RELIABILITY OF DETERIORATED MARINE STRUCTURES BASED ON MEASURED DATA

(DOI No: 10.3940/rina.ijme.2016.a4.372)

Y Garbatov and **C Guedes Soares**, Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Portugal.

SUMMARY

Reliability assessment of a corroded deck of a tanker ship subjected to non-linear general corrosion wastage is performed, accounting for an initial period without corrosion due to the presence of a corrosion protection system, and a non-linear increase in wastage up to a steady state value. The reliability model is based on the analysis of corrosion depth data. Two types of uncertainties are accounted for. The first one is related to the corrosion degradation trend as a function of time, which is identified by a sequence independent data analysis. The second uncertainty is related to the variation of the corrosion degradation around its trend, which is identified as a stochastic process, and is defined based on the time series analysis. The time series determines the autocorrelation and spectral density functions of the stochastic process applying the Fast Fourier transform. The reliability estimates with respect to a corroded deck of cargo tank of a tanker ship is analysed by a time variant formulation and the effect of inspections is also incorporated employing the Bayesian updating formulation.

1. INTRODUCTION

Marine structures operate in a complex environment. Seawater properties such as salinity, temperature, oxygen content, pH level and chemistry can vary according to site location and water depth and as a result of that different types of corrosion may be generated that can waste the metals. Corrosion may be identified as rusting of the iron base alloys, but that is only one possible mechanism of corrosive degradation. Corrosion wastage may take the form of general corrosion, pitting corrosion, stress corrosion cracking, corrosion fatigue, fretting corrosion, filiform corrosion, weld corrosion, bimetallic corrosion and bacterial corrosion etc.

A study of factors governing marine corrosion phenomena on the structural steel component level and an identification of the key parameters of corrosion and corrosion fatigue has been presented in [1, 2]. The large number of parameters that can influence corrosion demonstrates the difficulty of developing a model of corrosion wastage that explicitly considers them. Therefore, the estimation of the corrosion depth needs to be empirical in nature and very much based on the historical data collected for a certain type of ship.

The conventional models for general corrosion wastage are presented in [3], assumed a constant corrosion rate, leading to a linear relationship between the corrosion thickness and time. Experimental evidence of corrosion reported by various authors shows that a nonlinear model is more appropriate [4-8].

Recognizing that corrosion is a very complex phenomenon and influenced by many factors, a new corrosion wastage model was proposed, based on a non-linear time-dependent corrosion model accounting for various immersion environmental factors, including the effects of salinity, temperature, dissolved oxygen, pH and flow velocity including the effect of ship's service life in different routes was developed in [9-11].

A key parameter for the assessment of engineering structures subjected to stochastic processes is the average rate with which the degradation processes cross the boundary separating the safety domain from the failed one. An approximation of the first passage probability is obtained by assuming that the threshold level crossings occur independently according to a Poisson process. Cramer [12] has shown that this assumption is in fact asymptotically exact when the threshold level increases to infinity. Engelund, et al. [13] showed also that for engineering applications, the Poisson assumption as modified by Ditlevsen [14] such that the initial conditions are considered provides good results.

In many situations, the expected value of the reliability at a random point in time is not enough and information about the time variation of reliability is desired. To achieve this objective, a model has been proposed in [15-17] to describe the time dependent reliability of a ship hull in which the plates are subjected to time dependent degradation and repair actions. However, the effect of degradation was represented by an uncertain, but a constant degradation rate, which resulted in a linear decrease of plate thickness with time. A non-linear time variant corrosion degradation model was adopted in [6] to study the reliability of a plate element under compressive forces. Based on a fast integration technique, an algorithm was also developed to assess the structural reliability of ship hulls efficiently in [18, 19].

Classical theory of system maintenance describes the failure of components by probabilistic models often of the Weibull family, which represents failure rates in operational phases and in the ageing phases of the life of components as described in various textbooks [20-22].

Garbatov and Guedes Soares [23] adopted that type of approaches and demonstrated how they can be applied to structural maintenance of ships that are subjected to corrosion. The applied approach is based on historical data of thickness measurements or corresponding corrosion thickness in ships. Based on the progress of corrosion degradation, the critical corrosion thickness levels are defined as failure, which is modelled by a Weibull distribution. Existing formulations obtained for systems are applied to this case, leading to results that agree with standard practice.

The present work improves the existing reliability models by applying a non-linear function of time that describes the growth of corrosion in three different phases and the descriptor factors of deterioration process are defined based on the analysis of measurement corrosion thickness data for a long-period of time. Two types of uncertainties are accounted for. The first one is related to the corrosion degradation trend as a function of time, which is identified by a sequence independent data analysis. The second uncertainty is related to the variation of the corrosion degradation around its trend, which is identified as a stochastic process, and it is defined based on the sequence data analysis. The sequence analysis identifies the autocorrelation and spectral density functions of the stochastic process applying the Fast Fourier transform. The reliability estimates with respect to a corroded deck of cargo tank of a tanker ship is studied by a time variant formulation and the effect of inspections is also incorporated using a Bayesian updating formulation. Reliability is updated based on the information of the corrosion degradation gathered during the inspection.

