18 Damage to Ship Structures Under Uncertainty: Evaluation and Prediction

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Abstract

Ship structures are subjected to various deteriorating mechanisms throughout their service life. This deterioration is highly uncertain and can adversely affect the performance and safety of the vessel, and if not addressed properly, catastrophic failures may occur. In this chapter, deteriorating mechanisms affecting ship structures and their prediction models under uncertainty are discussed. In addition, the integration of these models into a general evaluation and management framework is introduced. This integration can support the optimal decision-making process regarding future structural interventions and, eventually, may

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lead to safe and efficient service life extension. The role of structural health monitoring and nondestructive evaluation techniques in damage identification, assessment, and prediction is also discussed.

Introduction

Ships are often subjected to sudden and/or gradual (i.e., time-dependent) damage mechanisms throughout their service life. Sudden structural failures due to extreme events include collision, grounding, fire, and explosions, while time-dependent deterioration mechanisms include fatigue and corrosion. Each damage mechanism requires its own assessment methods suitable to support intervention decisions related to this damage type. Sudden structural damage requires fast damage quantification and assessment of the structural residual strength in order to make effective decisions regarding the future use of the ship. Although the occurrence of such events may be unpredictable, their effects can be correctly managed through the proper emergency response protocols imposed by the ship owners, in addition to various active and passive safety measures. For sudden structural damage, multiple methods can be used to assess the degree of damage and determine the residual structural strength ranging from complex nonlinear finite element analysis (FEA) to simplified formulae (Wang et al. 2002). Reliability and risk of failure due to insufficient residual longitudinal strength of ships damaged by collision or grounding have been also topics of active research (e.g., Fang and Das 2005; Hussein and Guedes Soares 2009; Saydam and Frangopol 2013).

Damage due to time-dependent deterioration, on the other hand, can be predicted through the appropriate modeling of the deterioration phenomena. This prediction process involves multiple sources of uncertainties; thus, it has to be performed probabilistically (Frangopol 2011; Frangopol et al. 2012; Soliman and Frangopol 2013b). Part of these uncertainties is associated with the natural randomness (i.e., aleatory uncertainties) and the other part is associated with inaccuracies in the adopted prediction models (i.e., epistemic uncertainties) (Ang and Tang 2007). The proper modeling of such uncertainties is a key factor affecting the effectiveness and accuracy of the prediction process.

Inspection actions provide valuable information on the actual damage level found at the time of inspection. This assists in the damage evaluation and enables updating the damage propagation model in order to achieve a better damage prognosis process (Soliman and Frangopol 2013a). Various nondestructive testing (NDT) methods can be employed to assess the time-dependent damage of ships. Some of these methods, such as the acoustic emission technique, received noticeable attention within the last decades. The acoustic emission technique was found to provide useful results regarding the damage identification and localization in ship structures.

Structural health monitoring (SHM) systems used to record the ship response are employed to study the structural performance of the ship under normal operational conditions and to validate the assumptions placed during the design phase.

SHM techniques have the potential for the detection and localization of structural damage occurring under severe operational conditions or slam impacts (Salvino and Collette 2009). Multiple approaches have been recently proposed to fulfill this task. However, most of these approaches, which have demonstrated their feasibility in laboratories and controlled environments, still require additional research before they are widely implemented on large and complex structures such as ships (Salvino and Brady 2008).

This chapter presents a brief overview of the damage evaluation and prediction techniques for ship structures, with emphasis on time-dependent damage prediction models. The probabilistic performance evaluation methods suitable to consider the uncertainties associated with these models are emphasized. The role of SHM and NDT in the damage identification process and the recent developments in the service life prediction and extension methodologies for ship structures are also presented.

Time-Based Structural Deterioration Under Fatigue and Corrosion

Time-based damage deterioration mechanisms, such as fatigue and corrosion, are among the major threats affecting ship performance and safety. Due to this deterioration, ship structures require frequent inspections and repairs. Ship deterioration occurs progressively as a result of normal ship operation in the surrounding environment (ISSC 2009). Corrosion can lead to thickness reduction in the affected areas which can ultimately reduce the hull bending capacity. Fatigue, on the other hand, results in cracks that may cause sudden fracture and drastically reduce the structural reliability. These aging effects, when combined with rough sea conditions, may lead to catastrophic ship failures. Generally, time-dependent deterioration initiation and propagation processes are highly uncertain. This adds challenges to the performance assessment and service life estimation. The time-dependent damage level with the effect of uncertainties is shown schematically in Fig. 1. As shown, at any point in time, the damage level can be described by its probability density function (PDF). Additionally, the time required to reach certain damage level carries significant uncertainty.

Maintenance actions applied throughout the service life of ships can either reduce the damage level (e.g., by replacing the damaged component), or prevent further damage propagation for a certain period of time (e.g., by applying corrosion coatings) (Kim et al. 2013). Both maintenance types, denoted as M_1 and M_2, respectively, result in an extension in the service life. The effect of both maintenance types on the time-dependent damage level is shown in Fig. 2.

Predicting fatigue and corrosion damage initiation and propagation has been an active research topic for decades. As a result, several analytical models have been proposed for predicting the structural capacity and service life. The next sections present the commonly used fatigue and corrosion damage prediction models. Later in this chapter, probabilistic performance assessment considering uncertainties associated with these models will be discussed.

