [24, 27, 28, and 29]. Based on concrete cover, the effective depth of GPR is varied. GPR was employed by Huston at el. [30] 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.

5.2.1.1.3 *Pulse Velocity Testing (PVT)*

Arrival time, amplitude and frequency are the three important parameters of different types of velocity testing methods [31], particularly in Pulse Velocity Testing (PVT). PVT techniques are, generally, used for evaluating existing element by transmission approach which is divided into two main propagation techniques [32]:

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

5.2.1.1.4 *Ultrasonic Testing (UT)*

Ultrasonic Testing (UT) is one of the most commonly techniques among other PVT testing methods which is used to evaluate various types of internal cracks and voids in the concrete by utilizing the sound waves at frequencies above the audible range [33]. High frequency sound waves, typically above 2 MHz is used in UT method in which the monitor displays the reflection of the sound wave indicating the exact distance of any sub-surface or internal defect from the surface [34]. 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 [24]. UT is limited to test on smooth concrete surface [27], and very applicable to defect evaluation in different types of materials. UT is a relatively quick nondestructive evaluation test and its cost is moderate [26].

5.2.1.1.5 *Phased Array Ultrasonic Testing (PAU)*

Phased Array Ultrasonic Testing (PAU), uses an array of probes each of which is individually controlled by computer program. 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. An array of elements (sensors) within a distinctive relatively large transducer can be utilized for making spatial diversity in PAU systems [35]. A linear array of 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. A quantitative numerical analysis for damage evaluation in concrete using PAU has been studied by Freeseman and Khazanovich [36]. As another application of PAU, the localization of multi-defect has been experimentally carried out by Senyurek at el. (Fig. 8-a) [37].

5.2.1.1.6 *Infrared Thermography Testing (ITT)*

Infrared thermography testing (ITT) has been used widely for detection of material variation based on variation of temperature. In this method an infrared camera is used that measures the emitted infrared radiation from a structural member [24]. This method is based on emissivity of individual components 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 [27]. ITT method is categorized into the two classes of passive and active thermography by Lee et al. [24]. In the former type, the Infrared Thermography testing is performed without any external cooling or heating source. One of the drawbacks in the use of ITT method is its high sensitivity to contaminants on the bridge deck [24 and 33]. Hurlebaus et al. [26] stated that ITT is applicable only to non-metal elements, and any uneven heating could have negative effect on the results in testing by ITT. Application of the ITT method for evaluation of bridge stay cabels is shown in Fig. 9-a [38].

5.2.1.1.7 *Acoustic Emission Testing (AE)*

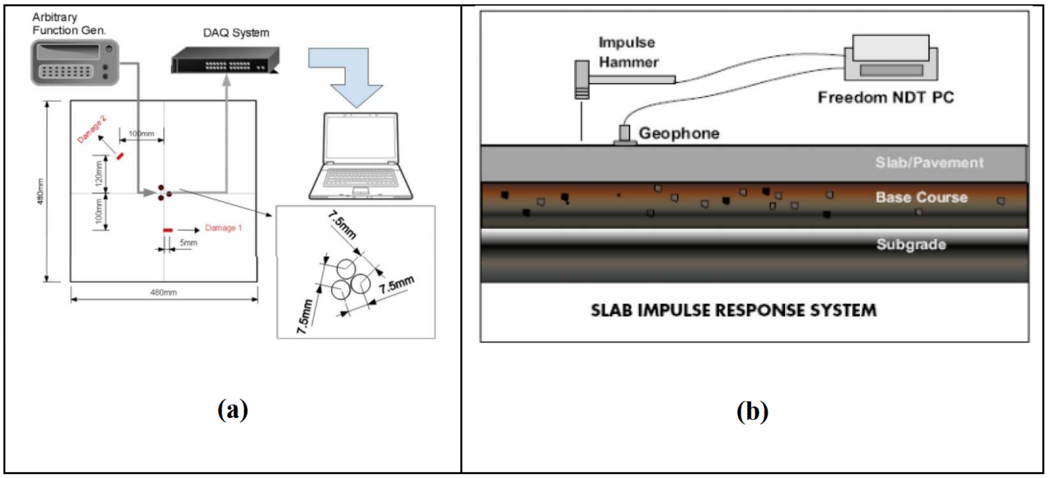
The primary basis for Acoustic Emission testing lies in the propagation of acoustic waves originated within a structure from external or internal sources. This wave is sensed by acoustic sensors attached to the element surface [33]. These events can be generated by applying a localized external force either as sudden mechanical load or a rapid temperature or pressure change to the element being investigated [24 and 28]. It can also be used as a continuous monitoring system for recording events within a specified timeframe [24]. Apparently, this method is not applicable for detection of damages prior to installation of the sensor, unless a continuous activity at the damage location creates sound waves.

