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Corrosion Localization of Steel Structures Using Fiber Bragg Grating Sensors

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Abstract

Steel, which has high tension and compression strength, is a widely used civil engineering material in constructing building, bridge, pipelines, and other structures. However, steel has a well-known weakness, which is suspected to corrosion. Steel corrosion would significantly impact the reliability and safety of steel structures. Accurately locating and assessing the corrosion of steel structures would contribute to timely maintenance and thus, extend the service life of the steel structures. Although advances have been made to use nondestructive evaluation (NDE) technologies to locate and assess corrosion on steel structures, due to the lack of labor and budget for frequent NDE assessment on steel structures, remote and real-time approaches to locate and assess corrosion are still in great needs. Fiber optic sensors, especially, fiber Bragg gating (FBG) sensors, with unique advantages of real-time sensing, compactness, immune to EMI and moisture, capability of quasi-distributed sensing, and long life cycle, will be a perfect candidate for long-term corrosion assessment. However, due to the fact that FBG is a localized sensor, it is very challenging to locate corrosion using FBG sensors. In this study, algorithms are developed to locate corrosion on steel structures using FBG sensors. Detail sensing principle, localization algorithm development and calibration are introduced in this paper together with experimental validation testing. Upon validation, the developed corrosion localization algorithm could give some guidance to locate corrosion using in-situ FBG sensors on steel structures across nation and would possibly reduce the corrosion induced tragedies.

1. Introduction

Steel components are vulnerable to corrosion attack (Pierre 1999, and Fontana et al 1987). Corrosion happens naturally when structure steel meets with water and oxygen concurrently. The corrosion reaction consists of a sequence of sub-reactions, ended in consuming steel as well as producing rust. Corrosion had been long recognized as one of the main reasons of structural steel component degradation due to its ability to substantially lower the cross-section area of component, causing a substantial deterioration in load-carrying capability of associated structure. Not only because the corrosion reduces load capacity of steel bars in concrete, but also rust has much less density so that the enormously increased volume leads to severe cracks in concrete, resulted in unexpected component failure. Based U.S. DOT report (Koch et al. 2002), the estimation for corrosion cost had been 1.1 trillion USD, which accounts for about 6% of the gross domestic product (GDP) of United States.

To analyze the corrosion risk of a steel pipeline, the first priority is to locate the corrosion. Corrosion brings several direct changes that could be used for either destructive or non-destructive techniques such as electric potential and alternation of surface properties. The former one is the fundamental of weight loss measurement and electrochemical corrosion research, and the latter is the origin of wave-based non-destructive corrosion detection methods. For destructive corrosion assessment, there are mainly two approaches including weight loss measurement and electrochemical measurement (Mansfeld et al, 1980). Both weight loss and electrochemical measurement are destructive corrosion assessment. Though they are able to obtain corrosion rate directly, they are not suitable for conducting corrosion assessment on an existing steel structures and could only be used to determine the corrosion resistance of a type of metal before it is placed.

Several non-destructive corrosion assessment methods are used to evaluate corrosion severity including ultrasonic and acoustic tools (Bescond et al, 2007 and Miguel et al, 2003), and other and embedded or attached sensors. Ultrasonic measurement methods are one of the most popular corrosion assessment methods used in the pipeline industry. It provides of high sensitivity, accurate, and immediate assessment for pipeline thickness. However, the ultrasonic measurement methods are having difficulties perform assessment on irregular shape parts, and the extensive knowledge requirement for operating and understanding the instrument often limits its application. Furthermore, the ultrasonic measurement requiring human operation on-site could hardly become a candidate for real-time monitoring system of large area. Acoustic emission (AE) has been widely used for damage monitoring in loaded structures, and researches is trying to adapt it in corrosion assessment and monitoring (Miguel et al, 2003). AE method as one type of passive detection method is suitable for real-time monitoring and provides high sensitivity, however, it would have low signal-to-noise ratio in field for small cracks.