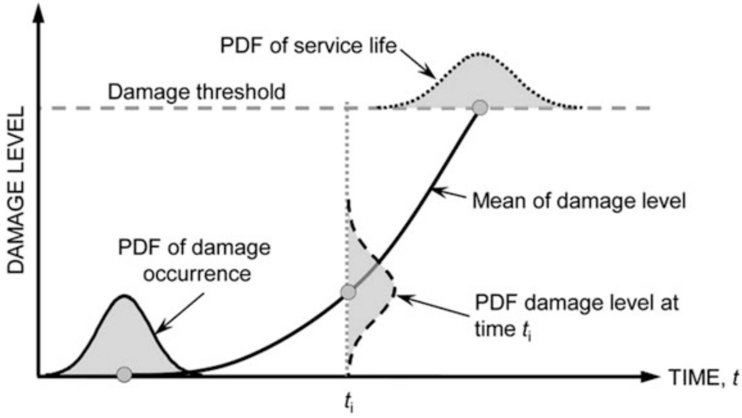

Fig. 1 Damage initiation and propagation under uncertainty

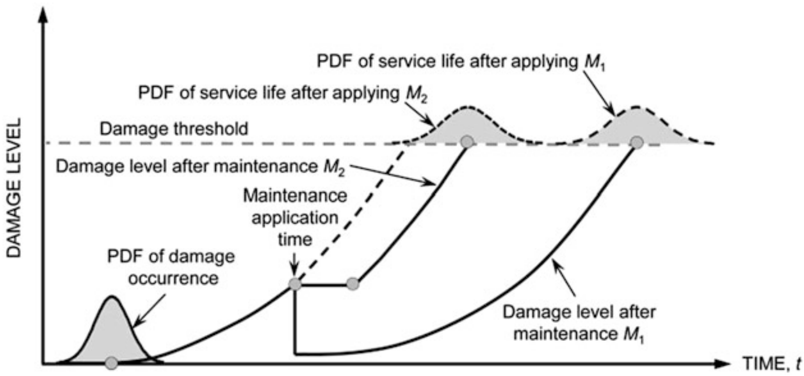

Fig. 2 Effect of maintenance on the damage level and service life

Corrosion in Ships

Several types of corrosion wastage in mild and low alloy steels in marine environments exist, such as uniform (general), pitting, stress, and galvanic corrosion. For corrosion management and control, both localized and general corrosion must be considered. The former can cause oil or gas leaks, while the latter, which spreads over the surface of the affected area, is more likely to lead to structural strength problems. Stress corrosion occurs in some alloys when exposed to corrosive environments while mechanically stressed. Furthermore, when two different metals are physically connected, galvanic accelerated corrosion occurs in the less noble metal (ISSC 2009). Factors affecting marine immersion corrosion include the type of structural material, corrosion protection method (e.g., coating, cathodic protection), type of cargo or stored material, cycles of loading/unloading of cargo or stored material, humidity, and temperature (ISSC 2006).

In recent years, extensive work has been performed to investigate different parameters affecting general corrosion wastage and to formulate corrosion wastage prediction models (Paik et al. 2003a, b; Melchers 2002, 2003a, b, 2004c, 2006; Guedes Soares and Garbatov 1999; Guedes Soares et al. 2005). For example, Guedes Soares et al. (2005) investigated the influence of salt content, water temperature, dissolved oxygen, PH value, and water velocity on the general corrosion rate and included these effects in the nonlinear corrosion wastage model proposed in Guedes Soares and Garbatov (1999). Their model consists of three corrosion loss stages. The first is penetration of the water particles through the corrosion coating, the second is the formation of the two-dimensional monolayer oxide film, and the third is the start and growth of the three-dimensional oxide nuclei. In this model, the first two stages represent the coating effectiveness period where the corrosion depth at any time t can be found as (Guedes Soares et al. 2005)

$$d(t) = d_\infty \left(1 - e^{\frac{-(t-\tau_C)}{\tau_t}} \right) \quad \text{for} \quad t > \tau_c \tag{1a}$$

$$d(t) = 0 \quad \text{for} \quad t \leq \tau_c \tag{1b}$$

where $d(t)$ is the time-dependent corrosion depth and d_∞, τ_c, and τ_t are model parameters depending on the coating type and operational and environmental conditions.

Melchers (2003a, b, 2006) developed a corrosion wastage prediction model consisting of the following phases of average corrosion loss: (a) short-term initial phase in which the corrosion is governed by the chemical kinetics, (b) approximated linear function dependent on the oxygen diffusion from surrounding water, (c) nonlinear function governed by oxygen diffusion through corrosion product layer, (d) anaerobic bacterial corrosion phase, and (e) linearly approximated long-term anaerobic bacterial corrosion phase.

Research work has also been performed to model pitting corrosion. However, the scarcity of corrosion depth measurements for this type of corrosion compared to the general corrosion poses additional challenges. In this context, Melchers (2004a, b) proposed a multiphase model for pitting corrosion loss as a function of exposure time.

Due to the importance of the corrosion assessment and repair topic, multiple classification societies issued recommendations and regulations for corrosion coating, prevention, inspection, and repair of corroded steel ships (e.g., DNV 1998, 1999; IACS 2003). Corrosion wastage prediction is a process covered by various uncertainties; thus, it has to be conducted probabilistically. Although many corrosion models are available, these models are based on statistical data collected from different vessels; as new construction techniques and materials emerge, these models should be updated and refined.

