SUMMARY

Today’s fleet of dry bulk carriers has been built to a variety of design standards. The associated safety level varies over the fleet and is quite difficult to assess, especially for ageing ships. Probabilistic analysis methods, making use of statistics based corrosion models, have been proposed and start seeing practical application. Traditional hull condition monitoring has gravitated towards hull life cycle management, using advanced 3D hull modelling which can provide effective assistance to communication and decision making processes.

Bureau Veritas is working on a practical methodology for monitoring the structural health of bulk carriers based on reliability techniques to predict thickness diminution, which enables the identification of weak areas in the structure. The basis is formed by a statistical corrosion model presented in this paper. The time varying residual thickness can be estimated statistically in a rigorous manner on the basis of the as built thickness and the annual corrosion rate. The local and global geometric hull and stiffener properties can then be estimated as time varying functions. Consequently, the probability to comply with a variety of structural criteria can be assessed, like for example having 90% of the section modulus after X years of service life.

Given that the method is as good as the corrosion model applied for the mathematical representation of the thickness diminution, it is proposed to utilize the thickness measurements in a predictor-corrector scheme to update the corrosion model as new information flows in. Recently developed advanced hull condition monitoring tools, such as VeriSTAR HLC, provides a practical and efficient basis for the implementation of such scheme.

1. INTRODUCTION

Today’s fleet of dry bulk carriers, comprising about 7,000 ships, shows a wide spread in age. Fleet statistics show that 38 per cent of the ships in service is 20 years of age or older, with the highest contribution coming from the handysize segment (60 per cent), see Figure 1. For handymax, panamax and capesize bulk carriers the corresponding percentages are 23, 25 and 18 per cent, respectively [1].

Figure 1: Age distribution of bulk carriers in service [1]

Due to the continuous enhancement of structural requirements over the years, first by individual class societies and later in harmonised from within IACS and IMO, the in-service fleet has been built to a variety of design standards. Following high loss rates in the 1980s and early 1990s, important steps in the development and harmonisation of class rules for bulk carriers have been made by the subsequent introduction of a series of IACS Unified Requirements (URs) related to structural strength. The first series, comprising UR S12, S17, S18, S20 and S21 was introduced for bulk carrier contracted for construction on or after 1 July 1998 and considers enhanced scantlings of side structures, strength requirements (longitudinal strength, strength of transverse watertight corrugated bulkheads and allowable hold cargo loading) in flooded condition (of any cargo hold) and enhanced scantlings of hatch covers. This was followed by a second series, comprising UR S25 and S28, which are applicable to bulk carriers contracted for construction on or after 1 July 2003 and 1 January 2004, respectively. With UR S25 harmonised notations (BC-A, BC-B and BC-C) and associated loading conditions were introduced, while UR S28 makes the fitting of a forecastle mandatory. Finally, on 1 April 2006 the Common Structural Rules (CSR) have entered into force, marking the beginning of a new era in the design and construction requirements for bulk carriers. Key features are the introduction of a harmonised net scantling approach, extended fatigue design lifetime (25 years in North Atlantic conditions) and the Performance Standard for Protective Coating (PSPC, applicable to seawater ballast tanks and double skin spaces of bulk carrier with L ≥ 150 m).

As a consequence of the step-by-step introduction of enhanced requirements, the (design) structural safety level related varies over the fleet and is quite difficult to assess and compare, especially for older ships which
have been built prior to any rule harmonisation (which today is the majority of the in-service fleet).

Traditionally, class renewal criteria for local and global strength for structural members are based on a permissible percentage of wastage relative to the as-built thickness\(^1\). The permissible wastage depends on the size of the considered area (highest in isolated areas and lowest in zones such as the deck zone) \(^2\). The percentages of permissible wastage are based on experience feedback from class surveys and thickness measurements. Other criteria considered are buckling strength (ratio between frame spacing and, stiffener web height or stiffener flange width to the associated plating thickness) and pitting (maximum average depth as function of the pitting intensity) \(^2\). Generally speaking, these criteria are a relatively simple approach, implicitly including a number of complex issues such as the corrosiveness of the environment, the coating condition, wear and tear damage caused by the carriage and loading/discharging of bulk cargoes and the stress condition. This has changed with the introduction of the CSR, where the required gross scantlings are obtained on the basis of explicitly defined corrosion additions which are a function of the type of structural member considered and its position in the ship (type of compartment as well as location within that compartment). The corrosion additions thus obtained also serve as the allowable wastage margins considered for class renewal, providing a direct and explicit link between the design criteria and the class renewal criteria. The CSR corrosion additions are based on extensive analysis of thickness measurement data and include a margin of 0.5 mm for the anticipated thickness diminution that may occur during a survey interval of 2.5 years \(^3\).

Although the introduction of the CSR has significantly improved the relation between rules and reality, the approach still does not allow for a reliable prediction of the development of corrosion over time \(^2\). Such a corrosion model would be very useful, as it enables the assessment of the expected future condition of the ship structure against a chosen set of strength criteria. In this way an estimation of the structural areas which are likely to fail with (rule) criteria within a given time frame can be made, regardless of the set of design rules applied during construction. Ship owners can use this information to take rational decisions with regard to maintenance planning or even ship scrapping in the case of aged vessels. Today this is an important point as there is a large number of ageing bulk carriers in service, while at the same time an even larger number of new ships is expected to be delivered over the next years (only in the handysize segment the total tonnage on order is less than the total in-service tonnage of 20 years and over). In the present depressed freight market owners are considering their options for continuing trading or scrapping their ageing and often less efficient vessels. This decision hinges on the expected revenues in the market versus the cost of keeping the vessels in service, for which maintenance cost is a key factor.

In recent years new technologies for the reliability assessment of ship structural strength taking into account corrosion have emerged. The proposed methodologies are generally based on a probabilistic assessment of both the structural strength properties and the loads. Such analysis can be done at the level of the hull girder (ship as a beam approach) to assess the resistance against global collapse, as well as at the level of local structural elements to assess the resistance against yielding, buckling or fatigue. The structural strength properties are predicted by adopting some corrosion model to predict thickness diminution over time. The corrosion models are usually derived from statistical analysis on a large amount of thickness measurement data and typically predict the annual corrosion rate as function of time or ship age. As a result, the time dependent probability density function (PDF) of the strength properties (e.g. the hull girder section modulus at the deck level) is obtained. Probabilistic methods for determining global (hull girder) loads and local loads are generally based on statistical treatment of the still water loads (which also follow a probabilistic distribution themselves) and the wave loads (on the basis of hydrodynamic analysis results, typically spectral analysis of radiation-diffraction calculation results in the frequency domain). The probability density function of the total load is then obtained by combining the PDFs of the still water and wave loads. In the next step the PDFs of the total load and strength properties are combined to obtain the PDF of the structural response in terms of stresses. Assessment of this time dependent PDF against limit state criteria yields the probability of passing or failing a set of strength criteria at a certain point in time.