Strain sensor-based corrosion assessment methods are gaining attention recently. When corrosion reactions happen, though original metal is consumed, the corrosion products (oxidized metal) would occupy several times of volume compared with original metal. If the corrosion reaction happens in a confined space, the excessive increased volume would induce a noticeable amount of strain, which could be used as an indicator of corrosion reaction. However, electrical strain gauges may have difficulties applying in pipeline corrosion assessment due to the underground nature for most of the pipelines with moisture and intensive electromagnetic noise (Diler et al, 2017).

Fiber optic sensors which are made by silica materials have a great potential as a sensing tool in strain based corrosion assessment of steel structures. Among all fiber optic sensors, fiber Bragg grating (FBG) sensors are well-known for its reliability and high sensitivity. Fiber Bragg grating (FBG) sensors had received lots of attention due to their simplicity in installation, high sensitivity and exceptional durability (Friebele 1998). Other than being an alternative to strain and temperature sensors, FBG sensors were proven to have the capability to detect and locate cracks on concrete and metallic structures, if properly cooperated with other non-destructive detection methods such as acoustic emission and ultrasonic (Moyo et al, 2005 and Betz et al, 2006). FBG sensors also had the advantages of chemical inertness because FBG sensors do not require any metallic components, which made them outstanding choices in corrosion monitoring system. A few recent attempts to apply FBG sensors in corrosion monitoring of steel rebar in reinforced concrete and the previous attempt to apply FBG sensors in hard coating in preliminary study had shown the possibility of FBG sensors in corrosion monitoring. Relatively low cost of

FBG sensors also made large-scale application practical and thus made FBG sensors strong candidate in corrosion monitoring system (Maryoto et al, 2013 and Deng et al, 2017).
However, since the FBG sensors are point sensors, the corrosion status of the steel structures can only be assessed if the sensors were installed exactly at the corrosion locations, which is an unknown location in practical applications. Thus, if the corrosion does not occur exactly at the locations of the embedded sensors, or near the sensors, the effectiveness of the corrosion assessment system is questionable. To solve this challenge, this paper tends to develop a two dimensional (2D) sensor network with a limited number of sensors along the way of the steel structure that would possibly identify the locations of the corrosion. The theoretic algorithm followed by the parametric study through numerical analysis.

2. Plate Theory for Corrosion Localization

When corrosion does not directly occur beneath the embedded point FBG sensor, multiple sensors can be embedded and form a sensor network to locate the corrosion and conduct the following risk management. However, with a sensor network, the relationship between the sensed strains on the point FBG sensors and corrosion would be a two dimensional (2D) problem. There are two assumptions in this paper: 1) The corrosion analyzed in this study is a pitted (localized) corrosion so its corrosion production is accumulated within a relatively small area comparing to the total span of the packaged FBG sensor; and 2) the expansion of corrosion products mainly accumulates vertically. The corrosion induced strains on the FBG sensors can be analyzed using a simply supported plate for a 2D problem as shown in Figure 1.

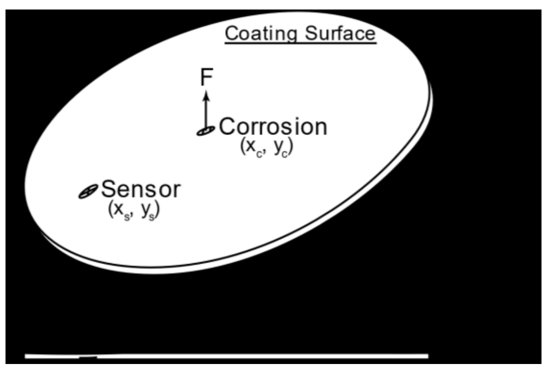


Figure 1 Corrosion plate theory demonstration.

