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Original Research Article

Stochastic Evaluation of Structural Steel Plates Corrosion in Offshore Platforms

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Abstract

This study presents the structural reliability of steel plates on offshore platforms exposed to corrosion during their design period and beyond. The reliability-based design of steel plates exposed to corrosion was carried out with First Order Reliability Method coded in a computer based program, (FORM 5) and a Finite element method in a software (ABAQUS). The rate of corrosion of the steel plates was determined using a standard expression for extreme marine environment. From the results obtained using FORM 5, the safety indices ranged from 1.18 to 11.0, and a non-linear relationship exist between safety indices and thickness for different parameter variations. However, it was also noted that the design formulation is robust enough to exceed the design life prediction in the code by about 20% of the current prediction.

Keywords: Steel Plates, FEM, Corrosion, Offshore Platforms, Resistance Moment.

1.0 INTRODUCTION

Reducing the lifecycle cost and lifecycle environmental impact of civil engineering infrastructures is one of the significant issues in construction [1]. It is necessary to consider not only efficiency and low cost toward constructing but also the lifecycle assessment (LCA) including the stages of construction, service and maintenance and demolition and reconstruction of engineering structures. The exposure to aggressive media of steel or alloy stability depends on the protective properties of the surfaced film formed [2] because its chemical composition, conductivity, adherence, solubility, hygroscopicity and morphological characteristics which determine the film capacity to work as a controlling barrier. The process of chloride-induced corrosion for offshore steel component is by diffusion of chlorides through the damaged coating while the chloride builds up with time on the steel component surface [3], whenever the chloride attains critical threshold, the passive oxide layer which is highly protective and grows at a low rate. As long as the steel remains in good alkaline condition, the passive layer will prevent corrosion initiation on the surface of the steel.

The prediction of the performance of steel structures subjected to chlorides and wave/wind forces requires a thorough understanding and reliable modeling of several complex mechanisms, which include (i) transport of chlorides (ii) corrosion initiation through depassivation of the steel and destruction of the protective film layer; (iii) damage initiation and accumulation and (iv) impact of force on bond and strength [4].

The problem is further complicated by considering the combined effects of stresses and damage-induced corrosion and mechanical loads. This is critical for a reliable prediction of the safety and serviceability of steel structures and their remaining life [4].

Depending on the importance of the structure (offshore oil producing platforms) and the consequences of its failure, various rehabilitation options may be implemented to upgrade the structure in order to ensure its safety, serviceability and functionality using a reliability analysis based method.

2.0 LITERATURE REVIEW

2.1 Corrosion on Offshore Platforms

Offshore platform structures require various levels of impact resistance according to the utilization of the different zones, storage, accommodation, helidecks, production, etc [5]. Given such a bewildering variety of situations which may be encountered, marine structures have in the past been obliged to rely on static dimensioning and large safety factors. This approach is slowly changing as a hutch number of uncertainties exist and sophisticated numerical models are being developed. The reliability of such models can only be established by confronting their predictions with results from realistic tests [5].

In offshore platforms, accidental discharge of drilling mould, waste water, and gas flaring which consist of hydrochloric gas is attributed to chloride accumulation around offshore platforms [3]. Chloride ion is transported in solution through damaged steel coating into the surface of steel members in several ways which include diffusion and water capillary process [6]. Developed a finite element analysis model that uses convection and conduction modeling of chloride transport process.

However, most models assume that the dominant process is diffusion for a reasonable well-constructed structure with good quality of coating. Diffusion calculation is a reasonable approximation of the overall real process for chloride ion transportation. The diffusion process is modeled by solving one dimensional equation for Fick's second law of diffusion given as [3]:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial t^2}\right) \qquad (1)$$

Where;
C = Salt ion concentration
t = Time
D = Diffusion coefficient.

Equation (2) can be derived from Fick's first law and the mass balance.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}J = \frac{\partial}{\partial x}\left(D\frac{\partial}{\partial x}C\right) \qquad (2)$$

The diffusion coefficient 'D' is constant, so we can exchange the orders of the differentiation and multiply by the constant, thus;

$$\frac{\partial}{\partial x}\left(D\frac{\partial}{\partial x}C\right) = D\frac{\partial}{\partial x}\frac{\partial}{\partial x}C = D\frac{\partial^2 C}{\partial x^2} \qquad (3)$$

For the case of diffusion in two or more dimensions, Fick's second law becomes:

$$\frac{\partial C}{\partial t} = D\nabla^2 C \qquad (4)$$

In a condition when the concentration does not change with time, the above Equation (4) becomes zero which is Laplace's equation. This equation is usually solved using the error function solution. Hence we obtain Equation (5) as:

$$C_{(x,t)} = C_0\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \qquad (5)$$

Where;
$C_{(x,t)}$ = Salt concentration at depth x at time t.
C_o = Surface concentration
erf = error function
∇ = used for two or more dimensions.

2.2 Philosophy of Structural Reliability

Reliability theory with respect to structural engineering deals with the methods for assessing the serviceability of structures and its safety through rational treatment of uncertainties [7]. Reliability analysis involves a numerical and probabilistic method to evaluate and determine the level of safety in structural elements or systems. Reliability can be defined as the probability of a system or a structure or a structural element in structural engineering to adequately perform under stated or given conditions over a specified period of time [8]. In other words, structural reliability is concerned with the calculation and prediction of a limit state violation for engineering structures at any stage during their lifetime [9]. The violation of a limit state is the attainment of an undesirable condition for the structure, that is, damage to a part of the structure (serviceability limit state) or total collapse of the structure (ultimate limit state) which could lead to loss of human lives.

2.2.1 Reliability analysis method

There are a handful of methods applied to determine if a structure satisfies the performance criteria. Some of the commonly used methods include; Limit state, Reliability index, simulation techniques, Hasofer-Lind Reliability index and Rackwitz and Fiessler procedure. Some of the listed methods are discussed succinctly in the following sub-sections.

2.2.1.1 *Limit state*

Limit state is employed in structural reliability analyses in order to predict and checkmate failure. Limit state is the boundary that exists between the undesired and the desired performance in structures. For an offshore structure, an undesired performance occurs when it can no longer sustain the design load during its design period. Collapse is also one of the features of an undesired performance. There are two categories of Limit states which includes; Serviceability limit state and Ultimate limit states [10].

Ultimate Limit States (ULS) is often related to collapse which is the loss of load bearing capacity of the structure. When a structure exceeds its Ultimate Limit State (ULS), a serious failure of the structure occurs, such as collapse or loss of operability. Buckling or loss of stability, the formation of a plastic hinge, and crushing of concrete are the limit states considered in a reliability-based design code [11].

