Comprehensive Inspection System for Concrete Bridge Deck Application: Current Situation and Future Needs

By

Sherif Abdelkhalek[1] and Tarek Zayed[2]

ABSTRACT

Concrete bridge decks are the vital parts that provide the driving surface to the bridge users. Partial or complete failure of this part has a significant impact on the overall performance of the bridge and consequently on the subsequent highway network(s). In this regard, periodical inspections are typically conducted to ensure the integrity of bridges and to identify the required maintenance, rehabilitation, and replacement work. Nevertheless, current practices in inspection (i.e. visual inspection) are time-consuming and suffer from several limitations, such as subjectivity and uncertainty. In addition, visual inspection provides limited defect detection capabilities. Therefore, non-destructive technologies, such as impact echo, ultrasonic surface wave, half-cell potential, ground penetrating radar, infrared thermography, and image-based techniques, were incorporated in the inspection process to tackle such limitations. However, none of these technologies can identify all types of defects, which reveals the critical need for a comprehensive inspection system. Accordingly, several studies have incorporated multi-technology systems in the inspection process to allow more defect detection capabilities and to ensure successful inspection outcomes. Previous studies have also investigated the performance criteria of different non-destructive technologies, which provide beneficial information to choose the most effective techniques for inspection purposes. The present research aims at assessing the capabilities of different non-destructive technologies, providing an overview of the developed multi-technology systems and reviewing the main criteria to measure the performance of non-destructive technologies. The review provides insight into the recent developments in the inspection process, which helps in identifying the future needs in this field.

Keywords: Concrete bridge deck; Inspection; Non-destructive technologies.

[1] PhD student, Department of Building and Real Estate, The Hong Kong Polytechnic University, (corresponding author) Email: sherif.abdelkhalek@connect.polyu.hk)

[2] Professor, Department of Building and Real Estate, The Hong Kong Polytechnic University, Email: tarek.zayed@polyu.edu.hk

INTRODUCTION

Bridges represent the critical links in highways as a partial or complete failure for such links significantly impacts traffic flow, increases the possibility of accidents occurring, and consequently causes economic losses. Thus, it is mandatory to maintain all bridge components in such a way that ensures their standard service level. Accordingly, periodical maintenances are typically conducted during the bridge life to fulfil this purpose. Some maintenance activities, such as expansion joint cleaning, should be performed frequently as this non-costly and straightforward process plays a significant role in prolonging bridge life. On the other hand, maintenance activities, such as patching and deck replacement, are much more expensive than expansion joint cleaning. Therefore, conducting such maintenance activities depends on the current condition of the bridge deck.

In this regard, periodical inspections are usually conducted to provide the required information to assess the current condition of the bridge elements and to determine the most appropriate maintenance strategy on time. Identifying the most appropriate maintenance strategy on time is a critical step to ensure the integrity of the bridge, to prevent deterioration proliferation, and to avoid unneeded maintenance, rehabilitation, and replacement work. This, in turn, saves money for other mandatory work, and thereby reduces the gap between the cost of the needed maintenance, rehabilitation, and replacement work and the limited budget for this work.

Indeed, the limited budget allows conducting maintenance for severe-condition bridges, while maintenance activities for less risky bridges are usually delayed until a new fund is provided. This, in turn, proliferates the deterioration in these bridges, increases the needed maintenance cost, and consequently raises the required budget in the future. As an example, in the USA, a recent federal estimate puts the backlog of rehabilitation projects for the nation's bridges at $123 billion (American Society of Civil Engineers, 2017). A bridge deck is one of the key components in the bridge system that has significant implications on the life cycle cost of the bridge as maintenance, rehabilitation, and replacement of the bridge deck cost between 50 to 80 percent of the overall expenditures on bridges (Gucunski et al., 2013). Thus, optimizing the maintenance, rehabilitation, and replacement work for the bridge deck can significantly reduce the overall expenditures on bridges.

Unfortunately, maintaining the bridge deck and other components within the standard service level is a very complicated job due to several reasons. As mentioned above, the limited budget represents a core obstacle to implement all needed maintenance, rehabilitation, and replacement work. Furthermore, the large number of bridges that need intensive monitoring (i.e. inspection) is considered another challenge in this situation. For example, in the USA, there are 614,387 bridges, 39% of these bridges are more than 50 years old, 15% are between the ages of 40 and 49, and 9.1% of these bridges were structurally deficient in 2016 (American Society of Civil Engineers, 2017). These statistics reflect the current situation for only bridges over 20 feet in length as the National Bridge Inventory (NBI) does not count bridges less than 20 feet in length (Federal Highway Administration, 2012). Nevertheless, small bridges also need regular inspection and maintenance as the big bridges, which worsens the current situation.

Due to this large number of bridges, inspection should characterize by two main aspects. The first aspect is the high accuracy level, which reflects a precise image of the bridge deck's condition to determine the most appropriate intervention on time. Second, inspection using the proposed techniques should not consume too much time to increase the opportunity to inspect this large number of bridges within the determined time window. Nevertheless, 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). These techniques are time-consuming and suffer from several limitations, such as subjectivity, uncertainty, and inability to detect all subsurface defects. Therefore, non-destructive technologies (NDT), such as impact echo (IE), ultrasonic pulse echo (UPE), ultrasonic surface wave (USW), half-cell potential (HCP), electrical resistivity (ER), and polarization resistance (PR), were incorporated in the inspection process to address more accurate assessment for surface and subsurface defects. Recently, non-destructive technologies, such as ground penetrating radar (GPR), infrared thermography (IRT), and image-based techniques, were employed in the inspection process as well. Using such technologies not only improves the inspection process, but it also improves the inspection speed and eliminates the need for traffic disruption or total lane closure (Vaghefi et al., 2012).

Unfortunately, each inspection technique has specific defect detection capabilities, and it cannot be used individually to detect all types of defects. Therefore, multi-technology systems (i.e. hybrid systems) are typically employed in the inspection process to tackle the above challenge. Several studies have examined the possibility of technologies integrations, and consequently, several hybrid inspection systems were developed (Gucunski et al., 2005, Maser, 2008, Kee et al., 2012, Gucunski et al., 2015, Khan and Bartoli, 2015, Abu Dabous et al., 2017, Omar et al., 2017a, Ahmed et al., 2018, Alsharqawi et al., 2018). To provide a useful guidance in selecting the most effective technologies for inspection purposes, previous studies have tested the performance of different non-destructive technologies according to different criteria (Scott et al., 2003, Yehia et al., 2007, Gucunski et al., 2013, Omar et al., 2017b). The present research aims to provide a review of the capabilities of non-destructive technologies, the developed hybrid systems, and the performance criteria used to evaluate non-destructive technologies. The findings of this review are useful in identifying the current situation and the future needs to develop a comprehensive inspection system.

This paper starts with reviewing the deterioration types in the concrete bridge deck. Then, the current practices in the inspection of the bridge deck and their applications will be highlighted. Next, the recent efforts in developing multi-technology inspection systems will be summarized.

After that, the performance indicators and parameters used in evaluating non-destructive technologies will be discussed. Then, a discussion of the findings and future needs will be provided. Finally, the most important findings of the present research will be summarized.

DETERIORATION OF CONCRETE BRIDGE DECKS

Concrete bridges are exposed to several deterioration factors, which include aging, aggressive environment, excessive loads, accidents, natural disasters, construction deficiencies, and insufficient maintenance. These factors initiate several types of deterioration mechanisms in concrete which impact its integrity and serviceability. Figure 1 categorizes the common deterioration mechanisms in concrete bridge deck into three groups: chemical, physical, and biological (Maksymowicz et al., 2006, Bien et al., 2007). Detailed description and causes of these mechanisms can be found in (Maksymowicz et al., 2006, Bien et al., 2007, Yehia et al., 2007, Gucunski et al., 2013).

Deterioration mechanisms provide surface and subsurface symptoms, which make deterioration diagnosis possible. These symptoms are known as defects. As an example, freeze and thaw cause cracks, scaling, and spalling. Corrosion causes rebar rust, cracks, and delamination. Concrete defects provide visible and/or measurable signs for the deterioration mechanisms, which become clearly visible when the deterioration reaches to a sever stage and hardly detectable in the early stages of deteriorations. Figure 2 categorizes the different kinds of defects into two groups: surface and subsurface defects. The first group includes defects that provide visible signs on the surface of concrete such as cracks, spalling, and abrasion. The second group comprises the defects that are located beneath the surface of concrete, such as rebar corrosion, delamination, and voids. These defects are often deteriorated and extended to the surface.

Concrete is usually deteriorated due to several types of deterioration mechanisms, which have complicated relations among each other. These deterioration mechanisms negatively impact the integrity of concrete and threaten the surrounding environment. For example, shrinkage/expansion of concrete and alkali-silica reaction cause cracks. Cracks represent paths for water and corrosive agent to get inside concrete and reach to reinforcements (Prasanna et al., 2016). Corrosion causes delamination, which deteriorates and causes spalling. Spalling exposes the reinforcements to the environment leading to accelerating the corrosion process. In addition, spalled concrete threatens passing people and vehicles underneath the bridge (Washer et al., 2010).