2. DATA ANALYSIS

Having obtained the corrosion depth time records, several different methods can be used to analyse the data. The methods for analysing the corrosion records may be divided into two types, the one that treats the collection of measured corrosion depths without regard to their position in the sequence of readings and the second one that takes the that sequence into.

2.1 TIME INDEPENDENT DATA ANALYSIS

The analysis of the real measurement corrosion data covers the identification of the trend and its statistical descriptors. The model of Guedes Soares and Garbatov [6] that has been validated by with some corrosion data supplied in [24, 25] was used to identify the mean value (trend) of corrosion depth as a function of time [26]. The model is based on the solution of a differential equation, leading to the mean value of the corrosion wastage as:

$$E\left[d\left(t\right)\right]=\begin{cases} d_\infty\left(1-e^{-\frac{t-\tau_c}{\tau_t}}\right), & t\geq\tau_c \\ 0, & t<\tau_c \end{cases} \tag{1}$$

where d_∞ is the long- corrosion wastage, $E[d(t)]$ is the mean value of the corrosion wastage at time *t*, τ_C is the time without corrosion which corresponds to the start of the failure of the corrosion protection coating (when there is one), and τ_t is the transition time duration.

Since the corrosion data has a very large variability, the approach taken has been to model separately the time variation of the mean corrosion wastage and of the standard deviation. This allows the main tendency of the data (mean) to be described by the above corrosion model and the uncertainty of the model to be described by the standard deviation as a function of time.

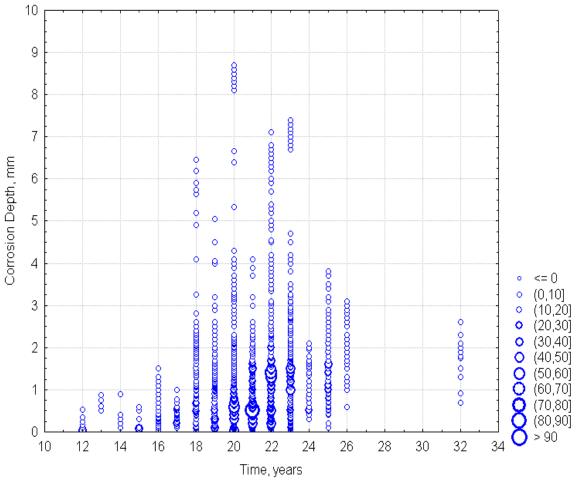

Figure 1. Frequency scatter diagram of corrosion wastage of deck plates of cargo tanks.

A set of corrosion data, deck plates of cargo tanks of tankers includes 4665 measurements of deck plates from cargo tank with original nominal thicknesses varying from 12.7 to 35 mm on ships with lengths between perpendiculars in the range of 163.5 to 401 m. The frequency scatter diagrams of corrosion wastage are shown in Figure 1 for deck plates of cargo tanks. The scatter plot displays the frequencies of overlapping points between time and corrosion wastage in order to visually represent the frequencies of the overlapping points and categorize those frequencies according to the number specified in the right hand side of figures. The sizes of the point markers in the plots represent the frequencies.

The long-term wastage $d\infty$ is defined as the maximum value in the observed time interval for cargo tanks respectively. The period without corrosion, or the time of initiation of corrosion τ_C, and the transition time, τ_t are defined based on the least squares approach to fit the data using a quasi-Newton algorithm, which determines the direction to search used at each iteration considering the mean value of the corrosion depth taken from the yearly subset of data histograms.

The parameters of the regressed line of the mean value of corrosion depth as a function of time were determined under the assumption that it is fitted by the exponential function given in Eqn (1). The long-term corrosion wastage for deck plates of d_∞=1.91 mm for cargo tanks, the time without corrosion is τ_C =11.49 years and the transition period for deck plates of cargo tanks is τ_t=11.23 years (see Figure 2).

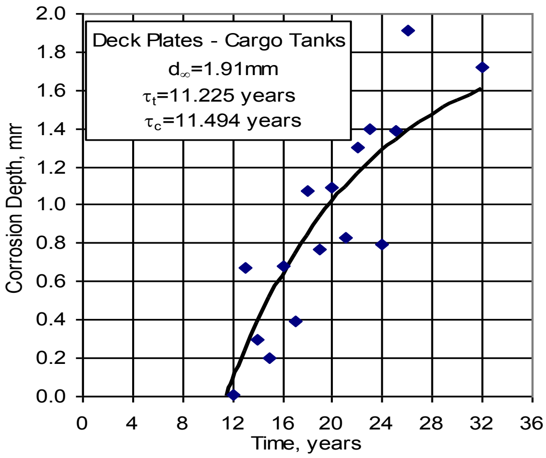

Figure 2. Time dependent mean value of corrosion wastage of deck plates of cargo tanks

Another important statistical descriptor of the data set is the standard deviation, for each yearly subset of data. The standard deviation as a function of time is fitted to a logarithmic function:

$$StDev\left[d\left(t\right)\right]=a\ln\left(t\right)-b \tag{2}$$

where a=0.834 and b=1.838. Although it has to be pointed out that the regression line correlation coefficient is very low and the regression is not significant. In fact, there is a large variation in the data, which is the dominant feature.