Serviceability Limit States (SLS) are related to gradual deterioration of a structure or structural element causing user's discomfort. This limit state does not involve immediate structural collapse. SLS can involve an immoderate bending on an offshore structure or structural element during its design life [10].

Engineering judgment (arbitrary decision) is usually based on acceptability criteria. For example, if the moment due to the loads acting on a beam exceeds the moment carrying capacity. Its limit State equation can be written:

$$g(x) = g(x_1, x_2, x_3, \dots, x_n) = R - Q \;\dots\dots (6)$$

Where; x_n is the random variables of load and resistance such as live load, dead load, depth, length, etc., Q is the load effect (total moment applied) and R is the resistance (moment carrying capacity). The Limit state gives a boundary in which if exceeded, the structure no longer functions adequately.

The probability that the undesired performance will occur is equivalent to the probability of failure, P_f. This can be expressed mathematically with respect to limit state function as Equation (7):

$$P_f = P(R - Q < 0) = P(g(x) < 0) \;\dots\dots\dots\dots (7)$$

Both R and Q have a Probability Density Function (PDF) if they are continuous random variables. Furthermore, R - Q is also a random variable having its own PDF. The probability of failure is given by Equation (8):

$$P_f = \int_{-\infty}^{+\infty} F_R(x_i)\, f_Q(x_i)\, d\, x_i \;\dots\dots\dots\dots\dots\dots (8)$$

Where: $F_R(x)$ is the Cumulative Density Function (CDF) of resistance R and $f_Q(x_i)$ is the PDF of the load Q.

2.2.1.2 *Reliability index*

An official definition of the reliability index is that it represents the shortest distance from the origin of standard space (reduced variable space) to the limit state line $g(Z_R, Z_Q) = 0$, in the reduced variables space, where Z_R is the reduced random variable for resistance and Z_Q is the reduced variable for load [10]. The reduced form of a random variable, *X*, is given by Equation (9) [12]:

$$Z_x = \left|\frac{X - \mu_x}{\sigma_x}\right. \;\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (9)$$

2.2.1.3 *Simulation techniques*

Sometimes, the methods for the computation of reliability stated above can become very complicated. This happens especially when the limit state function is very complex or cannot be expressed in a closed form. In these situations, simulation methods are used. Examples of simulation methods used in computation of reliability includes; Monte Carlo Simulation (MCS) and Rosenblueth's 2K + 1 Point Estimate Method [13].

2.3 Probabilistic Design

The deterministic design criteria in Equation (6) describes that the resistance should be greater than the load effect parameter to avoid a failure. The problem becomes probabilistic when statistical distributions of the variables are taken into account. There are three detail levels when talking about theoretical probabilistic methods. The first method considers the uncertainty with one parameter per uncertain variable. The generally accepted *Partial Coefficient Method* (PCM) that is used in Eurocodes falls into this category. The PCM is calibrated against other probabilistic methods and is really not a probabilistic method. The next method, called *First Order Reliability Method* (FORM), considers the uncertainty with two parameters, mean value and variance, for each uncertain parameter. A measure of the safety is given by the safety index, β. The risk of failure could be estimated as presented by [14]:

$$P_f = \phi\,(-\beta) \;\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (10)$$

The third and most fundamental theory utilizes the exact statistical properties for all variables. This method gives the most realistic measure of the probability of failure, P_f, and often requires numerical methods to be solved. One method which utilizes the exact statistical properties of all variables is the *Monte Carlo method* (MC). This is really a simulation method which randomly picks numbers in pair from the R and S distributions. Each pair of numbers is compared in between. Now, let R be the resistance of the structure and S the load on the structure. If failure occurs, when R < S, the result is 1 otherwise 0. Mathematically, this will be expressed by an indicator function, I ( ), which returns 1 if the failure function is less than zero, G $(x) \le 0$, otherwise it returns 0. This leads to an approximation about the failure probability, P_f, and variance, given by [16] as:

$$P_f \approx \acute{P}_f = \frac{1}{N}\sum I\,(G(x)) \le 0 \;\dots\dots\dots\dots\dots\dots\dots\dots (11)$$

$$\text{Var}\,|\acute{P}\,| = \frac{1}{N}\,P_f\,(1 - P_f) \;\dots\dots\dots\dots\dots\dots\dots\dots (12)$$

3.0 METHODOLOGY

3.5 Reliability Equations for Steel Plates.

The reliability equatios for steeel plates used as platform are as shown below;

NOTATIONS

$w_{pl} = x_1 = plate\ plastic\ moment$

$f_y = x_2 = plate\ yield\ strength$

$w = x_3 = uniformly\ distributed\ load$

$l = x_4 = span$

$b = x_5 = plate\ width\ along\ shear\ plan$

$t = x_6 = plate\ thickness$

$V_h = x_7 = design\ wind\ velocity\ (m/s)$

$u = x_8 = Velocity\ of\ the\ water\ surface\ normal\ to\ the\ member\ surface\ (m/s)$.

$t_i = x_9 = duration\ of\ inundation\ (s)$

$G(x_i) = Reliability\ Equation$

(a) Plate under bending

Maximum bending moment,

$$M_{Max} = \frac{w_t l^2}{8} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

With reference to plastic moment of a steel plate,

$$M_{Max} \leq M_{Pl} \text{ (BS EN 1993-1-1: 6.2.5 (1)) } \ldots\ldots\ldots\ldots\ldots (14)$$

Where,

$$M_{Pl} = \frac{w_{pl} f_y}{\gamma_{mo}} \text{ (BS EN 1993-1-1: 6.2.5(2)) } \ldots\ldots\ldots\ldots (15)$$

Therefore, $\frac{w_t l^2}{8} \leq \frac{w_{pl} f_y}{\gamma_{mo}}$ …………… (16)

And,

$w_{pl} = plastic\ moment$

$f_y = yield\ strenght$

$\gamma_{mo} = 1.0$

This implies that;

$$0.125 w_t l^2 \leq w_{pl} f_y \quad \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

At failure point,

$$w_{pl} f_y - 0.125 w_{Ft} l^2 = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Where;

$w_{pl} = x_1,\ f_y = x_2, and\ l = x_4$

$$G(x_i) = x_1 x_2 - 0.125 x^2{}_4 \{x_3 + 0.612 x_7^2 + \rho \left(9.81 + 3x_8^2 + \frac{0.5 C_l x_4 x_8}{x_6} + C_m x_4 \frac{x_8}{x_9}\right)\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