Time-dependent corrosion losses have an effect on the structural resistance of a ship and should be considered in its life-cycle performance assessment (Kwon and Frangopol 2012a). Corrosion losses may cause reduction in the hull structural

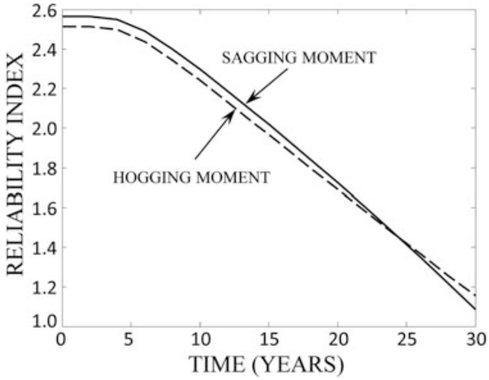

Fig. 3 Effect of corrosion on the time-variant performance (Adapted from Frangopol and Okasha (2010))

resistance, reduction in the local strength, and increase in the fatigue crack propagation within the affected areas. Considering general corrosion, multiple studies have been performed to predict the time-variant hull structural resistance by estimating the loss in the hull girder section modulus due to corrosion (e.g., Ayyub et al. 2000; Paik and Wang 2003; Okasha et al. 2010; Decò et al. 2011, 2012). Figure 3 shows the time-variant reliability index of a steel ship studied in Frangopol and Okasha (2010). As shown, the performance of the ship drops significantly due to corrosion. It is observed that most of the analytical studies tend to overestimate the effect of corrosion on the hull girder strength. In an attempt to address this point, Wang et al. (2008) presented a statistical study showing the loss in the hull girder section modulus in a database of 222 steel ships. This type of analysis can support the verification and calibration of the hull resistance prediction models.

Aluminum alloys used in ship construction, mainly 5xxx-series alloys, have excellent corrosion resistance in marine environments. Part of the corrosion resistance of aluminum is attributed to the formation of a thin oxide layer which prevents the core metal from any further corrosion. This layer is hard and renews itself almost instantly in case of any mechanical abrasion. It is very stable under most conditions except for extreme PH values where it may lose its stability; additionally, the self-renewal may not be fast enough to prevent further corrosion. However, since aluminum is a very active metal, it is highly prone to galvanic corrosion if not properly isolated. Galvanic action, especially at areas where both steel and aluminum are connected, makes the aluminum vulnerable to corrosion. The corrosion damage in this case may be very fast (ISSC 2009). An example of this type of problem was observed in the USS Independence LCS-2, a 127.4 m, high-speed trimaran capable of speeds up to 44 knots, in which corrosion initiated at the locations where the aluminum hull was in contact with the steel propulsion system (O'Rourke 2012). However, this mode of corrosion can be easily prevented by the use of appropriate isolations or cathodic protection systems.

Another mode of deterioration of aluminum ships is sensitization, which is a degradation mode that occurs in high-magnesium aluminum alloys (e.g., 5083, 5086, 5456, and 5383) when exposed to elevated temperatures (Sielski 2007). Under certain conditions, these alloys may suffer intergranular corrosion due to the precipitation of the beta-phase (Mg_2Al_3) on the grain boundaries. This precipitate is electromechanically more active than the aluminum matrix and can cause further intergranular corrosion with the continued grain boundary migration. Furthermore, this process increases the material susceptibility to stress corrosion cracking, exfoliation, and decreased ductility. Recent studies were carried out to find the time required to sensitize the material based on the thermal profile of the ship. However, this is directly related to the location of the plate within the ship as it is heavily dependent on the stress profile acting on the studied location (Sielski et al. 2012).

Fatigue in Steel and Aluminum Ships

Fatigue is one of the major stressors affecting ship structures. Although many classification societies issued codes and regulations for the proper fatigue design and assessment, ship structures still suffer fatigue cracking. Fatigue is the process of damage accumulation caused by repeated fluctuating loads. Fatigue damage can exist in mild environments as well as aggressive ones (i.e., corrosion-induced fatigue). For a component subjected to elastic stress fluctuations, fatigue damage may accumulate at regions of stress concentration, where the local stress exceeds the yield limit of the material (Barsom and Rolfe 1999). Stress concentrations can occur in a component due to the presence of initial flaws in the material, welding process, or fabrication. Initiation and propagation of cracks in the plastic localized region occur due to the cumulative damage acting over a certain number of stress fluctuations. These cracks can eventually cause the fracture of the component. This process can be minimized by adopting better details, avoiding stress concentrations, and decreasing the number of welded attachments, among others. Currently, design specifications give the guidelines for maximizing the fatigue life and offer the means for selecting details associated with high fatigue resistance (Fisher et al. 1998).

Fatigue for ship structures can generally be assessed by the *S-N* (i.e., stress-life) approach and the fracture mechanics approach (also known as the crack growth approach). The former gives the relationship between the stress acting on the detail and the predicted number of stress cycles to failure, while the latter provides a theoretical model to calculate the crack size in relation to the number of cycles acting on the detail. A brief discussion on both approaches is provided in the next subsections.

The *S-N* Approach

In the *S-N* approach, the fatigue life of a certain detail is determined in a laboratory test by applying constant or variable amplitude stress cycles to the detail until a crack with predefined size grows through the detail. The test is repeated for several specimens and for different stress amplitudes. Next, the stress-range amplitude is