Another significant recent development is the introduction of sophisticated hull condition monitoring programmes, which are in fact hull life cycle management tools. Traditionally, thickness measurement reports and visual inspection reports are stored in paper archives or (more recently) in electronic format. In either case, it is difficult to readily obtain a good overview of the status or “health condition” of the ship structure as there is no clear graphical representation of the data which can be easily exchanged by interested parties. Modern hull life cycle management tools, using advanced 3D hull modelling software (similar to CAD tools), provide a very clear and detailed real-time overview of all inspection results, thickness measurement data, damages and repairs and can effectively assist the ship manager in maintenance planning, damage & repair

\(^{1}\) In addition, for bulk carriers subject to the Enhanced Survey Program (ESP) a number of retroactive IACS requirements apply, notably UR S19, S22, S30 and S31.

\(^{2}\) The assumption of a general annual corrosion rate of 0.2 mm per year, considered by the CSR rules is far too simplistic for this purpose.
issues, survey preparations & follow up, as well as vetting preparation.

If these sophisticated hull condition monitoring abilities are combined with the described reliability analysis of the ship structure, it becomes clear that such a tool can be used to correct and update the predicted structural strength properties (from the application of the corrosion model) in order to improve the reliability for future predictions. This would further increase the value of the reliability assessment of ship structures as a decision support tool, as the general statistical approach is adapted to the specific asset (ship) under consideration by feeding the actual thickness measurements back into the prediction system, effectively creating a predictor-corrector system.

In this paper a practical methodology for monitoring the structural health of bulk carriers is proposed, which is utilising reliability techniques to predict thickness diminution and identify weak areas in the structure, while active hull life cycle management is deployed to monitor the actual structure and correct the predictions over time. The main focus is on the resistance of the hull girder against global collapse criteria. In this way the risk associated to operating older bulk carriers, as seen from the perspective of both safety and economic viability, can be better assessed.

In section 2 the probabilistic representation of the hull girder properties is considered. Mathematical models for corrosion wastage and the resulting probabilistic representation of residual thickness are discussed as the basis for the probabilistic representation of the hull girder strength properties. Special attention is paid to the effect of fatigue cracks. The section ends with a number of application examples on a handysize bulk carrier is shown. The latest developments with regard to hull condition monitoring using hull life cycle management tools are described. For this purpose VeriSTAR HLC, the Bureau Veritas hull life cycle management tool for ship owners and technical managers, is introduced. Section 4 discusses a methodology for the improvement of the reliability of predictions from the probabilistic model by feeding the thickness measurements back into the model. Finally, in section 5 the main conclusions are drawn and further recommendations are made.

2. PROBABILISTIC HULL GIRDER STRENGTH ANALYSIS USING STATISTICS BASED CORROSION MODELS

2.1 MATHEMATICAL MODELS OF CORROSION WASTAGE

Corrosion is one of the dominant factors which lead to ship structural failures. Corrosion induced degradation embeds substantial uncertainty primarily due to the loading and exposure conditions such as type of cargo, temperature and material properties. One of the key factors for the safety assessment of an aging bulk carrier is the choice of the corrosion model, which will describe how the structural degradation evolves with time. The model should not only reflect the inherent uncertainties but should also be flexible enough such that the information collected at inspections and surveys may be utilized to update the predicted corrosion model parameters. It is thus necessary to choose a model which will be amenable to mathematical manipulation and at the same time will grab the basic physics involved in the process. It is well known that models which assume a uniform corrosion rate, i.e. a linear thickness reduction fail to correspond to reality.

Substantial research on mathematical modelling of corrosion, meaning the uniform corrosion as opposed to the localized pitting corrosion, took place primarily over the last decade. Melchers and Gardiner [4] and Melchers [5] later have proposed a phenomenological model which on the other hand requires many parameters to be defined. The corrosion process is divided into four stages: initial corrosion, oxygen diffusion controlled by corrosion products and micro-organic growth, limitation on food supply for aerobic and anaerobic activity. Guedes Soares and Garbatov [6] proposed a three-phase, three-parameter nonlinear model to describe the growth of corrosion:

\[ d(t) = d_c (1 - e^{-(t - \tau_c)}) \quad \text{for} \quad t > \tau_c \]
\[ d(t) = 0 \quad \text{for} \quad t \leq \tau_c \]

where \( d(t) \) is the corrosion induced thickness reduction, \( \tau_c \) is the coating life, equal to the time between painting until loss of coating effectiveness, \( \tau \) is the transition time and \( d_c \) is the long term corrosion rate as depicted on Figure 2.

![Figure 2: Guedes Soares-Garbatov Corrosion model](image)

Although the Guedes Soares-Garbatov model is more amenable to fit to corrosion measurements, it has been found that there is significant scatter in the resulting computed parameters of the model.

The behaviour of corrosion as envisioned by Paik [7] is depicted schematically in Figure 3. The convex curve in Figure 3 shows the corrosion rate to decrease with the progress of the corrosion. This behaviour reflects the phenomenon of gradual build-up of protective rust layers. It is observed for example in the upper parts of cargo
holds. The concave curve is representative of accelerating corrosion. This occurs at areas where there is high strain in dynamically loaded structures, like for example at the toes of the web frame brackets in the cargo holds [8]. Although the protecting coating is normally very ductile when it is fresh, it loses ductility with age resulting to cracking. Cracking is typically occurring in areas of stress concentrations such as bracket toes, structural transitions, etc. The linear curve is applicable where the rust layers are continually removed due to abrasion or wear or relatively minor surface strains. Such corrosion type is predominant at the lower part of cargo holds of vessels carrying coal, for example.

Figure 3: Representation of corrosion phases by Paik [7]

The Paik model can be expressed mathematically by the following relation:

\[ d(t) = C_1(t - T_t)^{C_2} \quad \text{for } t > T_c \]  
\[ d(t) = 0 \quad \text{for } t \leq T_c \]  

where \( d(t) \) is the uniform wear due to corrosion, \( T_t \) can be viewed as the coating life, \( C_1 \) is the annual rate coefficient and \( C_2 \) is assumed to be between \( \frac{1}{3} \) (optimistic) and 1 (pessimistic). The Paik model is further refined by assuming that the coating life \( T_t \) is a random variable and it follows the normal distribution. The corrosion rate \( C_1 \) has been also found to follow the Weibull distribution.

Last but not least, the Ivanov model [9] also assumes three phases of corrosion wear. As depicted on Figure 4, in Phase I, there is coating protection and the corrosion rate is zero. At time \( T_c \), following coating break-down, the corrosion rate starts increasing until time \( T_t \) when the steady value of corrosion rate is reached (ε in mm/year). The wastage is given by the following relations:

\[ d(T) = 0 \quad \text{for } T \leq T_c \]  
\[ d(T) = \varepsilon \left( T - T_c \right)^2 \quad \text{for } T_c \leq T \leq T_t \]  
\[ d(T) = \varepsilon \left( T - T_c + T_t \right) \quad \text{for } T > T_t \]  

where \( \varepsilon \) is the steady annual corrosion rate.

The algebraic similarity between the Ivanov and the Paik models is quite evident. For \( T > T_c \), the annualized corrosion rate is equal to \( \frac{d(d(T))}{dT} = \varepsilon \) for a sampling point \( \varepsilon = \varepsilon' / (T - T_0) \), where \( \varepsilon' \) is the measured corrosion depth and \( T_0 = 0.5(T_c + T_t) \).