COMMON PRACTICES IN BRIDGE DECK INSPECTION

The inspection process is concerned with identifying the presence of defects and their severity in the inspected element. Inspection can be conducted using different techniques; visually and/or using non-destructive technologies. The different approaches and technologies that are used in the inspection are shown in Figure 3. Figure 3 categorizes non-destructive technologies into five groups: acoustic, electro-chemical, electro-magnetic, thermal, and image-based. The concepts, advantages, and limitations of these techniques can be found in (Yehia et al., 2007, Gucunski et al., 2013, Omar and Nehdi, 2018, Abdelkhalek and Zayed, 2019).

Incorporating non-destructive technologies in the inspection process improves the capabilities to detect a wide range of surface and subsurface defects, accuracy, inspection speed, etc. To reflect the interest of the research community in using different non-destructive technologies, a survey was conducted to find the publications in this area using the Scopus database. Keywords, such as concrete bridge, inspection, GPR, infrared thermography, images, impact echo, ultrasonic surface wave, ultrasonic pulse echo, half-cell potential, electrical resistivity and polarization resistance, were used (Scopus Database 2019). Journal papers, conference papers, and books were considered in the search. The search period was limited from 2000 to

2018. The results were categorised by year of publications, country of publications, and publication type. Figures 4, 5, and 6 show the findings of this survey.

Figure 4 presents the total number of publications, the number of journal papers, the number of conference papers, and the number of published books for each technology. As shown in Figure 4, the total publications in image-based, GPR, and infrared thermography techniques reflect the interests of the research community to develop those technologies and to incorporate them in the inspection process. Figure 5 shows the number of publications per year, which emphasises that the interests in investigating these three technologies have been increased since 2008. On the other hand, Figure 6 displays the contributions of different countries to the literature. The findings show that the USA is the leading country in investigating the capabilities and limitations of all non-destructive technologies. For example, researchers in the USA published 43 publications out of 93, 35 publications out of 64, 53 publications out of 156 in investigating GPR, infrared thermography, and image-based techniques, respectively. Indeed, the contribution of the USA to the literature ranges from 34% to 70 % of the total publications in different technologies.

APPLICATIONS OF NON-DESTRUCTION TECHNOLOGIES IN BRIDGE DECK INSPECTION

The capability or functionality of an inspection technique describes the ability to detect a specific type of defect. To accurately identify the defect detection capabilities of different non-destructive techniques, a review was conducted based on two types of studies. The first type includes studies that were conducted in the laboratory using specimens with prefabricated artificial defects (Yehia et al., 2007, Washer et al., 2010, Azari et al., 2014, Gucunski et al., 2014, Hiasa et al., 2018, Lin et al., 2018). The second type includes studies that investigated the capabilities of non-destructive technologies based on field test, and the results were verified using core test method (Scott et al., 2003, Vaghefi et al., 2012, Oh et al., 2013). The findings of this review were summarised in Table 1.

As shown in Table 1, there are some similarities in defect detection capabilities of some technologies. For example, impact echo, ultrasonic surface wave and infrared thermography can be used to detect delamination. Nevertheless, each technique can detect the same defect with different degrees of accuracy (e.g., infrared thermography can effectively detect surface delamination). On the other hand, the number of defects that each technology can detect is extremely different from one technology to another. For instance, half-cell potential can only detect corrosion. GPR can detect corrosion, delamination, voids and honeycombing. Infrared thermography can detect delamination, cracks, voids, overlay debonding, scaling and spalling.

The findings in Table 1 show that some studies have provided more specific features in investigating the defect detection capabilities of different technologies (Lin et al., 2018, Sultan and Washer, 2018a). For example, delamination detection capability can be classified into capability to detect surface delamination, capability to detect deep delamination and capability to detect delamination induced due to corrosion. Some technologies can detect all types of delamination, such as impact echo, while others can only identify one type of delamination (e.g., GPR can effectively detect delamination induced due to corrosion). In fact, providing more details about each defect addresses a more accurate assessment for defect detection capabilities of different non-destructive technologies.

In an interesting study conducted by Lin et al. (2018), the defect detection capabilities of nine non-destructive technologies were investigated using laboratory specimens with artificial defects. The experiment was conducted in two stages. In the first stage, the samples were tested without an overlay layer, while in the second stage, these specimens were covered by seven types of overlays: epoxy, latex modified concrete, silica fume modified concrete, polyester polymer, asphalt with a liquid membrane, asphalt with a sheet membrane, and asphalt without a membrane. In each specimen, the overlay layer was constructed in a way that makes half of the overlay layer bonded, while the other half unbonded. Each defect type was constructed in both bonded and unbonded halves. The findings of this study were categorized into five cases (Table 1): without overlay, with bonded non-asphalt overlay, with unbonded non-asphalt overlay, with bonded asphalt overlay, and with unbonded asphalt overlay.

The findings of this study demonstrated the defect detection capabilities of the nine non-destructive technologies under different types of overlay layers. As listed in Table 1, GPR demonstrated consistent defect detection capabilities regardless of the type of overlay and the presence of the overlay layer or not. IRT can detect surface delamination in specimens without overlay and with bonded non-asphalt overlay. The performance of IE, USW, UT and HCP in the specimens without overlay and with bonded non-asphalt overlays is almost the same. Nevertheless, the capabilities of these technologies are greatly influenced by the presence of asphalt overlay (i.e., they can detect overlay debonding only). On the other hand, ER could not demonstrate any defect detection capabilities in all specimens with overlay layer.

HYBRID INSPECTION SYSTEMS

Non-destructive technologies can be used individually to investigate one or more kinds of defects, or can be combined to allow more defect detection capabilities. Incorporating more than one technology in the inspection process is mandatory for two reasons. First, there is no complementary technology that can detect all types of defects (Table 1). In addition, each technology has its merits and limitations. These, in turn, make incorporating multi-technology systems in the inspection is the typical way to ensure successful inspection outcomes.

In addressing the above challenges, several studies have investigated the integration of non-destructive technologies to provides an effective inspection system (Gucunski et al., 2005, Cheng et al., 2008, Maser, 2008, Choi et al., 2011, Kee et al., 2012, Gucunski et al., 2015, Khan and Bartoli, 2015, Vaghefi et al., 2015, Kim et al., 2016, Li et al., 2016, Abu Dabous et al., 2017, Gucunski et al., 2017, Kim et al., 2017, Omar et al., 2017a, Ahmed et al., 2018, Alsharqawi et al., 2018). Table 2 outlines the details of these studies. For example, the Federal Highway Administration (FHWA) initiated in 2011 a project to automate and to improve the speed of data collection and analysis, and consequently to reduce the inspection cost. Accordingly, a robotic system named RABIT (Robotics Assisted Bridge Inspection Tool) was developed, which utilized several technologies, such as Global Positioning System (GPS), ER, IE, GPR, USW, and two cameras. GPS is used to control the movements of the robot. IE, USW ER, and GPR are used to investigate subsurfaces defects in bridge deck, such as delamination, elastic modulus, corrosion. Optical images captured by the two cameras are used to detect cracks, spalls, previous repairs and other surface anomalies (Gucunski et al., 2015).

Vaghefi et al. (2015) integrated 3D optical bridge evaluation system (3DOBS) and infrared thermography to investigate surface and subsurface defects in the bridge deck. 3DOBS was employed to detect surface defects (i.e. spalling), while IRT was used to investigate subsurface delamination. ArcGIS software was used to develop a multi-layer map to provide the location of spalled and delaminated areas within the bridge deck. Furthermore, the software offers the opportunity to incorporate the results of other technologies, such as GPR and chain drag, in developing multi-layer map.

Kim et al. (2017) employed IE, USW, ER, and images to develop a bridge deck inspection system. In this system, subsurface defects, such as delamination, elastic modulus, and corrosion, were investigated using IE, USW, and ER, respectively, while, images were used to detect surface deterioration, previous repair, and surface wear. Gucunski et al. (2017) deployed IE, GPR, HCP, USW, and ER to detect subsurface flaws in the bridge deck, such as delamination, elastic modulus, and corrosion.

As listed in Table 2, two to five technologies were employed to develop these hybrid systems, and delamination has received considerable attention in developing these systems. Figure 7 shows the frequency of using different technologies in the developed inspection systems in Table 2. Figure 8 provides the frequency of integrating two specific technologies in the same system. As shown in Figure 7, GPR and IE are the most used technologies in the developed inspection systems. Similarly, Figure 8 shows that GPR and IE were used frequently in the same system which emphasises their popularities and capabilities. In general, the integration of non-destructive technologies generates promising systems that can eliminate the limitations of wide-used inspection practices (i.e. visual inspection). This could stimulate a wider acceptance for non-destructive technologies in the inspection applications.

RANKING OF NON-DESTRUCTIVE TECHNOLOGIES

Most developed hybrid systems aim to address specific detection capabilities (Cheng et al., 2008, Khan and Bartoli, 2015, Omar et al., 2017b). However, when a broad perspective is considered, such as the large number of bridges, it is crucial to optimize the components of such systems to reduce total inspection cost, increase inspection speed, improve accuracy, etc. In order to optimize the system components, an in-depth investigation of the capabilities, features, advantages, and limitations of each technology is needed.