(b) Plates under shear

The basic design requirement is,

$$V_{max} \leq V_r \text{(BS EN 1993-1-1: 6.2.6(2)) } \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

But;

$$V_r = V_{pl} = \frac{A_v(\frac{f_y}{\sqrt{3}})}{\gamma_{mo}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

$$A_v = shear\ area = bt \quad \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Therefore,

$$\frac{w_t l}{2} \leq \frac{bt\left(\frac{f_y}{\sqrt{3}}\right)}{1.0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

Therefore at failure point;

$bt\left(\frac{f_y}{\sqrt{3}}\right) - 0.5w_t l = 0$ if $b = x_5, and\ t = x_6$ …………………. (24)

This implies;

$G(x_i) = 0.577x_2x_5x_6 - 0.5x_4\{x_3 + 0.612x_7^2 + \rho\left(9.81 + 3x_8^2 + \frac{0.5C_l x_4 x_8}{x_6} + C_m x_4 \frac{x_8}{x_9}\right)\}$ ………. (25)

(c) Plate under deflection

The basic design requirement is;

$Maximum\ deflection = \delta_{max} \leq \frac{span}{360}$ (BS EN 1993-1-1NA 2.23) ……………. (26)

But $\delta_{max} = \frac{5w_t l^5}{384EI}$ $and\ I = \frac{lt^3}{12}$ ……………………. (27)

This implies that;

$7.44 \times 10^{-7} w_t l^4 t^{-3} \leq 2.7778 \times 10^{-3} l$ ………………. (28)

Thus at failure point,

$2.7778 - 7.44 \times 10^{-4} w_t l^3 t^{-3} = 0$ ……………………. (29)

Therefore,

$G(x_i) = 2.7778 - 7.44 \times 10^{-4} {x_4}^3 {x_6}^{-3}\left\{x_3 + 0.612x_7^2 + \rho\left(9.81 + 3x_8^2 + \frac{0.5C_l x_4 x_8}{x_6} + C_m x_4 \frac{x_8}{x_9}\right)\right\}$ ………………. (30)

3.7.1 Compressive strength of plates under uniaxial compression

The most important parameter that governs the compressive strength of plate elements is the slenderness, that is:

$\lambda = \frac{b}{h}\sqrt{\frac{\sigma_y}{E}}$ ……………………. (31)

Where b and h are the plate breadth and thickness, respectively, σ_y is the yield stress and E is the Young's modulus of the material. This parameter is included in the classical formula due to Bryan for the critical elastic buckling stress, σ_{cr} of infinitely long thin elastic plate with simply supported edges; thus,

$\frac{\sigma_{cr}}{\sigma_y} = \frac{4\pi^2}{12(1-v^2)}\frac{1}{\lambda^2}$ ……………………. (32)

Where v is the Poisson ratio.

3.7.2 Failure criteria

Applying the exponential approximation for corrosion depth allows two-failure criteria for a plate element to be formulated. Failure is considered to be caused by reaching a specified value of thickness reduction or by the plate ultimate strength. Having a reduction of the original thickness does not mean that the plate will reach the level of ultimate strength and the opposite is also true.

The ultimate strength does depend not only of the thickness but also of many other factors. It is assumed that these two failure modes are independent. Using the limiting thickness as an additional failure criteria accounts for the fact that in addition to ultimate strength there may exist other design or operational considerations that need to be taken care of [17]. Thus Equation (33) gives the limit state function due to compression.

G(x) = $\boldsymbol{\sigma_{u(t)} - \tau_{xav}}$ …………………. (33)

The limit state equation for failure due to compression is thus given by;

G(x) = $\sigma_y\left(0.8 + \frac{1.09}{\lambda} + \frac{1.26}{\lambda^2}\right) - \tau_{xav}$ …………….. (34)

Recalling equation (30), hence,

$$\boldsymbol{G(x_i) = x_1x_2 - 0.125{x^2}_4\{x_3 + 0.612x_7^2 + \rho\left(9.81 + 3x_8^2 + \frac{0.5C_l x_4 x_8}{x_6} + C_m x_4 \frac{x_8}{x_9}\right)\}}$$

3.6 Corrosion model

The conventional models of corrosion assume a constant corrosion rate, leading to a linear relationship between the material lost and time. Experimental evidence of corrosion reported by various author's shows that a non-linear model is more appropriate.

The oxidised material that is produced remains on the surface of the plate and does not allow the continued contact of the plate surface with the corrosive environment, stopping corrosion. They proposed a linear Equation (35) and a bilinear Equation (36) model, which were considered appropriate for design purposes. That is;

d(t) = 0.076 + 0.038t ………………. (35)

d(t) = $\begin{cases} 0.090t & 0.00 \leq t < 1.46 \\ 0.076 + 0.038t & 1.46 \leq t < 16.0 \end{cases}$ ……….. (36)

Both models are conservative in the early stages in that they overestimate the corrosion depth, which could occur at the initial phases of the corrosion process [18]. Suggested a steady-state model for corrosion wastage thickness, which is given by:

$$d(t) = \begin{cases} 0.170t & 0 \leq t < 1 \\ 0.152 + 0.0186t & 1 \leq t < 8 \\ -0.364 + 0.083t & 8 \leq t \leq 16 \end{cases} \quad \ldots\ldots\ldots (37)$$

And they also proposed a power approximation for the corrosion depth given as;

$$d(t) = 0.1207t^{0.6257} \ldots\ldots\ldots\ldots\ldots\ldots (38)$$

Where;
t = time

The reference to these earlier works shows that the non-linear time dependence of corrosion rate has been already identified experimentally. The model proposed here in addition to being a more flexible alternative to the previous ones also generalize the concept by including an early phase with corrosion protected surface. In fact, the model proposed has free parameters to be adjusted to the data of specific situations.

The time-dependent model of corrosion degradation may be separated into three phases. In the first stage there is in fact no corrosion because the protection of the metal surface works properly, this stage depends on many factors and statistics show that in offshore platforms it varies in the range of 1.5 - 5.5 years.

The second phase is initiated when the corrosion protection is damaged and corresponds really to the existence of corrosion, which decreases the thickness of the plate, This process was observed to last a period around 4 -5 years.

The third phase corresponds to a stop in the corrosion process and the corrosion rate becomes zero, Corroded material stays on the plate surface, protecting it from the contact with the corrosive environment and the corrosion process stops. Cleaning the surface or any involuntary action that removes that surface material originates the new start of the non-linear corrosion growth process.