\( \varepsilon \) can be calculated for all thickness measurements. Subsequently, the relative/frequency histogram can be generated. Typically \( \varepsilon \) follows a Weibull distribution. We need to determine the mean value and the variance of \( \varepsilon \) from the gathered corrosion data. The best fit of the measured corrosion data to a Weibull distribution function can be made by using a least squares method.

The plate thickness is then calculated by:

\[ t_n = t_o - d(T) \]  

where \( t_o \) is the as built thickness.

2.2 PROBABILITY REPRESENTATION OF RESIDUAL THICKNESS

Following First Order Reliability Methods (FORM) via Taylor series expansion we obtain for the mean \( \overline{S_n} \) and the variance \( \sigma^2 \) of any hull girder property \( S_n = f(x_n) \) [11]:

\[ \overline{S_n} = f(\overline{x_n}) \]  
\[ \sigma^2 = \sum_n \left( \frac{\partial f}{\partial x_n} \right)^2 \sigma^2_n \]  

where \( \overline{x_n} \) is the mean value of the vector \( x_n \) representing the multi-variable dependence of the hull girder property \( S_n \) and \( \sigma^2_n \) is the variance vector of \( x_n \).

Subsequently the mean and the variance of the residual plate thickness \( t_n \) is given by:

\[ \overline{t_n} = t_o - \overline{d(T)} \]  
\[ \sigma^2_n = \sigma^2_o + \sigma^2_d \]  

where \( \overline{t_o} \) and \( \overline{d(T)} \) are the mean values of the as built thickness and the corrosion-induced thickness reduction. Similarly, \( \sigma^2_o \) and \( \sigma^2_d \) are the corresponding variances.
For \( T_c \leq T \leq T_i \):

\[
\bar{t}_a = \frac{d}{2} \left( \frac{T - T_c}{T - T_i} \right)^2
\]

\[
\sigma_a^2 = \sigma_d^2 + \frac{(T - T_c)^4}{4(T - T_i)^2} \sigma_d^2
\]

For \( T \geq T_i \):

\[
\bar{t}_a = \frac{d}{2} \left( T - \frac{T_i + T_c}{2} \right)
\]

\[
\sigma_a^2 = \sigma_d^2 + (T - \frac{T_i + T_c}{2})^2 \sigma_d^2
\]

The as built thickness follows the normal distribution with mean equal to the mean of the structural tolerances plus the nominal value and standard deviation (square root of the variance) a percentage of the tolerance range, typically equal to 20\%. The corrosion induced thickness reduction follows a Weibull distribution. According to Paik et al. [7], the steady annual corrosion rate \( \varepsilon \) follows a Weibull distribution with the same shape parameter as the annual corrosion rate. The mean and the standard deviation at various locations of a bulk carrier from [7] are depicted on Table 1.

Table 1: Corrosion wastage statistics [7]

<table>
<thead>
<tr>
<th>Scantling</th>
<th>Mean (mm)</th>
<th>SD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \bar{d}(T) )</td>
<td>( \sigma_d^2 )</td>
</tr>
<tr>
<td>Bottom</td>
<td>0.0307</td>
<td>0.0415</td>
</tr>
<tr>
<td>Inner bottom</td>
<td>0.1256</td>
<td>0.1111</td>
</tr>
<tr>
<td>Side shell @ hopper</td>
<td>0.0836</td>
<td>0.0768</td>
</tr>
<tr>
<td>Side shell @ hold</td>
<td>0.0534</td>
<td>0.0725</td>
</tr>
<tr>
<td>Side shell @ top tank</td>
<td>0.0440</td>
<td>0.0468</td>
</tr>
<tr>
<td>Sloping plate @ top tank</td>
<td>0.0362</td>
<td>0.0333</td>
</tr>
<tr>
<td>Deck plate</td>
<td>0.0865</td>
<td>0.0558</td>
</tr>
<tr>
<td>Bottom longitudinal</td>
<td>0.0254</td>
<td>0.0196</td>
</tr>
<tr>
<td>Inner bottom longitudinal</td>
<td>0.0269</td>
<td>0.0390</td>
</tr>
<tr>
<td>Side shell tank long.</td>
<td>0.0336</td>
<td>0.0637</td>
</tr>
<tr>
<td>Sloping plate tank long.</td>
<td>0.0348</td>
<td>0.0376</td>
</tr>
<tr>
<td>Deck longitudinal</td>
<td>0.0758</td>
<td>0.0815</td>
</tr>
<tr>
<td>Bottom girder</td>
<td>0.0288</td>
<td>0.0497</td>
</tr>
<tr>
<td>Hopper plate</td>
<td>0.0836</td>
<td>0.0768</td>
</tr>
</tbody>
</table>

Having obtained the mean and the standard deviation of the wastage distribution, the shape parameter \( \lambda \) and the scale parameter \( \kappa \) of the Weibull distribution of the corrosion wastage \( d(T) \) can be found as:

\[
\bar{d}(T) = \kappa \Gamma \left( 1 + \frac{1}{\lambda} \right)
\]

\[
\sigma_d^2 = \kappa^2 \left[ \Gamma \left( 1 + \frac{2}{\lambda} \right) - \Gamma \left( 1 + \frac{1}{\lambda} \right) \right]^2
\]

where \( \Gamma \) represents the (complete) gamma function. The equations above are nonlinear and can be easily solved by trial and error.

The residual thickness given by equation (4) can be found, since it is composed of random variables with known distributions, namely normal distribution for the as built thickness and Weibull distribution for the corrosion wastage. The PDF of the residual thickness can be found a convolution integral summation:

\[
f(t_a) = \int_0^\infty f_d(d(T))f_{\varepsilon}(t_a + d(T))d(d(T))
\]

where \( f_d(d(T)) \) is the Weibull PDF of the corrosion wastage with parameters determined from equations (10) and (11) above and \( f_{\varepsilon}(t_a) \) is the normal distribution PDF of the as built thickness.

It is noted that the residual thickness and the hull girder properties have distributions which do not extend from minus to plus infinity. Typically, it is desirable to truncate the distributions between a lower limit \( t_{min} \) and an upper limit \( t_{max} \). This is accomplished by adjusting the PDF by a correction factor which is computed in such a way that the corrected PDF yields a number equal to 1 when integrated from \( t_{min} \) to \( t_{max} \).

2.3 PROBABILISTIC REPRESENTATION OF HULL GIRDER PROPERTIES

Although, we cannot deduce directly the distribution of the residual thickness on the basis of the central limit theorem, the hull girder geometric properties obey the normal distribution [12]. According to the central limit theorem, if \( S_n \) (where \( S_n \) is for example represents the Section Modulus or the Cross Sectional Area) is the sum of \( n \) mutually independent random variables, then the probability density function of \( S_n \) is well approximated by the normal distribution. The probability density function is fully defined if the mean value and the standard deviation of the hull girder properties can be defined at any given time. Temporal variation is introduced through the variation in time of the corrosion wastage.