2.2 TIME SERIES ANALYSIS

Methods that take into account the data sequence within the time records are more complex than the sequence-independent methods, and they produce outputs that are more complex.

The power spectra assessment that is employed here is a sequence-dependent analysis, estimating the power present at various frequencies included in the record. This process is known as a spectral estimation, on the basis that the objective is to estimate the power present, treating the record being analysed as a sample from a population of records extending backwards and forwards in time. To estimate a power spectrum, different methods can be used, of which the Fourier transform [27] method is the most common.

The discrete Fourier transform can be done in the form of the fast Fourier transform algorithm. The power spectrum is then determined as the amplitude squared of the sine waves, divided by the frequency separation. In order to minimize irregularities in the spectrum, trend removal and windowing (a process that reduces the amplitude of the time record towards the start and finish in order to minimize errors associated with the sharp changes in the value) are generally applied to the time record before computing the spectrum.

The Fourier transform [28] is a generalization of the Fourier series and instead of the sines and cosines in the Fourier series. The discrete Fourier transform is defined as:

$$F\left(k\Delta t\right)=\sum_{n=0}^{N-1}f\left(n\Delta t\right)e^{-i\left(2\pi k\Delta t\right)\left(n\Delta t\right)} \tag{3}$$

where k=0, 12, …N-1..

In general, the period of the record ahead of time is not known and the sampling may stop at a different phase in the record than where sampling started, the last point is then not identical to the first data point. Consider a periodic record that repeats itself, which has been shown in Figure 3, it starts at t=0, and stops at t=14th year, the phase at t=T differs from the one at t=0. This is because, unlike the Fourier series analysis, T in the discrete Fourier transform is not necessarily equal to the fundamental period of the original record.

The sequence-dependent analysis method relates to the calculation of the autocorrelation function. The autocorrelation function is the expected value of the product of the time series at one time and at certain later times and consequently, it is a function of the lag time, the time difference between the two samples.

It can be shown that the autocorrelation function $K_d(\tau)$ fulfils all the requirements for utilizing the Fourier analysis and its inverse for the stationary random process may be defined by so called Wiener-Khintchine relations [29]:

$$K_d\left(\tau\right)=\int_{-\infty}^{\infty}S_d\left(\omega\right)\cos\left(\omega\tau\right)d\omega \tag{4}$$

where $S_d(\omega)$ is the spectral function.

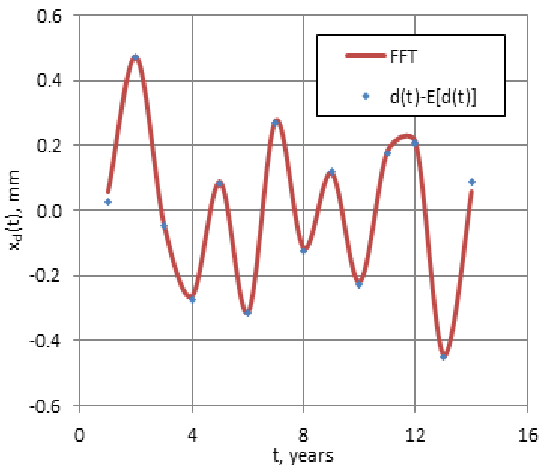

Figure 3 Corrosion depth variation around the mean value

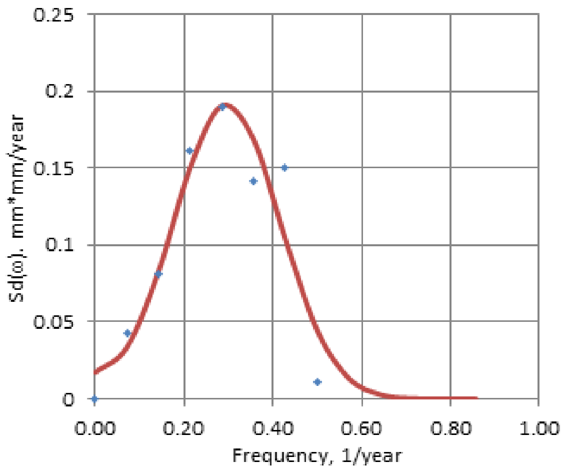

Figure 4 Spectral function

It has been considered here that the variation of corrosion depth, $x_d(t)$ around the corrosion depth mean value, $E[d(t)]$ (see Figure 3) is a normal stationary process with a zero mean value and spectral function, $S_d(\omega)$ is assumed to be of the form (see Figure 4):