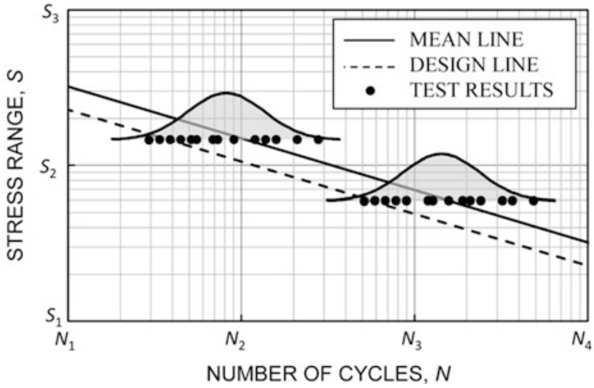

Fig. 4 *S-N* mean and design lines

plotted versus the number of cycles to failure in a logarithmic scale plot, as shown in Fig. 4, and a linear or multi-linear fitting of the data is performed yielding the mean *S-N* lines. Due to the variability in test results, a design line is usually defined by codes in which the mean line is shifted to the left by a certain amount sufficient to achieve a satisfactory probability of survival for designed structures. For example, the AASHTO LRFD design specifications (AASHTO 2010) shift the mean line to the left by two standard deviations indicating that approximately 95 % of the specimens would survive the associated number of cycles (Fisher et al. 1998). The resulting *S-N* relationship of a detail can be expressed, for a single-slope *S-N* relation, as

$$S = \left(\frac{A}{N}\right)^{\frac{1}{m}} \tag{2}$$

in which S is the stress range (i.e., fatigue resistance), A is a fatigue detail coefficient for each category, N is the number of cycles, and m is a material constant defining the value of the slope of the *S-N* line.

Ship details are normally subjected to variable amplitude stress-range cycles; hence, an equivalent constant amplitude stress range is needed for fatigue assessment. Miner's rule (Miner 1945) is widely used for ship structures to quantify the fatigue damage accumulation at details subjected to variable amplitude loading with a known stress-range histogram. By assuming a linear damage accumulation, Miner's damage accumulation index D is

$$D = \sum_{i=1}^{n_{ss}} \frac{n_i}{N_i} \tag{3}$$

where n_{ss} is the number of stress-range bins in a stress-range histogram, n_i is the number of stress cycles in the ith bin with stress range S_i, and N_i is the number of cycles to failure under the stress range S_i. According to Miner's damage accumulation rule, the failure of the detail occurs when $D = 1.0$. However, research showed that this value is subjected to significant variability, and, up to date, no value is widely accepted by all research communities.

Based on Miner's damage accumulation rule, an equivalent constant amplitude stress range can be defined as

$$S_{re} = \left[\sum_{i=1}^{n_{ss}} \frac{n_i}{N_T} \cdot {S_i}^m \right]^{\frac{1}{m}} \tag{4}$$

where $N_T = \sum_{i=1}^{n_{ss}} n_i \cdot S_{re}$ can be alternatively calculated using the PDF $f_S(s)$ of the stress range S as

$$S_{re} = \left[\int_0^{\infty} s^{m_1} \cdot f_S(s) \cdot ds \right]^{\frac{1}{m_1}} \tag{5}$$

For ship details, the stress range can follow lognormal, Rayleigh, or Weibull distributions. The three-parameter PDFs of these distributions, including the cutoff threshold s_c, are expressed, respectively, as

$$f_S(s) = \frac{1}{(s - s_c) \cdot \zeta \cdot \sqrt{2\pi}} \cdot \exp\left[-\frac{1}{2} \cdot \left(\frac{\ln(s - s_c) - \lambda}{\zeta} \right)^2 \right] \tag{6}$$

$$f_S(s) = \left(\frac{s - s_c}{S_{ro}^2} \right) \cdot \exp\left[-\frac{1}{2} \left(\frac{s - s_c}{S_{ro}} \right)^2 \right] \tag{7}$$

$$f_S(s) = \frac{\kappa}{\alpha} \cdot \left(\frac{s - s_c}{\alpha} \right)^{\kappa - 1} \cdot \exp\left[-\left(\frac{s - s_c}{\alpha} \right)^{\kappa} \right] \tag{8}$$

where $s > s_c$, α, and κ are the scale and shape parameters of the Weibull distribution, respectively; λ and ζ are the location parameter and scale parameters for the lognormal distribution, respectively; and S_{ro} is the mode of the Rayleigh distribution. Needless to say, depending on the stress-range bin histogram, a two-parameter PDF can also be used considering $s_c = 0$.

Using the equivalent constant amplitude stress range, fatigue life, measured as the number of cycles to failure, is calculated as

$$N = \frac{A}{S_{re}^m} \tag{9}$$

This number of cycles can be used in conjunction with the average annual number of cycles N_{avg} to estimate the fatigue life in years using the following equation:

$$t(\text{years}) = \frac{N}{N_{avg}} \tag{10}$$

The *S-N* approach has been widely used for fatigue assessment of steel and aluminum ship details. Multiple design specifications and research reports are available for fatigue design and assessment of ship details (e.g., BS 5400 1980; ABS 2010; DNV 1997, 2010; Eurocode 3 2010; Eurocode 9 2009). Since the estimation of the resistance and demand terms in the *S-N* approach is straightforward, this approach has been successfully used for the reliability-based fatigue assessment of ships. In this context, Ayyub et al. (2002) proposed reliability-based design guidelines for fatigue of ship details. They briefly discussed the available fatigue assessment methods for ship structures and their associated parameters. Kwon et al. (2013) conducted fatigue reliability assessment, based on SHM data, by estimating the probabilistic lifetime sea loads for high-speed ship structures. The British Standards *S-N* relationships (BS 5400 1980) were used in their approach.