5.2.1.1.8 *Impulse Response Testing (IRT)*

Impulses Response Testing (IRT) uses a stress wave method for determining sonic mobility of a structural element. Its prominent use has been for structural deck and slab on grades. Figure 8-b shows application of IRT on slab-on-grade [39]. 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 [40]. As a result, returning signals are collected by data acquisition system, and recorded data is interpreted for defects detection in concrete structure. Gucunski et al. [25] 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 [25]. 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. Figure 9-b shows a result of IRT testing on deck slab.

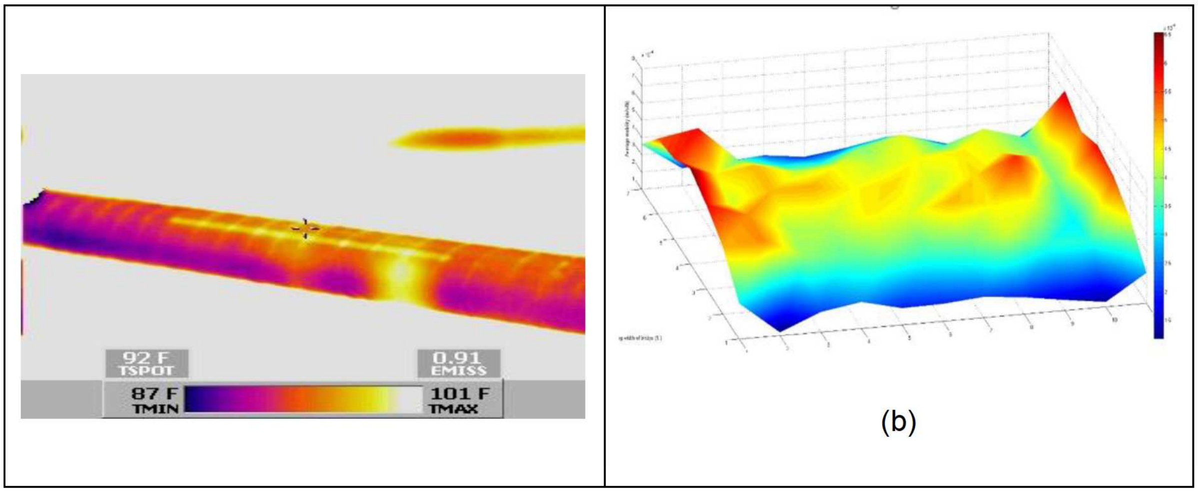
5.2.1.1.9 *Global Structural Response Testing (GSR)*

Damage detection based on Global Structural Response could be also categorized among applicable methods in ABC nondestructive evaluation. Modal parameters may not be sufficiently sensitive for identifying many types of structural damage and their locations unless the level of damage is significant [41]. Another method used by Banan et al. [42] and Sanayei et al. [43] is parameter estimation and model updating using experimental static measurements. Mehrabi et al. [44] 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.



(a) (b)

Figure 8: Examples of NDT test set-up. (a) A test set-up of PAU [37]. (b) IRT application [39].



(b)

Figure 9: Examples of NDT results. (a) Infrared thermography image [38]. (b) IRT result [45].

5.2.2 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 [46]:

- Impact Echo Testing (IET)
- Microwave Testing (MT)- Ground Penetrating Radar (GPR)
- Pulse Velocity Testing (PVT) – Ultrasonic Testing (UT)
- Phased Array Ultrasonic Testing (PAU)
- Infrared Thermography Testing (ITT)
- Impulse Response Testing (IRT)
- Laser Testing (LT)
- Radiographic Testing (RT)
- 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 study.