$$S_d(\omega) = 2\sigma_d^2 \left\{ \frac{1}{4\sqrt{\pi}} \frac{1}{\alpha_d} exp\left[-\frac{(\omega+\beta_d)^2}{4\alpha_d^2} \right] + exp\left[-\frac{(\omega-\beta_d)^2}{4\alpha_d^2} \right] \right\} \quad (5)$$

with an autocorrelation function, $K_d(\tau)$ as:

$$K_d(\tau) = \sigma_d^2 e^{-\alpha_d^2 \tau^2} cos \beta_d \tau \quad (6)$$

where for the analysed record, (Figure 1 to Figure 3) the descriptors of Eqn (8) and (9) after fitting them to the points of Figure 3 are given as α_d= 0.0842 1/year, β_d=0.2963 1/year and the variance is σ_d^2=0.0571 mm*mm. The spectral function $S_d(\omega)$ is shown in Figure 4.

3. RELIABILITY ASSESSMENTS

3.1 RELIABILITY-BASED DESIGN OPTIMIZATION

The probability of failure during any period, based on the first passage concepts, is considered equal to the probability of occurrence of any crossing of the corrosion depth out of the safe domain during the same period. This is also equivalent to the probability that the safety margin becomes zero or less during the same period.

The corrosion degradation is considered to be a normal non-stationary process that is modelled as a sum of one monotone increasing function d(t) and a stationary zero mean process $x_d(t)$:

$$z(t) = d(t) + x_d(t) \quad (7)$$

The normal stationary process $x_d(t)$ is described by the autocorrelation function, $K_d(\tau)$ and the spectral function, $S_d(\omega)$ as defined by Eqn (5) and (6). The normalized autocorrelation and spectral functions are defined as:

$$r_d(\tau) = K_d(\tau) / \sigma_d^2 \quad (8)$$

$$s_d(\omega) = S_d(\omega) / \sigma_d^2 \quad (9)$$

where in the special cases, when $x_d(t)$ is a normally distributed, $\dot{x}_d(t)$ is also normally distributed with zero mean value [30], the mean zero up crossing rate may be calculated as:

$$v_{d,o} = \frac{\sqrt{-r_o^*}}{2\pi} \quad (10)$$

and the variance of $\dot{x}_d(t)$ is given as:

$$\sigma_d^2 = -r_o^* = \int_{-\infty}^{+\infty} \omega^2 s_d(\omega) d\omega \quad (11)$$

where $r_o^* = \frac{\partial^2 r_d(\tau)}{\partial \tau^2}\Big|_{\tau=0}$.

The repair condition for replacing the corroded deck plate of cargo tank of tanker ship, which is analysed here, is defined as suggested by the Common Structural Rules [31], for the wastage allowance (see Figure 5) for the corroded deck plate as a d_{cr}=3.0 mm corrosion depth. It has to be stressed that different levels of corrosion wastage allowance lead to different replacement times of the corroded plates.

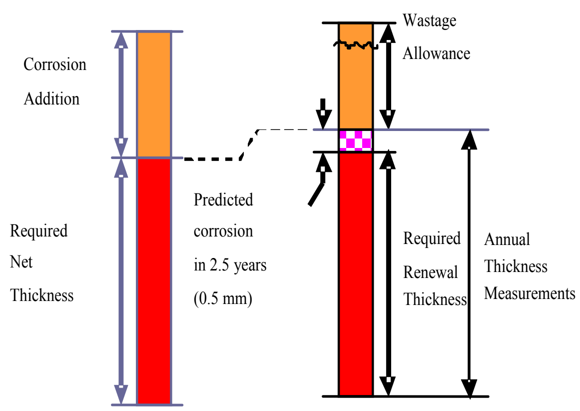

Figure 5 Corrosion additions [31]

The wastage allowance, d_{cr} is identified as a threshold, and the corrosion growth, z(t), see Eqn (7), is a time-varying independent random process. Failure occurs when the corrosion growth process crosses over the threshold, which is defined as a first passage problem. The probability that failure occurs at a time *t* can be formulated as:

$$P_{nf}(t) = Pr\left[d_{cr} > z(t)\right] \tag{12}$$

$$P_{nf}(t) = Pr\left[z^*(t) < 0\right] \tag{13}$$

where $z^*(t) = z(t) - d_{cr}$ is a stationary process with a mean value of $E\left(z^*\right) = E(z)$ and with a correlation function $K^*(\tau) = K_x(\tau)$.

In the first passage concepts, the probability of failure during any period of time *t* is considered equal to the probability of occurrence of any crossing of d_{cr} by the corrosion growth processes out of the safe domain during the same period. This is also equivalent to the probability that the safety margin becomes zero or less during the same period.