The model proposed here can be described by the solution of a differential equation of the corrosion wastage as:

$$d_\infty * \dot{d}(t) + d(t) = d_\infty \ldots\ldots\ldots\ldots\ldots\ldots (39)$$

Where, d_∞ is the long-term thickness of the corrosion wastage, d(t) is the thickness of the corrosion wastage at time *t*, and $\dot{d}(t)$ is the corrosion rate.

The solution of Equation. (39) can have the general form

$$d(t) = d_\infty(1 - e^{-t/\tau_t}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (40)$$

And the particular solution leads to;

$$d(t) = d_\infty\left(1 - e^{-(t-\tau_c/\tau_t)}\right) \; t > \tau_c \quad \ldots\ldots\ldots\ldots\ldots (41)$$

$$d(t) = 0, t \leq \tau_c$$

Where, τ_c is the coating life, which is equal to the time interval between the painting of the surface and the time when its effectiveness is lost, and τ_t is the transition time, which may be calculated as;

$$\tau_t = \frac{d_\infty}{tg\alpha} \ldots\ldots\ldots\ldots (42)$$

4.0 RESULTS AND DISCUSSION

4.1 Results

4.1.1 First Order Reliability Analysis result (FERUM IN MATLAB)

The program developed for the reliability-based design of an offshore steel plate subjected to corrosion at time (t), using First Order Reliability Method (FORM), and the procedure was repeated for different variation of factors and parameters.

The yield stress of the material (steel plate) was varied from $275N/mm^2$ to $690N/mm^2$, Compressive Stress from $100N/mm^2$ to $500N/mm^2$ and thickness h(t) from 5mm to 50mm.

Figures 1 to 4 show the relationship of safety indices to thicknesses at time (t) for relevant parameters of the steel plate subjected to corrosion.

(a) Yield stress, 275N/mm²

Figure 1 shows the reliability based result/relationship when yield stress is $275N/mm^2$, and the plate thickness is varied from 5mm to 50mm. This is so to demonstrate the effect of corrosion on platforms with an anticipated lifespan of 100 years. The results and safety indices are taken at intervals of 5 years.

Careful observation from Figure 1 show that the safety indices decreased with an increase in compressive stress and increased with an increase in thickness.

With a thickness of 5mm and variation of compressive stress from $100N/mm^2$, $200N/mm^2$, $300N/mm^2$, $400N/mm^2$ and $500N/mm^2$ the safety indices obtained were, 2.61, 1.48, -0.40, -2.22, -3.81 respectively. This signifies the ultimate limit state of the deck which requires complete rehabilitation. That is age approaching 100 years after failure of corrosion protection.

When the plate thickness increases to 20mm with the same variation in compressive stress from $100N/mm^2$, $200N/mm^2$, $300N/mm^2$, $400N/mm^2$ and $500N/mm^2$ was maintained, the safety indices obtained were -0.01, 1.05, 2.23, 3.75.4.85 respectively. This signifies the serviceability limit state of the platform with significant impact of corrosion damage with age above 50 years and a constant dead and imposed load.

When the plate thickness increases to the ranges of 30mm to 50mm with the same variation in compressive stress from 100N/mm^2, 200N/mm^2, 300N/mm^2, 400N/mm^2 and 500N/mm^2 was maintained, the safety indices obtained include, 8.97, 7.59, 5.84, 4.71, 6.32, 6.99, 5.31, 6.38, 7.66, 4.20 respectively. This signifies the safe state and early age of the platform.

With a constant compressive stress of 100N/ mm^2 and variation in thickness from 5mm, 10mm, 15mm, 20mm, 25mm, 30mm, 35mm, 40mm, 45mm and 50mm, the safety index obtain were 2.61, 3.36, 4.11, 4.85,5.58, 6.28, 6.98, 7.66, 8.32, 8.92 respectively. Signifying the safety and stability of the platform with respect to loading. When the compressive stress is increased to 500N/ mm^2 and variation in thickness from 5mm, 10mm, 15mm, 20mm, 25mm, 30mm, 35mm, 40mm, 45mm and 50mm the safety indices obtained were -3.81, -2.39, -1.10, -0.01, 0.87, 1.62, 2.26, 2.84, 3.37, 3.84 respectively. This signifies the degradation level of the platform with steel properties and yield stress of 275N/mm^2.

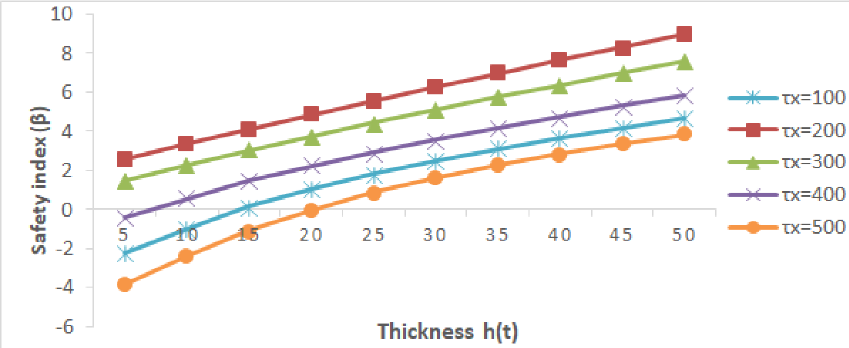

Figure 1: Relationship of Safety index (β) to Thickness h(t) when $f_y = 275N/mm^2$

(b) Yield stress, 690N/mm^2

Figure 2 shows the reliability based result/relationship when yield stress is 460N/mm^2, the safety indices ranged from 1.18 to 11.10 with variation in compressive stress and thickness.

Careful observation from Figure 2 shows that the safety indices decreases with increases in Compressive stress and increases with increases in thickness. This signifies the safety and stability of the deck from a corrosion free state with reduction in degradation level due to higher property of steel and corrosion effect for high steel grade of yield stress (f_y = 690N/mm^2)

With a thickness of 5mm and variation of compressive stress from 100N/mm^2, 200N/mm^2, 300N/mm^2, 400N/mm^2 and 500N/mm^2 the safety index obtained were 5.84, 4.69, 3.17, 2.09 and 1.18 respectively. This signifies the load impact on a corroded deck with higher steel property (f_y = 690N/mm^2) in relation to exposure time.