Both plates and stiffeners contribute to the geometric property of a section. In reality, we can assume, without loss of generality, that the stiffeners can always be decomposed to a family of plates. For bulb profiles an equivalent angle profile can always be defined as described for example in CSR for bulk carriers, Chapter 3, Section 6.4.1.1 [3]. Then the cross sectional area \( A \) of a ship section will be given by:

\[
A = 2 \sum_n t_i b_i
\]

where the factor of 2 is due to the fact that only half section is typically considered (in general), \( t_i \) is the \( n^{th} \) plate thickness at time \( T \) and \( b_i \) is the \( n^{th} \) plate breadth. Summation takes place over the total number \( n \) of plates and plates from stiffener decomposition.
Then, on the basis of equations (5) and (6), we can write for the mean and the variance of the cross sectional area:

\[ A = 2 \sum_n t_n b_n \]  
\[ \sigma_a^2 = 4 \sum_n b_n^2 \sigma_n^2 \]  

where \( \sigma_n^2 \) is the variance of the plate thickness at time \( T \).

Similarly the mean and the variance of the first moment of area are given by:

\[ \bar{Q} = 2 \sum_n t_n b_n z_n \]  
\[ \sigma_Q^2 = 4 \sum_n b_n^2 \sigma_n^2 \]  

The vertical position \( Z \) of the neutral axis is found by division of the first moment of area by the cross sectional area. This is also a time varying variable, with a mean and variance given by:

\[ \bar{Z} = \frac{\bar{Q}}{A} = \frac{1}{2} \sum_n t_n b_n z_n \] 
\[ \sigma_Z^2 = 4 \sum_n b_n^2 \sigma_n^2 \]  

where the derivative of \( Z \) with respect to the plate thickness is given by the following relation:

\[ \frac{\partial Z}{\partial t_n} = \frac{2}{A} \left( \frac{\partial Q}{\partial t_n} - \bar{Z} \frac{\partial A}{\partial t_n} \right) = \frac{4}{A} \left( b_n z_n - \bar{Z} b_n \right) \]  

Then equation (19) can be written as:

\[ \sigma_Z^2 = \frac{16}{A} \sum_n b_n^2 \left( z_n - \bar{Z} \right)^2 \sigma_n^2 \]  

The area moment of inertia relative to an axis passing from centre is given by Steiner’s theorem (also known as the parallel axis theorem) as [13]:

\[ I = \sum_n I_n - \bar{Q}^2 \]  
\[ \sigma_I^2 = \sum_n \left( \frac{\partial I}{\partial t_n} \right)^2 \sigma_n^2 \]  

where the first derivative of the moment of inertia is further given by:

\[ \frac{\partial I}{\partial t_n} = 2 \left[ \frac{\partial Q}{\partial t_n} - \bar{Z} \frac{\partial A}{\partial t_n} \right] \]  

The factor of 2 above stems once again from the fact that typically only the half cross section is considered. The total moment of inertia of the \( n \)th plate element, which lies at an angle \( \alpha \) with the horizontal, with the baseline as reference is given by:

\[ I_n = b_n t_n \left( z_n^2 + \frac{1}{12} b_n^2 \sin^2 \alpha + \frac{1}{4} t_n^2 \cos^2 \alpha \right) \]  

On the basis of (25) we obtain:

\[ \frac{\partial I_n}{\partial t_n} = b_n \left( z_n^2 + \frac{1}{12} b_n^2 \sin^2 \alpha + \frac{1}{4} t_n^2 \cos^2 \alpha \right) \]  

Equation (26) can then be utilized in (23) to obtain the variance \( \sigma_I^2 \). The mean value of the section modulus of a section with respect to the deck, which is typically controlling the design, is given by:

\[ SM = \frac{T}{D-Z} \]  

where \( D \) is the depth of the ship. The variance of the section modulus is obtained from the following relation:

\[ \sigma_{SM}^2 = \sum_n \left( \frac{\partial SM}{\partial t_n} \right)^2 \sigma_n^2 \]  

The derivative of the section modulus is given by:

\[ \frac{\partial SM}{\partial t_n} = \frac{1}{(D-Z)} \left( \frac{\partial I}{\partial t_n} + \frac{SM}{\partial t_n} \frac{\partial Z}{\partial t_n} \right) \]  

The derivatives in (29) are expressed through (20), (24), (25) and (26) above.

### 2.4 INCORPORATION OF FATIGUE CRACKS

Fatigue cracks can also lead to catastrophic failure of the structure. Consequently, it is imperative to put in place relevant crack tolerant design procedures, complementing maintenance and inspection. This can be accomplished by employing a time dependent fatigue crack model. It is assumed that a crack with a certain length at a critical detail has been initiated. The crack is assumed to grow in accordance with a Paris-Erdogan law.

The crack growth rate is a function of the cyclic stress intensity factor at the crack tip [14]:

\[ \frac{d\alpha(T)}{dN} = C \Delta K^n \]  

where \( \alpha(T) \) is the crack length at time \( T \), \( N \) is the number of cycles, \( \Delta K \) is the stress intensity factor range and \( C \) and \( m \) are material properties.

The stress intensity factor is given by:

\[ \Delta K = \Delta \sigma \Phi(a) \sqrt{a} \]  

where \( \Delta \sigma \) is the stress range and \( \Phi(a) \) is the geometry function depending on the shape and location of the crack.
Assuming that the later is independent of the crack length, integration of the crack growth relation yields:

\[
 a(T) = a_0 \left[ 1 - m/2 \right] C \Delta \sigma \Phi^n \pi^{m/2} N \]  

(32)

where \( a_0 \) is the initial crack length.

Similarly to the FORM based corrosion equations, we can write for the mean and the variance of the crack length:

\[
 \bar{a}(T) = a_0 \left[ 1 - m/2 \right] C \Delta \sigma \Phi^n \pi^{m/2} N \]  

(33)

\[
 \sigma^2_a = \left( \frac{\sigma_{\Delta \sigma} \Phi^n \pi^{m/2} N a(T) a_0}{ a_0 \left[ 1 - m/2 \right] C \Delta \sigma \Phi^n \pi^{m/2} N} \right)^2 \]  

(34)

where \( \sigma^2_{\Delta \sigma} \) is the variance of the initial crack size and \( \sigma^2_{\Delta \sigma} \) the variance of the stress range. The dash above a variable denotes mean value as described above.

The crack propagates until it reaches a critical length at which the fracture toughness is exceeded. The effect of the fatigue crack presence can be considered in the reliability of the aged vessel in conjunction with the corrosion-induced degradation. Such consideration is introduced through the area and the section modulus of the plate members. A crack of length \( a(T) \) will reduce the area by \( b - a(T) \), and similarly the section modulus.

The effect of fatigue cracks is localized and it cannot be assumed that all plates are degraded by cracking. Further elaboration is under way.

2.5 EXAMPLES

Application of the mathematical models presented in 2.2 and 2.3 above on a handysize bulk carrier yields the time dependent truncated probability distribution functions (PDFs) for the cross sectional area and the deck section modulus. These are depicted on Figures 5 and 6 for time windows spaced every 5 years. Both hull girder properties have been normalized by the “as built” values. In these calculations, we have followed the Ivanov corrosion model and the Paik corrosion wastage statistical data described above, as it has the advantage of reflecting the physics of the corrosion process while requiring the definition of the minimum number of parameters. It was assumed for the purpose of this demonstration that the coating longevity or durability \( T_c \) is equal to 5 years and \( T_t = 7 \) years. This is a rather pessimistic assumption in light of the recently unveiled coating standards PSPC, which aim at a 15 year coating life without repairs involving blasting. In both the case of the cross sectional area and the deck section modulus the variance/standard deviation increases with time and the distributions show increased spread. If it is desired to retain at least 90% of the as built area or section modulus, it is obvious from Figures 5 and 6 that this will be the case for both the area and the section modulus for \( T < 10 \) years and \( T < 15 \) years respectively.

