Nondestructive Testing Method for Detecting and Quantifying Steel Corrosion Using Vipulanandan Impedance Corrosion Model

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Abstract: Corrosion of steel will not only affect the exposed surfaces but also the integrity of the bulk material. Corrosion changes have to be quantified point-to-point or section-by-section to better understand the corrosion processes and also to develop mitigation methods. In this study, carbon steel corrosion was evaluated in salt water solutions using the newly developed nondestructive electrical method was to detect and quantify the surface and bulk corrosion in the field. Tests were performed to first verify the best electrical property that will be highly sensitive and represent the steel corrosion. The findings from this study indicated changes in the newly developed electrical corrosion index for the surface (2D representation) and the resistivity (second order tensor, 3D representation) for the bulk material using the Vipulanandan Corrosion Impedance model. Corrosion development in 30 inches long steel specimens were studied in the 3.5% salt solution (simulating sea water) for 500 days. The surface corrosion was quantified using the new electrical corrosion index parameter, which changed from point to point on the surface of the corroding steel and the change was over 200%. The change in the bulk resistivity along the length of the steel specimen was over 40,000 times (4,000,000%) in 3.5% salt solution compared to about 1.05% change in the weight in 10% salt solution in one year. Hence the electrical resistivity for the bulk material and the corrosion index for the surface corrosion are highly sensing parameters for detecting and quantify the corrosion in the steel.

1. Introduction:

In order to improve the maintenance operations and also extend the service life of oil and gas wells, petrochemical plants and supporting infrastructures it is very important to detect and quantify corrosion real-time (Vipulanandan et al. 2002-2018). Corrosion degrades the material by bio-chemical reactions, stress fatigue degradation, temperature cycles with the exposed environments. In addition to daily encounters with this kind of degradation, corrosion causes oil and gas well failures, fire hazards due to pipeline leakages, plant shutdowns, waste of valuable resources, loss and contamination of product, reduction in productivity and expensive maintenance. Hence, understanding the rate of steel property degradation due to corrosion is essential to designing the steel based facilities to avoid excessive deflection and failure (Decker et al. 2008). Corrosion occurs in unprotected steel structures in any location, and varies in intensity depending on the local variables, BCPST. Accelerated Low Water Corrosion (ALWC) is defined as the localized and aggressive corrosion phenomenon that typically occurs at or below low-water level and is associated with microbially induced corrosion. ALWC corrosion rates are typically 0.5 mm/side/year averaged over time to the point of complete perforation of steel plate. (Vipulanandan et al. 2012).

Major Issues and Concerns: Corrosion of materials including steel will not only affect the exposed surfaces but also the integrity of the bulk material. On the surface corrosion will be two dimensions (2D). Within the bulk steel, corrosion will be in all directions (3 dimensional-3D) and also not homogenous and hence changes have to be quantified point-to-point or section-by-section to better understand the corrosion processes. Corrosion of steel is a bio-chemo-physical-stress-thermo (BCPST) induced parallel and/or series

processes (representing varying environments and usage) and the corrosion and degradation are very much time depended. The physical properties will represent the material composition, density, shape of the sample and surface conditions. The stresses can be multi axial static and fatigue loading. Over the past 200 years several corrosion measurement methods have been developed to measure the changes in weight, rate of thickness loss, color changes, critical current density, linear polarization resistance, potential difference, ultrasonic wave travel time and many more. Unfortunately none of these methods clearly separate the surface corrosion from the bulk corrosion in all types of materials including steel.

2. Objective: The overall objective was to verify the sensitivity of the new nondestructive two probe alternative current method to detection and quantify the surface and bulk corrosion using steel specimens. The specific objectives were as follows:

3. Materials and Methods:
Steel Plates: Corrosion of carbon steel, ASTM A1018, was used for this study. Based on the manufacturer's data sheet, the iron content varied from 98.8% to 99.3% with a carbon content of 0.18%. For the weight loss and potential difference study the samples uses were 3 inches in length. For the electrical characterization of corrosion, the steel bars used were 30 inches in length 1.2 in in width and 0.16 in thickness. The specific gravity of the carbon steel was 7.86 (ASTM G1-03).

