Non-destructive Evaluation Techniques for Steel Bridges Inspection

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Abstract

Bridges, roadways, transit, water and sewer networks are main components of a civil infrastructure system. Billions of dollars are invested annually on infrastructure assets in Canada and the United States to cope up with growing population and to maintain serviceability and safety. Civil infrastructure systems contribute to social and economic welfare through serving large number of population and businesses. Thus, evaluating these systems' condition and performance is a necessity. One in four Canadian roads is operating above capacity, highlighting a real challenge to moving goods and people within our communities in the short and medium term. Steel bridges deterioration has been one of the problem in North America for the last years. Steel bridges deterioration mainly attributed to the difficult weather conditions. This paper review the steel bridges defects and the current practices for steel bridges inspection. Visual inspection is the most common technique for steel bridges inspection but it depends on the inspector experience and conditions. So many NDE models have been developed use Nondestructive technologies to be more accurate and non-human dependent. Nondestructive techniques such as The Eddy Current Method, The Radiographic Method (RT), Ultra-Sonic Method (UT), Infra-red thermography and Laser technology have been used. Through this paper these NDT will be reviewed with the advantages and disadvantages of each technique. Then recommended improvements will be presented to enhance the current practices and overcome their drawbacks and limitations.

1 Introduction

Bridges, roadways, transit, water and sewer networks are main components of a civil infrastructure system. Billions of dollars are invested annually on infrastructure assets in Canada and the United States to cope up with growing population and to maintain serviceability and safety. Civil infrastructure systems contribute to social and economic welfare through serving large number of population and businesses. Thus, evaluating these systems' condition and performance is a necessity. In North America, infrastructure condition is reported by a grade or percentage, similar to schooling system, which known as infrastructure report cards. Table 1, represents the infrastructure ratings for Canada and US. In the United States, the American Society of Civil Engineers (ASCE) report card shows an overall rating for America's infrastructure is poor. Furthermore, the cost to improve infrastructures including but not limited to solid waste, drinking water, wastewater, roads, bridges and rail is estimated as $3,635 billion (ASCE 2013).

According to Infrastructure Canada Rating (Canadian infrastructure report card 2016) the four asset categories show that a significant amount of municipal infrastructure ranks between fair and very poor, on average about 35%. The replacement cost of these assets alone totals $388 billion, nationally. Municipal roads require urgent attention. More than one third of the roads & bridges network fall below a rating of “good”. One in four Canadian roads is operating above capacity, highlighting a real challenge to moving goods and people within our communities in the short and medium term. The estimated replacement cost of the roads and bridges in fair to very poor condition is shown in fig. 1. For the average Canadian household, this amounts to a cost of $9473.

Historical and forecasted figures indicate that ‘transportation’ sector forms the largest portion of the Canadian infrastructure industry value. Roads and bridges segments have the largest portion within the transport infrastructure representing the highest worth share according to the estimates by the Business Monitors International report on Canadian infrastructure (BMI 2013). However, large parts of these infrastructures were constructed during the 1960’s and 1970’s. Accordingly, they are facing an increasingly deteriorating problem (Dori et al. 2011). Statistics Canada reports evaluate condition of infrastructure in terms of useful life expended by the infrastructure. Many of the nation’s bridges are approaching or exceeding their design life where the average age of Canada’s 75,000 highway bridges is 24.5 years compared to their mean service life of 43.3 years (Statistics Canada 2007). Aging problem of the bridge infrastructure is similar in the US as the average age of the nation’s 607,380 bridges is 42 years compared to their service life of 50 years as stated in ASCE report card. The report also graded bridges’ conditions as “C+” which refers to mediocre that requires attention (ASCE 2013). The growing problem of the bridges deterioration imposes challenges on ministries of transportation to maintain and preserve them. In 2011-2012 Quebec province alone spent more than $800 million for structural improvements, mainly for bridges (MTQ 2012). While about 28% of concrete bridge decks in the US is either structurally deficient (SD) or functionally obsolete (FO) as of December 2013. ASCE estimated that $20.5 billion of annual investment is needed to eliminate the country’s bridge deficient backlog by 2028.

2 Steel Bridges

At the time the first iron and steel bridges were being built there was little knowledge about the special advantages and disadvantages of these new materials. Research on steel bridges often was initiated by dramatic bridge failures or a series of smaller defects. From an engineer’s point of view, it is easy to reduce bridge collapses to errors in design or to material flaws. However, human and economical losses should be reminders of the importance to study the causes carefully in order to avoid repetition.

