CIB World Building Congress 2019
Hong Kong SAR, China
17 – 21 June 2019

State-of-the-Art Review of Defect Detection in Concrete Bridge Deck

Sherif ABDELKHALEK,
PhD Candidate, Department of Building and Real Estate, The Hong Kong Polytechnic University
(email: sherif.abdelkhalek@connect.polyu.hk)
Tarek ZAYED,
Professor, Department of Building and Real Estate, The Hong Kong Polytechnic University
(email: tarek.zayed@polyu.edu.hk)

Abstract

Bridges are considered vital structures in any country. Complete or partial failures that may happen to such structures risk people lives and cause economic losses. Accurate condition assessment of bridge elements is a mandatory step to choose the most appropriate maintenance strategy. In most countries, visual inspection plays the dominant role in assessing the current condition of bridge elements. Nevertheless, visual inspection suffers from several limitations such as subjectivity and uncertainty. Accordingly, a need was arisen to deploy new techniques in the inspection process to precisely assess the condition of bridge elements and to avoid the shortcoming of visual inspection. In this regard, researchers incorporated several nondestructive and remote-sensing technologies in the inspection of bridges such as GPR, Infrared Thermography, sensors, etc. This paper provides an overview of current technologies used in inspection of concrete bridge decks. The main features, advantages, and limitations of each technology are analyzed. The proposed evaluation approaches to rank these technologies are reviewed. The review revealed that combining several complementary technologies in inspection process effectively builds a comprehensive inspection system. However, more studies about the performance aspects of the nondestructive and remote-sensing technologies are needed to optimize the design and application of such inspection systems.

Keywords: Bridge, Condition Assessment, Remote-Sensing.

1.Introduction

Bridge deck represents the most important component in the bridge system, as it provides the driving surface to the bridge users. Major or minor failure to maintain these elements has great implications on the overall performance of the bridge system and consequently on the highway network. Therefore, maintaining bridge deck in a good condition is a mandatory step to provide the standard service level. Accordingly, periodical inspections should be conducted to provide the required information to assess the current condition of the bridge deck and to determine the most appropriate maintenance strategy. Accurate condition assessment reflects a precise assessment of the bridge deck's condition to determine the needed intervention on time and consequently to save people lives and money. Current inspection practices mainly rely on visual inspection and very elementary tools such as hammer sounding and chain drag (Gucunski et al., 2011, Agdas et al., 2016). Nevertheless, these techniques suffer from several limitations such as subjectivity and uncertainty. Nondestructive technologies (NDT), such as impact echo, ultrasonic pulse echo, half-cell potential, electrical resistivity, and polarization resistance were incorporated in the inspection process to address more accurate condition assessment. Recently, new nondestructive and remote-sensing technologies, such as sensors, Ground Penetrating Radar, Infrared Thermography, and images were employed in the inspection process. Using such technologies not only improves the inspection process but also eliminates the need for traffic disruption or total lane closure (Vaghefi et al., 2012). Nevertheless, using these technologies have not fused in the inspection process. The main objective of this research is to review bridge defects and the corresponding inspection technologies including their features, advantages, and limitations.

2. Common Defects of Concrete Bridge Decks

Deterioration of bridge deck is caused due to several factors, which include aging, aggressive environment, excessive loads, accidents, natural disasters and construction deficiencies. These factors lead to different types of bridge deck defects, which have visible or/and measurable signs. However, several defects do not offer visible or/and measurable signs, but their deterioration mechanisms cause another type of defects. For example, freeze and thaw do not provide visible and measurable signs, but its deterioration mechanism causes cracks, scaling and spalling. On the other hand, corrosion shows measurable signs and causes delamination. The common defects in concrete bridge deck are outlined below (Gucunski et al., 2013, Yehia et al., 2007, Omar et al., 2017, Alsharqawi et al., 2018). Detailed description and causes of these defects can be found in (Gucunski et al., 2011, Yehia et al., 2007)

- Corrosion
- Delamination
- Cracks
- Voids
- Debonding of rebars
- Carbonation
- Patching
- Creep
- Degradation of concrete strength
- Alkali-silica reaction
- Delayed ettringite formation
- Shrinkage
- Chloride concertation
- Living organisms activity
- Chemical attack
- Freeze and thaw
- Crystallization
- Expansion joints problems
- Overlay debonding
- Honeycombing
- Scaling
- Spalling
- Crumbling
- Abrasion
- Popouts
- Holes