The mean values and the standard deviation of the cross sectional area and the deck section modulus are also presented in Figures 7 and 8. It is concluded that the mean values for the section modulus are degraded at a lower pace than the ones for the cross sectional area. Classification society gauging acceptance requirements are based on either to retain 90% of the area or 90% of the section modulus. It is evident that it is easier to achieve that for the section modulus. In both the section modulus and the sectional area cases the reduction of the mean after the coating break-up starts (at 5 years time in this example) is not significant. For this example, it is less than 10%, which means that the rule requirement for 90% of the as built values is complied with for both the area and the deck section modulus. The variability is more significant for the standard deviation, which increases practically linearly with time. The relatively low variability for the hull girder properties analysed yields an interesting conclusion. If quick conclusions are sought for the normalized PDF of other hull girder properties, such as the moment of inertia for example, we can assume the same mean and standard deviation values.
to hold true and define the statistics on the basis of these. Although this approximation will not yield exact results, it is an acceptable approximation. Furthermore, this is an acceptable assumption if we want to evaluate the hull reliability on a relative scale.

Although this approximation will not yield exact results, it is an acceptable approximation. Furthermore, this is an acceptable assumption if we want to evaluate the hull reliability on a relative scale.

If relation (12) is utilized for the determination of the residual thickness, we can also assess the buckling strength of the plate elements on the basis of the empirical relations described in BV Rules [2]. The buckling strength criterion is based on limiting the ratio of the length over thickness for plate elements and the web height over the web thickness equivalently for stiffeners. The PDF of the ratio can be determined following integration of equation (12), which will also be time dependent. It can then be assessed in advance whether the various elements of the section will satisfy the buckling criterion and the most critical areas can be pinpointed. Although it is evident that the accuracy of the conclusions is highly dependent on the accuracy of the corrosion model, the conclusions derived on the basis of the probabilistic model described in section 2.3 are valid on a relative basis. It can be utilized for example to assess the influence of the input parameters like for example the statistics of the corrosion wastage and the coating durability on the design target like for example not to exceed 10% degradation of the cross sectional area and deck section modulus.

The envelope of the PDFs for the area and the section modulus is plotted for all times on Figures 9 and 10. Having the envelope of the PDF, we can obtain the probability that these hull girder properties will be between any set of limits at any given time interval. This probability is given by the following relation:

$$P(s_1 \leq S \leq s_2) = \frac{1}{(T_2 - T_1)} \int_{T_1}^{T_2} (PDF) dSdT$$

where $S$ is the hull girder property (cross sectional area, section modulus, etc.), $s_1$ and $s_2$ are the lower and upper bound limits (for example $s_1 = 0; s_2 = 0.9$) and $T_2 - T_1$ is the time interval. In case counting starts from the beginning, the lower limit of the time period will be $T_1 = 0$.

In conclusion, corrosion growth is modelled as a time dependent random function that decreases the thickness of the ship’s structural members with time. The methodology for computing the time dependent reliability of the corroding ship structure is developed and various ways to utilize the measured corrosion values in a predictor-corrector scheme to assess the time-variant hull reliability are presented.

3. HULL GIRDER MONITORING AND HULL LIFE CYCLE MANAGEMENT

3.1 INTRODUCTION

In order to update the corrosion predictions during the ship’s lifetime and make the predictions more accurate for the specific ship under consideration (as opposed to a static corrosion model making use of statistical data from...
a large fleet of ships) the on-board thickness measurement data need to be fed back into the corrosion model (predictor). A methodology for updating the predictions with measurement results is presented in section 4. It should be realised, however, that in order to practically operate the predictor-corrector scheme, the data generated by both the corrosion model as well as the thickness measurements need to be dealt with in a comprehensive and efficient way. As the amount of data involved can be enormous (in particular for the thickness measurement results of ageing bulk carriers subjected to the Enhanced Survey Programme (ESP), [2,15]), a computerised system incorporating data storage and the (updated) corrosion predictions in a user-friendly way seems the most promising way to implement the scheme. In fact, the classic way of processing thickness measurement data by using Excel tables and sketches is considered as unsatisfactory, as the processing and reporting time is very long, structural weaknesses can easily be overlooked and the results of different thickness measurement campaigns cannot be compared [16], which is an essentially feature for the predictor-corrector scheme.

In recent years sophisticated hull condition monitoring software has been introduced. The basis for these tools has been laid by the European Commission financed ‘CAS’ project (Condition Assessment of ageing ships for real-time Structural maintenance decision), which took place from 2005 to 2008 [17,18]. The project participants are depicted in Table 2. The scope of the ‘CAS’ project was to develop fully electronic processing of the hull inspection results, mainly covering coating condition, structural defects (cracks, deformations, etc.) and thickness measurement data, by making use of a standard interface and an electronic hull model. Such a 3D CAD/CAM based model can be fully visualised and navigated for easy overview, comparison and interpretation of large amounts of data and is considered ideally suited for the predictor-corrector scheme.

Table 2: Participants to the ‘CAS’ project

<table>
<thead>
<tr>
<th>Bureau Veritas</th>
<th>Class Society</th>
<th>FRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germanischer Lloyd</td>
<td>Class Society</td>
<td>GER</td>
</tr>
<tr>
<td>Materiaal Metingen Groep</td>
<td>Thickness measurements</td>
<td>NLD</td>
</tr>
<tr>
<td>SENER</td>
<td>Shipyard software</td>
<td>SPA</td>
</tr>
<tr>
<td>Instituto Superior Técnico</td>
<td>University</td>
<td>POR</td>
</tr>
<tr>
<td>Lisnave Estaleiros Navais</td>
<td>Repair shipyard</td>
<td>POR</td>
</tr>
<tr>
<td>Cybernetix</td>
<td>Robotics</td>
<td>FRA</td>
</tr>
<tr>
<td>Intertanko</td>
<td>Owners association</td>
<td></td>
</tr>
<tr>
<td>TOTAL (TAM)</td>
<td>Charterer</td>
<td>FRA</td>
</tr>
<tr>
<td>Russian Maritime Register</td>
<td>Class Society</td>
<td>RUS</td>
</tr>
</tbody>
</table>

3.2 VERISTAR HLC

On the basis of the results of the ‘CAS’ project, Bureau Veritas (coordinating the ‘CAS’ project) has developed the VeriSTAR HLC (Hull Life Cycle) software. Within this tool the thickness measurements are entered into a standardised (simplified) 3D model of the ship, which can be navigated to inspect structural details, see Figure 11. The software enables fast and efficient checking of class renewal criteria and automatically generates thickness measurement reports and structural degradation diagrams. It functions as a through-lifetime condition monitoring tool, containing the full history of inspections, damages and repairs. As the electronic format developed within the ‘CAS’ project is utilised, it is easy to exchange information digitally.