Salt Solution: Both, 3.5% sodium chloride (NaCl) salt solution is representing the sea water and for the accelerated test, 10% sodium chloride (NaCl) solution is representing the hydraulic fracturing fluids with high salt contents, were used. The steel specimens were placed in the selected solution in a plastic container for the entire duration of testing.

4. Results, Verification and Discussion:
Method 1: Visual Inspection Study: The 30 in long steel specimens placed in 3.5% NaCl solution were visually inspected on a regular basis. Images of the corroded steel surfaces long the length in three locations are shown in Fig. 5 and the corrosion was not uniform and it changed from point to point. As shown in Fig. 5, Locations #2 and #3 showed more corrosion than Location #1. For the new NDT method Locations #1 and #2 were used as the Contacts #1 and #2 respectively.
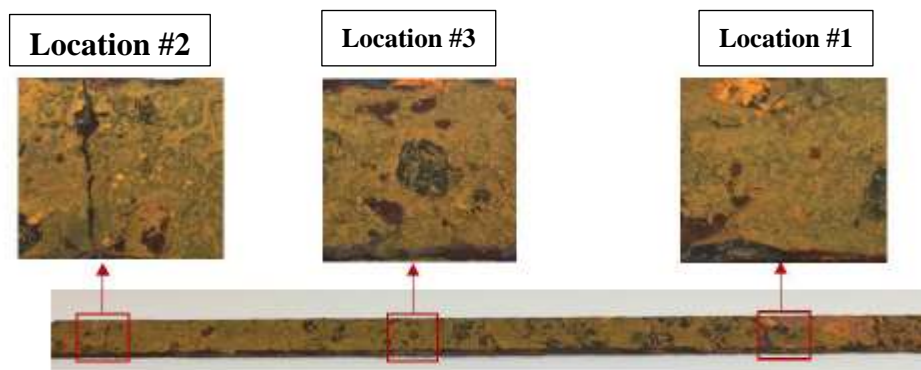

Figure 1. Visual Inspection of Surface Corrosion of Steel Specimen Corroded in 3.5 % NaCl solution for a testing period of 1 Year