3. Bridge Deck Inspection Techniques

Inspection process aims to ensure the condition level of the inspected element and to determine the required maintenance strategy. Inspection can be conducted in different ways; visually and/or using one or more nondestructive technologies. The different approaches and technologies that are used in the inspection are shown in Figure 1. Figure 1 categorizes nondestructive technologies into six groups: acoustic, electro-chemical, remote-sensing, electro-magnetic, thermal, and image-based. A brief description and the capabilities of these approaches and technologies are explained in the next subsections. Moreover, Table 1 summarizes the capabilities of each technique to detect different defects. As shown in Table 1, there are some similarities in the functionality of some techniques. For examples, cracks can be detected using visual inspection, impact echo, ultrasonic pulse echo, infrared thermography, and image-based techniques. Nevertheless, there are significant differences in the defect detection capabilities of different techniques. For example, half-cell potential can only detect corrosion, GPR can detect corrosion and delamination, and infrared thermography can detect delamination, cracks, voids, overlay debonding, scaling and spalling.

3.1 Visual Inspection (VI)

Visual inspection plays the dominant role in the inspection process in Bridge Management Systems. In this technique, different bridge components are visual monitoring by experienced inspector. The inspector usually uses simple tools in defects investigation such as measuring tape, marker, chalk and flashlight. After inspection, the inspector reports his evaluation of the current condition of bridge components and determines the need to investigate certain components with nondestructive techniques and the time for the next inspection. Visual inspection is often conducted within 24-month interval except if there is a need to conduct an emergency inspection to evaluate failure of one of bridge components (Omar and Nehdi, 2018).

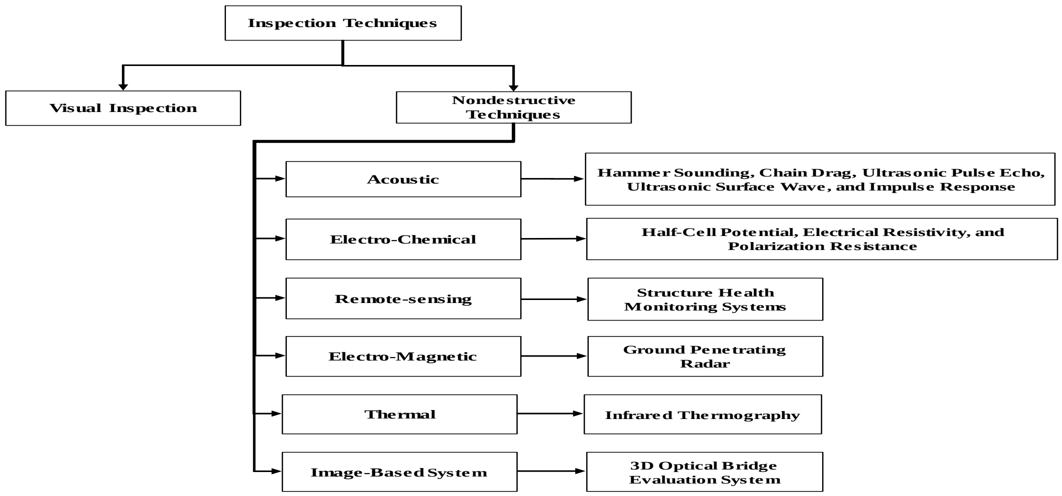


Figure 1: Inspection approaches and technologies

Table 1: Defects-technologies matrix

Defect Technology	**VI**	**CD**	**HS**	**IE**	**UPE**	**HCP**	**ER**	**PE**	**GPR**	**IRT**	**Image-Base technologies**
Delamination		Y*	Y*	Y	Y				Y	Y**	
Cracks	Y			Y	Y					Y	Y
Voids				Y	Y					Y**	
Honeycombing	Y***			Y	Y						Y***
Overlay debonding				Y						Y	
Degradation of concrete strength					Y						
Debonding of reinforcement bars					Y						
Corrosion						Y	Y	Y	Y		
Scaling	Y									Y	Y
Spalling	Y									Y	Y
Abrasion	Y										Y
Expansion joints problems	Y										Y