The Fracture Mechanics Approach

Although the *S-N* approach is widely used for the fatigue assessment of ships, it cannot be used to study the crack condition at a given detail since it does not provide a direct relation between the crack size and the number of cycles affecting the detail. The approach based on fracture mechanics, on the other hand, can be used to study the crack conditions and stability in a damaged detail. In this method, the stresses near the crack tip, which are responsible for the crack propagation, are related to the stress intensity factor K. Linear elastic fracture mechanics (LEFM) can be applied through Paris' equation (Paris and Erdogan 1963) for assessing fatigue behavior of steel details. This equation relates the crack growth rate to the range of the stress intensity factor as follows:

$$\frac{da}{dN} = C \cdot (\Delta K)^m \tag{11}$$

where a is the crack size, N is the number of cycles, and ΔK is the range of the stress intensity factor. C and m are material parameters. The values for C and m can be found through experimental reports or code specifications. For example, the British Standards BS 7910 (2005) provides the values for C and m of 2.3×10^{-12} and 3.0, respectively, using the units of mm/cycle for da/dN and N/mm$^{3/2}$ for ΔK, for simplified assessment of steel details operating in marine environment. The range of the stress intensity factor can be expressed as

$$\Delta K = Y(a) \cdot S \cdot \sqrt{\pi a} \tag{12}$$

where S is the stress range and $Y(a)$ is a correction factor which depends on the crack orientation and shape. This correction factor takes into account the effects of the elliptical crack shape, free surface, finite width (or thickness), and nonuniform stress acting on the crack. More detailed empirical and exact solutions for these correction factors can be found in Tada et al. (2000).

Using Eqs. 11 and 12, the number of cycles associated with a growth in the crack size from an initial size of a_o to a size of a_t can be calculated as

$$N = \frac{1}{C \cdot S^m} \cdot \int_{a_o}^{a_t} \frac{1}{\left(Y(a) \cdot \sqrt{\pi a}\right)^m} da \tag{13}$$

By setting a_t in Eq. 13 to be equal to the critical crack size a_f, the number of cycles to failure of the detail is obtained. This approach can also be implemented in the probabilistic fatigue life assessment and inspection and monitoring planning of ships. For instance, Kim and Frangopol (2011c) used this approach to find the optimum inspection times which minimize the damage detection delay in steel ship details.

Probabilistic Performance Assessment and Prediction

Probabilistic performance assessment methods are suitable for ships due to the presence of various uncertainties associated with sea loading, ship operation, damage initiation and propagation, and their impact on the structural resistance. Several probabilistic approaches are available to assess the structural performance (e.g., Ayyub et al. 2000; Okasha and Frangopol 2010b; Okasha et al. 2011; Kim and Frangopol 2011a, b, c; Kwon and Frangopol 2012b; Decò and Frangopol 2013). Some of them use solely the time-variant damage level, quantified by simulation techniques, to assess the performance, while others use probabilistic performance indicators such as reliability, redundancy, and risk. Each of these probabilistic performance indicators represents a distinctive structural feature that can be useful for performance assessment and life-cycle management under uncertainty. In the next example, probabilistic fatigue life estimation for a steel ship detail is performed using Monte Carlo simulation. Later in this section, structural reliability analysis is briefly discussed and an example of the reliability assessment and maintenance scheduling is presented.

Example 1 Fatigue cracking is a major safety concern for ship structures. Probabilistic simulation methods can be used to predict the fatigue damage propagation and provide an indication about the expected service life of the investigated location. As an example, a welded joint between the bottom plate and longitudinal stiffener in the hull structure of a steel ship, shown in Fig. 5, is considered. During the routine inspection, a crack with a mean size of 2.0 mm was found to initiate from the stiffener to bottom plate weld and was propagating transversally as shown in Fig. 5.

Crack propagation for such detail can be studied using Eq. 13 after determining the parameters C, m, a_{o}, and S. Moreover, if the average annual number of cycles N_{avg} is known, the crack length over time can be found. For this example, the fatigue crack growth parameters C, m, and a_{o} are assumed to follow lognormal distributions, whereas the stress range is treated as a random variable following a

Fig. 5 Critical fatigue detail

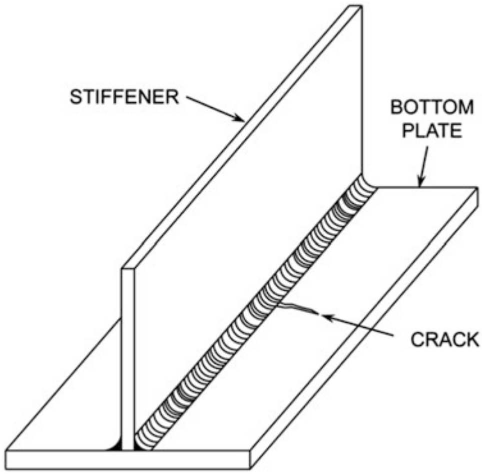

Table 1 Random variables and deterministic parameters associated with the crack growth model

Variable	Notation (units)	Mean value	Coefficient of variation	Distribution type
Material crack growth parameter	C	3.54×10^{-11}	0.3	Lognormal
Material crack growth exponent	m	2.54	–	Deterministic
Initial crack size	a_o (mm)	2.0	0.2	Lognormal
Daily number of cycles	N_{avg} (cycles/year)	1.0×10^6	0.3	Lognormal
Stress range	S (MPa)	30	0.1	Weibull

Weibull distribution. The mean value of the parameter C is assumed 3.54×10^{-11}, using units of MPa for stress range and mm for crack size (this translates to 1.77×10^{-9} using units of ksi for stress and in for crack size), and m is assumed 2.54 (Dobson et al. 1983). The descriptors of the variables associated with the crack growth are given in Table 1. In this example, the geometric function $Y(a)$ is assumed to be one (Akpan et al. 2002).