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

- Test Speed: The speed of coverage and data collecting in using the NDT test.
- Surface Scanning: This indicator measures the test ability in detecting surface defects
- Internal Detection: This index shows the test ability in examining the internal defects.
- Accuracy: Considers the precision of the method.
- Analyzing Speed: This indicator is related to the speed of data analysis collected by the NDT method.

- Cost: Shows the cost of associated with the usage of the method, equipment and tools.
- Ease of Use: Indicates user friendliness, regardless of required skill for the ND technique.
- Safety: This indicator shows the safety of use of the NDT method for operators and public.
- Skill: This index considers the level of training and skill requirement for utilizing each method.
- Repeatability: Indicates the level of repeatability of measurement results.

Table 3: Comparison and rating of NDT methods for ABC closure joints – Good=G, Fair=F, Poor=P.

NDT Method	Test Speed	Surface Scanning	Internal Detection	Accuracy	Analyzing speed	Cost	Ease of Use	Safety	Skill	Repeatability
IET	F	F	G	F	G	G	G	G	G	G
GPR	G	F	G	F	G	G	G	G	G	F
PVT	F	P	G	G	G	F	G	G	F	G
PAU	F	P	G	G	G	G	F	G	F	G
ITT	G	G	F	F	G	G	G	G	G	F
IRT	F	G	F	F	G	G	G	G	G	F
LT*	G	G	G	G	G	P	P	F	P	F
RT	P	P	G	G	G	P	P	P	P	G
MFL	F	F	F	F	F	P	P	P	P	F

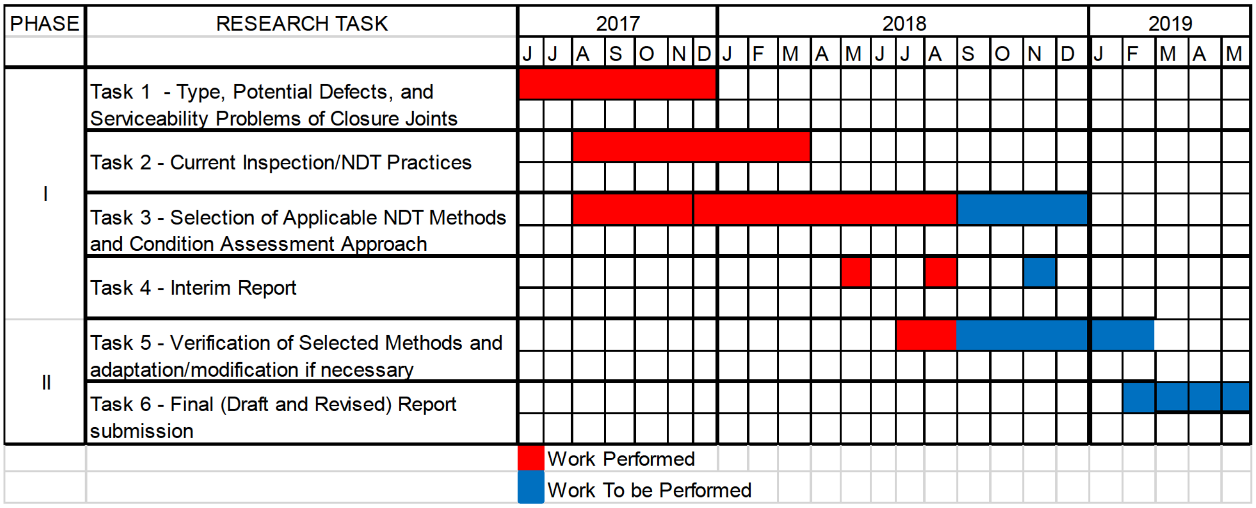
6 REMAINING WORK

Laboratory and field verification work will be included in this study. To this end, NDT equipment and accessories have been purchased and training for their use is in progress.

7 SCHEDULE

Progress of tasks in this project is shown in the Table 4.