VI=Visual Inspection, CD=Chain Drag, HS=Hammer Sounding, IE=Impact Echo, UPE=Ultrasonic Pulse Echo, HCP=Half-Cell Potential, ER=Electrical Resistivity, PE=Polarization Resistance, GPR=Ground Penetrating Radar, and IRT=Infrared Thermography.
*Can detect late stages of delamination
**Can detect near surface delaminated areas and voids
***Can detect surface signs of honeycombing

Despite the simplicity of visual inspection, it suffers from three major shortcomings, that make visual inspection an inefficient technique to measure the current condition of bridge elements. First, the visual inspection process is a time-consuming and the process duration extremely changes according to the size of the bridge and number of flaws in the bridge system. Second, the condition rating of the bridge component is evaluating according to the experience of inspector. Hence, the inspector should have sufficient technical knowledge and experience to be able to conduct accurate assessment. Finally, visual inspection can only identify visible defects such as spalling, patching, wear, surface cracks and holes (Huston et al., 2007). Accordingly, internal defects such as delamination, corrosion, and voids cannot be identified using visual inspection (Agdas et al., 2016).

3.2 Acoustic Techniques

Hammer Sounding (HS) and Chain Drag (CD) are usually used as complementary tools to visual inspection, as surface flaws such as spalling, patching, wear, surface cracks and holes are detected using visual monitoring and the hammer and the chain drag are used to detect delaminated areas. The mechanism of the hammer sounding and chain drag depends on shocking the surface of concrete with a hammer or metal chains and the inspector listens to the generated sound. Delaminated areas cause a dull sound when concrete surface is struck while solid pinging sound refers to sound concrete (Nehdi and Omar, 2016).

Impact Echo (IE) is used to detect delamination, cracks, voids, honeycombing, overlay debonding and thickness of bridge deck (Omar and Nehdi, 2018, Yehia et al., 2007). In this technique, the inspected object is struck by a metal ball introducing a stress wave. When this wave reaches an external (i.e. object boundaries) or internal flaws, the wave will be reflected and a receiving transducer which is placed near the concrete surface is used to measure this reflected wave. The type of concrete flaws can be detected by analyzing the arrival time and the amplitude of the reflected wave.

Ultrasonic Pulse Echo (UPE) is used to detect delamination, cracks, voids, honeycombing, homogeneity and strength of concrete, debonding of reinforcement bars and thickness of bridge deck (Omar and Nehdi, 2018, Yehia et al., 2007). Transmitter probes in the ultrasonic transducer introduce high amplitude pulses through the inspected object. When pulses interface with a defect, part of these pulses is reflected back to the surface. Receiver probes in the same transducer receive the reflected pulses. The arrival time and the velocity of the reflected ultrasonic waves provide a useful information about the existing flaws, as defected concrete has lower velocity than sound concrete.

3.3 Electro-Chemical Techniques

Half Cell Potential (HCP) is used to identify corrosion status in reinforced concrete (i.e. active or passive). The device measures the potential voltage difference between the reinforcement bars embedded in concrete and standard reference electrode using a voltmeter. On the other hand, Electrical Resistivity (ER) test identifies the severity degree of corrosive environment around the steel bars. This can be done through measuring electrical resistivity of concrete, as the electrical resistivity of fully saturated concrete ranges between 100 to 1000 Ω.m, while the electrical resistivity of dried concrete is higher than 10^6 Ω.m (Gucunski et al., 2013). The amount of water and chloride in concrete represents the main factors affect the electrical resistivity of concrete and describe its corrosive environment.

Polarization Resistance (PR) test is used to identify corrosion rate of steel reinforcement embedded in concrete. In this technique, the concrete surface is exposed to a short-time anodic current pulse which consequently polarizes the reinforcement anodically. Measurement of electrochemical potential is conducted to detect the change of the present current of concrete. Corroded reinforcement possesses an active current which will not be greatly affected by the applied current. On the other hand, noncorroding reinforcement possesses no current, so it has a high resistance to the applied current which make a significant change in the measurement.