Method 2: VIPULANANDAN IMPEDANCE CORROSION MODEL

New Nondestructive Two Probe Resistivity Study

The 30 in long steel specimens placed in 3.5% NaCl solution were tested regularly to detect and quantify corrosion using the two probe alternative current method (Fig. 2). The alternative current frequency was varied from 20 Hz to 300 kHz.
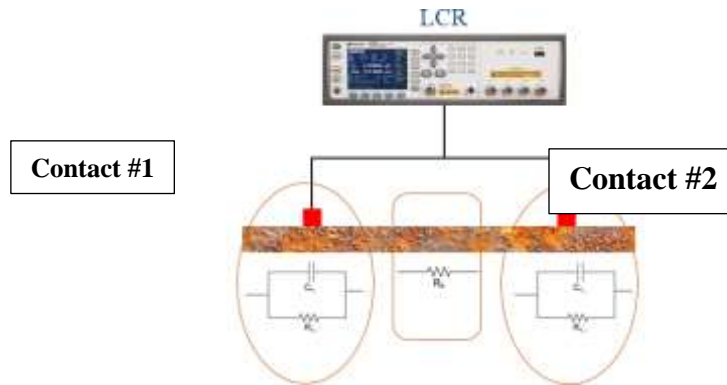
Figure 2 Testing Configuration for the New NDT Resistivity Method
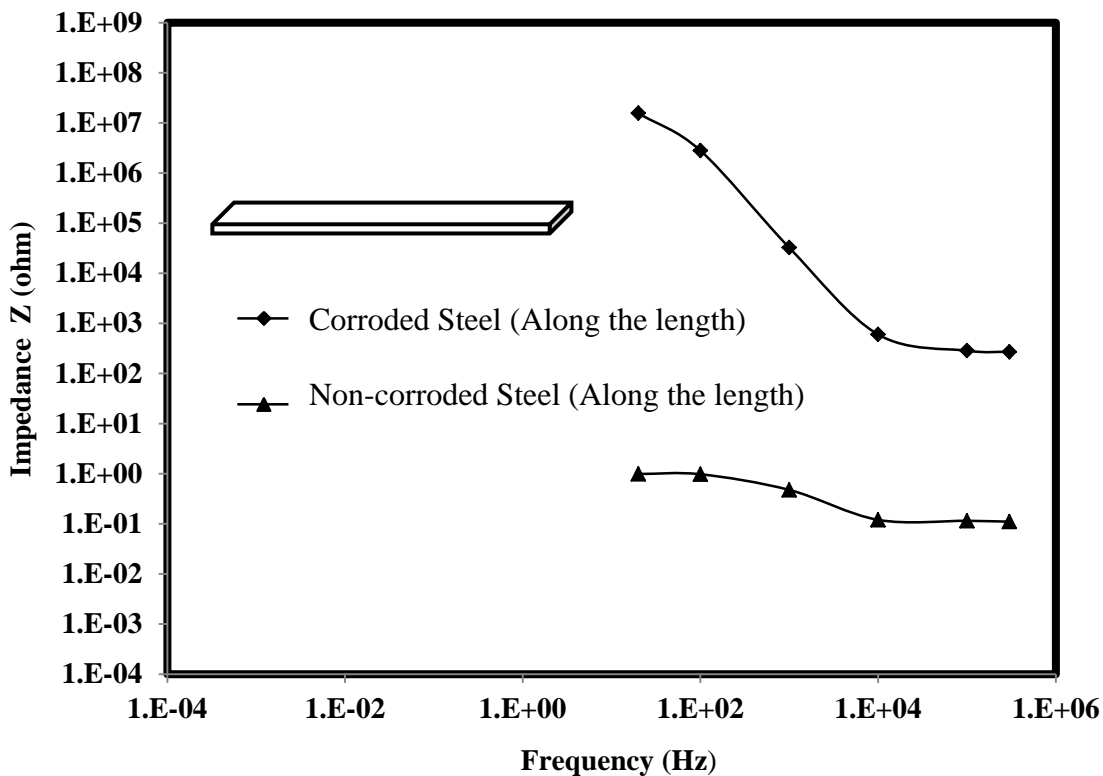
Figure 3 Impedance – Frequency Responses for Non corroded and Corroded Steel

The responses for both non-corroded and corroded steel were CASE 2 as shown in Fig.3. This is the identification of the impedance circuit for the current corrosion study.
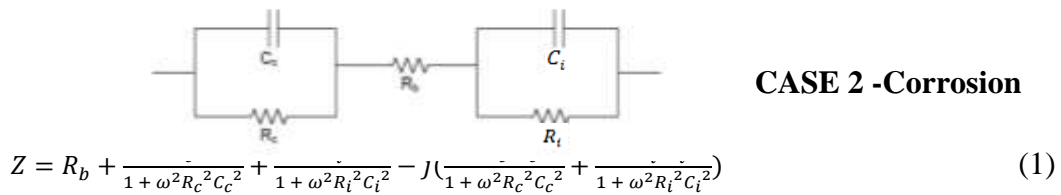

CASE 2 -Corrosion

$$Z = R_b + \frac{}{1 + \omega^2 R_c^2 C_c^2} + \frac{}{1 + \omega^2 R_i^2 C_i^2} - J\left(\frac{}{1 + \omega^2 R_c^2 C_c^2} + \frac{}{1 + \omega^2 R_i^2 C_i^2}\right) \tag{1}$$

Figure 4 Vipulanandan Corrosion Impedance Model Circuit

Based on the impedance-frequency response of the steel, CASE 2 equivalent circuit was used to determine the contact electrical resistances with time (t) at each contact locations (R_c (t) and R_i(t)) and contact capacitances (C_c(t) and C_i(t)) on the surface of the steel specimen. During the impedance characterization at least 15 data were collected for each test and the data was used to determine the five unknowns (Rb, Rc, Ri, Cc, Ci) in the Eqn. (1) using the least square method.