Table 4: Schedule



PHASE	RESEARCH TASK	2017							2018												2019				
		J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
I	Task 1 - Type, Potential Defects, and Serviceability Problems of Closure Joints	🟥	🟥	🟥	🟥	🟥	🟥	🟥																	
	Task 2 - Current Inspection/NDT Practices			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥														
	Task 3 - Selection of Applicable NDT Methods and Condition Assessment Approach			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟦					
	Task 4 - Interim Report												🟥			🟥			🟦						
II	Task 5 - Verification of Selected Methods and adaptation/modification if necessary														🟥	🟥	🟦	🟦	🟦	🟦	🟦	🟦			
	Task 6 - Final (Draft and Revised) Report submission																					🟦	🟦	🟦	🟦

🟥 Work Performed

🟦 Work To be Performed

8 REFERENCES

1) Culmo, M. P., Sadasivam, S., Gransberg, D., Boyle, H., Deslis, A., Duguay, W., Rose, D., Mizioch, C. and Mallela, J., 2011, 'Contracting and Construction of ABC Projects with Prefabricated Bridge Elements and Systems,' Federal Highway Administration, Washington, D.C., Rep. FHWA-HIF-17-020.
2) Mashal, M., White, S. and Palermo, A., 2012, 'Concepts and Developments for Accelerated Bridge Construction and Dissipative Controlled Rocking,' 15 WCEE LISBOA.
3) Bowers, R., Klaiber, F. W., Kevern, S., Landau, C., Kieffer, R. and Nelson, J. S., 2007, 'Construction and Testing of an Accelerated Bridge Construction Project in Boone County,' Proceedings of the 2007 Mid-Continent Transportation Research Symposium.
4) Jahromi, A. J., Dickinson, M., Valikhani, A. and Azizinamini, A., 2017, 'Toward Development of Best Practices for Closure Joints in ABC Projects,'.
5) Culmo, M. P., 2011, 'Accelerated Bridge Construction - Experience in Design, Fabrication and Erection of Prefabricated Bridge Elements and Systems,' Federal Highway Administration, McLean, VA, Rep. FHWA-HIF-12-013.
6) Adjacent precast box beam bridges,' The Construction Specifier CSI, Available: https://www.constructionspecifier.com/adjacent-precast-box-beam-bridges/4/. [Accessed: 1-Jan-2018].
7) Culmo, M. P., 2009, 'Connection Details for Prefabricated Bridge Elements and Systems,' Federal Highway Administration, Rep. FHWA-IF-09-010.
8) Porter, S. D., Julander, J. L., Halling, M. W. and Barr, P. J., 2012, 'Shear Testing of Precast Bridge Deck Panel Transverse Connections.' Journal of Performance of Constructed Facilities, 26(4), 462-468.
9) Russell, H., Ralls, M., Tang, B., Bhide, S., Brecto, B., Calvert, E., Capers, H., Dorgan, D., Matsumoto, E., Napier, C., and Nickas, W., 2005, 'Prefabricated Bridge Elements and Systems in Japan and Europe,' Federal Highway Administration, Rep. FHWA-P.
10) French, C., Shield, C., Ma, Z. J, Klaseus, D., Smith, M., Eriksson, W., Zhu, P., Lewis, S. and Chapman, C. E., 2011, 'Summary of Cast-In-Place Concrete Connections for Precast Deck Systems,' National Academy of Sciences.
11) Wipf, T., 2009, "Iowa's Perspective on ABC," FHWA ABC workshop International Bridge conference.
12) Marin III, D., 2008, 'Accelerated Bridge Construction,' Iowa DOT ABC Workshop Bridge Devision Texas DOT.
13) URS, 2014, 'Lessons Learned After Construction: Bridge County Road Over I-80,' Salt Lake City, Utah, Project No. IBHF-80-4(90)160.
14) 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.
15) Megrio "Cracked Bridge in Rio de Janeiro Brazil," CNN, 09-Apr-2014. [Online]. Available: http://ireport.cnn.com/docs/DOC-1118550. [Accessed: 08-Feb-2018] , 2014.
16) [26] Concrete Internal Defect Location, NeoDex, [Online]. Available: http://neodexndt.com/en/concrete-internal-defect-location-2/. [Accessed: 08-Feb-2018].
17) [27] D. Carden, "Valpo prof tries to crack case of MLK bridge defects," The Times nwi.com, 05-Jul-2010. [Online]. Available: http://www.nwitimes.com/news/state-and-regional/indiana/valpo-prof-tries-to-crack-case-of-mlk-bridge-defects/article_287deb0, 2010.
18) [28] N. Gucunski, A. Imani, F. Romero, S. Nazarian, D. Yuan, H. Wiggenhauser, P. Shokouhi, A. Taffe, and D. Kutrubes, "Nondestructive Testing to Identify Concrete Bridge Deck Deterioration, Transportation Research Board," Washington, D.C. , 2013.
19) [29] R. Rogerson, "HAC concrete," Sandberg. [Online]. Available: https://www.sandberg.co.uk/investigation-inspection/inspection/hac-concrete [Accessed: 02-Feb-2018].
20) [30] 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%, 2010.