It can be seen in Fig. 2 that every introduction of a new material or construction method began with short span bridges. The bridge at Coalbrookdale, mentioned before, was the first cast iron arch bridge and had a span of only 30 m. Twenty years later the Southwark Bridge, U.K. was built with a span of 73 m and has remained the largest cast iron arch bridge.

2.1 Steel Bridges Main Defects

Cracks

Ductile failure, brittle fracture, and buckling/instability usually occur under static loading conditions wherein the applied load exceeds a critical load. In contrast, most structures are subjected to repeating loads of varying magnitude, which are most often below yield strength and design stress levels. Such repeated or fatigue loading occurs in bridges, buildings, etc. Fatigue failure is characterized by the initiation and growth of a cracks due to the repeated loading of the structure, which generates microscopic inelastic damage at regions of local stress concentration. If sufficient inelastic damage accumulates then a small crack develops, which then propagates through the structure. Failure occurs when the crack attains a critical size. Fortunately, fatigue is a progressive damage mechanism and is often identified before significant structural damage arises. Fatigue failures are typically characterized by flat fractures, little or no associated macroscopic inelastic deformation, and crack growth bands (beach marks) on the fracture surface. Fatigue cracks most frequently initiate from the more severe stress concentrations, which in steel structures occur most often at welds (fillet weld toes, etc.) and penetrations such as bolt and rivet holes. In this regard, recent reviews revealed the vast majority of fatigue failures to have occurred at welded connections (Robert S. Vecchio and Lucius Pitkin 2006) .

Corrosion

Corrosion is one of the most important causes of deterioration of steel bridges. In the United States 40% of the bridges are built of steel. In some states, such as Michigan, the number exceeds 60%(Kayser and Nowak 1989). There is a need for rational criteria which can be used to determine the actual strength and remaining life of existing structures. The primary cause of corrosion is the accumulation of water and salt (marine environment or deicing media) on bridge steel. The source of water and salt is either from deck leakage or from the accumulation of road spray and condensation. The source of the moisture often determines the pattern of corrosion on a bridge. The rate of corrosion will depend upon the contaminants in the moisture and the ambient temperature.

According to (Kayser and Nowak 1989) there are five main forms of corrosion which can affect a steel girder bridge. The most prevalent form is a general loss of surface material; this condition will lead to the gradual thinning of members.

General corrosion accounts for the largest percentage of corrosion damage. **Pitting corrosion** also involves loss of material at the surface. However, it is restricted to a very small area. Pits can be dangerous because they extend into the metal, showing little evidence of their existence. Pit occurrence is serious in high stress regions because it can cause local stress concentrations.

Galvanic corrosion occurs when two dissimilar metals are electrochemically coupled. Such situations may occur at bolted or welded connections. Galvanic corrosion can be local, leading to pit formation. **Crevice corrosion** occurs in small confined areas, such as beneath peeling paint or between faying surfaces. It is usually caused by a low concentration of dissolved oxygen in the moisture held within a crevice. Deep pits can also provide locations for crevice corrosion to occur. **Stress corrosion** occurs when metal is subjected to tensile stress in a corrosive environment. For mild carbon steel in ordinary bridge environments, stress corrosion is usually not a problem. In general, the lower the fracture resistance of a metal, the higher its susceptibility to stress corrosion (Karpenko, G. V., and Vasilenko, I. I. 1979). Corrosion fatigue has been identified as a corrosion phenomenon. It is actually a combination of pitting, crevice, and stress corrosion. The effect of corrosion fatigue is a reduction in the fatigue life of the metal. This can result when pits cause stress concentrations or when crevice or stress corrosion causes the advancement of cracks.

To evaluate the effects of corrosion on structural performance, the various regions where corrosion will occur must be evaluated in terms of net remaining area, structural behavior, and structural loading. The loss of section in a component will cause a reduction in the carrying capacity of that component. The amount of capacity reduction will depend on whether the component is in tension or compression. Tension capacity is computed as the net remaining area times the tensile strength. Compressive capacity depends upon the net area, geometry, and boundary conditions of the element. In a steel girder, corrosion may affect the capacity in bending, shear, and bearing. Bending will be considered mainly at the mid-span of a girder or above an intermediate support.