With plate thicknesses from 5mm to 50mm and a variation in compressive stress from 100N/mm^2, 200N/mm^2, 300N/mm^2, 400N/mm^2 and 500N/mm^2 maintained, the safety indices obtained ranges from 11.10 to 1.18 respectively. At this stage, the safety indices with thickness 5mm to 50mm show a good level of platform stability even after the de - passivation of the anti-corrosion property and aging of 100 years and above.

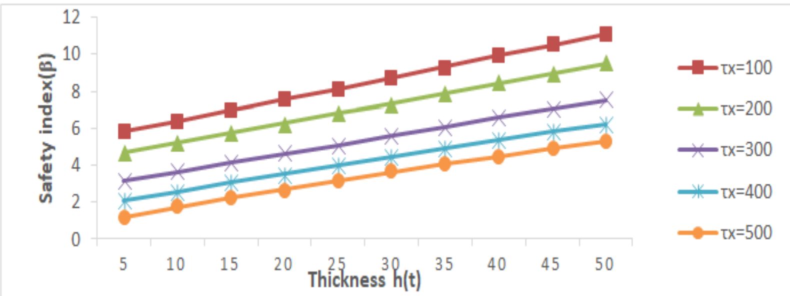

Figure 2: Relationship of Safety index (β) to Thickness h(t) when $f_y = 690N/mm^2$

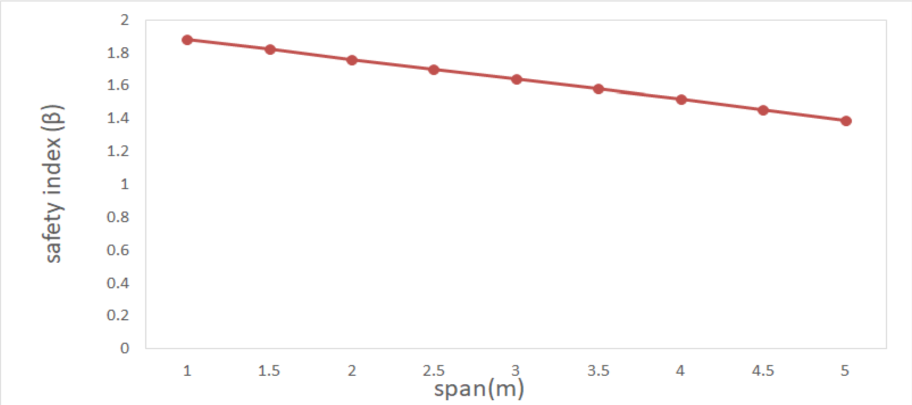

Figure 3: Relationship of safety index to span of plate

Figure 3 shows the result of reliability – based design of offshore steel plate decks subjected to bending. The result demonstrates that the safety indices decrease with increase in the span of plates. The indices varies from 1.88, 1.82, 1.76, 1.70, 1.64, 1.58, 1.52, 1.45 to 1.39 at spans of 1m, 1.5m, 2m, 2.5m, 3m 3.5m, 4m, 4.5m and 5m respectively thus drawing close attention to span and effective depth ratio.

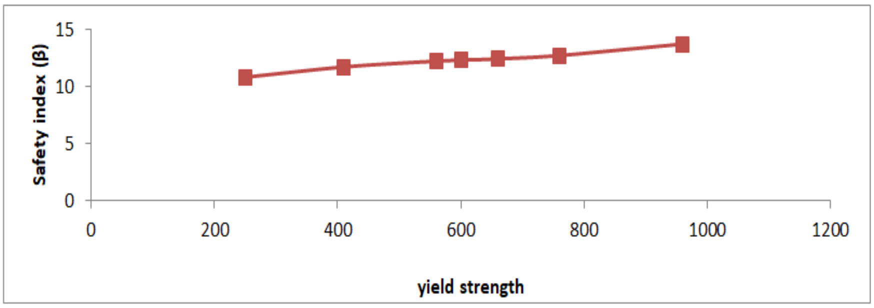

Figure 4: Relationship between safety index and yield strength of steel plate under bending

Figure 4 shows the relationship of safety indices and yield strength with the indices varying from 10.8 to 13.7 and the yield strength varying from 250 to 960 N/mm^2 respectively. This signifies durability and safety of various steel grades as it affect the choice for design and construction of platforms.

The optimum thickness of plate and strength determined are shown in Table 1:

Table 1: Optimum thickness of plates and corresponding strength

Optimum thickness (mm)	Yield strength (N/mm^2)
30	235
25	275
20	355
18	420
17	460
15	500
15	550
10	620
5	690

Table 1 shows the optimum thicknesses of steel plates in relations to various steel strengths obtained from the reliability analysis. The results indicate that the higher the material strength, the more effective and durable the structure.

4.2 DISCUSSION OF RESULTS

Table 2, presents results of the reliability taking into account that a corrosive depth of the element will be approximated by a linear or an exponential relation. The formulation presented can be used to assess the effect of various parameters in the reliability evaluation. The important aspect related with reliability is transition time from the start of corrosion to reaching the steady-state. A relatively large transition time may keep reliability at a relatively higher level and to postpone the necessity of replacement of the corroded element.

Table 2: Shows the results of the Finite element analysis

Plate thickness (mm)	Von mises stresses (N/mm^2)	U1 (N/mm^2)	U2 (N/mm^2)	U3 (N/mm^2)	Magnitude (N/mm^2)
50	$+1.078e^{+03}$	$+7.832e^{-01}$	$+2.154e^{-06}$	$+6.821e^{-04}$	$+1.437e^{-02}$
45	$+1.336e^{+02}$	$+1.958e^{-01}$	$+2.167e^{-07}$	$+8.426e^{-05}$	$+2.783e^{-03}$
40	$+1.687e^{+02}$	$+5.723e^{-04}$	$+2.074e^{-07}$	$+1.066e^{-04}$	$+2.783e^{-03}$
35	$+2.235e^{+02}$	$+6.770e^{-04}$	$+2.070e^{-07}$	$+1.390e^{-04}$	$+4.140e^{-03}$
30	$+3.062e^{+02}$	$+4.332e^{-04}$	$+1.093e^{-07}$	$+1.892e^{-04}$	$+6.557e^{-03}$
25	$+4.436e^{+02}$	$+3.010e^{-04}$	$+1.724e^{-07}$	$+2.725e^{-04}$	$+2.205e^{-02}$
20	$+6.978e^{+02}$	$+2.211e^{-04}$	$+1.869e^{-07}$	$+4.257e^{-04}$	$+2.205e^{-02}$
15	$+8.1456e^{+02}$	$+1.691e^{-04}$	$+1.905e^{-07}$	$+3.599e^{-04}$	$+1.865e^{-02}$
10	$+8.779e^{+01}$	$+1.338e^{-01}$	$+2.015e^{-05}$	$+1.222e^{-01}$	$+1.270e^{+01}$
5	$+8.871e^{+01}$	$+1.082e^{-01}$	$+3.710e^{-04}$	$+4.887e^{-01}$	$+5.929e^{+01}$

As the plate thickness reduces, there is an increase in the von misses stresses on the member signifying loss in moment capacity and instability. The deterioration increases as the load is kept constant and the structural age increases.