The corrosion induced displacement Δ has its maximum value at the point of corrosion, and gradually decrease along the way to the lifting edge of coating surface to zero. Assuming a square plate, and let the radius of the plate to be *r*, in order to get the strain value at sensor location (x_c, y_c), a differential equation should be solved as below (Ugural et al, 1999):

$$D\left(\frac{\partial^4 w}{\partial x^4}+2\frac{\partial^4 w}{\partial x^2 y^2}+\frac{\partial^4 w}{\partial y^4}\right)=F(x,y), \qquad \text{where } D=\frac{Eh^3}{12(1-\rho^2)} \tag{1}$$

With the given boundary condition and the known material property (Young's modulus E, Poisson's ratio ρ, and coating thickness h) of the coating, the strains of any given locations on coating surface under the applied force F could be solved. As the actual boundary condition and the external force F are not explicitly known, and the strain has only one exact solution, the strain value could be implicitly as in Equation (2):

$$\varepsilon_s = f(x_c, y_c, r, F, E, \rho, h, x_s, y_s) \quad (2)$$

From Equation **Error! Reference source not found.**, it could be seen that the strains on embedded sensors were only related to the corrosion location and corrosion severity which can be assessed by FBG sensors.

3. Numerical and Experimental Analysis

Based on Figure 1, a finite element model (FEM) was set up in ANSYS as seen in Figure 2. The dimension of plate is 10mm × 10mm and the thickness of the plate is 2 mm, and the modulus of the plate is 5.157 Mpa with a Poisson's ratio of 0.29. The element type is SHELL181. The outer layer of the simply supported plate was fixed all degree of freedom (DOF) as boundary condition. The corrosion was simulated as a force applied at the center of the plate, with an amplitude of 1 N. The x-axis and y-axis were within the plate plane, and the z-axis was perpendicular to the plate plane with the positive value represent a direction point up side in **Error! Reference source not found.**1. Figures 3(a, b) show that the distributions of X-direction strain and Y-direction strain and Figures 3(c, d) show the distribution of the strain intensity (showing the all directional strain level) and Z-direction displacement. Figure 3 indicated that the X strains and Y strains had a 90 degree difference. Since the FBG sensors can only measure strains in its longitudinal direction, the difference between the strain distribution of X-direction and Y-direction suggested that the installation direction of FBG sensors should be carefully designed and recorded. These strain maps in Figures 3(a, b) can be used to derive the transfer function.

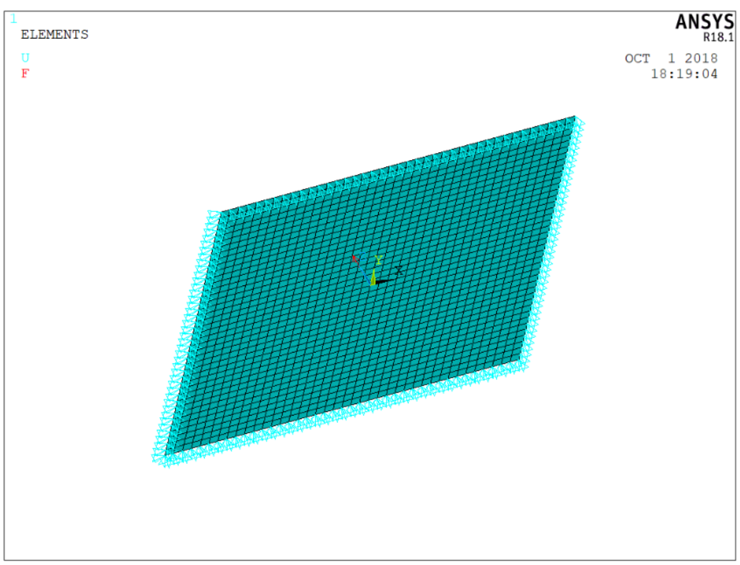
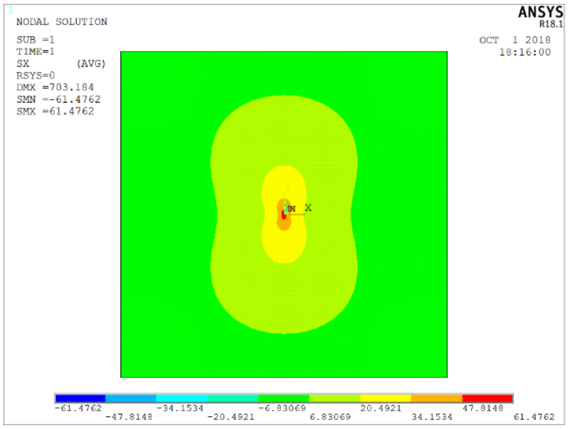
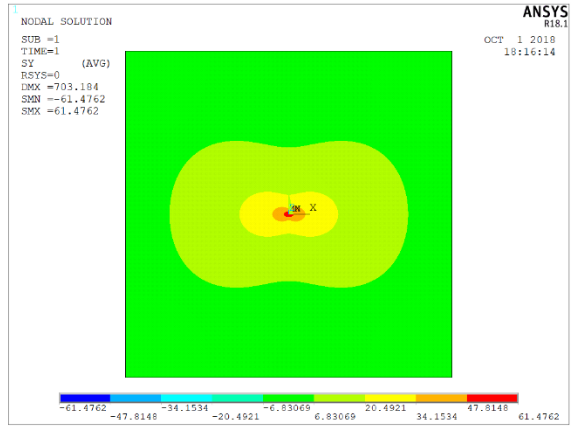