3.4 Remote-Sensing Techniques

Complex and mega civil structures are often monitored using Structural Health Monitoring (SHM) systems. SHM systems assess the condition of a structure based on combination of field measurements, modeling the structure using collected data, and analysis (Agdas et al., 2016). Multiple sensor types embedded in the structure are usually used to collect various measurements associated with loads and environmental conditions (i.e. deformation, creep, shrinkage, corrosion, etc.). The captured data is used in modelling the structure and analyzing the structural response to determine the current deterioration, capacity and service life (Omar and Nehdi, 2016). The functionality of SHM system depends on the types and number of sensors embedded in the structural (Agdas et al., 2016). There are various types of SHM sensing technologies that can be combined to measure different physical aspects. Table 2 shows the different types of sensing technologies and their functionalities.

Two systems of sensors are commercially available: wired and wireless sensors. Wired sensors send the collected measurements to data acquisition source through cables. Installing components of these systems is the main implementation and cost obstacles for wired-based systems (Agdas et al., 2016), especially in large and complex structures. Recently, many types of wireless sensors were developed to tackle the installation problems of cabled system. The new sensors are easier in installation and cost-effective alternatives in large and complex structures.

Table 2: Different types of sensing technologies and their functionalities

Sensor type	**Functionality**
Strain gauge	Reinforcement strain measurements
Accelerometer	Vibration monitoring
Anemometer	Wind velocity and direction
Tiltmeter	Pier settlement detection
Thermometer	Temperature measurements
Sonar	Scour detection
Reference electrodes	Corrosion monitoring
Robotic total station	Three dimensions coordinates
GPS, Radar sensors, video and 3D laser scanner	Displacement measurements
Fiber-optical sensors	Strain, temperature and vibration

Despite the recent development in sensing technologies, SHM systems suffer from three main challenges which are outlined below (Agdas et al., 2016):

- System Complexity: Multifunctional SHM requires installing a large number of sensors and developing data-processing algorithms, automated decision-making tool, and alert systems.
- Maintenance: Hardware and software failures in SHM systems will influence their functionality. Therefore, a routine maintenance is required to guarantee the continuity of the operation.
- Liability: To sustain long-term operation of the system, an agent should be responsible for operating the SHM systems.

3.5 Electro-Magnetic Techniques

Ground Penetration Radar (GPR) is usually used to determine thickness of concrete deck and concrete cover, to locate delaminated areas and reinforcement bars and to identify the corrosive environment (Omar and Nehdi, 2018). There are two types of GPR: air-launched GPR and ground-coupled GPR. An air-launched GPR provides higher speed inspection with lower resolution than ground-coupled GPR (Varnavina et al., 2015). The main components of GPR are antenna, control unit and batteries. Choosing the frequency of the antenna is a very important aspect that is determined based on the scope of the inspection, as high frequency antenna provides higher resolution but lower depth of penetration and vice versa. For concrete applications, one or more high frequency antenna (i.e. greater than 900MHz) are usually used (Varnavina et al., 2015).

The main concept of GPR relies on the sensitivity of electromagnetic waves to the dielectric properties of different materials (Dinh et al., 2015), as GPR antenna transmits electromagnetic waves through the inspected object. When these waves face different dielectric properties of the materials (i.e. reinforcement bars), part of the waves will be reflected. The antenna will receive the reflected waves and will send it to the control unit for processing and displaying. The strong reflections indicate higher change in dielectric properties which is mainly caused due to the existence of different materials inside concrete. Patterns and amplitudes of the reflected electromagnetic waves provide very useful information to detect corrosion and delaminated areas.

3.6 Thermal Techniques

Infrared Thermography (IRT) technique can detect cracks, spalling, scaling, and near surface voids and delamination (Omar and Nehdi, 2018, Yehia et al., 2007). This technique relies on three principles. First, all objects that have a temperature greater than zero Celsius emits a radiant energy. Second, all objects emit a certain amount of radiation depending on their temperature. Last, heat disruption inside the inspected object is caused by defects exist in the surface and subsurface of the object, which influence the amount of radiation emitted from the inspected object. Accordingly, in the concrete bridge deck, the concrete surface above defected areas are heated and cooled faster than those over solid concrete. IRT measures the intensity of surface radiation and recording the surface temperature differences. Areas over delaminated areas appear as hot spots when the test is conducted during daytime and cold spot during nighttime (Nehdi and Omar, 2016).