The resistance (R) and capacitance (C) for a material between two points of measurements is defined as:

$$R = \rho K = \rho \frac{L}{A} \tag{2}$$

$$C = \epsilon \frac{A}{L}, \tag{3}$$

where A = cross-sectional area, L = distance between the two probes, ρ = resistivity of the material, ϵ = absolute permittivity of the material. The product of equations given in (2) and (3) results as

$$RC = \rho\epsilon. \tag{4}$$

Since ρ and ϵ in equations (2) and (3) are material properties, RC at the point of contact is also material property and will be referred as electrical corrosion index. This parameter can be used in characterizing the surface corrosion at each point. The initial resistivity of non-corroded steel ρ_0 =1.59 E^{-07} Ωm (Douglas, 1991) and R_o is the initial resistance measure and $\Delta R(t)$ is the change in resistance (R_b(t) –R_o).

4a. Bulk Corrosion: The impedance-frequency measurements were performed on a weekly basis for 500 days. The frequency range used was from 20 Hz to 300 kHz. The R_b(t) increased non-linearly with time as shown in Fig. 5. After 500 days of corrosion, the bulk R_b(t) along the length of the corroded steel between Contact #1 (Location #1) and Contact #2 (Location #2) (2 feet apart, Fig 1) increased from 0.131Ω to 5810 Ω which showed a change of 44,351 (4,435,100 %). The resistivity of the corroding steel changed from 1.59 x10^{-7} Ωm to 7.05 x10^{-3} Ωm along the 2 feet length during the testing period of 500 days, the change is 44,340 times (4,434,000%) which indicated the resistivity was a highly sensing material property to represent the corrosion level within the bulk steel. The change in the electrical resistivity, a material property, is part of the corrosion of the steel, but could not be quantified by any other standard test methods.
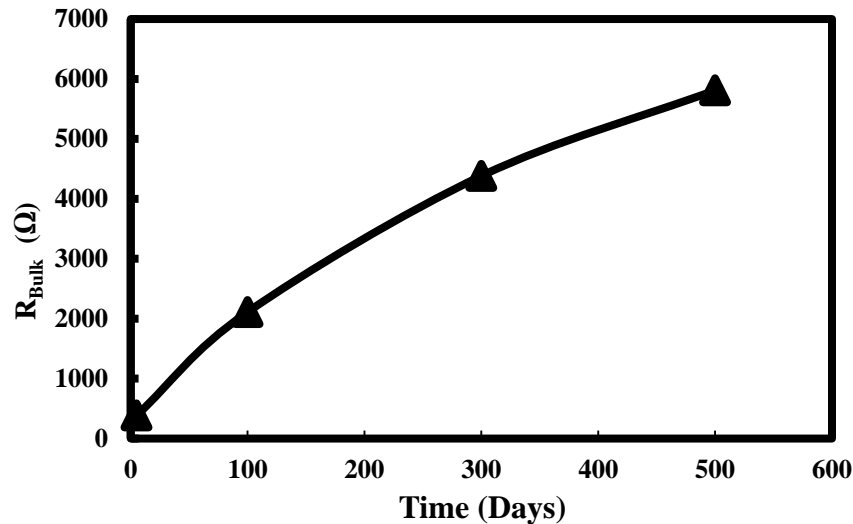
Figure 5. Variation of Bulk Resistance with Time in 3.5% Salt Solution (500 Days)

4b. Surface Corrosion (Contact Corrosion Index (RC)): The variation of contact corrosion index, material property (R*C), for the corroding steel at Contact #1 in 3.5 % NaCl solution is shown in Figure 6. From the Fig.1, the rust material on the surface of the corroding steel increased with time. The $R_C C_C$ at Contact #1 increased from 5.97 E^{-07} ΩF to 2.24 E^{-06} ΩF during the testing period of 500 days, 2.75 time (275%) increase. The Contact #2 corrosion index parameter $R_i C_i$ increased from 8.72E-07 ΩF to 2.77E-06 ΩF as shown in Fig. 6. The contact index parameter increased by 2.2 times (220%). The corrosion index parameter after 500 days of testing at Contact #2 was higher than Contact #1, by about 24%. The corrosion index clearly quantified the surface conditions at the measured two points, and the two points were not the same and also the visual inspection showed the difference on the surface.