In this regard, several studies have investigated the performance of non-destructive technologies (Scott et al., 2003, Rens Kevin et al., 2005, Yehia et al., 2007, Vaghefi et al., 2012, Gucunski et al., 2013, Oh et al., 2013, Azari et al., 2014, Agdas et al., 2016, Hesse et al., 2017, Omar et al., 2017b, Lin et al., 2018, Sultan and Washer, 2018a). Table 3 summarizes the main features of these studies, which include tested techniques, adopted methods to conduct the study, tested element(s), performance indicators, and recommendations of these studies. In these studies, several inspection techniques were evaluated. For example, Azari et al. (2014) investigated the performance of impact echo and ultrasonic surface wave, Scott et al. (2003) examined the performance of chain drag, impact echo, and ground-penetrating radar and Lin et al. (2018) tested the capabilities of sounding, ultrasonic surface waves, impact echo, ultrasonic testing, impulse response, ground-penetrating radar, electrical resistivity, half-cell potential, and infrared thermography.

Two strategies were adopted to investigate the performance of each technology: 1) collecting quantitative data based on laboratory and field tests; 2) collecting qualitative data based on the response of engineers and NDT experts (Omar et al., 2017b). In the laboratory test, different types of artificial defects with varying depths and sizes were built in laboratory specimens to test the performance of non-destructive technologies (Yehia et al., 2007, Gucunski et al., 2013, Azari et al., 2014, Lin et al., 2018). On the other hand, some studies employed field test to evaluate the performance of different technologies and most of them verified their findings using core test method (Scott et al., 2003, Rens Kevin et al., 2005, Oh et al., 2013, Agdas et al., 2016). On the contrary to the quantitative approach, the qualitative approach uses survey questionnaire as a base for the assessment (Hesse et al., 2017, Omar et al., 2017b).

Various indicators to measure the performance of non-destructive technologies, such as simplicity, cost, accuracy, and complexity of data collection, analysis, and interpretation, were considered. As listed in Table 3, Omar et al. (2017b) evaluated different technologies based on five indicators, which include capability, accuracy, speed, cost, ease of use. Various parameters were used to measure the performance indicators of non-destructive technologies (Table 4). These parameters provide more specific aspects to accurately measure the main indicator. Oh et al. (2013) employed ten parameters to assess the performance of different technologies, which include capability of detecting delamination, accuracy, speed, sensitivity to ambient noise and/or environmental conditions, operator experience, portability, traffic disruption, surface preparation, repeatability, and cost.

Gucunski et al. (2013) conducted a comprehensive 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). In this study, six performance indicators were considered to evaluate these technologies, which include functionality, accuracy, precision, ease of use, speed and cost. Seventeen parameters were used to measure these performance indicators. For example, delamination, corrosion, vertical crack, and concrete degradation were used to measure the capability indicator of different technologies. Parameters, such as detectability extent, detectability threshold, and severity of deterioration were used to investigate the accuracy level of non-destructive technologies. The time needed for data collection, analysis and interpretation, and potential for automation were used to measure speed performance indicator. Further details about the parameters considered in the other studies are shown in Table 4.

DISCUSSION AND FUTURE NEEDS

The capabilities of different non-destructive technologies were reviewed and summarized in Table 1. As has been seen, GPR proved more consistent performance in detecting defects in different cases (i.e. without overlay, with bonded non-asphalt overlay, with unbonded non-asphalt overlay, with bonded asphalt overlay, and with unbonded asphalt overlay). To ensure the accuracy of the collected data in Table 1, only two types of studies were considered to identify the defect detection capability of different non-destructive technologies. In the first type, laboratory tests using specimens with prefabricated artificial defects were conducted, while in the second type, field tests were conducted and the findings were verified using core test method. Indeed, incorporating just a small piece of destructive testing, such as core test method, provides accurate information about the situation inside concrete (e.g., the presences of delamination and voids, and depth of the flaws), which adds more confidence in the findings of any inspection.

Investigating the findings of these studies revealed some conflicts in identifying the capabilities of non-destructive technologies to detect different defects. For example, Gucunski et al. (2013) demonstrated the ability of GPR to detect delamination. On the contrary, Sultan and Washer

(2018b) had investigated the capability of GPR to detect delamination, and they concluded that GPR can only detect delamination induced due to corrosion. Furthermore, Yehia et al. (2007) proved the capability of impact echo to detect vertical crack. However, Lin et al. (2018) demonstrated the inability of impact echo to detect vertical crack. This, in turn, reflects the need for further investigation in this area as the capability of non-destructive technologies to detect different kind of defects represents a critical factor in their applications.

Previous studies have demonstrated that incorporating GPR, infrared thermography, and image-based technologies in the inspection process proves many promising benefits, such as accuracy, high inspection speed, and low traffic interruption (Bu et al., 2015, Dinh and Zayed, 2016, Omar et al., 2018, Morgenthal et al., 2019). In addition, image-based technique represents the best alternative for visual inspection technique, which dominates the current inspection practices. These have led the interests of the research community to conduct more research in the applicability of those technologies in the inspection process. Nevertheless, these technologies still suffer from some limitations, which control their applications in the inspection. These limitations are outlined below:

Limitations of ground penetration radar:

- Does not provide information about corrosion rate (Omar and Nehdi, 2018);
- Interpretation of the results is complex (Yehia et al., 2007);
- Interpretation of the results sometimes requires destructive testing (Yehia et al., 2007);
- Extremely cold weather and de-icing salt negatively influence the accuracy of the results (Gucunski et al., 2013);
- There are many factors affect the GPR results, such as variation of pavement thickness and cover thickness, rebar spacing, moisture percentage (i.e. moisture absorbs most of the radar wave), surface properties, and presence of main girders, beams and columns (Dinh et al., 2015, Dinh and Zayed, 2016, Abouhamad et al., 2017); and

- Interpreting GPR data depends on expert judgment on evaluating a specific threshold to differentiate between different conditions of concrete, picking or not picking a certain pattern of attenuation, or assigning a particular pattern of attenuation to a specific condition of concrete, which causes inconsistent results (Abouhamad et al., 2017).

Limitations of infrared thermography:

- Does not provide information about flaw depth (Yehia et al., 2007, Omar and Nehdi, 2018);
- Sensitive to environmental conditions (Yehia et al., 2007, Vaghefi et al., 2015, Omar and Nehdi, 2018);
- Optimal conditions for effective inspection are unknown (Hiasa et al., 2018);
- Defects which are deeper than 3 inches cannot be detected using infrared thermography (Vaghefi et al., 2015, Ellenberg et al., 2016, Prasanna et al., 2016);
- Defect detection errors can be happened due to obstacles such as water, stain, and debris. So, cleaning the concrete surface to remove such obstacles is typically required (Omar et al., 2018); and
- It is difficult to determine the exact size of delamination (Ellenberg et al., 2016).

Limitations of image-based techniques (data collection):

- Cannot detect subsurface defects;
- Strong wind impacts the stability and safety of UAV and the quality of the captured images (Hiasa et al., 2018, Morgenthal et al., 2019);
- Bridge metal railing impacts the GPS of the drone (Hiasa et al., 2018);
- Lighting condition significantly affects the quality of the captured images (Morgenthal et al., 2019);
- Robot or UAV path planning is typically required to ensure coverage of the whole area of the inspected element (Lim et al., 2014); and

- Full coverage for the inspected element, image overlap, and image quality are all needed to efficiently generate high accuracy defect detection (Morgenthal et al., 2019).

Limitations of image-based techniques (data processing):

- Edge or threshold detection algorithm to distinguish defected area and non-defected area is needed (Lim et al., 2014, Prasanna et al., 2016);
- Noisy images, in which there is a slight contrast between the defect and the background, are obstacles to distinguish the defected area (Prasanna et al., 2016). Noises can be caused by shading and blemishes (Mohan and Poobal, 2018);
- Variable Lighting condition significantly impact the quality of images (Bu et al., 2015, Prasanna et al., 2016);
- Randomness in shape and size of defects increase the complexity of defect detection (Mohan and Poobal, 2018, Morgenthal et al., 2019);
- Inhomogeneous surface pattern of concrete and texture cause false detection (Morgenthal et al., 2019);
- Thin cracks are hard to be detected (Morgenthal et al., 2019);
- Deep learning approach needs a huge amount of training images (Morgenthal et al., 2019);
- Randomness in view angle of the camera and the resolution of the images complicate image processing (Bu et al., 2015);
- Uncertainty of the exact position and orientation of the camera and UAV increases the complexity of image processing (Morgenthal et al., 2019);
- Size of the image which determines the processing complexity (Mohan and Poobal, 2018); and

- Coordinate transformation challenges, such as considering different coordinate systems for robot, camera, images, and local and global coordinate systems to map detected defects (Lim et al., 2014).

These limitations play a key role in limiting the wider acceptance of these technologies in the inspection applications. In this regard, several research efforts have been exerted to propose innovative solutions to tackle these limitations (Dinh et al., 2015, Dinh and Zayed, 2016, Ellenberg et al., 2016, Abouhamad et al., 2017, Lovelace, 2018). Eliminating the limitations of these technologies offers the opportunity to build a more robust inspection system that ensures successful inspection outcomes.