3.7 Image-Based Techniques

3D Optical Bridge Evaluation System was developed based on the photogrammetry science. This technique uses a camera to take photos for the same object from different angles and with at least 60% overlapping. These photos are used to build 3D model of the inspected object to extract information about area of spalling (Vaghefi et al., 2015). On the other hand, 2D images can also be used to detect concrete surface cracks and spall areas (Matsumoto et al., 2012). Several automated algorithms were developed to automatic detect crack width and length (Mohan and Poobal, 2018, Matsumoto et al., 2012). The camera that used to capture this images can be mounted on car or on unmanned aerial vehicles (UAVs) to provide faster mean in collecting data (Hiasa et al., 2018).

4. Evaluating Nondestructive Technologies

In the light of the abovementioned review, inspecting a specific defect can be done using different technologies. Nevertheless, each technology can detect the same defect with different degree of accuracy (Omar and Nehdi, 2016). Moreover, none of these techniques can detect all types of defects. Consequently, to perform a comprehensive inspection, multi-device systems that combine two or more technologies should be adopted. The components of such systems should be optimized to reduce total cost and improve their capabilities. In order to optimize the system components, a deep investigation in the capabilities, features, advantages, and limitations of each technology is needed.

In this regard, several studies investigated the advantages and limitations of nondestructive technologies (Gucunski et al., 2013, Yehia et al., 2007, Omar et al., 2017). Many factors were considered to count these aspects such as simplicity, cost, accuracy, complexity of data processing, analyzing, and interpretation, barriers to conduct the test, etc. Table 3 summarizes the advantages and limitations of nondestructive technologies. On the other hand, some studies compared the capabilities of different technologies to detect specific defects (Agdas et al., 2016, Yehia et al., 2007). Nevertheless, few studies conducted a comprehensive evaluation study to rank different technologies.

Table 3: Advantages and limitations of different types of nondestructive technologies

Technique	Advantages	Limitations
Chain Drag (CD)	• Low cost • Simple and Portable • One surface for the inspected object is needed to conduct the test	• Cannot detect early stage of delamination • Labour intensive and time consuming to investigate large areas • Can used only in the upper surface of bridge deck • Need to close the investigated lane against traffic • Traffic noise influence the results. • Heavily depend on the inspector experience
Hammer Sounding (HS)	• Low cost • Can be used to inspect upper and lower surface of bridge deck. • Simple and Portable • One surface for the inspected object is needed to conduct the test	• Cannot detect early stage of delamination • Labour intensive and time consuming to investigate large areas • Need to close the investigated lane against traffic • Traffic noise influence the results • Heavily depend on the inspector experience
Impact Echo (IE)	• High accuracy • One surface for the inspected object is needed to conduct the test	• In the presence of asphalt overlays, defects detection is possible only when the asphalt temperature is low. • The element boundary interference problem • The impact duration highly influences the results • Conducting the test and interpreting the results require an experienced operator and analyzer. • Labour intensive and time consuming to investigate large areas • Need to close the investigated lane against traffic
Ultrasonic Pulse Echo (UPE)	• Real time technique. • Simple and portable. • Low cost • Easy to interpret the results. • One surface for the inspected object is needed to conduct the test	• Does not provide information about the shape and size of the flaws • Labour intensive and time consuming to investigate large areas • Need to close the investigated lane against traffic • Require very close spacing between test point. • Large aggregate significantly effects the results
Half Cell Potential (HCP)	• Lightweight and portable equipment • Accurate to detect active corrosion. • Simple and Portable	• Cannot be used in the presence of asphalt overlays • Results affected by moisture content of concrete, concrete resistivity and cover thickness • The effect of concrete cover thickness has not yet been investigated • Cannot provide information about corrosion rate • Need to close the investigated lane against traffic
Electrical Resistivity (ER)	• Simple and Portable • Data processing is simple and easy • One surface for the inspected object is needed to conduct the test	• Interpretation of the results is more challenging • Need to close the investigated lane against traffic
Polarization Resistance (PR)	• Simple and Portable • One surface for the inspected object is needed to conduct the test	• No standards for interpretation of the results • Need to close the investigated lane against traffic
Ground Penetration Radar (GPR)	• Can be used with the existence of overlays • Low traffic interruption in case of using air-launched type. • One surface for the inspected object is needed to conduct the test	• Does not provide information about corrosion rate or cross section loss of rebars • Interpretation of the results is complex • Interpretation of the results sometimes requires destructive testing • Extremely Cold weather and deicing salt negatively influence the accuracy of the results
Infrared Thermography (IRT)	• Simple and Portable and can be mounted on drones • Easy to interpret the results • Low traffic interruption	• Does not provide information about flaw depth • Sensitive to environment condition • Can detect subsurface defects up to two inches under the surface
Image-Based Techniques	• Low cost • Simple and Portable and can be mounted on drones	• Does not use to identify subsurface defects • Image processing require an experienced analyzer