A careful observation on Table 2 shows the stresses rising from +1.078e^{+02} at a thickness of 50mm and +8.87e^{+01} at a thickness of 5mm.

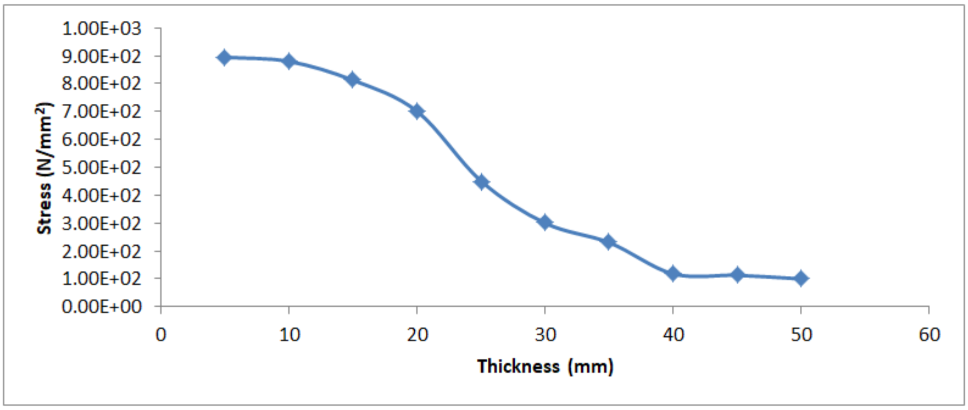

Figure 5: Relationship between stress and plate thickness

Also, careful observation on Figure 5 shows the load impact and stress level on an offshore structural element (steel plate) with relation to the age of structure. The corrosion infested component begin to deteriorate and there is a reduction in the sectional area as the time increases. The load effect and stresses tends to increase from 1.00e^{02} to 8.87e^{02} as the structure grows old and has a reduction in the component sizes (50mm to 5mm) due to the loss in member size caused by corrosion which is estimated at d_∞ = 49mm to 5mm and τ_t = 4 to 95yrs respectively.

This is a clear trend of the type of response that is reproduced by the model as shown. This trend is also similar to the one presented by Yamamoto. The relative corrosion depth is a function of time under the assumption that corrosion thickness is approximated as a linear and an exponential function. The linear approximation of corrosion depth is taken as *d*(*t*)"0.12*t*, mm.

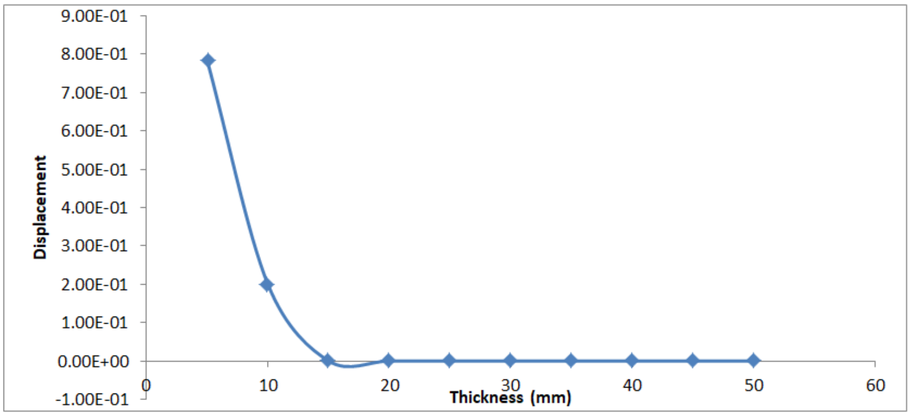

Figure 6: Relationship between thickness and displacement in X direction

Figure 6 shows results of the application of vertical loads and boundary conditions, the boundary conditions are encerstre restricting movement on the X, Y and Z axis depicting a fixed and statically stable structure. The load is simulated as a uniformly distributed load that ramps the deck momentarily as the wave inundates.

Obtained by measurements of repaired elements which have been transformed into piecewise time averages, and were imputed to the present model by estimating the model parameters with a least-squares approach; An initial steel plated model is designed with properties assigned to sections to demonstrate the reliability of a structural steel plate in offshore environment exposed to aggressive medium. The model was tested and it was observed that all the conditions of safety and stability were satisfied for plates of thickness 15mm with yield strength of 500N/mm^2. The properties are of steel grade S 375 and A53, with a yield stress (σ_y) = 620N/mm^2 and Modulus of elasticity (E) = 200,000N/mm^2, compressive stress (τ_x) = 500N/mm^2.

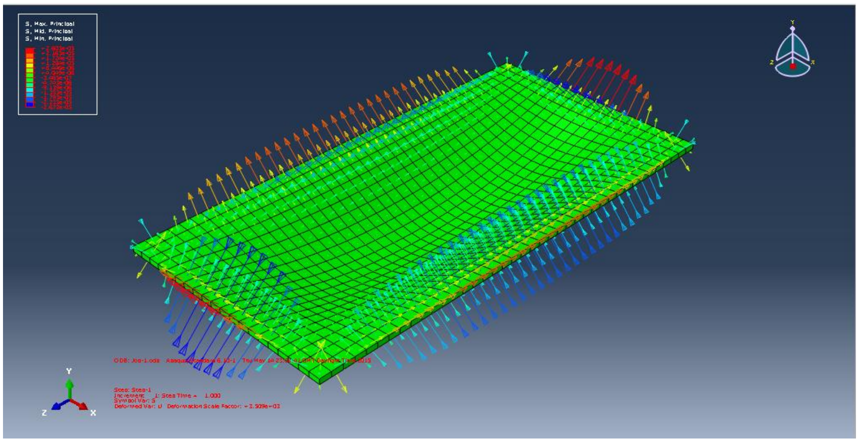

Plate I: Stress distribution on a 20mm steel plate exposed to corrosion environment. Depicting 60 years exposure period to aggressive medium