For this detail, knowing the average number of cycles enables calculating the time associated with crack growth from the initial size a_o to a given size a_t as

$$t(\text{years}) = \frac{1}{N_{avg} \cdot C \cdot S^m} \cdot \int_{a_o}^{a_t} \frac{1}{\left(Y(a) \cdot \sqrt{\pi a}\right)^m} da \tag{14}$$

Considering the final crack size to be 50 mm, the time associated with the growth from 2.0 to 50 mm can be found using Monte Carlo simulation in which the random variables are represented by their respective PDFs. For this example, a Monte Carlo simulation with 100,000 samples yields the histogram shown in Fig. 6 for the time

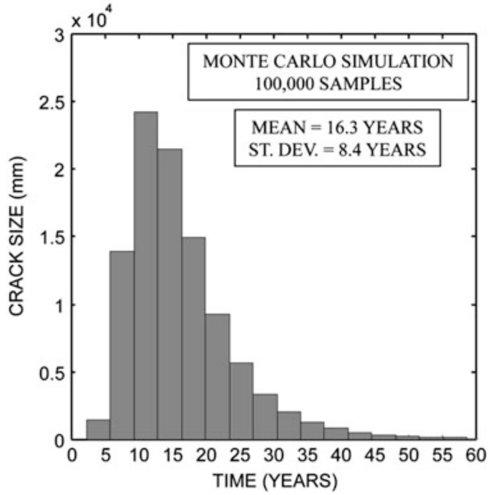

Fig. 6 Histogram of time required to reach a crack size of 50 mm

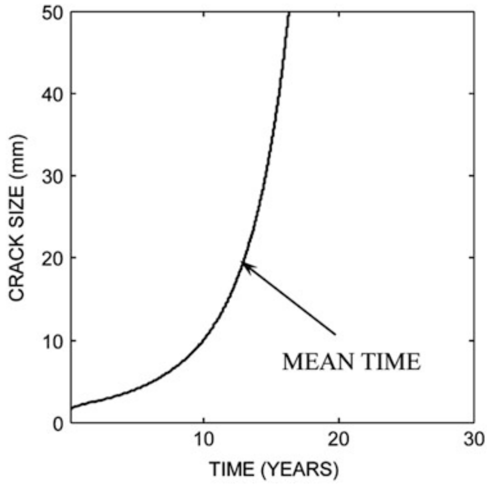

Fig. 7 Mean time to reach various crack sizes

to reach the final crack size. Additionally, as shown in Fig. 7, the simulation can be used to find the mean time for the crack to grow from the initial size to various crack sizes. Inspection and repair actions can be subsequently planned based on the required target safety levels.

Probabilistic performance indicators, such as the reliability index, provide measures for the structural reliability while considering the aforementioned uncertainties. Thus, they can be used to predict the service life and plan for future inspection, maintenance, and monitoring actions (Frangopol and Messervey 2009a, b; Frangopol and Kim 2011). Figure 8 shows schematically the probabilistic performance profile of a structure including effects of aging, sudden damage, and repair actions. Two maintenance types can be defined based on their application time and the performance

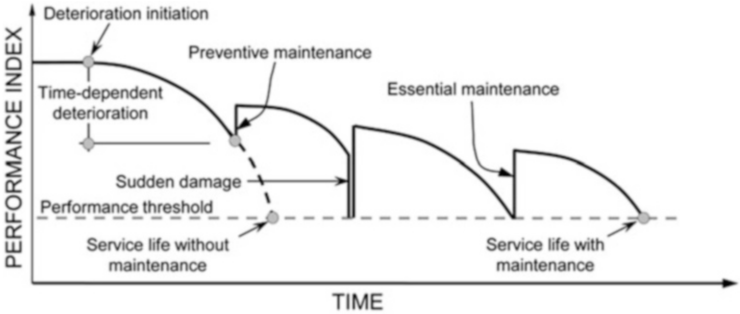

Fig. 8 Probabilistic performance index profile including effects aging, maintenance, and sudden damage

level at this time, namely, essential maintenance (EM) and preventive maintenance (PM). EM is performance based, in which the maintenance is performed when the performance indicator reaches its allowable threshold. In contrast, PM is usually time based in that it is typically applied at prescribed instants over the life cycle of the structure. PM can be performed either to delay the damage propagation for an effective period of time or to slightly improve the performance of the structure. EM, on the other hand, should significantly improve the performance of the structure in order to produce a substantial extension in the service life.

Structural Reliability Analysis

In general, the reliability of a structural component can be related to the probability of failure, defined as the probability of violating a certain limit state $g(\boldsymbol{X}) = 0$. The performance function $g(\boldsymbol{X})$ may be defined as the safety margin

$$g(X) = R - S \tag{15}$$

where R and S are the random capacity and demand of the structure, respectively, and $\boldsymbol{X}$ is the random variable vector. Based on the considered limit state, the probability of failure P_f can be defined as

$$P_f = P(g(X) \leq 0) \tag{16}$$

The PDFs of R, S, and safety margin (i.e., $R - S$) as well as the probability of failure P_f are represented in Fig. 9. Thus, the reliability index β can be defined as

$$\beta = \Phi^{-1}\left(1 - P_f\right) \tag{17}$$

where $\Phi^{-1}(\cdot)$ denotes the inverse standard normal cumulative distribution function (CDF).