A robust inspection system is typically the output of integrating complementary inspection techniques. This integration aims to improve different performance aspects of the generated system. In this regard, evaluating the performance of different non-destructive technologies can accurately demonstrate their characteristics, and thereby can improve the technology selection process to build a comprehensive inspection system. Two approaches were adopted to evaluate different techniques. The first approach depends on collecting qualitative data based on the response of engineers and NDT experts. On the other hand, the second approach relies on collecting quantitative data using two methods. In the first method, laboratory specimens with prefabricated artificial defects were tested to demonstrate the capability of non-destructive technologies, while the second method depends on conducting a field test on one of the existing bridges and verifying the results using core test method. Most studies used only one quantitative method to evaluate different technologies (Scott et al., 2003, Yehia et al., 2007, Azari et al., 2014, Omar et al., 2017b), however, some studies combined the two methods in their evaluations (Gucunski et al., 2013).

These studies evaluated the inspection techniques from different perspectives such as capability, accuracy, ease of use, speed, and cost (Gucunski et al., 2013, Oh et al., 2013, Omar et al., 2017b, Lin et al., 2018). Table 5 summarizes the performance indicators and the parameters used in the evaluation. The findings include six main indicators and 28 parameters. Nevertheless, some aspects have not been considered in the previous studies, such as the availability of standard specifications to conduct the test, the ability to compare the previous test results with the current one, the availability of standard scale to identify the severity of defect, ability to distinguish between defects types, training cost, etc. Therefore, current models should be extended to include these factors to address more reliable evaluation.

Several studies have also investigated the possibility of integrating various technologies in the inspection process (Gucunski et al., 2005, Cheng et al., 2008, Maser, 2008, Choi et al., 2011, Kee et al., 2012, Gucunski et al., 2015, Khan and Bartoli, 2015, Vaghefi et al., 2015, Kim et al., 2016, Li et al., 2016, Abu Dabous et al., 2017, Gucunski et al., 2017, Kim et al., 2017, Omar et al., 2017a, Ahmed et al., 2018, Alsharqawi et al., 2018). However, most of these studies targeted only two objectives: the capability to detect certain types of defects and the accuracy of the system. Practically, other factors should be considered in designing hybrid inspection systems, such as the total inspection cost, the effectiveness of the system under different inspection conditions (e.g., bridge deck with overlay layer) and the overall speed of the system. Considering such factors will positively affect the efficiency of the inspection systems.

In the light of the abovementioned discussion, the future needs to provide an effective inspection system can be summarized in the followings:

1. The capabilities and accuracy of non-destructive technologies represent essential features in the applications of non-destructive technologies in the inspection process. Therefore, these two features need more investigation by identifying the effective

parameters to measure these criteria. After that, laboratory and field tests can be conducted to measure these parameters. This, in turn, will help in accurately addressing the capabilities and accuracy of each technology and eliminating any existing conflict in this matter.

2. Performance Indicators to evaluate different non-destructive technologies should be extended to include all factors that significantly impact the inspection process (e.g., capability, accuracy, cost and speed). Thus, there is a critical need to identify these factors and incorporate them into a comprehensive framework that can accurately evaluate the performance of different inspection techniques.
3. Identifying the component of multi-technology system to investigate a specific bridge network should consider many factors besides the capabilities and accuracy of this system. In this regard, a decision tool should be developed to optimize the component of this system, considering all critical factors.

SUMMARY AND CONCLUSIONS

This study highlighted the most recent interests in the inspection process of the concrete bridge deck. These interests focused on three main directions: assessing the defect detection capabilities of different non-destructive technologies, developing a robust and efficient inspection system and evaluating the performance of non-destructive technologies.

The capabilities of different non-destructive technologies were discussed based on two types of studies. The first one relies on the results obtained from testing laboratory specimens with prefabricated artificial defects, while the second type used core test method to verify the results of field tests to demonstrate the capabilities of different non-destructive technologies. The findings showed that different studies have investigated this issue considering different degree of details, such as considering more details in identifying delamination detecting capabilities (e.g., delamination depth: shallow delamination or deep delamination) and investigating the impact of overlay layer on the performance of non-destructive technologies to detect different defects. Nevertheless, some conflicts were identified in the findings of these studies, such as the capabilities of GPR to detect all types of delamination. These raise the need for further investigation in this area as the defect detecting capabilities of non-destructive technologies represent a key factor in their applications.

Developing a robust and efficient inspection system was fulfilled by integrating two or more non-destructive technologies. The main focuses of the developed system were to address specific defect detection capabilities and/or accuracy. Nevertheless, the scope of this direction needs to be extended to involve other critical factors, such as total inspection cost, the effectiveness of the system for different inspection conditions, the overall speed of the system, traffic interruption, the complexity in implementing specific technologies, etc. Considering such factors will improve the performance of the developed systems.

The most crucial step to address the above challenge is to assess the performance of different technologies to identify their strengthens and weakness. This, in turn, will enhance the technology selection process to offer more effective inspection systems. Several studies have evaluated the inspection techniques from different perspectives such as capability, accuracy, ease of use speed, and cost using two approaches: qualitative and quantitative approaches. Nevertheless, current evaluation models should be extended to include other significant factors to address more reliable evaluation.

DATA AVAILABILITY

No data, models, or code were generated or used during the study.

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Table 1: Defects-technologies matrix

Technolog / Reference	Test type	CD	HS	IE	USW	UT	HCP	ER	PE	GPR	IRT	Image-Base technologies
Yehia et al. (2007)	Laboratory			SD*,SD,DV,VC						SD*,DD*,SV*,DV*	SD*,SV*	
Scott et al. (2003)	Field	DC		DC						DC		
Azari et al. (2014)	Laboratory			SD, DD	SD							
Oh et al. (2013)	Field	SD		SD (Air-coupled IE)							SD	
Gucunski et al. (2014)	Laboratory	D	D	D	D,VC,CQ		C	C	C	D,C	D	
Sultan and Washer (2018b)	Laboratory + Field									DC,CCE		
Vaghefi et al. (2012)	Field	SD*									SD*	SP
Hiasa et al. (2018)	Laboratory											SC
Washer et al. (2010)	Laboratory										SD	
Lin et al. (2018)	Laboratory	**Case 1: Without overlay**										
		SD,SV*	SD,SV*	SD,DD,V,HC	SD,DD,V,HC,VC	SD,DD,V,HC*	ARC	VC,CCE	-	SD,DD,V,HC,CCE	SD,V,VC*	
		Case 2: With non-asphalt overlay (bonded)										
				SD,DD,V,HC	SD,DD,V*,HC*	SD*,DD*,V*,HC*				SD,DD,V,HC,CCE*	SD,V*	
		Case 3: With non-asphalt overlay (unbonded)										
		OD	OD	OD	OD	OD	ARC*	OD*		SD,DD,V,HC,CCE*	OD	
		Case 4: With asphalt overlay (bonded)										
				SD**,DD**,SV**,DV**,HC**						SD,DD,V,HC,CCE	SD*	
		Case 5: With asphalt overlay (unbonded)										
		OD	OD	OD	OD	OD				SD,DD,V,HC,CCE	OD	

Technology: VI=Visual Inspection, CD=Chain Drag, HS=Hammer Sounding, IE=Impact Echo, UT=Ultrasonic, USW=Ultrasonic Surface Wave, HCP=Half-Cell Potential, ER=Electrical Resistivity, PE=Polarization Resistance, GPR=Ground Penetrating Radar, and IRT=Infrared Thermography.

Defect: D=Delamination, DC= Delamination induced due to corrosion, SD=Shallow Delamination, DD=Deep Delamination, V= Voids, SV=Shallow Voids, DV=Deep Voids, HC=Honeycombing, VC=Vertical Cracks, SC=Surface Cracks, C=Corrosion, ARC=Active Rebar Corrosion, CCE=Concrete Corrosion Environment, CQ=Concrete Quality, SP=Spalling and OD=Overlay Debonding.

*The defect cannot be detected in some specimens

**The defect can be detected in specimens without membrane

Table 2: Hybrid systems

Reference	Techniques	Element	Targeted defect
Gucunski et al. (2005)	GPR, IE	Bridge deck	Delamination
Maser (2008)	GPR, IRT	Bridge deck	Overlay debonding and delamination induced due to corrosion.
Cheng et al. (2008)	IRT, IE	Concrete specimens	Voids and honeycombing.
Choi et al. (2011)	GPR, SPA	Bridge joint	Delamination under joint and deboning of joint armor.
Kee et al. (2012)	Air-Coupled IE, IRT	Bridge deck	Delamination
Vaghefi et al. (2015)	3DOBS, IRT	Bridge deck	Spalling and delamination
Gucunski et al. (2015)	RABIT (ER, IE, GPR, USW, images)	Bridge deck	Delamination, elastic modulus, corrosion, cracks, spalls, previous repairs and other surface anomalies
Khan and Bartoli (2015)	IE, IRT	Concrete Slab	Delamination
Li et al. (2016)	2D images, GPR	Pavement	Pothhole
Kim et al. (2016)	IE, GPR, ER	Bridge deck	Delamination, corrosive environment and corrosion rate
Kim et al. (2017)	IE, USW, ER, images	Bridge deck	Delamination, elastic modulus, corrosion, surface deterioration, previous repair, and surface wear.
Gucunski et al. (2017)	IE, GPR, HCP, USW, ER	Bridge deck	Delamination, elastic modulus, and corrosion.
Abu Dabous et al. (2017)	GPR, IRT	Bridge deck	Delamination
Omar et al. (2017a)	VI, IRT, GPR	Bridge deck	Cracks, scaling, spalling, popouts, delamination and corrosion.
Ahmed et al. (2018)	GPR, IE, HCP, ER	Bridge deck	Delamination and corrosion.
Alsharqawi et al. (2018)	VI, GPR	Bridge deck	Cracks, scaling, erosion, corrosion, delamination, spalling, expansion joint problem and popouts

SPA= Seismic Properties Analyzer, 3DOBS= 3D Optical Bridge Evaluation System.