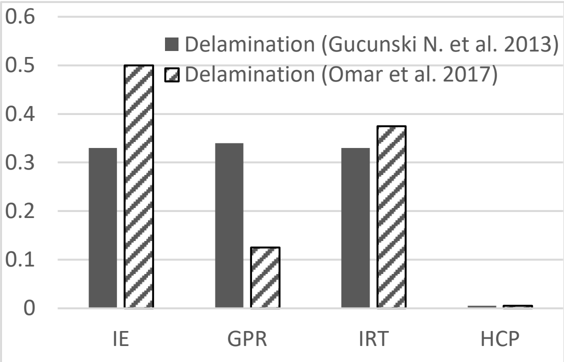
Conducting a comprehensive evaluation study should consider many aspects such as accuracy, cost, speed, precision, simplicity and functionality of different technologies. This study can be done according to one of the following strategies: 1) collecting quantitative data based on laboratory and field tests; 2) collecting qualitative data based on response of engineers and NDT experts (Omar et al., 2017). In this regards, Gucunski et al. (2013) conducted a quantitative study to evaluate the performance of nine technologies (i.e. impact echo, ultrasonic surface wave, GPR, half-cell potential, polarization resistance, electrical resistivity, infrared thermography, hammer sounding, and chain drag). The study considered six performance parameters to evaluate these technologies. These parameters include functionality, accuracy, precision, ease of use, speed and cost. Field testing was conducting to measure the aforementioned parameters except accuracy aspect, which was investigated using laboratory testing. Each parameter was investigated based on several criteria as shown in Table 4.

Table 4: Criteria to measure the performance parameters for different technologies

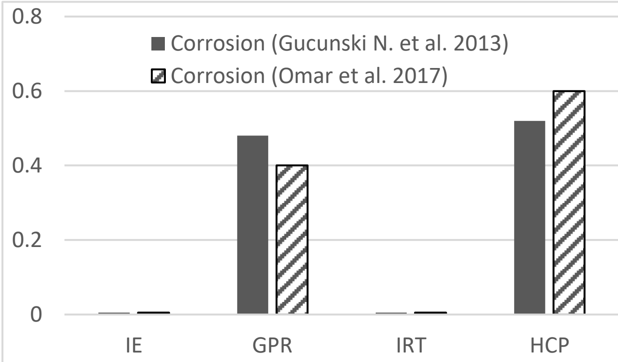
Parameter	**Criteria (Gucunski et al., 2013)**	**Criteria (Omar et al., 2017)**
Functionality	• Delamination • Corrosion • Vertical Crack • Concrete degradation	• Delamination • Corrosion • Vertical Crack
Accuracy	• Detectability extent • Detectability threshold • Evaluation of severity of deterioration	• Extent and severity of delamination • Crack depth and width • Presence of active corrosion
Precision	• Repeatability	Not considered
Ease of use	• Expert level needed in data collection • Analysis and interpretation	• Experiment and Traffic Effect • Experience of operator and analyzer
Speed	• Required time for data collection and analysis • Potential for automation	• Required time for data collection, analysis and interpretation. • Potential for automation
Cost	• Cost of data collection, analysis and interpretation • Cost of equipment, supplies, maintenance • Cost of traffic interruption	• Cost of data collection, analysis and interpretation • Cost of equipment

On the other hand, Omar et al. (2017) adopted the qualitative approach to collect the evaluation data. They focused on using five technologies (i.e. impact echo, ultrasonic pulse echo, GPR, half-cell potential, and infrared thermography) and five performance parameters to evaluate these technologies (Table 1). A survey questionnaire was designed. Bridge experts from Canadian and U.S. transportation agencies, NDT consultants and researchers were targeted to conduct this survey.