Creep

(Vecchio and LPI 2006) Described Creep as the damage accumulated from inelastic deformation of plain carbon and alloy steel under constant load even if the service stress is substantially below the yield strength as a result of thermal activation at elevated temperatures.

3 Non-Destructive Techniques used for steel Bridges inspection

3.1 Visual inspection

The most common form of NDE is the visual inspection. They require no special testing equipment, and they can be completed more quickly and economically compared to more advanced NDE techniques. However, due to subjective nature of visual inspections, variability of inspection results is common.

According to (Bader 2008) in 2001, the FHWA conducted an investigation into the reliability of visual inspections for highway bridges. The results of the study presented some interesting findings. The study showed that often a Professional Engineer is not present at the site during an inspection. Only two states required that their inspectors have their vision tested prior to performing inspections. Many inspectors did not note important structural components such as fracture critical members and fatigue prone details. Routine inspection results often varied greatly, with Condition Ratings sometimes being assigned range of 4 or 5 values. In-Depth inspections often did not reveal defects for which they were intended, and the in-depth inspections often did not reveal any additional defects than those found during a Routine inspection.

3.2 Digital Image Processing

In (Lee 2011) two method was illustrated and compared the Neuro-Fuzzy Recognition Approach method (NFRA) and the Simplified K-Means Algorithm (SKMA) method. However both methods goes through different procedures, both start with the conversion of original color images to grayscale images and use the grayscale images for processing.

The NFRA method uses artificial intelligence techniques to separate rust pixels from background pixels. The SKMA method separates object pixels and background pixels in a digitized image using a statistical method, called the K-means algorithm.

The NFRA and the SKMA methods failed to generate reliable results under specific environmental conditions. The two methods use the grayscale images for processing and this is a drawback for them as the color of the rust is one of the most distinguish characteristics.

Lee develop an automated recognition of surface defects using digital color image processing. This method was developed to fix the drawback of the previous two methods and use the color images instead of the grayscale one. The developed model gives better results but it fails to solve the environmental effects and to detect some subsurface defects as cracks. Another problem with lee's model that the collected data was not well defined which lead to questioning the reliability of the results.

(Shen et al. 2013) Developed an automated steel bridge coating rust defect recognition method based on color and texture feature. The methodology consists of two models, Fourier- transform-based steel bridge coating defect detection approach (FT-DEDA) and rust-colour-spectrum-based rust defect recognition method (RUDERM). The FT-DEDA approach used to detect any changes on the collected images. The used tools detects the rust and sharp edges but cannot discriminate rust so the RUDERM approach was used. The RUDERM approach used the color space to define the rust spots and discriminate it from the background and other defects.

With the comparison of Shen's model and Lee work Shen shows better results especially with the non -uniform illuminated images which simulate the some of the environmental condition as it was one of the Lee's drawback. Shen model cannot define other types of defects than the rust and other types of defects as cracks. The classification of the images gives defective and non-defective images and did not define the percentage of defect in each image which does not give an accurate result for the whole steel bridge coating.

3.3 The eddy current Method

Continuous wave eddy current testing is one of several non-destructive testing methods that use the electromagnetism principle. Conventional eddy current testing utilizes electromagnetic induction to detect discontinuities in conductive materials.

The eddy current method has several advantages that make it a practical choice for field inspections. The testing equipment consisting of a probe and data acquisition device is portable and available at a relatively low cost. The eddy current can penetrate both conductive and non-conductive steel coatings, so that the coating system can remain Intact during the inspection (Bader 2008). Figure 3. below shows a crack indication on a butt weld, represented by the large spiking area.

One of the greatest advantages of the Eddy Current test is that it can penetrate most of the coatings applied in bridge structures. The inspections can be carried out without the removal of the coatings, as it is required in most of NDT.

(Ichinose et al. 2007) apply eddy current method as a tool for detecting cracks in steel bridges. The detected crack was confirmed by penetration test and its measured length almost coincided with the length evaluated by the Eddy Current testing. In the application the detected crack was under coating as in fig.4. and was not detected by visual inspection several times.

The coating was removed in the area was a crack signal was detected and it was confirmed by Magnetic Particle Inspection revealing a 23 mm crack under the coating.

3.4 The radiographic method

The radiographic method is an older, more traditional method of NDE. It is used to inspect the quality of butt welds in the fabrication of steel plates for bridge girders. It works similar to an X-ray. Penetrating radiation is absorbed to produce a high contrast image. Indications of cracks and discontinuities in the welds will show up as darker areas on the high contrast image. Fig. 5. shows an example of a radiograph, with the locations of two known cracks shown as dark horizontal lines.