Table 3: Comparative studies of non-destructive technologies

Reference	Techniques	Method of collecting the data	Element	Performance indicators	Recommendation
Scott et al. (2003)	Chain drag, impact echo and GPR.	Field test and verifying the findings with core testing results.	Bridge deck	Capability to detecting corrosion-induced delamination, accuracy, and speed.	Chain drag and IE shows more accuracy in detecting delamination when the inspection is carefully conducted. However, Chain drag is very subjective techniques that needs well-trained inspector, while IE is time-consuming test. The ability of both techniques is reduced to far extend when they are implemented in asphalt-overlaid decks. On the other hand, GPR showed less accurate results but it is faster and easier than other techniques and can work well in asphalt-overlaid decks.
Rens Kevin et al. (2005)	Acoustic emission, electrical methods, impact echo, magnetic methods, radar, radiography, sonic methods, surface hardness methods, infrared thermography, acoustic tomography and ultrasonic.	Field test	Bridge pier	Capability to detect Efflorescence, Cracking, Delamination and spall,	The findings proved the ability of magnetic methods to detect efflorescence, IE, acoustic tomography and ultrasonic to detect cracking and IE, radar, sonic methods, IRT, acoustic tomography and ultrasonic to detect delamination and spall.
				Cost	The inspection cost of using acoustic emission, radar, radiography and IRT is expensive.
Yehia et al. (2007)	Impact echo, GPR and infrared thermography.	Laboratory test using specimens in which artificial defects of various sizes and different depths were built (i.e. cracks, delamination and voids).	Laboratory slab	Capability and accuracy	IE is the most effective approach to detect cracks, delamination and voids, especially for defects located at a depth more than 2 inches. GPR comes in the second place in detecting delamination and voids, especially for defects located at a depth more than 1 inch. IRT can only detect delamination and voids within 2 inches deep.
				Speed	IRT provides high inspection speed, then GPR. On the other hand. IE is a time-consuming test method.

				Surface preparation	IE, IRT and GPR need surface cleaning. Furthermore, IE needs surface chipping if the surface is rough.
				Equipment cost	The order according to equipment cost from the highest to the lowest is GPR, then IRT, then IE.
				Traffic disruption	Air-coupled GPR and IRT cause little traffic disruption, while ground coupled GPR and IE require lane closure.
				Data processing	GPR and IE need data processing. On the other hand, IRT provides real-time inspection results.
Vaghefi et al. (2012)	GPR, Spectra, 3D photogrammetry, electro-optical airborne satellite imagery, optical interferometry, LiDAR, infrared thermography, acoustics, digital image correlation, InSAR and streetview-style photography.	Using literature and professional experience.	Bridge deck	Deck surface capability and accuracy	3D Photogrammetry proved better results to detect surface defects than other technologies.
				Deck subsurface capability and accuracy	GPR and IRT are effective approaches to detect expansion joint defects. Similarly, acoustic to detect delamination, GPR and radar to detect corrosion and chloride ingress.
				Availability of instrument, cost of measurement, pre-collection preparation, complexity of analysis, ease of data collection, stand-off distance, and traffic disruption	Not mentioned for each indicator.
				Overall performance	3D Photogrammetry is the best technique to assess surface defects, while GPR is the best in assessing subsurface defects.
Oh et al. (2013)	Two types of air-coupled impact echo (type A and B), infrared thermography and chain drag.	Field test and verifying the findings with core testing results.	Bridge deck	Capability of detecting delamination and accuracy	Air-coupled IE (prototype A) and IRT have the highest accuracy level.
				Speed	IRT is the fastest technique regarding operation time, while chain drag provide real-time analysis of defects (zero analysis time).
				Sensitivity to ambient noise and/or environmental conditions	IRT is highly sensitive to environment conditions (i.e. wind, temperature, etc.). Chain drag has high sensitivity to the surrounding noise. On the other hand, IE is low sensitive to environment conditions and surrounding noise.
				Operator experience	Chain drag needs low operation experience.
				Portability	IRT and chain drag are more portable than IE.

				Traffic disruption	Chain drag needs more traffic control to conduct the test than IE and IRT.
				Surface preparation	IE and chain drag do not need surface preparation, while IRT needs surface cleaning.
				Repeatability	The result of IE is more consistent than other techniques, while the consistency of the chain drag results are very low.
				Cost	Chain drag is the cheapest tool then IE (prototype A), then IE (prototype B), then IRT. The operating cost for chain drag is more expensive than other techniques, while the operating cost for IRT is low.
				Overall grade	IE type A and IRT were highly graded.
Gucunski et al. (2013)	Impact echo, ultrasonic surface wave, GPR, half-cell potential, polarization resistance, electrical resistivity, infrared thermography, chain drag and hammer sounding.	Using field test (i.e. verified by core testing) and laboratory test. In laboratory test, two kind of specimens were used: concrete slab with built-in defects and part of bridge deck.	Bridge deck	Capability	GPR is the most effective technique to detect delamination, then IE and USW. ER, then HCP, then GPR are the best technologies to detect corrosion. USW is the most efficient technique to detect vertical crack and evaluate concrete degradation.
				Accuracy	IE and USW are the most accurate technique to detect delamination. Likewise, ER and HCP to investigate corrosion and USW to detect vertical cracks and concrete degradation.
				Precision (repeatability)	IE, GPR, and ER provide more consistent results.
				Speed	IRT, then GPR offer high inspection speed than other techniques.
				Ease of use	Chain drag and IRT are the simplest technologies to use, then ER, then HCP.
				Cost	Chain drag and hammer sounding are the most cost-effective inspection approaches, then the electrochemical techniques (i.e. excluding traffic control cost). When traffic control cost is considered, electrochemical techniques, provides the lowest inspection cost, then IRT. On the other hand, Acoustic techniques are the most expensive technologies in the both cases.

				Overall grade	GPR maintained the high grade in the overall ranking, then USW and IE.
Azari et al. (2014)	Impact echo and ultrasonic surface wave.	Laboratory test using specimens in which artificial defects of same sizes and different depths were built.	Laboratory slab	Capability to detect delamination and voids, and accuracy	IE can accurately detect defects at different depths, while USW has limited ability to accurately locate 8 inches deep defects.
Agdas et al. (2016)	Visual inspection and structural health monitoring system	Field test	Bridge girders and piers	Capability	Visual inspection has a good ability to effectively investigate defects in small bridges with no known structural problems. On the other hand, structural health monitoring system is more appropriate to conduct in-depth inspection for large structures.
				Cost	Cost of visual inspection is greatly less than structural health monitoring system. Furthermore, using wireless sensors is more cost-effective than wired sensors in structural health monitoring system.
Omar et al. (2017b)	Impact echo, ultrasonic pulse echo, half-cell potential, GPR and infrared thermography.	Survey questionnaire	Bridge deck	Capability	IE is the best technique to detect delamination, then IRT. UPE, then IE can effectively detect vertical crack. Corrosion can be effectively assessed using HCP and GPR.
				Accuracy	IE and IRT are the most accurate technique to detect delamination. Similarly, IE and UPE to detect cracks. HCP, then GPR to detect corrosion.
				Speed	GPR and IRT provide high data collection rate, while analysing data of HCP and IRT requires very short time.
				Cost	HCP, then IRT provide the lowest inspection cost, while IE and UPE are the most expensive methods.
				Ease of use	IRT, then HCP are the simplest technologies to use and to analyse their results.
				Overall grade	IE is the best non-destructive technology to detect defects in concrete then HCP and GPR.
Hesse et al. (2017)	Cover meters, radar, ultrasonic testing,		Bridge	Bias	Results of most non-destructive approaches are slightly less than the true value.

	visual inspection, half-cell potential, mechanical sounding, rebound hammer and thermal	Survey questionnaire using four-round delphi method		Accuracy	The accuracy of most non-destructive technologies is about 80%, except thermal techniques which has 60% accuracy level. Half-cell potential is the most accurate technique.
				Reliability	Cover meters, ultrasonic testing, and mechanical sounding are the most reliable techniques.
				Cost	Mechanical sounding is the cheapest inspection approach, then visual inspection.
Lin et al. (2018)	Sounding, ultrasonic surface wave, impact echo, ultrasonic testing, impulse response, GPR, electrical resistivity, half-cell potential and infrared thermography.	First, laboratory test was conducted on specimens with prefabricated artificial defects (i.e shallow and deep delamination, honeycombing, vertical crack, void, and corrosion), then these specimens were covered with seven types of overlays. The half of overlay was bonded, and the other half was debonded.	Laboratory slab	Capability	GPR is an effective tool to detect different types of defects in all specimens with and without overlay except overlay debonding defect and active rebar corrosion. However, C-scan should be used besides the condition map to determine delamination, voids, honeycombing. USW and IE are effective techniques to detect overlay debonding in all specimens. In addition, they can detect delamination, voids and honeycombing in all specimens except those covered with asphalt overlays and in the case of presence of overlay debonding. Half-cell potential is an effective tool to investigate active rebar corrosion in all specimens without overlays and some specimens with overlays (i.e. not asphalt-based).
Sultan and Washer (2018a)	Infrared thermography and GPR.	Field test on two concrete bridge decks that having significant deterioration due to corrosion damage and comparing the results using receiver operator characteristics (ROC) analysis	Bridge deck	Accuracy	IRT is more accurate in detecting delaminated areas than GPR.