High-risk structures, as most of marine structures, are always designed and built according to high reliability levels. For such structures, the out-crossing events from the safe domain occur rarely. In this case, it will be appropriate to consider the different out-crossings as independent events. The number of out-crossing during any period of time *t* can be considered as a discrete random variable that follows the Poisson distribution. Hence, the probability of no out-crossing during *t* can be calculated as the probability of zero events during *t*. Therefore, the probability of failure can be calculated from [32]:

$$P_f(t) \approx 1 - \exp(-\nu t) \approx \nu t \tag{14}$$

In the stationary case, Ditlevsen [33] suggested numerical improvements to Eqn (14) taking into account the initial conditions. The instantaneous rate ν_{dcr}^+ by which the stochastic random process $x_d(t)$ up-crosses a safe barrier at $x_d(t)=d_{cr}$ can be given by [30]:

$$\nu_{dcr}^+ = \int_{\dot{d}}^{\infty} (\dot{x}_d - \dot{d}_{cr}) f_{x\dot{x}}(d_{cr}, \dot{x}_d, t)\, d\dot{x}_d \tag{15}$$

where $\dot{d}_{cr}$ is the first derivative of the safe barrier height, $\dot{x}_d(t)$ is the derivative process of the stochastic random process $x_d(t)$ and $f_{x\dot{x}}(x_d, \dot{x}_d, t)$ is the instantaneous joint probability density function of the stochastic process $x(t)$ and its corresponding derivative $\dot{x}_d(t)$ at *t*.

Evidently, $\dot{d}_{cr} = 0$ since d_{cr} is not a time dependent function. Assuming that the process $x_d(t)$ is a stationary normal one, then the up crossing rate may be obtained:

$$\nu_{dcr}^+ = \frac{1}{2\pi}\frac{\sigma_{\dot{x}}}{\sigma_x}\exp\left[-\frac{\left(d_{cr} - E_x\right)^2}{2\sigma_x^2}\right] \tag{16}$$

where E_x is the mean value of the random process $x_d(t)$ and if the Gaussian random process is assumed to have a zero mean, then:

$$\nu_{dcr}^+ = \nu_{d,0}^+ \exp\left[-\frac{d_{cr}^2}{2\sigma_x^2}\right] \tag{17}$$

The formulations presented here may be used to calculate the crossing rates and then the failure probability. The probability of non-failure, where the failure rate is very small, may be estimated as:

$$P_{nf}(t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{t} exp\left\{-\frac{1}{2}\left[\frac{d_{cr} - E\left[d(\tau)\right]}{\sigma^*(\tau)}\right]^2\right\}d\tau - \int_0^t \nu_{dcr}^+(\tau)\,d\tau \tag{18}$$

where:

$$\sigma^*(t) = \sqrt{\sigma_x^2 + StDev\left[d(t)\right]^2} \tag{19}$$

The mean up-crossing rate of the threshold level is calculated as:

$$\nu_{dcr}^+(t) = \nu_{d,o}\, exp\left\{\left[-\frac{1}{2}\left(\frac{d_{cr} - d_\infty\left(1 - exp\left(-t^*\right)\right)}{\sigma\left(t-\tau_c\right)^*}\right)^2\right]\right\} *$$
$$* \left\{exp\left[\frac{d^{*2}\, exp\left(-2t^*\right)}{2\sigma\left(t-\tau_c\right)^{*2} r_o^*}\right] + \frac{\sqrt{2\pi}\, d^*\, exp\left(-t^*\right)}{\sigma^*(t)\sqrt{-r_o^*}}\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{t-\tau_c} exp\left\{-\frac{1}{2}\left[\frac{d^*\, exp\left(-t^*\right)}{\sigma^*(\tau)\sqrt{-r_o^*}}\right]^2\right\}d\tau\right\} \tag{20}$$

where $d^* = d_\infty/\tau_t$, $t^* = t/\tau_t$, $d_\infty \geq 0$, and $\tau_t > 0$ (see Eqn (1)).

Since the coating life, τ_C is a random variable too, the reliability of the structural component subjected to corrosion degradation may be determined by un-conditioning over all possible corrosion initiation times:

$$R(t) = \int_o^t P_{nf}\left(\tau \middle| \tau_c\right) f_{\tau_c}(\tau)\, d\tau \tag{21}$$

where $f_{\tau C}(t)$ is the probability density function of the coating life, τ_C which is defined as an Exponential distribution [34]. Based on the analysis of the corrosion thickness measurement data, the mean value is assumed as $\lambda_{\tau C}$=11.49 years for deck plate of cargo tanks.

The reliability of the corroded deck plate is calculated as:

$$R(t)=\left[1-F_{\tau_c}(t)\right]P_{nf,b}(t)+\int_0^t f_{\tau_c}(\tau)P_{nf,b}(\tau)P_{nf,a}(t-\tau)d\tau \tag{22}$$

where the subscript *b* takes values that are related to the conditions before corrosion initiation and the subscript *a* after corrosion initiation respectively. The reliability can be related to the generalized index of reliability which is calculated [14] as:

$$\beta(t)=-\Phi^{-1}\left[P_f(t)\right] \tag{23}$$

where Φ is the standardized normal distribution (see Figure 6).