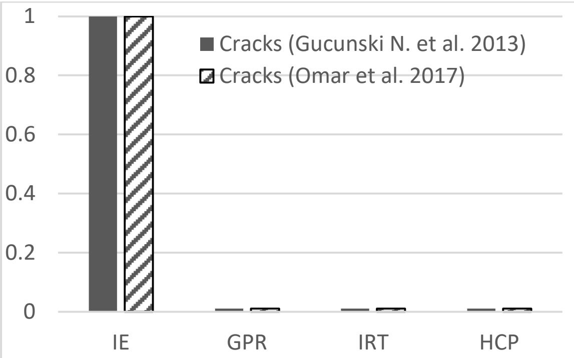
Figure 2 shows a comparison between the results of the two studies (Gucunski et al., 2013, Omar et al., 2017). The comparison considered the abovementioned parameters (Table 1) to rank four technologies: IE, GPR, IRT, and HCP. Four aspects were considered in ranking: delamination detection, corrosion detection, vertical cracks detection, and the overall grading. Regarding delamination detection parameter (Figure 2.a), close grades were assigned to GPR, IE, and IRT with a ranking priority to GPR (Gucunski et al., 2013). These findings are in contradiction with the results of Omar et al. (2017), as their results indicate big differences between the grades of those technologies, moreover, IE was ranked first. Turning to the corrosion grading results (Figure 2.b), both approaches show compatibility in ranking HCP as the highest technique to detect corrosion and GPR was ranked second. Similarly, both approaches approved that IE is the best technology to detect vertical cracks (Figure 2.c). Finally, the overall grading results showed incompatibility of both approaches (Figure 2.d), as Gucunski et al. (2013) recommended GPR as the highest overall grade with a big difference from other technologies, while Omar et al. (2017) recommended IE rather than GPR with a little difference in the overall grade from HCP and GPR.



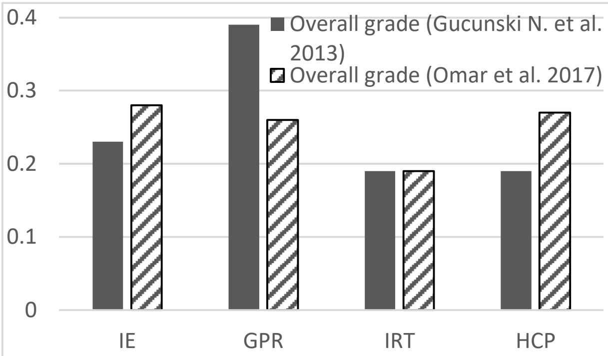
a) Delamination detection grading



b) Corrosion detection grading



c) Vertical Cracks detection grading



d) Overall grading

Figure 2: Ranking of different technology according to a) Delamination detection, b) Corrosion detection, c) Vertical cracks detection ranking and d) Overall grading

5. Conclusion

Inspection is a vital process to provide decision makers with the needed information to sustain long-term operation of bridge system, to conduct the appropriate intervention on time, and to save people lives and money. Several nondestructive technologies that have been developed based on different concepts were effectively employed in the inspection process to precisely determine the current condition of the concrete bridge deck. Each technology can detect one or more defect with different degree of accuracy. However, there is no comprehensive tool that can be used to detect all types of defects.

Promising benefits of nondestructive technologies preside concerns to develop multi-technology systems. In these systems, two or more nondestructive technologies are combined to generate a comprehensive tool that can detect all prospective defects. The most important challenge in designing such systems is to optimize the components of these systems to maintain high quality inspection with minimum possible cost. In this regard, several studies compared the capabilities of each technology based on different factors. The purpose of these studies is to provide a grading scales to rank different technologies based on different parameters. Two studies that were conducted based on different concepts (i.e. quantitative and qualitative data collection) were compared. The results show compatibility of each approach in ranking half-cell potential and impact echo as the highest detection tools to detect corrosion and cracks, respectively. However, quantitative approach recommended GPR as the highest detection tool in detecting delaminated areas and in the overall grading. This is not compatible with the qualitative approach, which recommended impact echo rather than GPR. Considering the findings of this comparison and other aspects (i.e. some technologies and parameters were ignored in the two studies) reflects a need for further research in this area.

6. References

AGDAS, D., RICE, J. A., MARTINEZ, J. R. & LASA, I. R. 2016. Comparison of Visual Inspection and Structural-Health Monitoring As Bridge Condition Assessment Methods. *J. of Performance of Constructed Facilities,* 30**:** 04015049.