Table 4: Parameters to measure non-destructive technologies performance

Reference	Capability	Accuracy	Ease of use	Cost	Speed	Others
Scott et al. (2003)	Corrosion-induced delamination.	Chain drag approach was implemented carefully and compared with core testing results. The generated data was considered as a ground truth to check the accuracy of other technologies.	N/A	N/A	Speed of collecting the data	
Rens Kevin et al. (2005)	Efflorescence, Cracking, Delamination and spalling.	N/A	N/A	Not mentioned.	N/A	N/A
Yehia et al. (2007)	Delamination, cracks and voids.	Sensitivity to detect defects of different sizes and depths.	N/A	Equipment cost	Speed of collecting the data	• Surface preparation • Traffic disruption • The need for data processing
Vaghefi et al. (2012)	Deck surface Capability (Expansion joint, cracks, scaling and spalling) Deck subsurface Capability (Expansion joint, delamination, corrosion and chloride ingress).	Defect can be detected within the upper and lower limit of resolution.	• Complexity of analysis and interpretation • Ease of data collection	• Capital cost • Operation cost	• N/A	• Availability of the instrument • Pre-collection preparation • Traffic disruption • Stand-off distance

Oh et al. (2013)	Delamination	Verifying the results with core testing results.	Operator experience	• Capital cost • Operation cost	• Time of operation • Time of analysis	• Sensitivity to ambient noise and/or environmental conditions • Pre-collection preparation • Traffic disruption • Portability (weight and size of the device) • Repeatability
Gucunski et al. (2013)	Delamination, corrosion, vertical crack and concrete degradation.	• Detectability extent • Detectability threshold • Evaluation of severity of deterioration	• Expertise needed for data collection • Expertise needed for data processing and data interpretation • Extent and potential for automation and improvement	• Cost of data collection; • Cost of data analysis and interpretation • Cost of equipment, supplies, and equipment maintenance	• Speed of data collection • Speed of data analysis and interpretation	N/A
Azari et al. (2014)	delamination and voids.	Sensitivity to detect defects at varying depths.	N/A	N/A	N/A	N/A
Agdas et al. (2016)	Vibration, Wind and thermal load assessment, Pier settlement detection, Scour detection, Strain/stress response and surface defects	N/A	N/A	• Equipment cost • Labour cost • Data analysis cost • System maintenance cost • Installing cost • Power cost	N/A	N/A
Omar et al. (2017b)	Delamination, vertical cracks and corrosion	• Extent and severity of delamination • Depth and width of cracks • Presence of active corrosion	• Experience of the operator and analyser • environmental and traffic effect	• Equipment cost • Cost of data collection • Cost of data analysing and interpretation	• Time needed for data collection, analysis and interpretation • potential for automation	N/A

Hesse et al. (2017)	N/A	Three options were offered to the participants to choose among them (i.e. false positive, false negative, and true response). False positive means the device indicates a damage when there is not a damage and so on.	N/A	• Data collection cost • Data analysis cost • Training cost • Monetary cost for equipment	N/A	• Bias • Reliability
Lin et al. (2018)	Overlay debonding, shallow and deep delamination, honeycombing, vertical crack, void and corrosion	N/A	N/A	N/A	N/A	N/A
Sultan and Washer (2018a)	Delamination	Using receiver operator characteristics (ROC) analysis	N/A	N/A	N/A	N/A

Table 5: Indicators and parameters used to evaluate the performance of non-destructive technologies

No.	Performance Indicators	Parameters
1	Capability	Surface defects (cracks, scaling, spalling, expansion joint problems, and efflorescence)
		Subsurface defects (delamination, corrosion, voids, honeycombing, concrete degradation., and overlay debonding
2	Accuracy	Defect depth
		Defect size
		Comparing the result with accurate method such as core test results
3	Ease of use	Complexity of analysis and interpretation
		Ease of data collection
		Expertise needed for data collection
		Expertise needed for data processing and data
		Extent and potential for automation and improvement
4	Cost	Equipment cost
		Labour cost
		Operation cost
		Data analysis cost
		Training cost
		System maintenance cost
		Installing cost
		Power cost
5	Speed	Time needed for data collection
		Time needed for data analysis and interpretation
6	Others	Availability of the instrument
		Pre-collection preparation
		Traffic disruption
		Stand-off distance
		Sensitivity to ambient noise and/or environmental conditions
		Portability
		Precision (Repeatability)
		Bias