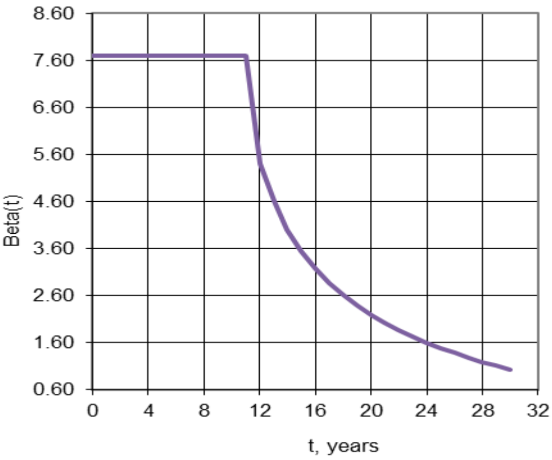

Figure 6. Time variant reliability of deck plates of cargo tanks

3.2 RELIABILITY UPDATING BASED ON INSPECTION RESULTS

For ship structures, degradation such as a corrosion depth growth is an important issue. To ensure that the structures remain safe throughout their service life the corrosion degradation must be controlled. Normally, the degradation process can be controlled efficiently by regular inspections, but other approaches such as monitoring of the response characteristics of the structure can be an effective alternative.

Probabilistic methods are being increasingly used to prepare an optimized in-service inspection plan. Since inspection plans involve shutting down in most of the cases, it is much imperative to inspect the minimum without compromising the safety.

It is important to take the uncertainty of the inspection method into account when performing the updating based on the inspection findings. The inspection uncertainty may be modelled as probability of detection, POD. For steel structures, corrosion is assumed present after coating life finished and thus the damage is expressed by a corrosion depth that increases with time. Inspections are routinely made for structures in-service and they may result in the detection or non-detection of corrosion. The size of a detected corrosion depth is also measured by a non-destructive method.

The inspection quality depends on the ability to detect the corrosion depth and to quantify its size. In principle, each detection technique will have a limited size of detection, d_o, under which corrosion will not be identified. The inspection quality may be described by the probability of detection as [35]:

$$P_d\left[d(t)\right]=\begin{cases}1-\exp\left[-\dfrac{d(t)-d_o}{\lambda_d}\right], & if \quad d(t)>d_o\\ 0 & , if \quad d(t)>d_o\end{cases} \tag{24}$$

It is assumed here that if a corrosion depth is detected and if $d(t) \geq d_{cr}$, the plate is replaced by a new one with its original thickness, increasing the reliability of ship structures. However, other assumptions about the effect of repair could easily be incorporated.

Inspection systems cannot detect a very small corrosion depth. A threshold limit defines its capability and corresponds to the detection level under which detection is no longer possible. This threshold detection corrosion depth size, d_o is the smallest detectable defect size depending on the inspection system. The minimum detectable corrosion depth, d_o does not depend only on the inspection system, but it also depends on various conditions of the inspection, including the environmental conditions, surveyor experience, location and others.

As an example here, POD is modelled as an exponential distribution, [35] and the severity of the conditions to inspect corrosion depths is defined by the statistical descriptors of POD as a mean value of λ_d=0.015 mm and a minimum detectable crack size of d_o=0.05 mm.

Inspection results can be used to update the reliability of the structure. It is assumed that the structural component is inspected at the year t_{insp}. The updated probability of failure as can be formulated as:

$$P_f^U\left(z(t)-d_{cr}\leq 0 \middle| d(t)-a_d\leq 0\right)=\frac{P\left(z(t)-d_{cr}\leq 0\cap d(t)-a_d\leq 0\right)}{P\left(d(t)-a_d\leq 0\right)} \tag{25}$$

where $z^*(t)=z(t)-d_{cr}<0$ is the safety margin and $h(t)-a_d<0$ defines that no corrosion depth is detected by the inspection.

If at some time, a corrosion depth is found the inspection plan is ready updated accordingly by conditioning on the observed corrosion depth, considering the sizing uncertainty. Because of the advent of damaging mechanisms, the condition of the structure deteriorates with time because of increasing the corrosion depth. These need to be calculated with the passage of time and by using the appropriate corrosion depth model (See Eqn (1)). The failure of the corroded structural component needs to be evaluated using Eqn (22).

The reliability of the corroded plate can be updated based on the inspection findings. The probability of detection of a corrosion depth is modelled by Eqn. The updated probability of failure given a no-find result of the first inspection is calculated by Eqn (25). The updating can then be repeated, assuming a no-finding result of the inspection performed. This scheme may be followed until the end of the service life and it is a simple way to establish an inspection plan, which satisfies a given requirement to the safety of the analysed structure. The different inspection interval will employ different influence on the updating of the probability of failure. Figure 7 shows the Beta index for different inspection intervals 4, 5 and 6 years.