5. Conclusions:

In this study the new nondestructive rapid detection and quantification of corrosion was verified and compared with some of the standard test methods using carbon steel. Base on this study following conclusions are advance:

1. The new nondestructive test separated the surface corrosion from bulk corrosion. The method clearly identified resistivity to be a highly sensing material property to characterize the bulk corrosion in steel. The bulk resistivity increase in corroding steel in 3.5% salt solution in 500 days was over 4,430,00%, much more sensitive than the weight loss method and potential difference methods.
2. Also a new corrosion index was developed and verified to characterize and quantify the surface condition on the corroding steel. The corrosion was different at the two tested points and the visual observation verified it. The corrosion index increased in corroding steel in 3.5% salt solution in 500 days was over 200%.
3. Based on the material property changes, the surface corrosion was less than the bulk corrosion based on the new test method.
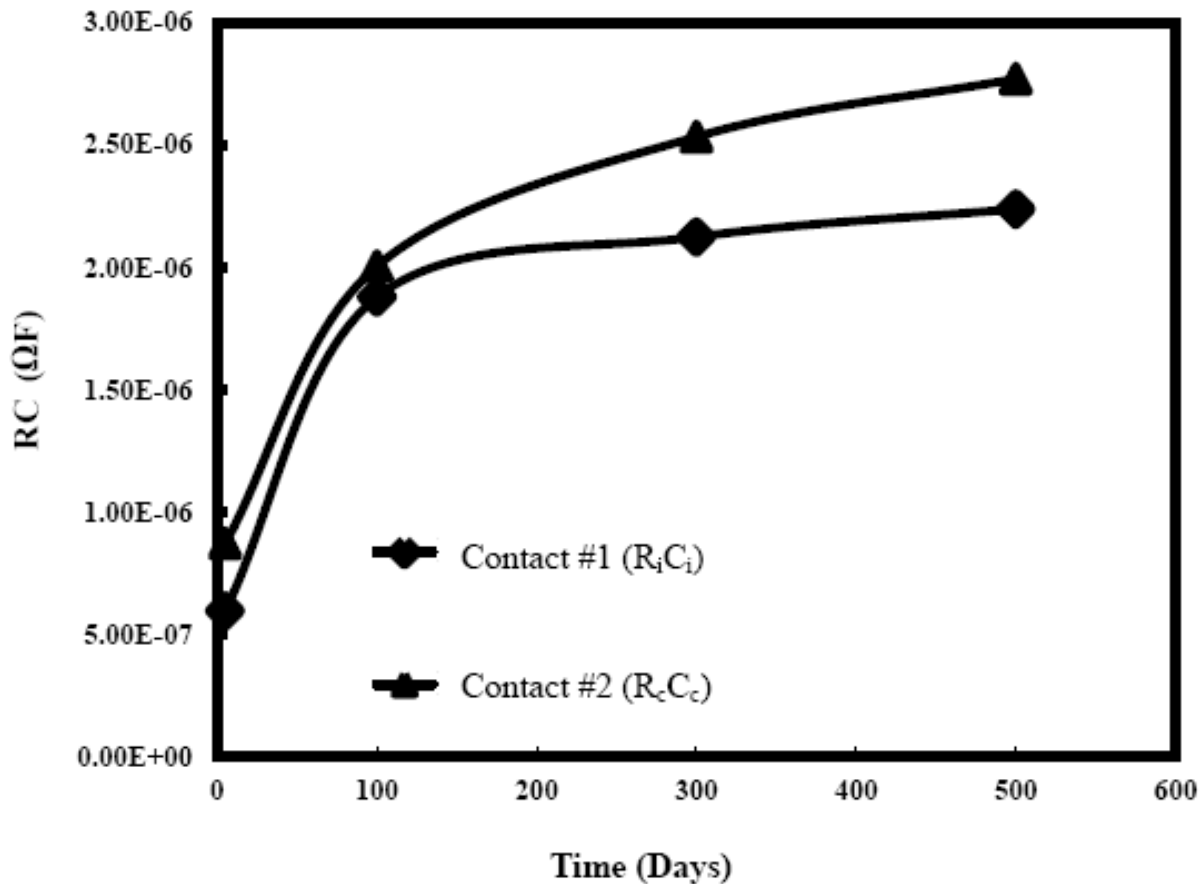
6. Acknowledgements:

Figure 6.
Corrosion Index Parameters for the Two Contact Locations on the Corroding Steel Surface in 3.5 % NaCl Solution

7. References:

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