For cases where R and S are statistically independent normally or lognormally distributed random variables, exact expressions for calculating the probability of failure can be formulated (see, e.g., Ang and Tang 1984). For more complex

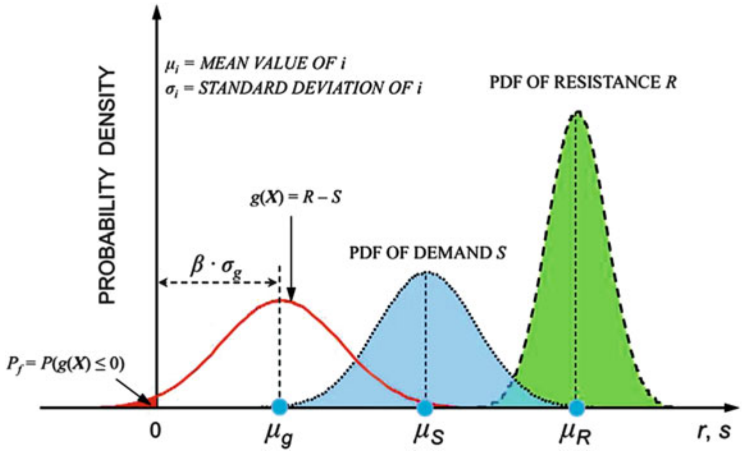

Fig. 9 PDFs of resistance, demand, and safety margin

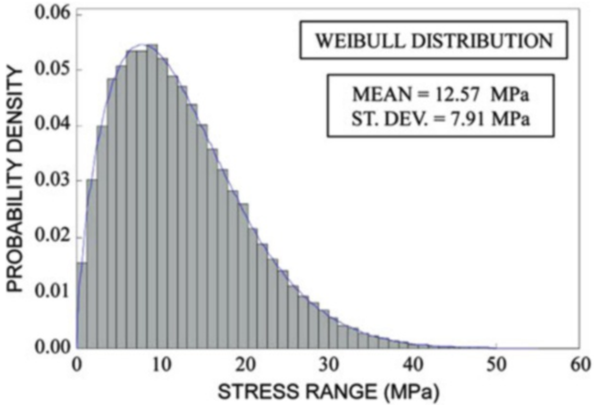

Fig. 10 Probability density of the stress range affecting the ship detail

problems, where R and/or S follow a PDF other than normal or lognormal, efficient reliability techniques can be used to evaluate the component reliability, such as the first-order reliability method (FORM), second-order reliability method (SORM), and Monte Carlo simulation. FORM and SORM have been widely employed in many structural reliability problems and various software packages, such as RELSYS (Estes and Frangopol 1998), to calculate the reliability indices of structural components and systems.

Example 2 To illustrate the reliability concepts for fatigue assessment of steel ship details, consider a steel ship detail subjected to the stress-range distribution shown in Fig. 10 with an average annual number of cycles of 1.5×10^6. Based on the *S-N* approach of the BS 5400 (1980) specifications, the detail is classified under fatigue category F of this code.

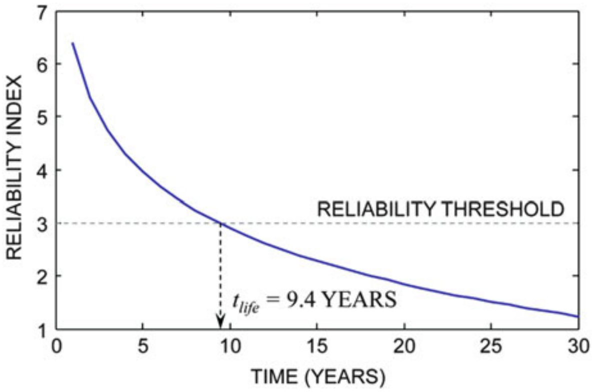

Fig. 11 Reliability index without maintenance

The material constant m for this detail is 3.0, while the constant A (see Eq. 2) is assumed to follow a lognormal distribution with mean of 6.29×10^{11} MPa^3 and a coefficient of variation of 0.54 (Kwon et al. 2013). Based on Eqs. 5 and 8, the equivalent constant amplitude stress range S_{re} is 17.64 MPa. To account for uncertainty in this value, S_{re} is assumed to follow a lognormal distribution with mean 17.64 MPa and coefficient of variation 0.1.

To study the fatigue reliability of the detail, a performance function can be defined as the safety margin

$$g(t) = \Delta - D(t) \tag{18}$$

where Δ = Miner's critical damage accumulation index, indicating the allowable accumulated damage and assumed lognormal distributed with mean 1.0 and coefficient of variation (COV) 0.3 (Wirsching 1984); $D(t)$ = Miner's damage accumulation index, which can be expressed as

$$D(t) = \frac{N(t)}{A} \cdot S_{re}^{m} \tag{19}$$

Based on Eqs. 18 and 19 and assuming that the random variables S_{re}, A, and Δ are also lognormally distributed, the fatigue reliability index β can be derived as (Kwon and Frangopol 2010)

$$\beta(t) = \frac{\lambda_\Delta + \lambda_A - m \cdot \lambda_{S_{re}} - \ln N(t)}{\sqrt{\zeta_\Delta^2 + \zeta_A^2 + \left(m \cdot \zeta_{S_{re}}\right)^2}} \tag{20}$$

where λ and ζ are the parameters associated with different random variables. Using Eq. 20, the reliability profile of the detail can be found as shown in Fig. 11. The fatigue life of the detail can be calculated by setting a threshold for the reliability index. For ship details subjected to fatigue, a reliability index threshold ranging

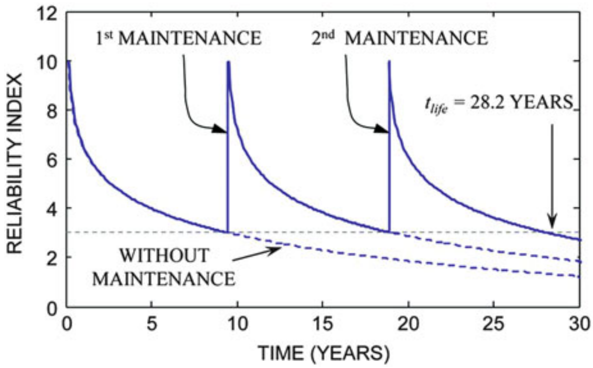

Fig. 12 Service life with EM maintenance

from 2.0 to 4.0 is appropriate (Mansour et al. 1996). For this example, this threshold is set to be 3.0 yielding a fatigue life without maintenance of 9.4 years.