New advances in radiography have made it possible for some applications to generate real-time X-ray continuous images video that can be stored digitally while the radiation source travels along the structural elements being inspected(Mehrabi 2006).
(Mehrabi 2006) stats that because of emitting high energy X rays, high dosages of which can be harmful to living tissues, X-ray equipment must be handled by highly trained and qualified personnel whose safety and safety of others on-site shall be considered strictly.

3.5 The ultra-sonic testing

This method relies on high frequency sound waves being introduced into the material and the fact that ultrasonic pulses are not transmitted through large air voids. A pulse generator is used to generate an electric wave, which is amplified and converted to mechanical vibrations by a piezo-electric crystal probe and transmitted through the material under test. The reflected signal is then picked up by the probe, converted back to an electric wave and registered as an echo (Dawson et al. 1990).

The UT method is based on interpretation of reflection and diffraction under material discontinuity of interest during ultrasonic wave propagating through metal, and are thus used for detection and sizing of defects in welds (Lin et al. 2015).

Recent advances in computer technology have led to research in the use of automated ultrasonic testing. Automated ultrasonic testing uses a robotic arm with a wide range of motion to move the transducer around the test location. This ensures complete coverage of the area under inspection, and minimizes human interaction during the test (Bader 2008). The UT is useful to detect surface, subsurface flaws and subsurface delamination but it needs a high skill in operating equipment. Table 2 illustrates the most advanced UT technologies for the NDE of steel Welds.

However the ultra-sonic technology has been developed and improved the quality of detection for cracks but it has been developed with the respect to speed and signal power and still there are some debates as the capability of detecting large cracks, Cracks in complex geometry structures and the surface defects as corrosion. Also Coating or paint may affect the accuracy of the UT method. The ultra-sonic Technique widely used for welds crack detection and the measurement of steel element (measurement of section loss due to corrosion (Damgaard et al. 2010) but it's capabilities for detecting other defects in steel bridges is still questioned.

3.6 Infra-red thermography

Also known as thermal imaging or photo thermal, radiometry and its multiplex version lock in-thermography are used for NDT. The advantages of phase sensitive modulation thermography make it a Reliable tool for rapid inspection of large surfaces. This method depends on the changes of the temperature in cracks and corroded parts. These changes can be noted under the normal temperature of the surrounding environment or by using some heat emitting tools which is more common and magnify the change of the temperature makes it more obvious to detect the infected parts. The thermal wave is launched from the surface into the inspected component by absorption of modulated radiation. It is reflected at internal discontinuities so that the superposition to the injected wave modifies the responding wave field. The resulting phase angle image displays hidden structures down to a certain depth underneath the surface. Fig. 6. Illustrate the mechanism of the infra-red thermography. Lately some research For example (Pan et al. 2012) combine eddy current method with IR and Uses eddy current as the temperature change technique.

(Sakagami et al. 2010) proposed self-reference lock-in thermography which does not require any external reference signals and can be employed even under random loading. The concept of this methodology depends on Thermoelastic Stress Analysis which defined by temperature change sue to Dynamic stress change under the adiabatic condition in solid. This phenomenon described by the following Lord Kelvin's equation that relates temperature change (*ΔT*) to a change in the sum of the principal stresses (*Δσ*) under the cyclic variable loading:

$\Delta T = -\frac{\propto}{\rho Cp} \mathrm{T} \Delta\sigma$ ……………………………….. (1)

Where α is the coefficient of thermal expansion, ρ the mass density, *Cp* the specific heat at constant pressure and *T* the absolute temperature. A change in the sum of the principal stress (*Δσ*) is obtained by measuring temperature change (Δ*T*) using the infrared thermography.
Remote detection of fatigue cracks in steel deck in steel bridge in-service was conducted by the self-reference lock-in thermography with telescope lens as shown in Fig.7. Infrared measurement was conducted from distant places in distances of 8m and 12m. Temperature change near the crack tip under variable wheel loading by the traffics on the bridge was measured by infrared camera. The experimental results obtained by the self-reference lock-in thermography are shown in Fig. 8 Examined the Compatibility of using thermoelastic stress analysis as nondestructive technique for steel bridges inspection and it was found that self-reference lock-in thermography was successful for detection of different types of fatigue cracks, such as weld-bead penetrant type crack and through-deck type crack. The limitation of this technique that it doesn't detect other types of common defects in the steel structure such as corrosion and painting rust.

