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THE EFFECT OF CORROSION ON THE STRUCTURAL RELIABILITY OF CARBON STEEL SUBSEA PIPELINE LOCATED IN NIGER DELTA NIGERIA

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ABSTRACT

Corrosion is one among the main causes of structural degradation especially in seawater. This study is aimed at predicting the effect of corrosion on the structural reliability of carbon steel Subsea Pipeline. This was achieved by using the corrosion model proposed by Qui and Cui to predict the corrosion wear and corrosion rate of the carbon steel plate immersed in seawater. The model result showed three stages of the corrosion process namely; no corrosion, corrosion accelerating and corrosion decelerating. No corrosion indicates the effectiveness of the coating; corrosion accelerating is the point at which the coating life is equal to zero. The corrosion rate at this point increased rapidly while corrosion decelerating is the point at which the corrosion rate reduced gradually due to corrosion wastages (material) on the surface of the metal preventing a direct contact with the environmental factors. The plot also showed that the maximum corrosion rate occurred in the 8th year (0.94816mm/yr). A formulated limit state function was developed to predict the structural reliability of carbon steel as a result of corrosion defect using a time dependent approach. The First Order Reliability Method was used in the structural reliability estimation of carbon steel. The results show that, the reliability of the structure due to corrosion defect decreased with time from (4.5643 to 3.8206) and also the probability of failure increased with time from (0.0000025 to 0.000067) over a period of 24 years. Therefore, the effect of corrosion on the structural reliability of a steel plate is majorly a function of material loss over time. The result validation between experimental thickness loss and the predicted corrosion wear shows a standard deviation of 0.3319 which is within the acceptable standard deviation of (± 2) according to statisticians.

Keywords: Pipeline, Corrosion, Reliability, Steel, Structure.

I. INTRODUCTION

Corrosion is as old as the earth and it is commonly called or referred to as rust. In a corrosive environment like seawater and soil, corrosion is inevitable no matter the level of protection in place. Corrosion is defined according to NACE [1], as the deterioration of a material, usually a metal that results from a reaction with oxygen in its environment, causing the degradation of its component. The corrosion of metals is an electrochemical process that involves the loss of material from one location virtually shown by the accumulation. A structure can be said to be a building or other object constructed from several parts. Offshore structures are the various kinds of engineering facilities, which are constructed and installed in the coastal regions or open sea for the maintenance of its continuous operations and for the exploitation of various marine resources. These structures can be classified into three types namely; the fixed structures, movable structures, and complimentary structures. Examples are the Jack-up platform, semi-submersible platform, floating and drilling ship, subsea pipelines, etc. Structural reliability refers to the ability of any structure been able to fulfill its intended function under given circumstances over a specified period without failure. Steel is one of the widely used materials for marine constructions more than 70 percent of offshore structural components are made up of steel materials. Most of the structural deterioration in a marine environment is majorly caused by corrosion-related problems. Corrosion can lead to failures in plant infrastructure and machines which are usually costly to repair, costly in terms of lost or contaminated product, in terms of environmental damage, and possibly costly in terms of human safety. Corrosion of steel structure in a marine environment follows an electrochemical process that requires the simultaneous presence of seawater and oxygen. Pitting corrosion has been regarded as one of the most hazardous forms of corrosion of marine and offshore structures among the various types of corrosion [2][3]. Predominantly, most offshore structures are constructed specifically for the exploitation of oil and gas deposits deep under the seabed. While applications may vary, all will have exposure to the effects of salt-water corrosion, powerful sea currents, and waves often dictated by the tides and strong winds. For reliability estimation and life cycle analysis, studying critical infrastructural systems and degradation of structures are essential in the analysis. This is important especially for structures located in corrosive environments with changing environmental conditions (high/low temperature, humidity, etc.) or subjected to frequent extreme events (e.g., earthquakes). In practice, changes in structural conditions are not taken into consideration during structural design (e.g., deterioration) over time, which would impair the reliability. "To Fathom the damage accumulation mechanisms, it is necessary to take into account the time-dependence of the structural properties as a result of the dynamic interaction with the external environmental demands" [4].

The aim of this research work is to predict the effect of corrosion on the structural reliability of carbon steel subsea pipeline located in the Niger Delta region of Nigeria. In order to achieve this aim, the following specific objectives were met; to analyze the various forms of corrosion, to predict the corrosion rate and corrosion wear of carbon steel, to predict the effect of corrosion on the carbon steel structural reliability and Development of a MATLAB code for the prediction of corrosion rate, corrosion wear and for the estimation of reliability index and probability of failure of carbon steel.