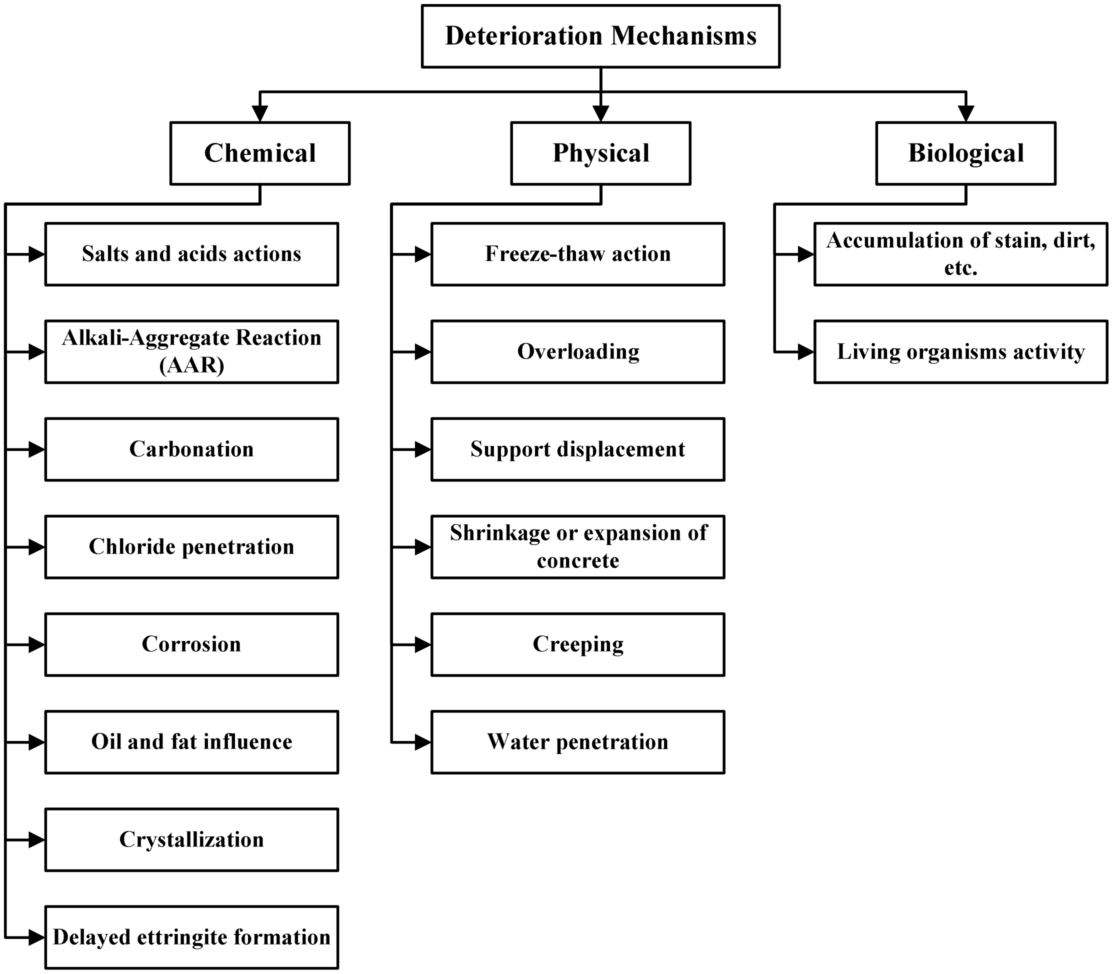


Fig. 1: Bridge deck deterioration mechanisms

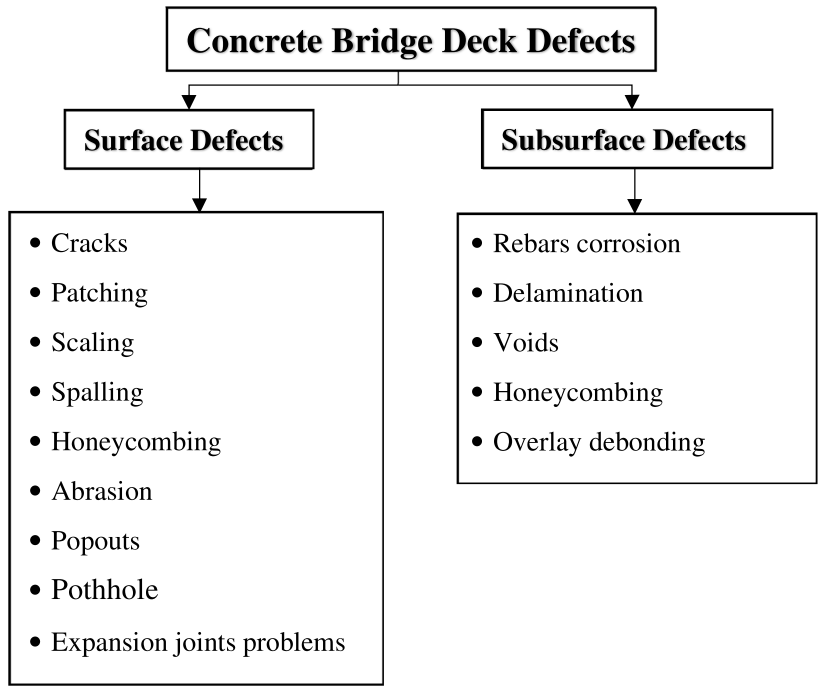


Fig. 2: Defects in bridge deck

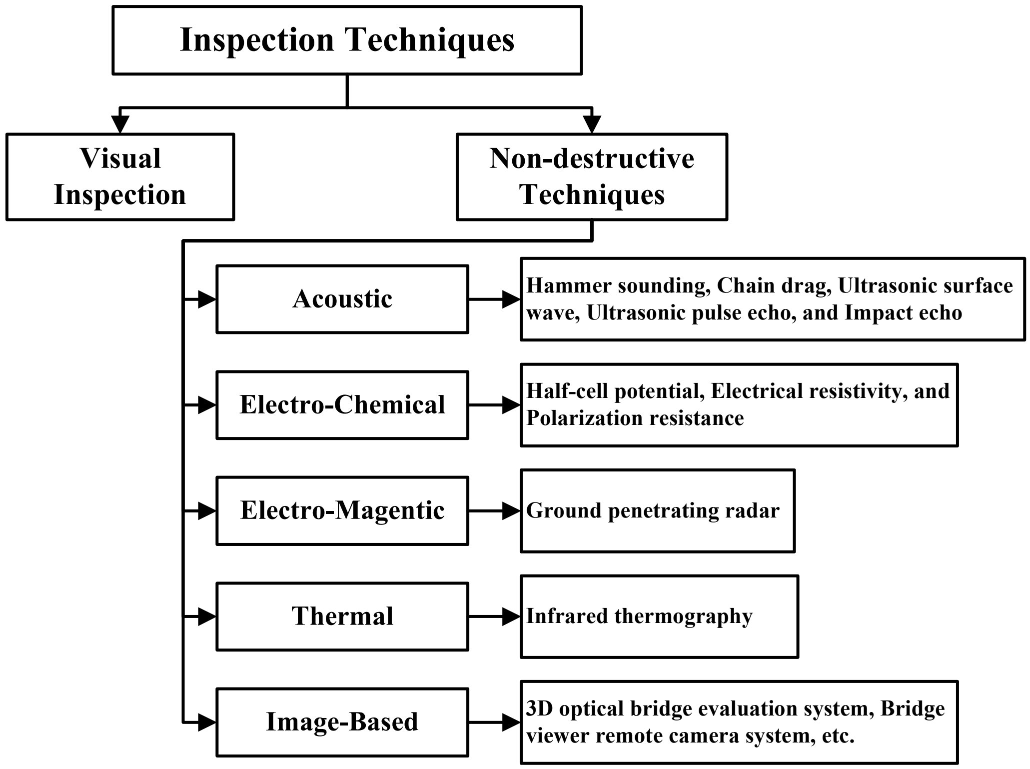
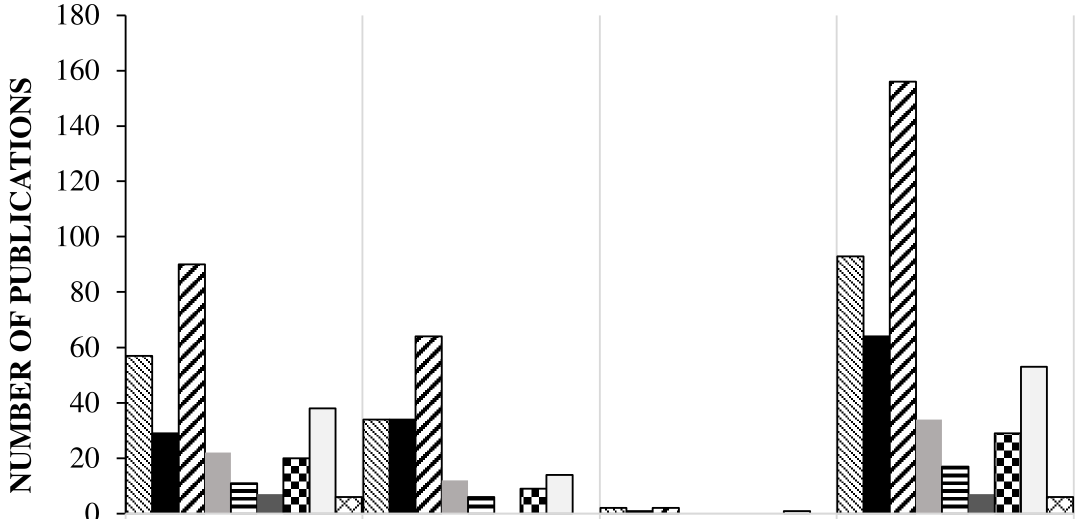


Fig. 3: Inspection approaches and technologies

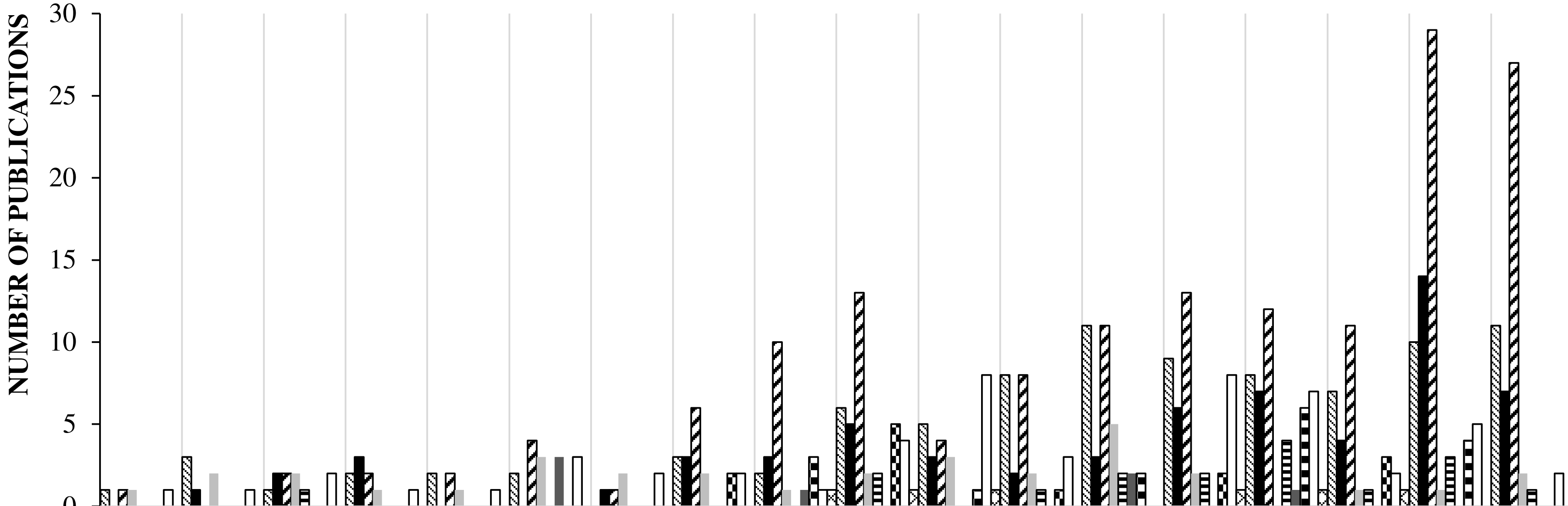


	Conference	Journal	Books	Total
GPR	57	34	2	93
IRT	29	34	1	64
Image	90	64	2	156
HCP	22	12	0	34
ER	11	6	0	17
PE	7	0	0	7
USW	20	9	0	29
IE	38	14	1	53
UPE	6	0	0	6

DOCUMENT TYPE

GPR = Ground Penetrating Radar, IRT = Infrared Thermography, HCP = Half-Cell Potential, ER = Electrical Resistivity, PE = Polarization Resistance, USW = Ultrasonic Surface Wave, IE = Impact Echo and UPE = Ultrasonic Pulse Echo.