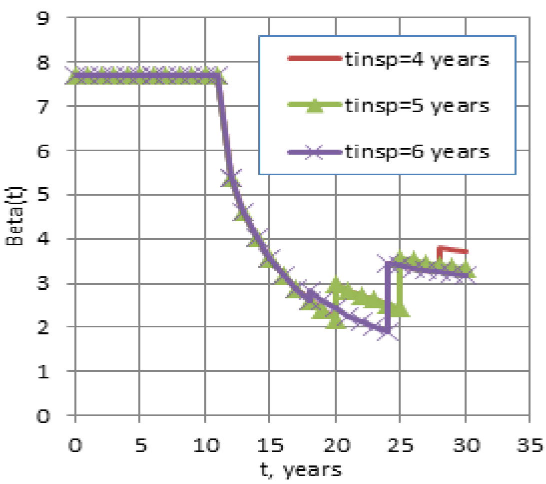

Figure 7. Updated reliability index accounting for inspection interval

6. CONCLUSIONS

Reliability assessment of corroded ship structural plate subjected to nonlinear time dependent corrosion wastage, considering an initial time of no-corrosion while the protection is active, was performed based on a measurement data assessment. A formulation was presented, which is employed to predict the reliability of a corroded deck of cargo tank subjected to random deterioration considering the nonlinear effect of corrosion on its corrosion deterioration acceptance. The statistical descriptors of the deterioration process have been defined by the analysis of corrosion data, which were collected during a long-term period, and the autocorrelation and spectral functions were identified applying the Fast Fourier transform. Reliability of the corroded deck plate of a cargo tank was updated based on the Bayesian theory using the information of corrosion degradation from inspections. Employing the formulation presented here and based on the systematic corrosion depth measurements during the service life of the structure, the inspection and maintenance plan can be easily developed to ensure that the probability of failure is lower than the target probability of failure.

7. REFERENCES

1. ZAYED, A., GARBATOV, Y., GUEDES SOARES, C. and WANG, G. Environmental Factors Affecting the Time Dependent Corrosion Wastage of Marine Structures. *In: Maritime Transportation and Exploitation of Ocean and Coastal Resources*, C. Guedes Soares, Y. Garbatov and N. Fonseca, editors. London, UK: Taylor & Francis Group, 2005, pp. 589-598.
2. PANAYOTOVA, M., GARBATOV, Y. and GUEDES SOARES, C. Corrosion Monitoring of Ship Hulls. *In: Maritime Industry, Ocean Engineering and Coastal Resources*, C. Guedes Soares and P. Kolev, editors. London, UK: Taylor & Francis Group, 2008, pp. 263-269.
3. SHI, W., 1993, In-service Assessment of Ship Structures: Effects of General Corrosion on Ultimate Strength, *Transactions Royal Institution of Naval Architects*, 135, pp. 77-91.
4. YAMAMOTO, N. and IKAGAKI, K., 1998, A Study on the Degradation of Coating and Corrosion on Ship´s Hull Based on the Probabilistic Approach, *Journal of Offshore Mechanics and Arctic Engineering*, 120, pp. 121-128.
5. GUEDES SOARES, C. and GARBATOV, Y. Reliability of Plate Elements Subjected to Compressive Loads and Accounting for Corrosion and Repair. *In: Structural Safety and Reliability*, Vol. 3. N. Shiraishi, M. Shinozuka and Y. K. Wen, editors. Rotterdam, The Netherlands: A. A. Balkema, 1998, pp. 2013-2020.
6. GUEDES SOARES, C. and GARBATOV, Y., 1999, Reliability of Maintained, Corrosion Protected Plates Subjected to Non-Linear Corrosion and Compressive Loads, *Marine Structures*, pp. 425-445.
7. PAIK, J. K., THAYAMBALLI, A. K., KIM, S. K. and YANG, S. H., 1998, Ship hull ultimate strength reliability considering corrosion, *Journal of Ship Research*, 42, (2), pp. 154-165.
8. PAIK, J. K., LEE, J. M., HWANG, J. S. and PARK, Y. I., 2003, A time-dependent corrosion wastage model for the structures of single- and double-hull tankers and FSOs and FPSOs, *Marine Technology*, 40, (3), pp. 201-217.
9. GUEDES SOARES, C., GARBATOV, Y., ZAYED, A. and WANG, G., 2008, Corrosion

Wastage Model for Ship Crude Oil Tanks, *Corrosion Science*, 50, (11), pp. 3095-3106.