VeriSTAR HLC is primarily intended as a new service for ship owners and technical managers, in order to enable them to improve maintenance planning and have better control over damage & repair cases issues. In addition, the tool can help to prepare class surveys, as well as vetting inspections (e.g. by Rightship). As the software is graphically available on-board as well as in the shore side technical office, the communication between ship’s crew and the superintendent is improved, allowing for better mutual understanding and a faster decision making process, in particular when in dry-dock, see Figure 12.

Figure 11: VeriSTAR HLC uses layers referring to reports, photographs and other data to be stored in the relevant ship area [16]

Figure 12: Step-by-step from on-board measurement to rules assessment through HCM (Hull Condition Monitoring) [16]

VeriSTAR HLC can be integrated with several other tools within the VeriSTAR family. The link with VeriSTAR HULL, the Bureau Veritas 3D finite element calculation programme, enables easy updating of the finite element model with the thickness measurement results, see Figure 12. This enables the optimisation of required steel renewal. The link with VeriSTAR AIMS (Asset Integrity Management Services) provides a real-time open web based system where controlled access
allows AIM teamwork worldwide. The system is designed to improve inspection management and information control for different types of ships and offshore units. Finally, the link with VeriSTAR RBI (Risk Based Inspections) provides a value added scheme for systematic identification of what to inspect, how to inspect, where to inspect and how often to inspect. Utilising risk based inspection techniques the efficiency of inspection regimes can be optimized while reducing risks to the ship or offshore unit, its operations and the associated inspection cost.

Within this context a further integration of VeriSTAR HLC with the reliability analysis scheme of the ship structure described in section 2 (predictor) would provide the possibility to systematically feed thickness measurement data back into the reliability analysis (corrector) to improve the accuracy of the prediction. A methodology for this correction is proposed in section 4.

4. PREDICTOR-CORRECTOR SYSTEM FOR IMPROVED RELIABILITY

4.1 CORROSION MODELS

Quantitative corrosion models applied by marine industry are generally developed for design purposes and represent a sort of “worst case model”. On the other hand, the large number of uncertainty in corrosion mechanisms calls for in-service inspections for corrosion control and model updating. The process of inspection and model updating requires that the uncertainties are quantified and that the models used for predictions are able to accurately represent the corrosion phenomena. This is because updating procedures are based on the application of Bayes’ rule using inspection results. In that perspective, it is clear that corrosion models for corrosion control and updating of corrosion predictions have to be based on models which are not “worst case models” but models which capture as far as possible the actual degradation process along the service life.

This is illustrated on a simple example from Straub and Faber [19]. Two linear models are compared with respect to corrosion predictions with and without inspection. The two models, the parameters used for the example and the reliability index before and after inspection are given respectively in Figure 13, Table 3 and Figure 14 below.

In the example the limit state function for corrosion failure is written as:

\[ g = d_{CR} - d_c(t) \]  \hspace{1cm} (36)

where \( d_{CR} \) is the critical loss of thickness and \( d_c(t) \) the loss of thickness at time \( t \):

\[ d_c(t) = \begin{cases} 0 & \text{for } t < t_i \\ r(t - t_i) & \text{for } t \geq t_i \end{cases} \]  \hspace{1cm} (37)

where \( t_i \) is the initiation time.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
<th>Distribution</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion rate</td>
<td>mm/year</td>
<td>Weibull</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Initiation time model A</td>
<td>year</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Initiation time model B</td>
<td>year</td>
<td>Log-normal</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Critical depth ( d_{CR} )</td>
<td>mm</td>
<td>deterministic</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Inspection time ( t_{INSPI} )</td>
<td>year</td>
<td>deterministic</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Corrosion measurement ( d_{insp} )</td>
<td>mm</td>
<td>Log-normal</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 13: Two corrosion models for updating after inspection

Figure 14: Updating of corrosion models with and without corrosion measurement

Observation at time \( t_{INSPI} = 8 \text{ years} \) is a random variable with mean value equal to 6 mm and standard deviation equal to 1 mm.

It is assumed that the correct corrosion model is model B, which takes into account some coating protection system. It is also assumed that for design purposes, model A is used. Before inspection at time \( t_{INSPI} \) (equal to 8 years) the reliability calculations using model A are conservative. Assuming that the corrosion measurement at 8 years, yields a mean value of the measurement equal to 6 mm (with a standard deviation equal to 1 mm), reliability calculations are updated according to the methods explained in 4.2.2. It can be seen that model A is no longer conservative: the probability of failure is equal to 0.01 using model A, whereas this probability equals to 0.5 using the correct model (model B). This simple example emphasises the fact that accurate models have to be used for any predictor-corrector system designed as a general system of Asset Integrity.
Management. The same observation can lead to different situations depending on the reference corrosion models.

4.1.2 Accuracy of models

Quantitative corrosion models should take into account the temporal and the spatial variability of the corrosion degradation process. Spatial variability is mainly related to localised corrosion (pitting), which requires specific models and specific probabilistic procedure for managing inspection effort, including updating after inspection. In this paper (see section 2.1) only uniform corrosion is addressed.

Various types of corrosion models for uniform corrosion can be found in literature, namely:

Type 1: Statistical models where various analytical formulations are fitted to thickness measurement data, i.e. using least-square approximation (single or multiple regression etc.)

Type 2: Semi-empirical models, such as the Melchers’, Guedes-Soares’ and Ivanov’ models, where driving mechanisms are partially modelled

Type 3: Pure phenomenological models which are directly based on the influencing factors as for example the concentration of oxygen in the environment, the humidity, the temperature etc.

Clearly, purely phenomenological models are not tractable due to the lack of data dealing with basic physical influencing parameters (temperature, humidity, pH, dissolved oxygen, microbial activity). Consequently, models used in engineering applications are Type 1 and/or Type 2 models.

Semi-empirical models (type 2) need to be checked against thickness measurements. In some cases, statistical treatment is performed to calibrate the parameters of the model or to calibrate some model error (the semi-empirical model is refined using additive or multiplicative model error).

Statistical models are the most commonly used in practice. One of the main drawbacks of empirical (statistical) models is the fact that extrapolation of the models outside the range of data to which they were calibrated, is not possible. As a consequence, statistical models have to be calibrated to a set of structural components (plates, stiffeners) identical from a structural point of view (same type of elements, same type of materials) and submitted to similar conditions: same loading, same environmental conditions, and same operational conditions. In other words preliminary clustering has to be performed to identify the basis for calibration and select the relevant thickness measurement data to be used for each calibration point. This task, which may be summarised as a “clustering” task, is a challenging task to be achieved in a transparent way either by class societies (using class society databases) or IACS (using common IACS databases). Some preliminary studies have been done but the work has to be completed.

Utilization of semi-empirical models needs to be defined regarding their range of applicability. Many models are based on modelling of driving corrosion mechanisms. The range of validity of these models is not always explicitly mentioned and this abnormal situation is detrimental to their use in practical applications. In any situation, a set X of random variables with distribution fx(x) has to be defined for use in reliability calculations as explained in 4.2.2.

4.1.3 Corrosion models for a particular ship

Empirical predictive corrosion models have to be based on thickness measurement databases established on a fleet basis, that is to say on a set of ships where thickness measurements corresponding to a specific calibration point (see above) are selected for the calibration exercise. These generic predictive corrosion models can then be used for a new building under the condition that they are used within the range of data utilized for establishing the models. Corrosion models for a particular ship are firstly generic models which are updated in a second step using thickness measurements performed on this particular ship at regular intervals.