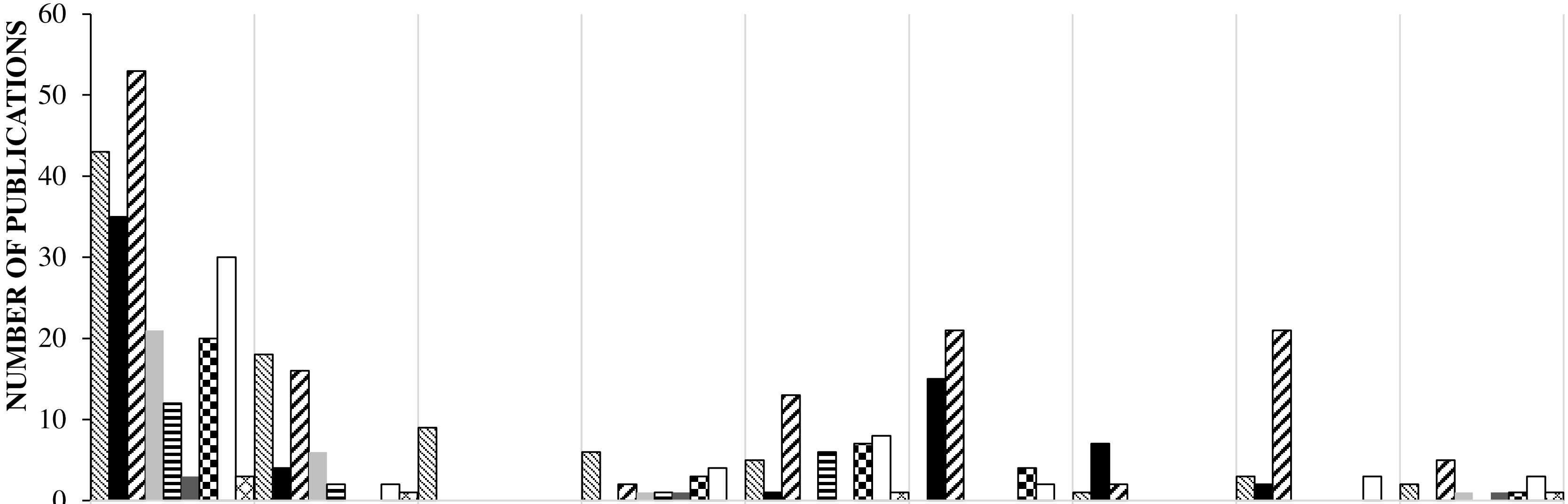
Fig. 4: Frequency of publications per type of publication



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
GPR	1	3	1	2	2	2	0	3	2	6	5	8	11	9	8	7	10	11
IRT	0	1	2	3	0	0	1	3	3	5	3	2	3	6	7	4	14	7
Image	1	0	2	2	2	4	1	6	10	13	4	8	11	13	12	11	29	27
HCP	1	2	2	1	1	3	2	2	1	2	3	2	5	2	0	1	1	2
ER	0	0	1	0	0	0	0	0	0	2	0	1	2	2	4	1	3	1
PE	0	0	0	0	0	3	0	0	1	0	0	0	2	0	1	0	0	0
USW	0	0	0	0	0	0	0	2	3	5	1	1	2	2	6	3	4	0
IE	1	1	2	1	1	3	2	2	1	4	8	3	0	8	7	2	5	2
UPE	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	0	0

YEARS

Fig. 5: Frequency of publication



	USA	Canada	Switzerland	Germany	South Korea	Japan	Turkey	China	UK
GPR	43	18	9	6	5	0	1	3	2
IRT	35	4	0	0	1	15	7	2	0
Image	53	16	0	2	13	21	2	21	5
HCP	21	6	0	1	0	0	0	0	1
ER	12	2	0	1	6	0	0	0	0
PE	3	0	0	1	0	0	0	0	1
USW	20	0	0	3	7	4	0	0	1
IE	30	2	0	4	8	2	0	3	3
UPE	3	1	0	0	1	0	0	0	1

COUNTRY

Fig. 6: Frequency of publications per country of publication

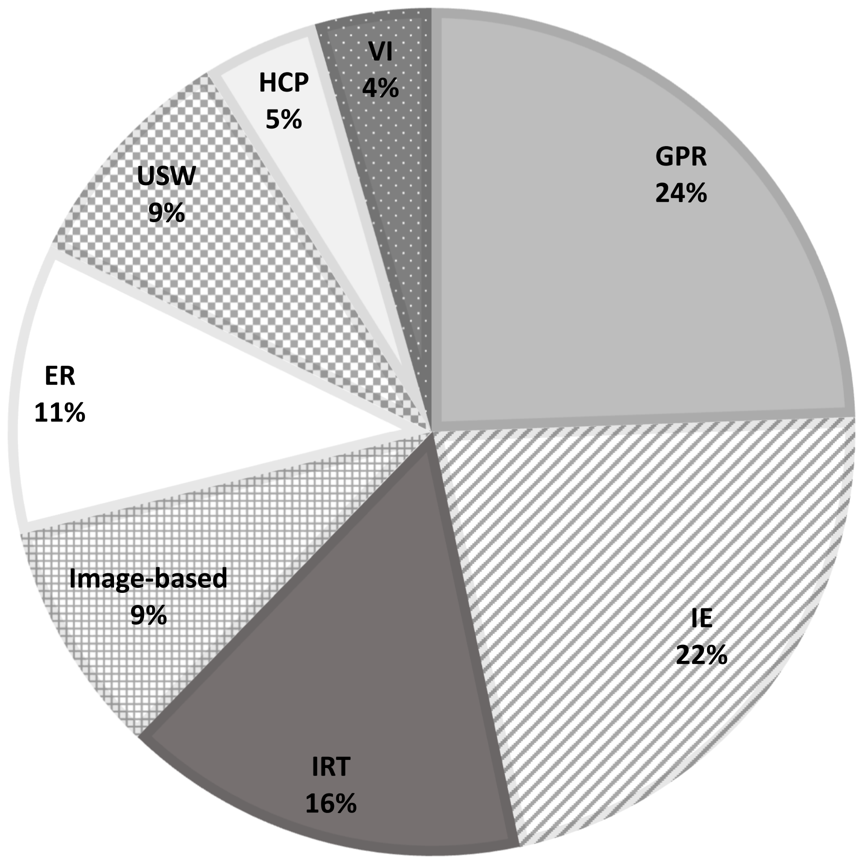


Fig. 7: Frequency of using non-destructive technologies in the developed systems

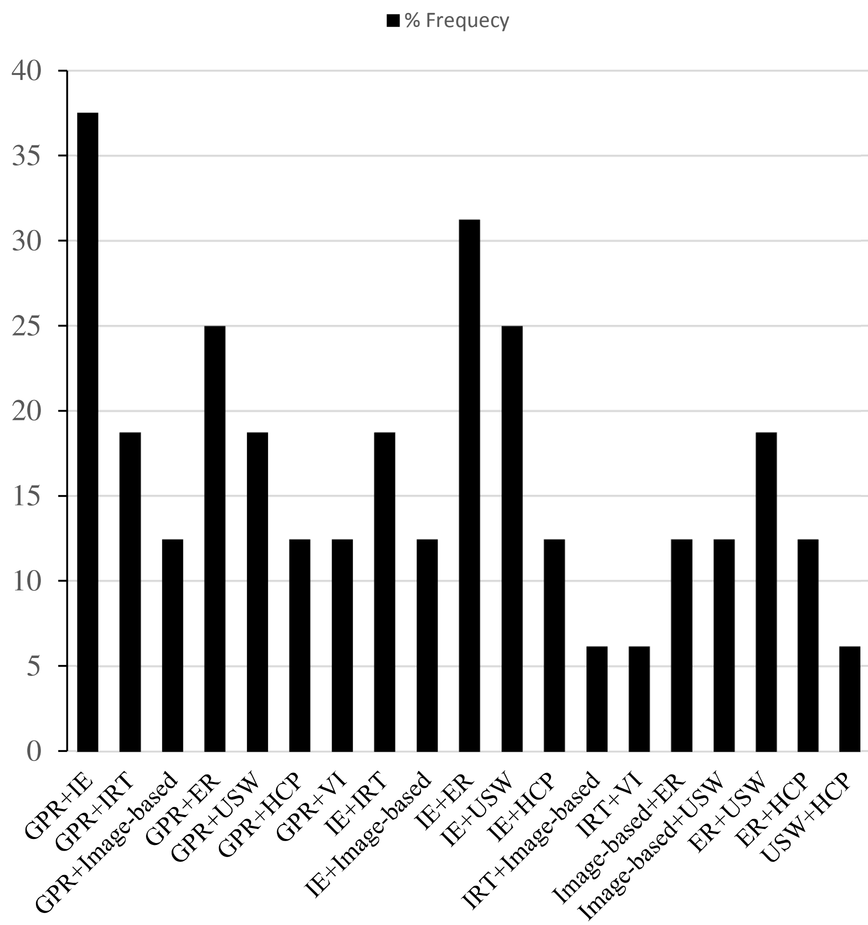


Fig. 8: Frequency of using specific technologies in the same system