ALSHARQAWI, M., ZAYED, T. & ABU DABOUS, S. 2018. Integrated condition rating and forecasting method for bridge decks using Visual Inspection and Ground Penetrating Radar. *Automation in Construction,* 89**:** 135-145.

DINH, K., ZAYED, T., ROMERO, F. & TARUSSOV, A. 2015. Method for Analyzing Time-Series GPR Data of Concrete Bridge Decks. *J. of Bridge Engineering,* 20**,** 04014086.

GUCUNSKI, N., IMANI, A., ROMERO, F., NAZARIAN, S., YUAN, D., WIGGENHAUSER, H., SHOKOUHI, P., TAFFE, A. & KUTRUBES, D. 2013. Nondestructive Testing to Identify Concrete Bridge Deck Deterioration. *92nd Annual Meeting, Transportation Research Board, Washington, DC*.

GUCUNSKI, N., ROMERO, F., KRUSCHWITZ, S., FELDMANN, R. & PARVARDEH, H. 2011. Comprehensive bridge deck deterioration mapping of nine bridges by nondestructive evaluation technologies. *Iowa Highway Research Board (IHRB Project SPR-NDEB(90)--8H-00)*.

HIASA, S., KARAASLAN, E., SHATTENKIRK, W., MILDNER, C. & CATBAS, F. N. 2018. Bridge Inspection and Condition Assessment Using Image-Based Technologies with UAVs. *Structures Congress 2018.*

HUSTON, D., GUCUNSKI, N., MAHER, A., CUI, J., BURNS, D. & JALINOOS, F. 2007. Bridge deck condition assessment with electromagnetic, acoustic and automated methods. *Proceedings of the 6th International Workshop on Structural Health Monitoring, IWSHM 2007.*

MATSUMOTO, M., MITANI, K., SUGIMOTO, M., HASHIMOTO, K. & MILLER, R. 2012. *Innovative Bridge Assessment Methods using Image Processing and Infrared Thermography Technology,* IABSE Congress Report 2012.

MOHAN, A. & POOBAL, S. 2018. Crack detection using image processing: A critical review and analysis. *Alexandria Engineering J.,* 57**:** 787-798.

NEHDI, M. & OMAR, T. 2016. Non-Destructive Testing of Bridge Deck Using Passive Infrared Thermography and Ground Penetrating Radar. Transp. Association of Canada, Annual Meeting.

OMAR, T. & NEHDI, M. 2016. Condition Assessment and Deterioration Prediction Tools for Concrete Bridges: A New Look. *Annual Conference of the Canadian Society of Civil Engineering.*

OMAR, T. & NEHDI, M. 2018. Condition Assessment of Reinforced Concrete Bridges: Current Practice and Research Challenges. *Infrastructures,* 3**:** 36.

OMAR, T., NEHDI, M. L. & ZAYED, T. 2017. Performance of NDT Techniques in Appraising Condition of Reinforced Concrete Bridge Decks. *J. of Performance of Constructed Facilities,* 31.

VAGHEFI, K., AHLBORN, T. M., HARRIS, D. K. & BROOKS, C. N. 2015. Combined Imaging Technologies for Concrete Bridge Deck Condition Assessment. *J. of Perf. of Constructed Facilities,* 29**:** 04014102.

VAGHEFI, K., OATS, R. C., HARRIS, D. K., AHLBORN, T. M., BROOKS, C. N., ENDSLEY, K. A., ROUSSI, C., SHUCHMAN, R., BURNS, J. W. & DOBSON, R. 2012. Evaluation of Commercially Available Remote Sensors for Highway Bridge Condition Assessment. *J. of Bridge Engineering,* 17**:** 886-895.

VARNAVINA, A. V., KHAMZIN, A. K., TORGASHOV, E. V., SNEED, L. H., GOODWIN, B. T. & ANDERSON, N. L. 2015. Data acquisition and processing parameters for concrete bridge deck condition assessment using ground-coupled ground penetrating radar. *J. of Applied Geophysics,* 114**:** 123-133.

YEHIA, S., ABUDAYYEH, O., NABULSI, S. & ABDELQADER, I. 2007. Detection of common defects in concrete bridge decks using nondestructive evaluation techniques. *J. of Bridge Engineering,* 12**:** 215-225.