A. **Forms of Corrosion**:

- **Uniform or General Corrosion**; This is basically a global corrosion occurring uniformly over the exposed surfaces of the metal. Typical example is the corrosion of offshore structures in seawater. This is type of corrosion attacks the exposed surface of the metal, spreads rapidly, it is easily detected and commonly seen as rust on the surface of the metal. This type of corrosion is usually the least expensive to deal with in industry. It's pretty consistent, and rates can be rapidly determined by exposing a sample to the outside world [5].
- **Galvanic Corrosion;** The difference in potential induces a flow of electrons, or current, between two metals when they are paired electrically, either through direct contact or an electrolyte. Between the two metals, a galvanic couple forms, with one metal acting as the anode and the other as the cathode. The anode, or sacrificial metal, corrodes and deteriorates more quickly than it would otherwise, while the cathode deteriorates more slowly [6]. The oxidation potentials of the two metals are used to determine the anode and cathode in a galvanic cell. The anode's oxidation potential is still greater than the cathodes. Galvanic corrosion is thus reduced by choosing metal pairs with comparable oxidation potentials, isolating dissimilar metals from one another, and isolating the anodic metal from the electrolyte. The use of a plastic isolating bushing in a fitting that connects two kinds of metal pipe, such as copper and steel, is an example of isolating dissimilar metals from each other. Also, there is no electrolyte if all moisture is removed, so a galvanic cell cannot exist.
- **Crevice Corrosion;** Is a localized, concentrated form of corrosion that occurs in a crack or gap between metal to metal or metal to non-metal surfaces. A corroding agent is present in the crevice, and one portion of the crack is exposed to it. It can be found in cracks, holes, and crevices in poorly gasket pipe flanges; lap joints, rivet and bolt heads, and everywhere else where small quantities of solution can remain motionless. The conventional corrosion cell, an oxygen concentration cell, is where crevice corrosion starts. The accumulation of acidic hydrolyzed salts in the crevice region drives the growth of the corrosion cell as oxygen is depleted. Concentration gradients may also cause this type of corrosion (due to ions or oxygen). The accumulation of chlorides in crevices can exacerbate the damage. Materials, alloy composition, and metallographic structure all have an impact on crevice corrosion. pH, oxygen concentration, halide concentrations, and temperature are examples of environmental factors. Surface roughness, geometrical characteristics of crevices [7].
- **Pitting Corrosion;** Pitting is a troublesome form of corrosion. It can cause a failure with very little metal loss. Pitting is an extremely localized form of attack that causes fast diffusion of the wall thickness, the holes that pitting cause can be very small in diameter. The fact that failure can occur with very little metal loss and with just one little area affected is what makes this type of corrosion so difficult to detect and prevent. Pitting in most cases is simply initiated by the chemical nature of the environments e.g. salt water, chloride bleaches, brackish water, and reducing inorganic acids. Metals such as stainless steel are prone to pitting attack [8].
- **Inter Granular Corrosion;** Inter granular attack is a form of corrosion that occurs preferentially at some point of higher energy usually the edges of individual grains that makes up the metal due to atomic disarray.

- **Microbiologically Induced Corrosion (MIC);** MIC occurs as a result of the interaction of bacteria with metals and metal alloys. Basically, it is initiated by microorganisms especially by chemoautotroph. It is applicable to both metals and non-metal materials, with or without the presences oxygen. Sulfate-reducing bacteria are active in the absence of oxygen (anaerobic); they produce hydrogen sulfide, causing SSC. In the presence of oxygen (aerobic), iron can be oxidized directly to iron oxides and hydroxides by some bacteria. Biogenic sulfide corrosion produce from sulfuric acid formed from the oxidization of Sulphur by bacteria. Localized corrosion can be formed due to concentrated cells formed in the deposits of corrosion products.

Steel pipes near the low water tide mark in saltwater media, is affected by accelerated low-water corrosion is a form of MIC but very aggressive form in nature. It has the smell of hydrogen sulfide when treated with an acid. Corrosion rates can be very high and design corrosion allowances can soon be exceeded leading to premature failure of the steel pile [9]. Coated Piles combined with the application of cathodic protection installed at the time of construction are not prone to Accelerated Low Water Corrosion (ALWC). For uncoated piles, sacrificial anodes can be locally applied to affected areas to mitigate the corrosion or a complete installation of the sacrificial anode system. altered areas can be treated by producing a calcareous deposit, which acts as a protective layer on the metal surface thereby shielding it from further attack. Calcareous deposits are formed when chlorine is applied or produce electrochemically to kill bacteria.