21) [31] Aging Structures, Infratech360 Advanced Civil Technologies, [Online]. Available: https://www.infratech360.com/single-post/2013/07/24/aging-structures. [Accessed: 08-Feb-2018], 2016.
22) [32] T. Record, "Spokane 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, 2012.
23) [33] L. M. Krieger, "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/, 2017.
24) 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.
25) Gucunski, N., Nazarian, S., Wiggenhauser, H. and Kutrubes, D., 2010, "Nondestructive Testing to Identify Concrete Bridge Deck Deterioration," SHRP 2–FEHRL Workshop, TRA 2010 Brussels, Belgium.
26) 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.
27) 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.
28) 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.
29) 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.
30) 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.
31) Farhangdoust, S., Kianifar, A., Najafpoor, A., 2011, "Designing and Manufacturing All-way Acoustic Generator for Testing the Frequency of Sound Transmission Loss (STL)", 1st ISAV, Tehran, Iran.
32) Schuller, M., 2017, "Nondestructive Evaluation and Testing of Masonry", Workshop, The American Institute of Architects Continuing Education Systems Course.
33) Hellier, C. J., 2001, Handbook of nondestructive evaluation, New York: McGraw-Hill, Columbus, OH.
34) Mohamed, O. and Rens, K. L., 2001, "Ultrasonic testing of properties of 50-year-old concrete," Materials Evaluation, 59(12), pp 1426-1430.
35) Hoegh, K. E., 2013, "Ultrasonic linear array evaluation of concrete pavements," Dissertation, University of Minnesota, MN.
36) 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.
37) 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, 413, pp 383-394.
38) Mehrabi, A. B., 2006, "In-Service Evaluation of Cable-Stayed Bridges, Overview of Available Methods and Findings," Journal of Bridge Engineering, 11(6), pp 716-724.
39) System Reference Manual 2008 Slab Impulse Response,' 2008, Manual. [Online]. Available: www.olsonengineering.com [Accessed: 10-Nov-2017].
40) 1998, 'Nondestructive Test Methods for Evaluation of Concrete in Structures ACI,' American Concrete Institute, Farmington Hills, Michigan, Rep. ACI 228.2R-98.
41) Liang, Z., Lee, G.C. and Kong, F., 1997, "On Detection of Damage Location of Bridges," Proceedings of the 15th International Modal Analysis Conference, Orlando, FL, 1, pp 308-312.
42) Banan, M. R., Banan, M. R. and Hjelmstad, K. D., 1994, "Parameter Estimation of Structures from Static Response. II. Numerical Simulation Studies," Journal of Structural Engineering, 120(11), pp 3259-3283.

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

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

45) Jahromi, A. J., Dickinson, M., Valikhani, A. and Azizinamini, A., 2018, "Toward Development of Best Practices for Closure Joints in ABC Projects", Transportation Research Board 97th Annual Meeting.

46) S. Farhangdoust, A.B. Mehrabi, S.F.A. Mowsavi, "NDT Methods Applicable to Health Monitoring of ABC Closure Joints," 27th Research Symposium - The American Society for Non-destructive Testing (ASNT), Orlando, Fl, 26-29 March, 2018.