4.2 PREDICTOR-CORRECTOR SYSTEM

4.2.1 Introduction

It is now recognised that the inspection and maintenance problem is an optimisation problem where the objective of the ship manager is to find some balance between the benefits of inspection and maintenance effort and cost. For example a manager should choose between dry docking and preventive maintenance (small repairs) in order to avoid a significant future amount of steel renewal. The general framework for this optimisation problem is the decision theory. One of the basic principles of this theory is that optimal decisions are those resulting in the highest expected utility.

Objective of the inspection and maintenance problem is therefore to minimise the total expected cost corresponding to the inspection and maintenance planning and at the same time to guarantee that given constraints in terms of safety (loss of lives) and environment (pollution) are continuously fulfilled. In other words, objective of Risk Based Inspection (RBI) or Asset Integrity Management (AIM) is to compare different inspection/maintenance strategies with respect to the risk they imply and to select the optimal one. Risk Analysis provides a consistent framework for decision making under uncertainties. Risk is traditionally defined as the product between likelihood and consequence of failure. Risks are evaluated with respect to Personnel (P),
Environment (E) and Asset (A). An overview of RBI approach can be found in Goyet & all [20].

Engineering problems may be classified according to the type of analysis used in decision analysis: prior analysis, posterior analysis and pre-posterior analysis [21]. Inspection and maintenance problem generally uses pre-posterior analysis where outcome of inspections and mitigation actions according to these outcomes are taken into account for establishing initial inspection plans, which have generally to be finalised at the beginning of the service life.

The whole predictor-corrector system as used in inspection and maintenance problem includes:

1. Quantitative models for degradation (fatigue, corrosion)
2. Inspection modelling (POD curves – Probability of detection curves, probability distributions of measurements for cracks and thickness loss)
3. Reliability updating
4. System analysis to be included in consequence analysis
5. General framework for pre-posterior analysis

All these ingredients may be defined and assembled in different ways according to the specific engineering applications under consideration. General procedures for reliability updating and pre-posterior analysis are given below.

4.2.2 Reliability updating

Updating deals with updating of random variables and updating of probabilities. In usual problems, observations of basic random variables or basic uncertainties cannot be observed directly. Additionally observations of uncertain phenomena (crack sizes or thickness measurements) cannot be directly connected to basic random variables. So updating of random variables is not practicable in most cases.

Observations in inspections of ships consist in inspections of outcome of functional relationships between several basic random variables. Using these observations, it is possible to update probabilities – in principle probabilities of failure – using Bayes’ formula and Structural Reliability Analysis (SRA) methods. This approach is summarised below (formula 36 to 39):

\[ P(F / I) = \frac{P(F \cap I)}{P(I)} = \frac{P(F \cap I) + P(F)}{P(F)} \]  \hspace{1cm} \text{(38)}

\[ P(F / I) = \frac{P(M(X) \leq 0 \cap H(X) < 0)}{P(H(X) < 0)} \]  \hspace{1cm} \text{(39)}

\[ P(F / I) = \frac{P(M(X) \leq 0 \cap H(X) = 0)}{P(H(X) = 0)} \]  \hspace{1cm} \text{(40)}

where \( F \) denotes a failure event, \( I \) denotes an inspection event, \( M(X) \) is the safety margin related to the failure event, \( H(X) \) is the event margin related to the inspection event and \( X \) is the vector of random variables with a distribution \( f_X(x) \).

Basic theory for reliability updating can be found in Madsen [22].

The failure event is for example defined by the fact the crack size \( a(t) \) is higher than some critical size \( a_{CR} \) or the residual thickness \( T(t) \) is lower than the renewal thickness \( T_{RENEW} \).

The inspection event can be:

1. The event of detection (of a crack) or, inversely, the event of no detection
2. The event of overtaking of some reference thickness \( (T(t) > T_{REF}) \) or no overtaking \( (T(t) < T_{REF}) \)
3. The event of crack size measurement \( (a(t) > a_{MES}) \) or thickness measurement \( (T(t) > T_{MES}) \) with \( a_{MES} \) and \( T_{MES} \) considered as random variables due to some random measurement error.

Inspection events listed in 1 and 2 above can be modelled using inequalities (expression 39) whereas events listed in 3 above can be modelled using equalities (expression 40).

For example, the probability of overtaking the thickness renewal at time \( t_2 \), given thickness measurement at time \( t_1 \):

\[ P(T(t_2) > T_{RENEW}) = \frac{P(T(t_2) > T_{RENEW} \cap T(t_1) = T_{MES})}{P(T(t_1) = T_{MES})} \]  \hspace{1cm} \text{(41)}

Probabilities as defined in (38) to (41) can be computed using FORM methods (component and system reliability analyses). The failure event \( F \) refers to component (crack size, thickness loss) or system levels. Failure is assessed through a particular global item (cross sectional area \( A \), area moment of inertia \( I \), section modulus SM, ultimate hull girder bending moment capacity etc). In a similar way, the inspection event \( I \) can deal with a set of inspection performed at different points in time.

In the fatigue case, the usual practice is to establish generic inspection plans using some particular assumptions in terms of the inspection results. For example, the assumption of no-detection can be employed for updating the probability of fatigue failure. This is due to the fact that some inspection techniques for fatigue are based on detection and do not deal with any crack size measurement. The assumption employed is correlated with the possible inspection result. In the corrosion case, the situation is quite different due to the fact that the inspection result is always some precise measurement. Establishment of generic inspection plans for corrosion is more complex and needs additional research.
4.2.3 Pre-posterior framework

Pre-posterior analysis is illustrated on Figure 15 [21]. Using pre-posterior decision analysis optimal decisions with knowledge-induced improvement may be identified. Furthermore, options are built into the decision making process in order to accommodate subsequent actions, which are optimal, subject to the improved knowledge. Such options may e.g. be formulated as decision rules \( d(k) \) which specify the line of action as a function of the achieved knowledge \( k \).

\[
\text{Planned investigations} \rightarrow \text{Results of investigations} \rightarrow \text{Risk reducing and mitigating actions} \rightarrow \text{Activity performance} \rightarrow \text{Utility/Consequences}
\]

Figure 15: Pre-posterior analysis

In figure 15, planned investigations are the scope of inspections (thickness measurements, NDT for fatigue degradation). These investigations give results; mitigation actions are then performed (crack repair, steel renewal) according to results of investigations. The utility function, usually the cost function, is a function of all sets included in pre-posterior analysis (planned investigations, results of investigation, mitigation actions and activity performance). Expected value of the utility function is calculated and alternative inspection and maintenance strategies are compared on the basis of the expected utility. This analysis is performed at the beginning of the service life “by anticipation”. The inspection and maintenance strategy is defined and is updated after each inspection campaign.

This general framework can be applied in different way for answering all questions dealing with the inspection & Maintenance strategy, basically:
- What to inspect (scope of inspection)?
- When to inspect (inspection frequency)?
- How to inspect (inspection technique: visual, close-visual, NDT)?

An example of application of the framework is given in Goyet and all [23].