- **Erosion Corrosion;** This type of corrosion occurs when the protective layer of oxide on the surface of the metal is dissolved or removed by the action of wind or water thereby exposing the underlying metal to corrode. The acceleration of corrosion due to relation motion between the metal surface and the corrosive fluid is known as the erosion corrosion. It is normally used to refer to instances or corrosion phenomenon where the mechanical component is associated with fluid wear due to extreme fluid flows. The fluid acts to remove the formed corrosion products on the surfaces thereby reducing the beneficial effect of passive or protecting surface film thus exposing the metal surface to the corrosive environment. It has the following attributes, short time periods to unexpected failures grooves, valleys in the metal surface, waves and valleys in the metal surface. It is propagated by impingement of high velocity fluids on the surface of the metal, high fluid velocity and turbulent flow. It is Very common in pipelines. This can be minimized by the reduction of the above-mentioned factors or parameters.
- **Stress Cracking Corrosion;** The phenomenon of SCC can be defined as the occurrence of macroscopic brittle fracture of a normally ductile metal due to the combined effect of stress and some specific environment. The environment need not be chemically aggressive in that high general dissolution rates are not required and the phenomenon is complicated by the fact that many different mechanisms can give rise to such cracking. It is often difficult to differentiate between the roles of anodic dissolution and hydrogen absorption on cracking. SCC is the formation of cracks where localized corrosion has combined with steady tensile stresses in the metal to cause the damage. This effect has been seen in low pressure turbine disks and blade roots and also in boiler tubes. The hostile electrolytic environment can attack particular metals or alloys, for example, chloride and stainless steels. Excessive SCC can cause failure, typically sudden and without warning [9]. Two general theories are used to explain the SCC mechanism. The electrochemical theory centers on galvanic cell action in the grains and between grain boundaries. The stress absorption theory suggests that SCC proceeds by weakening the cohesive bonds between surface metal atoms. The source of tensile stresses may originate during manufacture or from in-service conditions. Lowering tensile stress by decreasing applied load, stress relieving or introducing residual compressive stress through procedures such as shot preening will minimize SCC. SCC is also minimized through chemical control of the water in the system. Furthermore, applying coatings to reduce or eliminate contact between the metal and the hostile ion helps to reduce SCC.

II. METHODOLOGY

In order to predict the corrosion rate and corrosion wear, Qui and Cui corrosion model shall be employed and also with a formulated limit state function using a time dependent approach with the application of First Order Reliability Method (FORM) for the estimation of the reliability index and probability of failure.

For the purpose of this research, 24 years' corrosion data shall be used and the stress acting on the pipeline shall be limited to hoop stress and leakage failure mode.

III. MODELING AND ANALYSIS

A. Qui and Cui (9) Corrosion model;

$$r(t) = \left\{ d_\infty \frac{\beta}{\eta}\left(\frac{t-T_{St}}{\eta}\right).exp\left\{-\left(\frac{t-T_{St}}{\eta}\right)^{\beta}\right\}\right\} \quad 0 \le t \le T_{St} \quad T_{St} \le t \le T_L \qquad (1)$$

$$d(t) = \left\{ d_\infty \left\{1 - exp\left[-\left(\frac{t-T_{St}}{\eta}\right)^{\beta}\right]\right\}\right\} \quad 0 \le t \le T_{St} \quad T_{St} \le t \le T_L \qquad (2)$$

Where,

r(t)= Corrosion rate

d(t)= Corrosion wear

d_∞ = Long term thickness of corrosion wastage

T_{St}= Instant at which pitting corrosion will start

T_L = Life of the structure

Equation (1) can be re-written as;

$$-In\left(-In\left(1-\frac{d(t)}{d_\infty}\right)\right) = \beta In\eta - \beta In(t - T_{St}) \qquad (3)$$

Let us define

$$y = -In\left(-In\left(1-\frac{d(t)}{d_\infty}\right)\right) \qquad (4)$$

$$x = In(t - T_{St}) \qquad (5)$$

$$A = \beta In\eta, \quad B = -\beta$$

Then $y = A + Bx$

Where β, η, d_∞, T_{St} are the four random deterministic parameters of the model. Since the relationship between A and B is now linear, linear regression method is employed in order to get the values of β and η. While T_{St} is taken as 1.40. d_∞ is obtained from the equation below;

$$d_\infty = d_{MAX} + D_d \qquad (6)$$

d_{MAX} is the maximum thickness loss or wear in the distribution and D_d is subjectively chosen as $\frac{d_{MAX}}{100}$.