10. GUEDES SOARES, C., GARBATOV, Y., ZAYED, A. and WANG, G., 2009, Influence of Environmental Factors on Corrosion of Ship Structures in Marine Atmosphere, *Corrosion Science*, 51, (9), pp. 2014-2026.
11. GUEDES SOARES, C., GARBATOV, Y. and ZAYED, A., 2011, Effect of environmental factors on steel plate corrosion under marine immersion conditions, *Corrosion Engineering, Science and Technology*, 46, (4), pp. 524-541.
12. CRAMER, H., 1966, On the intersections between the trajectories of a normal stationary stochastic process and a high level, *Arkiv för Matematik*, 6, (4-5), pp. 337-349.
13. ENGELUND, S., RACKWITZ, R. and LANGE, C., 1995, Approximations of first passage times for differentiable processes based on higher order threshold crossings, *Probabilistic Engineering Mechanics*, 10, pp. 53-60.
14. DITLEVSEN, O., 1979, Generalised second moment reliability index, *Journal of Structural Mechanics*, 7, pp. 435-451.
15. GUEDES SOARES, C. and GARBATOV, Y., 1997, Reliability of Plate Element Subjected to Non-linear Corrosion and Compressive Load, *Colloquium of the European Mechanics Society "Reliability of Non-linear Structural Mechanics", (EUROMECH 372)*, O. D. Ditlevsen and J. C. Mitteau, editors Clermont-Ferrand, France, Vol. 1, pp. 1-15.
16. GUEDES SOARES, C. and GARBATOV, Y., 1996, Reliability of Maintained Ship Hulls Subjected to Corrosion, *Journal of Ship Research*, 40, (3), pp. 235-243.
17. GUEDES SOARES, C. and GARBATOV, Y., 1998, Reliability of Maintained Ship Hull Subjected to Corrosion and Fatigue, *Structural Safety*, 20, pp. 201-219.
18. GUEDES SOARES, C. and GARBATOV, Y. Reliability of Maintained Ship Hulls Subjected to Corrosion and Fatigue under Combined Loading. *Journal of Constructional Steel Research*. 1999; 52(1):93-115.
19. ZAYED, A., GARBATOV, Y. and GUEDES SOARES, C., 2013, Time Variant Reliability Assessment of Ship Structures Based on Fast Integration Techniques, *Probabilistic Engineering Mechanics*, 32, pp. 93-102.
20. MOUBRAY, M., 1997, *Reliability centered maintenace*: Butterworth Heinemann.
21. RAUSAND, M., 1998, Reliability centered maintenance, *Reliability Engineering & System Safety*, 60, (2), pp. 121-132.
22. JARDINE, A. and TSANG, A., 2005, *Maintenance, Replacement and Reliability, Theory and Applications*: Taylor&Francis.
23. GARBATOV, Y. and GUEDES SOARES, C., 2009, Structural Maintenance Planning Based on Historical Data of Corroded Deck Plates of Tankers, *Reliability Engineering & System Safety*, 94, (11), pp. 1806-1817.
24. WANG, G., SPENCER, J. and ELSAYED, T., 2003, Estimation of Corrosion Rates of Oil Tankers, *Proceedings of the 22nd International Conference on Offshore Mechanics and Arctic Engineering,* ASME *Paper OMAE 2003-37361*.
25. WANG, G., LEE, A. K., IVANOV, L., LYNCH, T. J., SERRATELLA, C. and BASU, R., 2008, A statistical investigation of time-variant hull girder strength of aging ships and coating life, *Marine Structures*, 21, (2-3), pp. 240-256.
26. GARBATOV, Y., GUEDES SOARES, C. and WANG, G., 2007, Nonlinear Time Dependent Corrosion Wastage of Deck Plates of Ballast and Cargo Tanks of Tankers, *Journal of Offshore Mechanics and Arctic Engineering*, 129, (1), pp. 48-55.
27. BOCHNER, S. and CHANDRASEKHARAN, K., 1949, *Fourier Transforms*: Princeton University Press.
28. BRACEWELL, R. N., 2000, *The Fourier Transform and Its Applications*, Boston: McGraw-Hill.
29. WIENER, N., 1930, Generalized Harmonic Analysis, *Acta Mathematica*, 55, pp. 117-258.
30. Rice, S. O., 1944, Mathematical analysis of random noise, *Bell System Technical Journal*, 23, pp. 282-332.
31. IACS, 2010, *Common Structure Rules for Double Hull Oil Tankers, Consolidated version, July 2010*.
32. CRAMER, H. and LEADBETTER, M. R., 1967, *Stationary and related stochastic processes*, New York: John Wiley & Sons.
33. DITLEVSEN, O., 1986, Duration of visit to critical set by Gaussian process, *Probabilistic Engineering Mechanics*, 1, (2), pp. 82-93.
34. GUEDES SOARES, C. and GARBATOV, Y., 1997, Reliability Assessment of Maintained Ship Hull with Correlated Corroded Elements, *Marine Structures*, 10, pp. 629-653.
35. GARBATOV, Y. and GUEDES SOARES, C., 2001, Cost and Reliability based strategies for Maintenance Planning of Floating structures, *Reliability Engineering & System Safety*, 73, pp. 293-301.