3.7 Laser technology

In recent years, the laser scanning technology rapidly evolved. Laser scanners have been used for several health monitoring and damage detection applications in order to capture the current status of structures. The most common application is tracking Original status on structures over a time period**.** It is also used to track changes, mostly during construction, by comparing two successive scans that are recorded throughout the process (Guldur et al. 2015) **.**

(Guldur et al. 2015)work on the inspection of bridges defects and determining the condition ratings of bridge components by using detected and quantified surface damage from 3D laser Image(point cloud image) , which compares the current state of the structure to its original state, which gives the overall condition of the structure based on all defects.

For defects detection he used two methods, Graph-based Surface Damage Detection and Surface Normal-based Surface Damage Detection. Graph-based Surface Damage Detection is used to detect and quantify Most of the surface defects: the ruptures, bent members, points of discontinuity, and concrete spalling. Surface Normal-based Surface Damage Detection is developed in order to expand the variety of the detected damage types; the damage types detected via the surface normal-based damage detection method consist of cracks and corrosion along with ruptures and spalling.

The developed condition assessment strategy provided the opportunity to document quantitative information on damaged area. As a result, that shows that laser scanners can be used for aiding the visual inspections, and they will enhance the quality of the collected information.

The previous model was validated through only two cases for concrete and timber bridges which means it need more validation and application on other different types of bridges. It was proven the availability of the model in the detection of surface defects but not the sub surface defects.

4 Proposed NDE

One of the major problems through the previous mentioned NDT the absence of a technology that can detect the two main defect of steel bridges, Surface defects as corrosion and sub-surface as cracks. A new series of IR Cameras has the ability to take images of both regular Digital Images and IR images which can be divided later and go in two different processes. The regular digital images go through an image processing to detect any surface defects. The IR images through IR image processing to detect different types of cracks. Both processes have been approved to be very effective and both processes can be combined under one condition assessment model to make a full condition assessment for steel bridges. Through this Method the inspection time will be reduced as it only need IR cameras installed on vehicle with up to speed of 50 MPH as used in (Matsumoto et al. 2015) which will not need the closure of the road or any interruption for the traffic.

5 Conclusions

This paper review the latest NDT for steel bridge inspection. The traditional method Visual inspection proved to has some problem as inspector condition, inspection condition and non-applicable for subsurface defects. Image processing has great results for surface defects and overcome the condition for inspection and inspector mentioned in visual inspection but steel cannot detect subsurface defects. Eddy current technique used for detecting cracks without removing the coating but it is not efficient in detecting the surface defects. The radiographic method is able to detect cracks but even the process and the equipment is too complicated I.e. X-rays or it uses dangerous type or radiation i.e. gamma rays. Ultra-sonic method mainly used in thickness measurement to assess the corrosion loss in steel section either used to detecting cracks. It proved to have high accuracy but this accuracy decreases in the large size cracks. The onther challenge that it need a high skilled crew to guarantee the accuracy of the inspection. The IR thermography application shows the ability to detect different types of crack in steel bridges but not the surface defects. 3D laser technology was capable to detect any surface defects any change in the structure from the original state but need more application. The proposed NDE combine two method, Image Processing and IR thermography to successfully detect both surface and subsurface defects. In future research application will be illustrated to prove the system Capabilities.

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7 Tables

Table 1: Infrastructure ratings for Canada and US (Alsharqawi et al. 2016)

Description	Canada	United States
Fit for the Future	80% or Higher; Very Good	A; Exceptional
Adequate for Now	70% to 80%; Good	B; Good
Requires Attention	60% to 69%; Fair	C; Mediocre
At Risk	50% to 59%; Poor	D; Poor
Unfit for Sustained Service/ Purpose	50% or Less; Very Poor	F; Failing/Critical

Table 2. Major advanced UT technologies for the NDE of Welds (Lin et al. 2015)