Since we know the values of d_∞ and T_{St} using equation (3) and (4) we generate the values of x and y, A and B before finally getting β and η using the formulas provided.

$$B = \frac{L_{xy}}{L_{xx}}, \qquad A = \bar{y} - B\bar{x} \qquad (7)$$

The linear regression coefficient R is as follows;

$$R = \frac{L_{xy}}{\sqrt{L_{xx}L_{yy}}} \qquad (8)$$

Where

$$x = \frac{1}{n}\sum x_i, \qquad y = \frac{1}{n}\sum y_i,$$

$U_{xy} = \frac{1}{n}\sum x_i y_i,$ $U_{xx} = \frac{1}{n}\sum x_i^2$

$U_{yy} = \frac{1}{n}\sum y_i^2,$ $L_{xy} = U_{yy} - \bar{x}\bar{y},$

$L_{xx} = U_{xx} - x^2,$ $L_{yy} = U_{yy} - y^2$

And so the values of β and η are as follows;

$$\beta = -B, \qquad \eta = \exp\left(\frac{A}{\beta}\right) \tag{9}$$

Table 1: Corrosion Data Obtained

Time (yr)	Wall thickness loss (mm)
2	1.15
3	1.243
4	1.256
5	1.35
6	1.37
7	1.40
8	1.425
9	1.45
10	1.49
11	1.53
12	1.545
13	1.56
14	1.59
15	1.61
16	1.63
17	1.65
18	1.69
19	1.71
20	1.721
21	1.73
22	1.742
23	1.765
24	1.782
25	1.81

Table 2: Result of the model parameters

Parameters	Result
d_∞	1.8281
T_{St}	1.40
β	0.368003
η	1.760866

B. Material Used;

Carbon steel ASTM A36 grade is used.

$E = 200$ GPa

$\sigma_y = 250$ MPa

UTS =400-550Mpa

Subsea Pipeline characteristics;

Pipe size = 254mm

Schedule 120

Pipe length= 3500m (900m was used in the analysis)

Nominal wall thickness =21.4mm

Internal diameter = 230mm

Outer diameter = 273mm

C. Environment

Seawater with a pH of 7.25, located in the Niger delta region of Nigeria

D. Reliability Estimation;

In reliability analysis, the resistance (strength capacity) and the loadings acting on the steel structure are the two important parameters needed in reliability estimation. Steel plates are the main structural component in pipelines and many other offshore structures. Assuming that the plate element is subjected to a uniaxial compression and undergoing pitting corrosion (leakage failure mode is considered), the limit state can be expressed as;

$$G(t)=\sigma_{u(t)} - \sigma_{xav} \qquad (10)$$

Where;

$\sigma_{u(t)}$ = The ultimate strength at time t (capacity or resistance) and

σ_{xav} = Axial compressive stress (Load)

Assuming that the loads are normally distributed and are independent, then the ultimate strength of a plate element without considering the effects of initial deflection and residual stresses can be calculated by [10]

$$\frac{\sigma_u}{\sigma_y} = \begin{cases} 1 & \text{If } \lambda \le 1.9 \\ \left\{0.08 + \frac{1.09}{\lambda} + \frac{1.26}{\lambda\text{^}2}\right\} & \text{If } \lambda > 1.9 \end{cases} \qquad (11)$$

Where;

$$\lambda = \frac{b}{h(t)}\left(\sqrt{\frac{\sigma_y}{E}}\right) \qquad (12)$$

h(t) = The thickness of the plate at time t

b = The length of the plate.

σ_y = yield strength of carbon steel

E = Young Modulus

The effect of corrosion on the steel structure undergoing pitting corrosion; the remaining thickness h(t) of a plate of initial thickness d_o is given by [11]

$$h(t) = h_o - h_p(t) \qquad (13)$$

where

hp(t) is the highest pit depth at time t.

The First perforation is caused by the first deepest pit which is a function of the highest probable pit depth. Therefore, this happens as h(t)→0.

Then the reliability index is given as;

$$\beta = \frac{\mu_G}{\mu_G} = \frac{\mu_{\sigma_U} - \mu_{\sigma_{xav}}}{\sigma_{\sigma_U} - \sigma_{\sigma_{xav}}} \quad (14)$$

Where

$\mu_{\sigma_U} =$ Mean of the Ultimate strength capacity of mild steel at time t

σ_{σ_U} = Standard deviation of Ultimate strength capacity of mild steel

$\mu_{\sigma_{xav}}$ = Mean of the Axial compressive stress acting on the mild steel plate