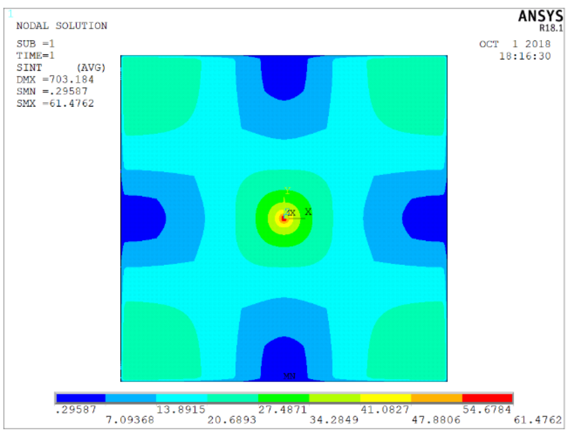
Figure 2 Simulation model of rectangular shape plate.



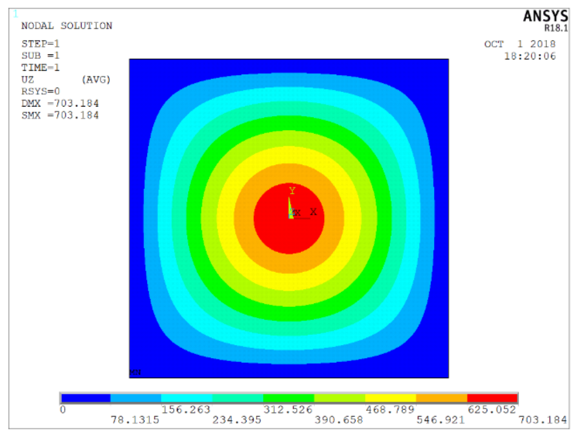
(a)



(b)



(c)



(d)

Figure 3 Simulation result of rectangular plate model (a) X-direction strain, (b) Y-direction strain, (c) strain intensity, (d) Z-direction displacement.

To validate the corrosion localization algorithm, steel plate samples with FBG sensors attached were prepared and buried in sand in laboratory to perform experimental analysis which is in progree. 3.5wt% NaCl solution was sprayed on to the sand every other day to maintain a corrosive environment. The experiment setup was shown in Figure 4, the results from the experimental analysis will be reported when it is done in near future.

Figure 4 Experiment set-up for corrosion localization.

4. Conclusions

In this paper, the corrosion location identification using FBG sensors was developed for steel structures. The 2D plate theory can be applied to identify the corrosion location using a sensor network with minimum of three embedded FBG sensors in the coating. The transfer function between the corrosion locations and the severity can be set up using FEM analysis. The proof-of-concept experimental analysis is in progress to validate the proposed corrosion assessment system could successfully locate the corrosion positions.

Acknowledgments

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