NDE	Capability	Advantages	Limitations
ToFD	-accurate sizing of defects	-very sensitive - permanent record	-skill in operating equipment -inaccuracy for certain orientation of defects -data interpretation is not straight forward -low signal to noise ratio in field
PA-UT (Tandem)	-accurate sizing of defects	-very sensitive -accurate -permanent record	-skill in operating equipment -inaccuracy for certain orientation of defects -data interpretation is not straight forward -low signal to noise ratio in field
PA-UT (Sectorial)	-accurate sizing, orientation and location of defects	-very sensitive -accurate -permanent record	-skill in operating equipment -data interpretation is not straight forward -low signal to noise ratio in field
AUT	-accurate sizing of defects	-provide efficient and repeatable inspections of standard weld	-skill in operating equipment -inaccuracy for certain orientation of defects -data interpretation is not straight forward -low signal to noise ratio in field
PA-AUT	-accurate sizing, orientation and location of defects	-significantly improve signal quality -high-speed -automatic -easier to interpret, especially in areas with complex geometries. - permanent record	-skill in operating equipment
IWEX	-better imaging -accurate sizing, orientation and location of defects	-high-speed -easier to interpret, especially in areas with complex geometries. - permanent record	-skill in operating equipment

8 Figures

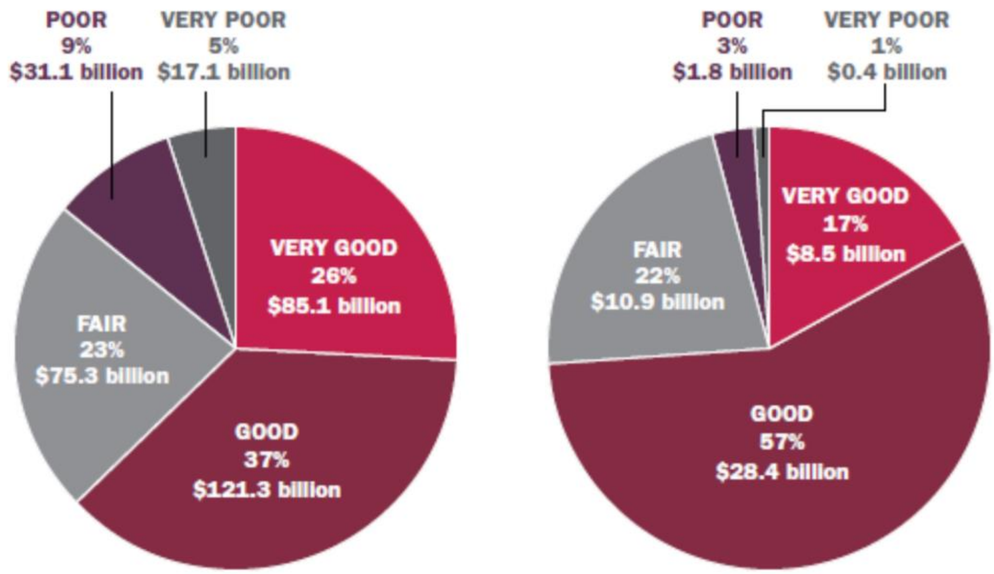

Figure 1: Physical condition rating by replacement value For Roads (Left) and bridges (Right). (Canadian infrastructure report card 2016)