$\sigma_{\sigma_{xav}}$ = Standard deviation of the Axial Compressive stress

The probability of failure according to first order reliability method is given by;

$$P_F = 1 - \boldsymbol{\Phi}(\boldsymbol{\beta}) \quad (15)$$

E. Hoop Compressive Stress Calculation, $\sigma_{xav} = \sigma_h$

The force per unit area acting on the pipe's wall thickness

Where

$\sigma_{h=}$ hoop stress

$$\sigma_{h=} \frac{P_i D_i - P_o D_O}{2t} \quad (16)$$

Where

$P_i = pipe\ internal\ pressure(operating\ pressure) = 20.5Mpa$

$P_o = External\ pressure\ (hydrostatic) = 301657.5$

$t = wall\ thickness = 21.4mm$

$D_i = internal\ diameter\ of\ pipe = 230mm$

$D_O = outer\ diameter\ of\ pipe = 273mm$

$D_m = \frac{D_i + D_o}{2} = 0.2515m$

$P_o = \rho g h$

Where,

$\rho = salt\ water\ density = 1025kg/m^\wedge 3$

$g = Acceleration\ due\ to\ gravity = 9.81m/s^\wedge 2$

$h = water\ depth = 30m$

$P_o = \rho g h = 301658N$

$\sigma_{h=} \frac{(P_i - P_o)D_m}{2t} = 119.86Mpa = 120Mpa$ with a standard deviation of 25 (Type 1 extreme)

The probability of failure according to first order reliability method is given by;

$$P_F = 1 - \Phi(\beta) \quad (17)$$

IV. RESULTS AND DISCUSSION

The following results were obtained from using equation (1) and (2). It shows that the corrosion rate of the carbon steel plate increases with time when being in saline medium. Similarly, tables 3 and 4 depict similar characteristics for corrosion rate and wear.

Table 3. Corrosion rates from Model

Time (year)	Corrosion rates
2	0.21589
3	0.46565
4	0.66385
5	0.80623
6	0.89591
7	0.94029
8	0.94816
9	0.92818
10	0.88807
11	0.83438
12	0.7724
13	0.70627
14	0.63913
15	0.57324
16	0.51021
17	0.45106
18	0.39641
19	0.34656
20	0.30155
21	0.26127
22	0.22552
23	0.19397
24	0.16632
25	0.14219

Table 4: Corrosion Wear

Time (year)	**Corrosion wear (mm)**
2	0.22939
3	0.54955
4	0.80559
5	1.01035
6	1.17412
7	1.30508
8	1.40982
9	1.49358
10	1.56057
11	1.61415
12	1.65699
13	1.69126
14	1.71866

15	1.74058
16	1.75811
17	1.77212
18	1.78333
19	1.7923
20	1.79947
21	1.8052
22	1.80972
23	1.81345
24	1.81639
25	1.81873

In Figure 1, the graph shows that the overall corrosion process is divided into three stages namely; no corrosion, corrosion accelerating, and corrosion decelerating. No corrosion is the point where the corrosion control system is still very effective (form the 1st year to the 2nd year). Corrosion accelerating starts from (2nd year to the 8th year), when the corrosion control system has completely lost its potency (I.e. coating life equals zero). At that point corrosion becomes very rapid until it gets to a saturation point where it becomes almost constant or starts decelerating. Corrosion decelerating (from 9th year to the 25th year) is due to corroded materials formed on the metal surface thereby preventing oxygen and other corrosion enhancing factors from having direct contact with the steel surface. It follows that the rate of corrosion increases to a point of maximum corrosion (I.e. where the impact is felt more) then it gradually decelerates to the point of failure.

In Figure 2, the graph of corrosion wear against time exhibit a bilinear behavior. There was a massive increment in material loss from the 2nd year to the 15th year due to the corrosion control system losing its complete effectiveness. Then from the 16th year, there was material build up on the steel surface and it began to flatten out at that point. and as a result the accumulative wear follows almost constant rate down to the 24th year.

Figure 3, shows the graph of reliability index against time. It shows a degradation curve which decreases with time. Reliability is the ability of a structure or material to fulfil its sevice or design life without failure over a specified period of time. Here the reliability index decreases with time from 4.5643 to 3.8206 over a period of 24 years due to the reduction of the thickness of the steel as a result of corrosion. This result shows that for the pipeline in the case of leakage failure can be in a safe condition for up to 25years in that environment.

Fig 4, the graph shows that the probability of failure increases significantly with time. The probability of exceeding a limit state within a given reference time period is defined as probability of failure. The probability of failure increased from 2.50*10^ -6 to 6.657*10^-5 over a period of 24 years due to thickness loss.