4.2.4 System analysis

Risk Based Inspection/Maintenance planning or Asset Integrity Management refers to Risk Analysis, based on probabilities and consequences. A correct way for performing risk analysis is to start with initial failure states (corrosion, fatigue), then to identify the failure scenarios leading to the so called “terminal events” (i.e. total collapse of the ship) and finally to analyse these terminal events in terms of safety, environment and economics. Thus, risk analysis has to include system analysis in order to propagate degradation mechanisms from initial to terminal events.

System analysis for RBI/AIM may deal with the probability that some global items are lower than given critical values: this concerns the cross sectional area (A), the area moment of inertia (I), the section modulus (SM), the ultimate hull girder bending moment capacity etc (see section 2.3).

This also concerns the ultimate strength of the ship. Due to the fact that ultimate strength of the mid-ship section is a non-linear function of the geometrical properties of the ship, its probability distribution in a particular damage state cannot be evaluated using explicit formulation. So advanced structural reliability analysis methods have to be used. One idea is to use surface response approaches, which require a plethora of preliminary deterministic calculations in a Monte-Carlo type fashion. Figure 16 [24] gives an example of these preliminary calculations, where a set of corroded states of a ballast tank are analysed using the Bureau Veritas MARS software:

\[
\text{Vertical axis represents moment boundary for ultimate strength.}
\]

Figure 16: Influence of corrosion on ultimate strength

4.3 RESEARCH NEEDS

All ingredients identified in sections 4.1 and 4.2 need further research. In general corrosion reliability analysis and corrosion reliability updating analysis are lagging in development, compared for example with fatigue analysis.

Correlation aspects are of prime importance and need a specific and complex research effort. Spatial variation of corrosion degradation, currently neglected, has to be emphasized. Some parts of the ship may be the subject of a thickness measurement activity, some other parts may not be. The question is to decide, for example, if thickness measurements performed at a specific location can be used to update corrosion degradation at a different location without additional thickness measurements. In the same context, how can we utilize the measurements to correct corrosion predictions incorporating spatial variability as well. It will be also possible to optimise the scope and the contents of thickness measurement campaigns.
Combination of uniform corrosion and localised corrosion is also an issue, which needs to be addressed. The concept of uniform corrosion has also to be clarified for correct use after inspection campaigns in particular, if thickness measurements show significant discrepancy in a zone initially considered as subject to uniform corrosion.

5. CONCLUSIONS

The development of mathematical corrosion models and the introduction of sophisticated hull condition monitoring programmes led to the utilisation of reliability techniques to predict the future structural behaviour of the ship structure. This work is a proposal to apply probabilistic representation of the residual thickness and subsequently of the main hull girder properties.

A comprehensive mathematical model has been presented which can be used to identify the weak areas of the structure a priori and to prioritize their maintenance and inspection. The inherent uncertainties in the prediction of the residual thickness have been demonstrated to increase with time. It is thus necessary to employ a hull life cycle management as a decision support tool in order to monitor and correct the residual thickness model. The developed mathematical models can be also utilized to evaluate the maintenance needs of the vessel even at the design stage. Furthermore, the developed model can be employed to perform parametric analyses to determine the effect of coating longevity on the hull girder properties and the ability to meet the renewal criteria. More importantly, various hull girder properties can be ranked through their probability distribution functions, estimated on the basis of the residual thickness model, to determine the most appropriate renewal criteria. In combination with probabilistic representation of the loads, the present model can serve for a full fledged stochastic analysis of the hull structure.

The use of an appropriate corrosion model is crucial for inspection and maintenance planning. The need for inspection/measurement-based updating of the corrosion prediction model has been demonstrated. Measurements reduce the uncertainty embedded in the deterioration model. It is proposed that the corrosion model be updated on the basis of Bayes’ law in pre-posterior framework analysis-based decision.

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7. AUTHORS’ BIOGRAPHIES

John Emmanuel Kokarakis, a 1979 graduate of National Technical University of Athens, he holds PhD (1986) and Masters degree in Naval Architecture (1983) and Masters in Mechanical Engineering (1984) from the University of Michigan. He worked for over ten years as a consultant undertaking technical problems worldwide. His specialization was in the area of technical investigation of marine accidents. In his capacity as a forensic engineer he participated in the technical investigation of the Exxon Valdez grounding, Sea-crest Capsize, Piper Alpha fire and explosion, Aleutian Enterprise foundering in Alaska as well as many other accidents of less notoriety.

The last eleven years he works in Greece, in the area of classification. Having served in the plan approval office of American Bureau of Shipping in Piraeus, he then joined Germanischer Lloyd heading their tanker and bulk carrier team in Greece. He is currently the Technical Director of Bureau Veritas in the Hellenic and Black Sea Region. In his duties Dr. Kokarakis is responsible for the smooth technical operation in the region as well as in the harmonic cooperation with the BV offices worldwide to the benefit of the BV clients in Greece. He was a member of the team which developed the Common Structural Rules.

Jean Goyet, is a graduate of ESTP (Ecole Spéciale des Travaux Publics, Paris). He worked about 12 years within the CTCIM (Centre Technique de la Construction Métallique) which is the French Technical Centre for steel construction. He joined Bureau Veritas in 1993 as Research Director within the Research Department of the Marine Division. Jean is an expert in Structural Reliability Methods and is member of the JCSS (Joint Committee on Structural Safety), a group of European experts in the field of structural reliability and risk analysis. Jean is currently Marine RBI Product Manager, in charge of the development of Risk Based Inspection approaches for floating offshore units as well as the implementation of these approaches in usual practice of offshore industry. He is preparing introduction of RBI in Bureau Veritas rules for Offshore Units. Jean is involved in Asset Integrity Management of ships and is participating in two European projects (RISPECT and FLAGSHIP) which deal with the optimisation of inspection and maintenance effort to be done during the in-service life of oil tankers and bulk carriers.

Gijsbert de Jong holds the current position of product manager at Bureau Veritas and is based in the Head Office in Paris. He is responsible for the international business development in the field of container ships and dry bulk carriers, as well as a number of specialised ship types.

Gijsbert joined Bureau Veritas in 2001 after obtaining an MSc in Naval Architecture & Marine Engineering from Delft University of Technology. Before moving to Sales & Marketing Management in 2007, he has worked as hull surveyor and department manager for the Bureau Veritas plan approval office in Rotterdam. During this period Gijsbert has built up extensive experience with dry cargo & container ships, dredgers, asphalt carriers, product tankers, reefers & tugs. In his present position he is working closely together with BV’s technical specialists and extensive international network to develop new products and services meeting with the maritime industry’s specific needs.

Gijsbert has published technical papers on container ships, bulk carriers, arctic shipping and fuel cell power systems and regularly writes articles for marine industry magazines.

Jean-Francois Segretain, Jean-Francois, 52, is presently Bureau Veritas Marine Regional Chief Executive for Southern Europe and North America. Graduated as a naval architect, Jean-Francois is within Bureau Veritas since 1983. Before serving in his present position, he was previously involved with propulsive installations approval and was in charge of hull & stability department then development department (rules and computer tools) in Bureau Veritas Head Office.

Jean-Francois was a member of the IACS Joint Bulker Project (JBP) steering group and is presently member of the SG/CSR, the small group of Class Societies representatives steering the IACS Common Structural Rules development and maintenance.