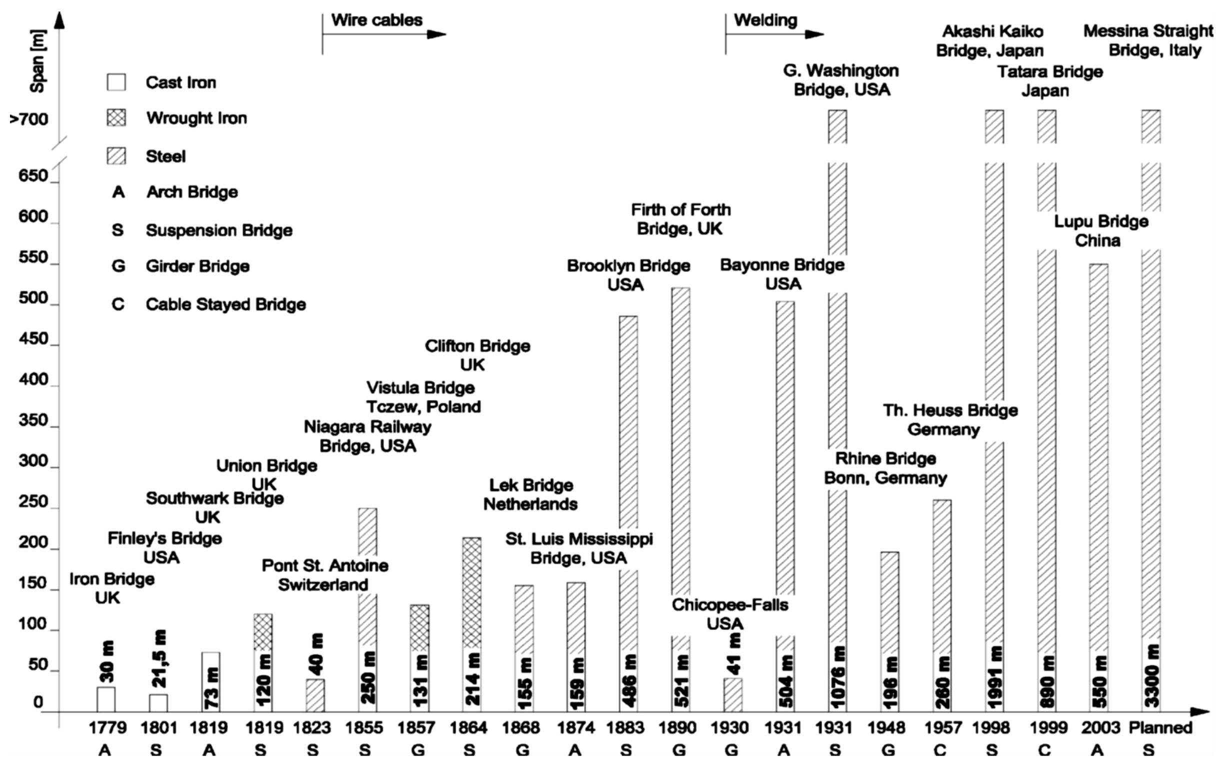

Figure 2: Histogram of the development of steel use in bridge construction since 1779 (Biezma and Schanack 2007)

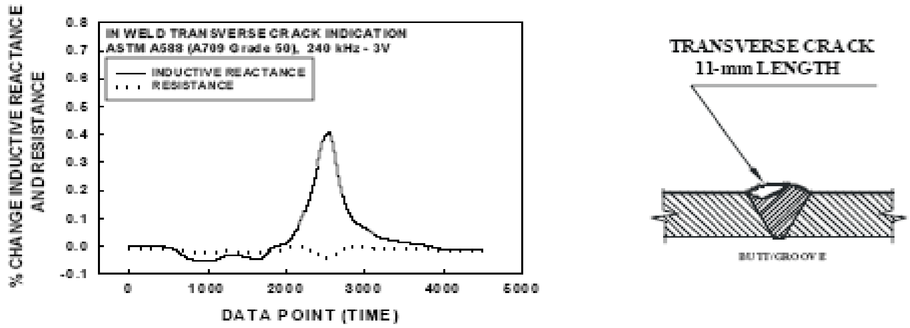

Figure 3: reactive and resistive components of signal response for transverse-to-weld Crack (Bader 2008).

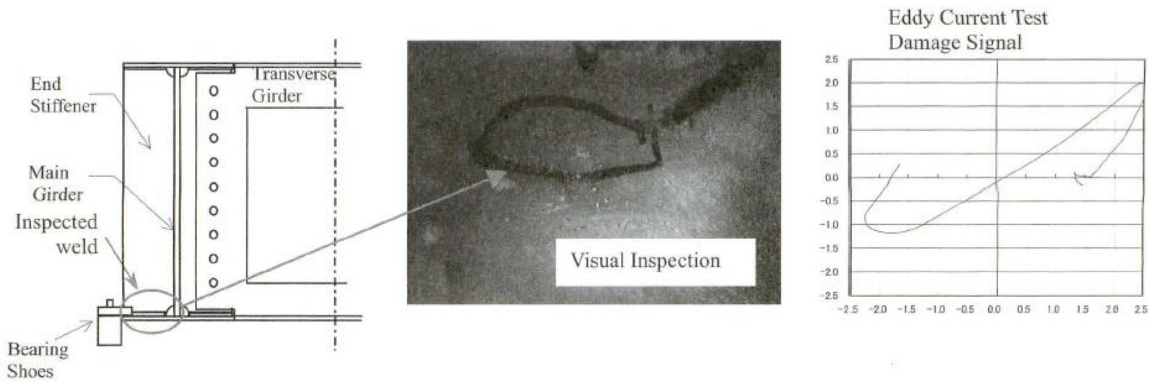

Figure 4: Detection of under coating cracks (Ichinose et al. 2007)