Figure 5, shows that the corrosion wear increased logarithmically with time, from the 2nd year to 15th year before it starts flattening out. This is due to the formation of corroded materials on the surface steel thereby hindering further reaction with the environmental factors. While the measured thickness loss has a linear progression with time. The measured thickness has a mean of 1.498125 and a standard deviation of 0.28243 while the predicted corrosion wear has a mean of 1.474178 and a standard deviation of 0.438085 which is close to the experimental values. now the standard deviation between each distribution is 0.3319, which is within the standard acceptable standard deviation (± 2) as stated by Statisticians. This shows how effective the model is by giving a true picture of reality.

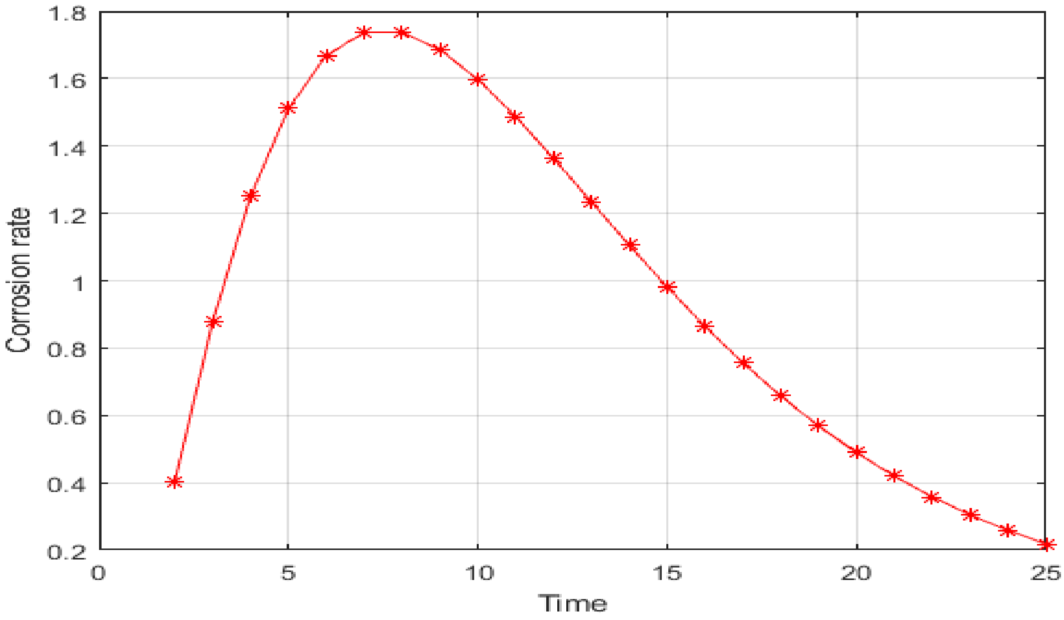

Figure 1: Corrosion Rate against Time