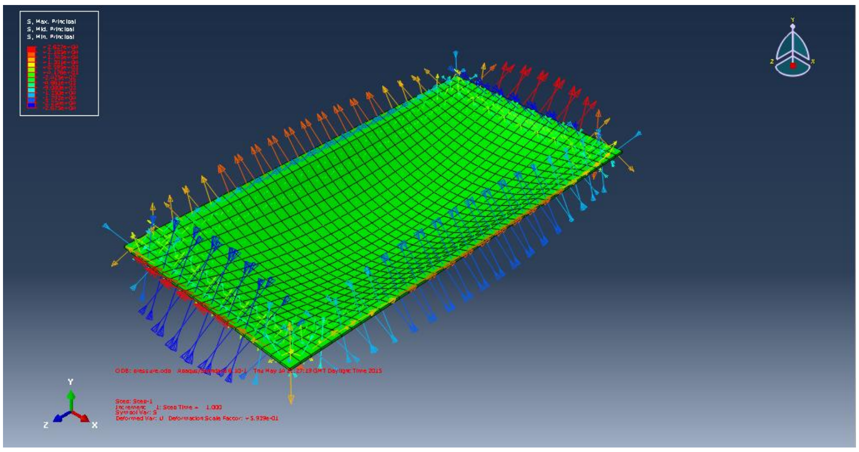

Plate II: Showing the stress distribution on the plate with respect to loading and corrosion rate (80 years exposure)

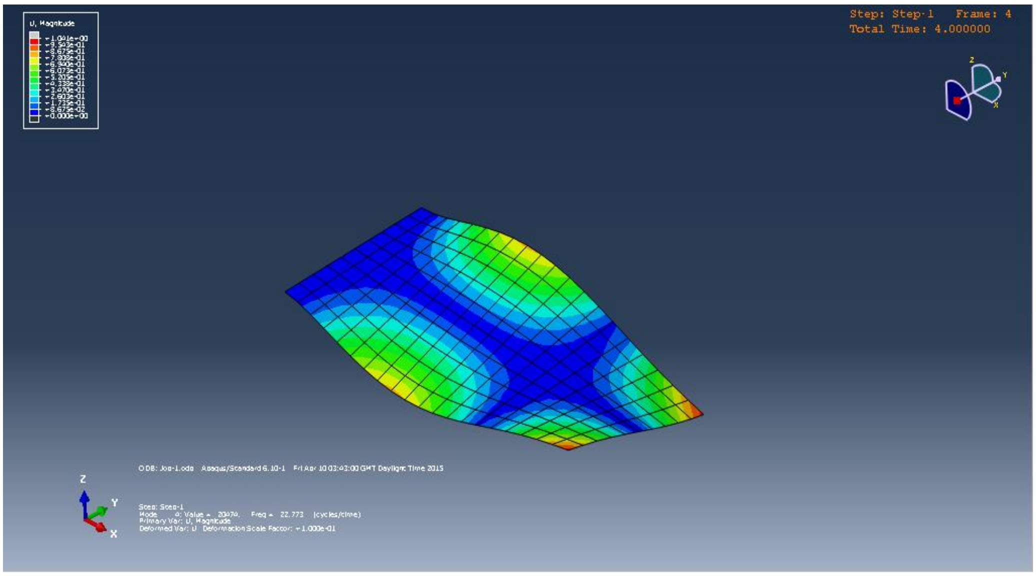

Plate III: Failure module due to applied load and corrosion damage

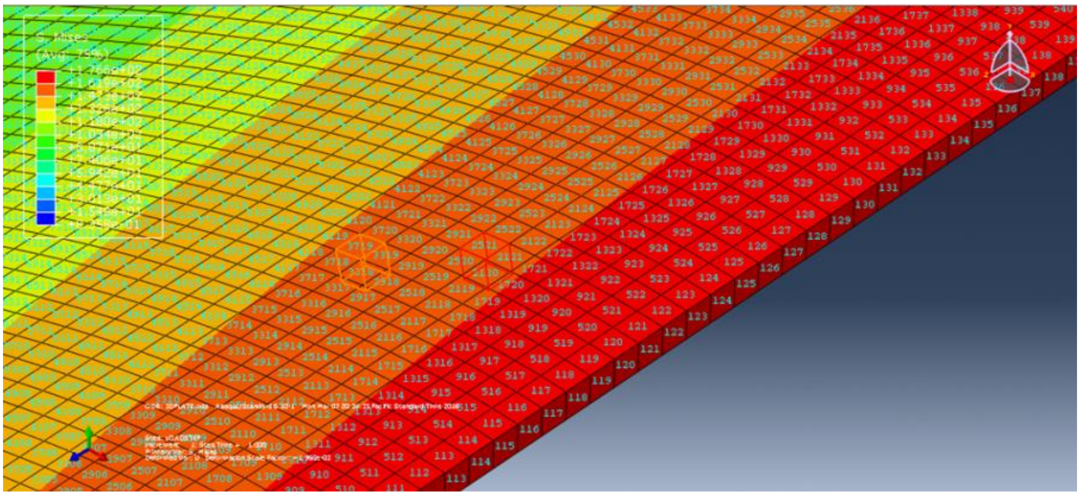

Plate IV: Shows various elements numbers, groups and their failure levels

Plate I show evaluated parameter from the data represented. d_∞ = 30mm and τ_t = 60yrs, the failure of the plated structure is a function of the applied stress as given EC 3, Table 3.1 and APS Table 15.

Plate II to IV shows the corrosion age and level of damage with d_∞ =40mm and τ_t = 90 yrs and above. At this stage of the structure, the corrosion level is said to have exceeded the 25% margin of the allowable corrosion level which does not compromise the stability and safety of the structure. As asserted by [17], that restoring action is provided when the thickness of a structural element (plate) is less than 75% of original thickness.

Thus for the plate thickness of 15mm and yield strength of 500N/mm^2 to 690N/mm^2 , and thicknesses of 20mm and yield strength of 355N/mm^2 to 460N/mm^2, it will be about 20 years of exposure to aggressive medium (chloride ion environment) after failure of protective coating before restoration action can commence for the structural rehabilitation of the offshore platform.

5.0 CONCLUSION

The reliability-based design of steel plate exposed to corrosion was carried out with First Order Reliability Method coded in a computer based program, FORM 5 and a Finite element method in a software ABAQUS.