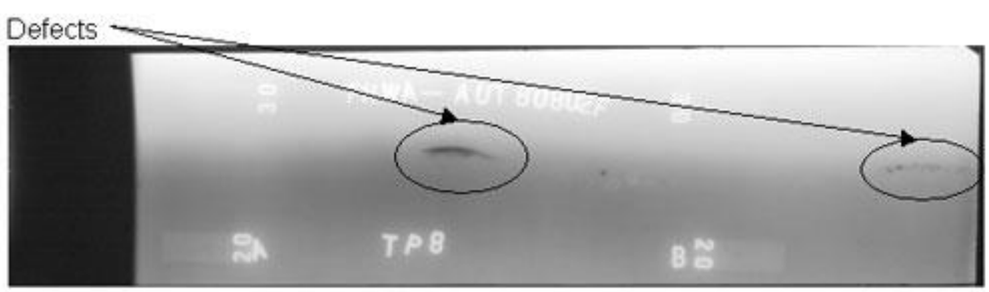

Figure 5: Typical radiograph image showing locations of two cracks (Bader 2008)

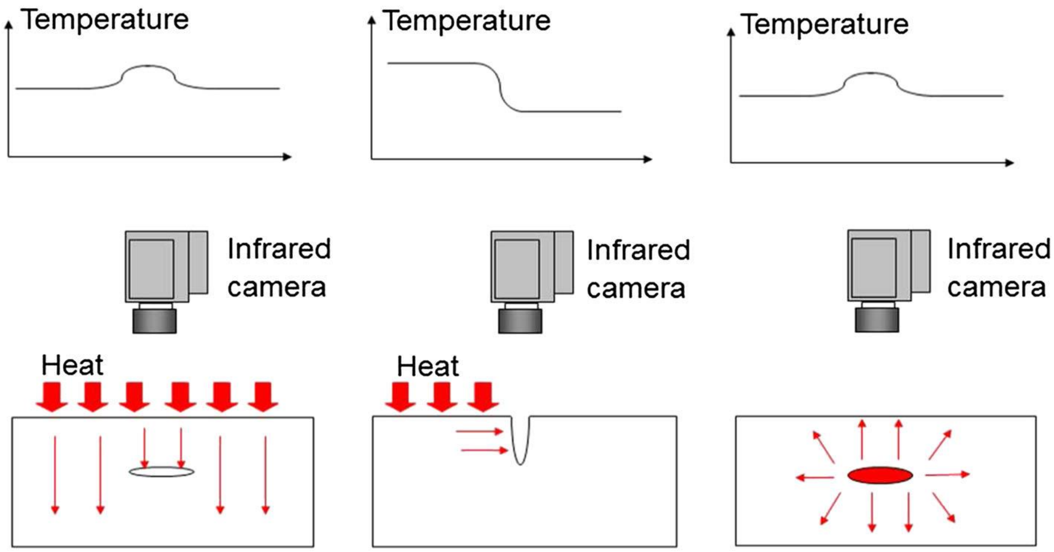

Figure 6: Illustrations of thermal nondestructive testing classification (Sakagami et al. 2010).

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Figure 7: Self-reference lock-in measurement with telescopic lens for actual steel bridge (Sakagami et al. 2010).

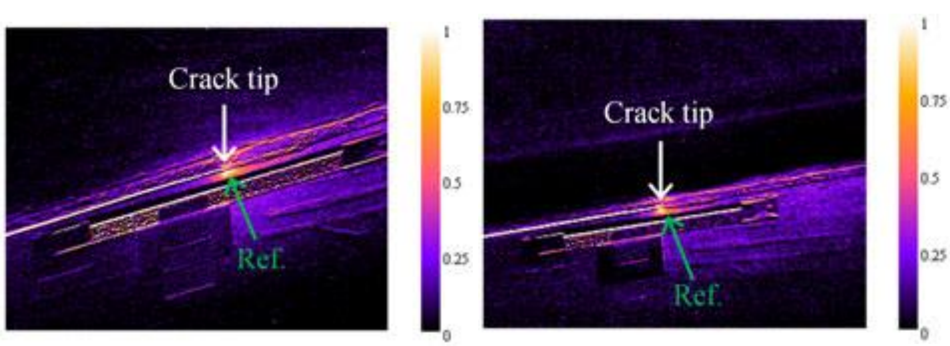

Figure 8: Result of crack detection in actual steel deck from distant place (Sakagami et al. 2010).