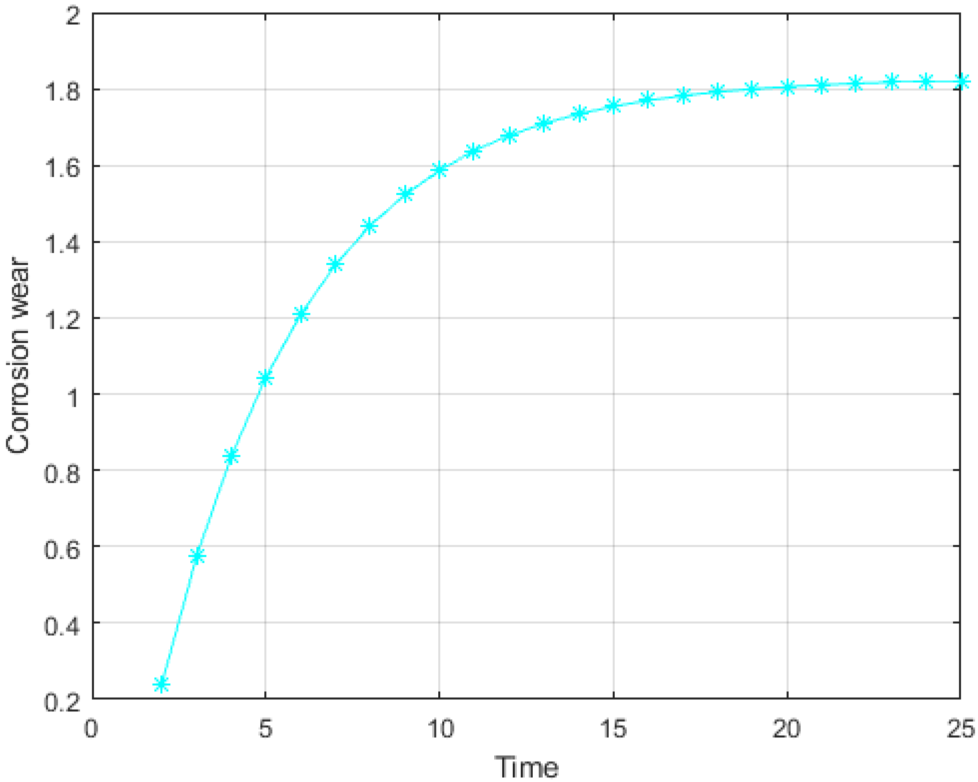

Figure 2: Corrosion Wear against Time

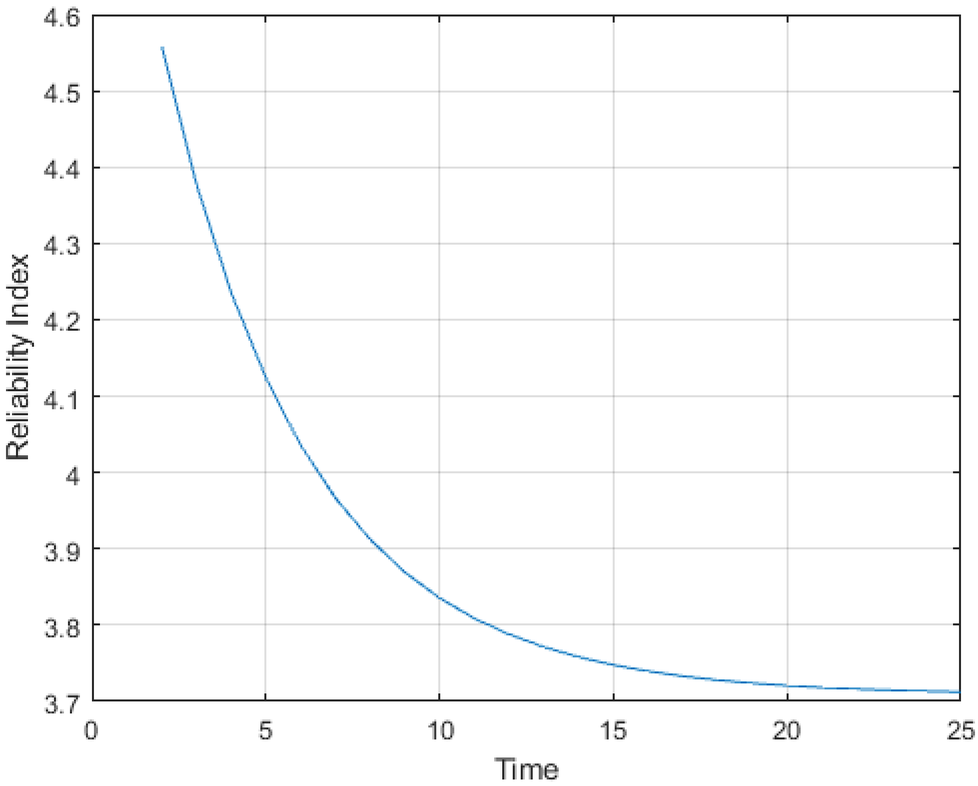

Figure 3: Reliability Index against Time

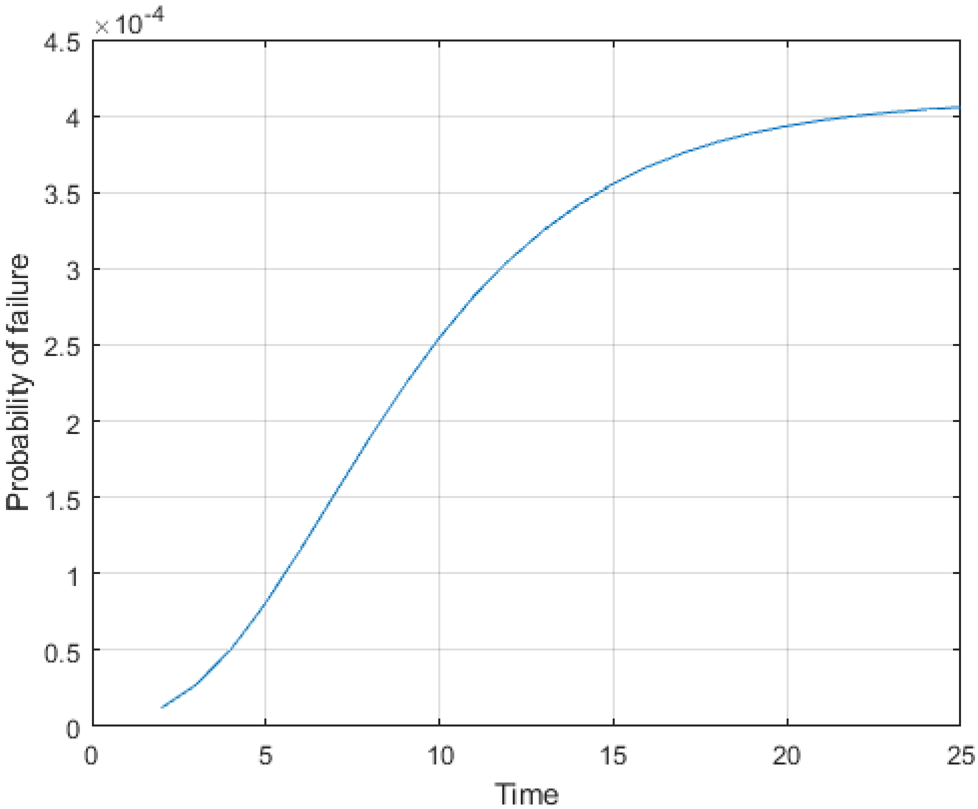

Figure 4: Probability of failure against time.

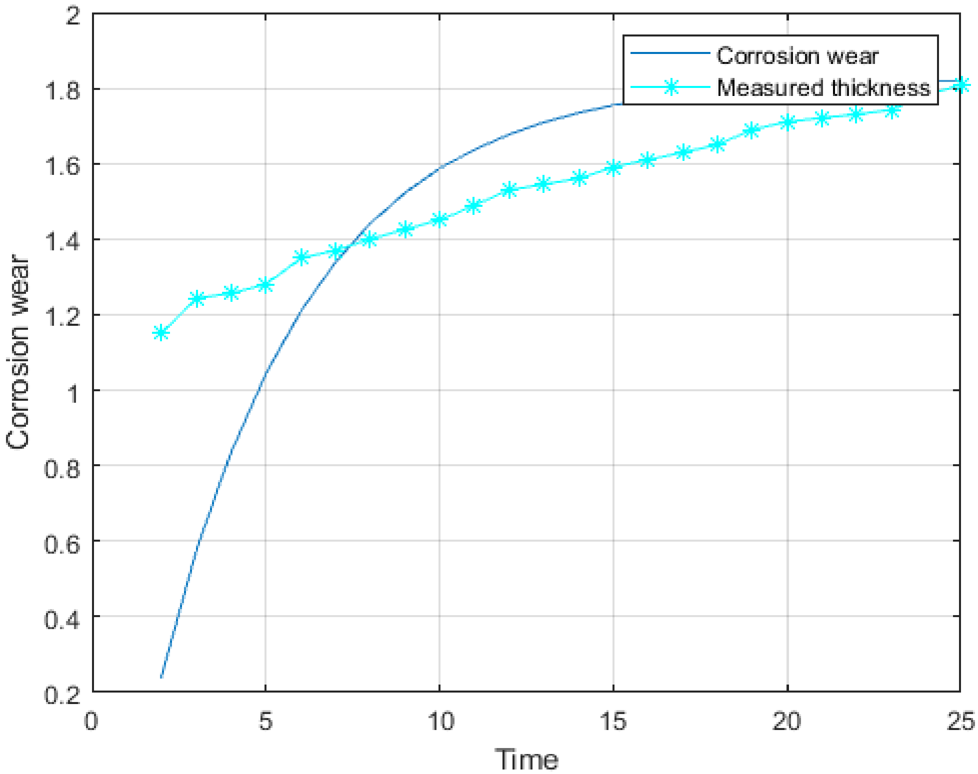

Figure 5: Measured Thickness Loss and Corrosion Wear against Time.

V. CONCLUSION

This research work has successfully shown the effect of corrosion on the structural reliability of carbon steel in seawater. This analysis was done using a transmission subsea carbon steel pipeline as a case study located in Niger Delta region of Nigeria. The objectives were achieved by using Qui and Cui, (2003) corrosion model to predict the corrosion rate and wear, a formulated mathematical limit state function using a time dependent approach with the application of first order reliability method to estimate the reliability index and probability of failure of the carbon steel structure. A MATLAB code was also written to carry out the analysis. The result showed that the reliability index decreased significantly with time while the probability of failure increased with time. It was established that the reliability of steel structures due to the effect of corrosion is a function of the material loss over time and the loadings acting on it. Also, the result of the corrosion model showed three stages of the corrosion process namely; no corrosion, corrosion accelerating and corrosion decelerating. It is worthy to note that this research considered only hoop stress and leakage failure mode. Further research could be carried out on other forms of stresses and failure mode.

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