From the results obtained using FORM 5, the safety indices ranged from 1.18 to 11.0, and a nonlinear relationship exist between safety indices and thickness for different parameter variations. Hence,

i. The safety indices for steel grades with yield stress 460N/mm^2 and above, the safety indices ranged from 3.5 to 10.20 at a minimum thickness of 10mm with variation in compressive stress, complying with the target reliability provision in EC3 (2004).

ii. It was also found that steel with lesser characteristics properties of yield stress, compressive stress are more susceptible to corrosion inhibition when exposed to aggressive environment and are fatigued under service.

iii. Safety indices also decrease in load ratio to plate thickness of different grades of steel. This signifies that, the higher the steel grade, Yield stress of 500N/mm^2 and above for example, the safer the optimum plate thickness during transition time.

iv. With a varying grade of steel and yield strength ranging from 235N/mm^2 to 690N/mm^2, from the simulation of a plate with thickness of 50mm and yield strength of 500N/mm^2 it is observed that the plate thickness reduces as time increases in years, and the reliability of the steel plate is compromised when the initial thickness is reduced by 25%.

v. There was substantial increase in von Mises stresses as corrosion rate increases and the initial thickness of plate decreases with applied load acting on the plate. The stresses tend to increase as steel with lesser properties are modeled with various degrees of surface deformity.

5.1 RECOMMENDATION

The state of general corrosion in a plate is assessed by measuring the plate thickness at several points. There are two sources of uncertainty in this procedure. One results from the precision of the measuring instrument and the other from sampling variability. Measurements are made at few points of a panel and they are considered to be representative of the thickness in the whole plate. To ensure the safety and durability of an offshore platform, safe life and property, the following are recommendations from this study:

(a) For offshore platforms and other aggressive environments prone to corrosion attack, a minimum plate thickness of 30mm of steel with yield strength 275N/mm^2, a minimum thickness of 25mm for steel with yield strength 355N/mm^2, a minimum thickness of 20mm for steel with yield strength 420N/mm^2, a minimum thickness of 20mm for steel with yield strength 460N/mm^2 a minimum thickness of 15mm for steel with yield strength 500N/mm^2, a minimum thickness of 15mm for steel with yield strength 550N/mm^2, a minimum thickness of 10mm for steel with yield strength 620N/mm^2, a minimum thickness of 5mm for steel with yield strength 690N/mm^2 with good anti-corrosion property (epoxy resins) to be used in the construction of platform decks as load carrying components.

(b) Inspections should be routinely made for structures in service were these may result in detection or no detection of a plate that has a mean thickness smaller than the acceptable value that is a fraction k of the original mean value.

(c) Platform deck may need redesigning the bearing area or adding bearing stiffeners according to the decrease of bearing resistance.

(d) The announced live load capacity of the examined steel deck may be reduced according to the results of this research to maintain safety operation.

(e) Repairs should be made when the thickness is less or equal to75% of its original value for thickness of the plate.

(f) Coating steel surfaces should be treated in accordance with the provisions in API (1999).

(g) This work can be used as a guide for offshore platforms design and reference for further academic research.

REFERENCES

1. Iwanowski, B., Grigorian, H., & Scherf, I. (2002). Subsidence of the ekofisk platforms: wave in deck impact study. Various wave models and computational methods. In: *Proceedings of the 21st international conference on offshore mechanics and arctic engineering* (OMAE) Oslo, Norway. Pp 567-652.
2. Elsner, C. I., Sere, P. R., & Di Sarli, A. R. (2012). Atmospheric corrosion of painted galvanized and 55% Al-Zn steel sheets: results of 12 years of exposure. *International Journal of Corrosion*, *2012*, 1, 107-111.
3. Omotoso Mathew, F., Salau, M. A., & Esezobor, D. E. (2011). Offshore steel structures corrosion Damage Model, *Int journal of science and Engg*, 2, 2229-5518.
4. Ufuah, E. (2012). Fundamental Behaviour of Offshore Platform Steel Decks Under Running Pool Fires, Faculty of Engineering and Physical Sciences, University of Manchester, England.
5. Lefebvre, X., Sauvant-Moynot, V., Choqueuse, D., & Chauchot, P. (2009). Durability of syntactic foams for deep offshore insulation: modelling of water uptake under representative ageing conditions in order to predict the evolution of buoyancy and thermal conductivity. *Oil & Gas Science and Technology-Revue de l'IFP*, *64*(2), 165-178.
6. Meijers, S. J. H. (2003). Computational modeling of chloride ingress in concrete, Delft University. pp 274-633.
7. Kostandyyan, E., & Sorensen, J., (2014). Dependent Systems Reliability Estimation by Structural Reliability Approach. *International Journal of Performability Engineering*, 16(6).
8. Ghasemi, S. H., & Nowak, A. S. (2017). Reliability Index for non-normal distributions of limit state

functions, *Structural Engineering and Mechanics*, 62(3).
9. Ditlevsen, O., & Madsen, H. O. (2007). *Structural reliability methods*. Internet Edition 2.3.7.
10. Ferrand, D. (2005). Reliability analysis of are in forced concrete decks lab supported on steel girders. Materials. University of Michigan, 2005. English.tel-00474728.
11. Ghasemi, S. H., & Nowak, A. S. (2016). Reliability Analysis for Serviceability limit state of bridge concerning deflection criteria, *Structural Engineering International Nr*.2/2016.
12. Ghasemi, S. H., & Nowak, A. S. (2017): *Target Reliability for Bridges with consideration of Ultimate Limit State*, Engineering Structures, 152 (2017), 226-237.
13. Ghasemi, S. H., & Nowak, A. S., (2016). Mean Maximum values of non-normal distributions for different time periods, *International Journal Reliability and Saftey*, 10(2).
14. Akadang, O. L. B. (2015). *Stochastic Evaluation of Offshore Carbon Fibre Reinforced Concrete Platforms on Aluminum Girders*, A Thesis Submitted to the Postgraduate School, Ahmadu Bello University Zaria, for the Award of Master of science Degree, Department of Civil Engineering, Ahmadu Bello University Zaria.
15. Melchers, R. E. (1987). Structural Reliability, Analysis and prediction. John Wiley, New York. USA. Pp 400.
16. Yamamoto, N. (1998). Reliability based criteria for measures to corrosion. In: *Proceedings of the 17th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE), Safety and Reliability Symposium, New York, USA: pp 890
17. Southwell, C. R., Bultman, J. D., & Hummer, Jr. C. W. (1979). Estimating of service life of steel in seawater. In: *Schumacher M, editor. Seawater corrosion handbook*. New Jersey: Noyes Data Corporation, pp 374.
18. Melchers, R. E. (1999). *Structural Reliability Analysis and Prediction England*: John Wiley & Sons.