Threshold-based EM, in which the performance is restored to the initial level, can be applied to extend the service life. As shown in Fig. 12, essential maintenance can be performed at 9.4 and 18.8 years yielding a total service life of 28.2 years (i.e., life extension of 18.8 years).

Although the maintenance planning provided in this example is straightforward, other cases of maintenance optimization are not as simple. This is especially true if multiple maintenance actions of varying types are applied to the structure specifically when each of them yields its own service life extension. In this case, probabilistic optimization techniques can be used efficiently to solve such problems. The topic of maintenance optimization is discussed in Okasha and Frangopol (2010a) and Kim et al. (2013).

Damage Evaluation Using NDT and SHM

NDT-based inspection plays a great role in the damage identification and assessment of ship structures. Up to date, the most widely adopted damage evaluation method is visual inspection. This is mainly due to the cost-effectiveness and the ease of application. However, successful visual inspection is challenged by multiple factors including the level of inspector's experience and accessibility problems due to fire protection and corrosion coating. On the other hand, NDT methods, such as ultrasonic inspection, face more challenges arising from the large scale of the structure and number of locations requiring inspection. In addition, the exact location of damage is generally required to apply these inspection methods, which is generally not the case. Research in the field of NDT methods that can identify the location and damage level is very active. These methods mostly rely on installing sensors that continuously record the structural response or emissions and attempt to identify and localize the damage based on the recorded data. These systems include regular strain gages, accelerometers, and acoustic emission sensors. Information from such systems can also be used to update and calibrate performance prediction and damage propagation models to achieve more reliable and accurate performance assessment process (Zhu and Frangopol 2013a, b). In the next subsection, the recent developments in damage identification using the acoustic emissions and SHM are briefly discussed.

Damage Identification Using Acoustic Emission Technique

Within the last decade, acoustic emission technique has received considerable attention for its use in the fatigue and corrosion damage detection and localization in ships. In this approach, stress waves emitted by the material during sudden changes in the internal structure are recorded using special sensors and used to detect structural damage such as crack initiation and growth, fracture, plastic deformation, corrosion, and stress corrosion cracking, among others (Anastasopoulos et al. 2009). In general, a uniform steel specimen with no stress raisers will start emitting acoustic emissions when stressed to a level of 60 % of its yield stress (Anastasopoulos et al. 2009). During normal operation of the ship, these emissions can be continuously detected and recorded such that structural damage can be monitored. This approach has been successfully applied to different types of structures such as bridges, pressure vessels, and pipelines. Recently, research programs in Europe (see, e.g., Baran et al. 2012; Tscheliesnig 2006) and the United States (see, e.g., Wang et al. 2010) have shown the feasibility of such an approach in detecting corrosion and crack damage in ship structures. In these research programs, the results of controlled laboratory testing of specimens subjected to fatigue and accelerated corrosion, as well as oil tankers showed the feasibility of the approach. Since acoustic emission signals can be very weak, especially for corrosion detection, damage detection may be significantly affected by the noise arising from the normal ship operation. The research in this area also aimed to evaluate and isolate the noise under real operation conditions. Special pattern recognition techniques can be used to filter the noise (Baran et al. 2012). Multiple damage detection approaches have been developed, along with their necessary hardware. Some approaches use immersed sensors to detect the acoustic waves travelling through liquids in tankers, while others use sensors attached directly to the structure. The results of such research programs show that using acoustic emissions for the continuous real-time monitoring of damage due to fatigue or corrosion is a promising approach.

Application of SHM for Damage Identification in Ships

A parallel effort has been running to develop approaches which can support the use of SHM systems for damage detection in ships. SHM systems employ various types of sensors, accelerometers, and strain gages to record the structural response during normal ship operation. These systems can be used on multiple fronts such as the validation of design assumptions, monitoring the structural response under normal operation, damage detection and diagnosis, prognosis, and useful life estimation (Salvino and Brady 2008). Validation of the design assumptions is performed typically after the ship is constructed. In this process, the ship is operated through predesigned seakeeping trial runs subjecting the ship to various combinations of operational conditions in terms of speed, sea state, and heading angles to ensure that the actual structural responses are within the design and allowable limits. Information from seakeeping trials may also be used to adjust the safe operational profile by removing some restrictive operational condition if the monitoring shows an acceptable response under these conditions (Salvino and Collette 2009). On the other hand, seakeeping trial data can be used to reduce the likelihood of the ship damage under conditions that were not shown to cause damage during design phase. Additionally, SHM systems can be also used to evaluate the integrity and vibration levels of the propulsion systems of ships (Brady 2004).

After the initial seakeeping trials, the monitoring system can be used for the continuous health assessment of the ship systems. Various high-speed ships are equipped with accelerometers that are always online and can warn the crew when the acceleration levels exceed the allowable threshold. Exceedance can occur due to slamming events and the crew can reduce the speed accordingly (Salvino and Collette 2009). The current research in this area aims to develop monitoring systems, acquisition systems, and the supporting software that is capable of providing real-time information to the ship crew regarding the structural system integrity and response under ship operation (Hess 2007; Salvino and Brady 2008; Swartz et al. 2012). Moreover, such a system should be able to enhance the ability for damage diagnosis and prognosis. These systems provide the possibility to identify damage at its early stages and support the scheduling of inspection and maintenance activities. SHM information can be used to aid in the detection of damage in the areas difficult to access. Moreover, it can be performed while the ship is in service; this minimizes the disturbance of ship operation and extends the operational time of the vessel. Up to date, the most common damage prognosis based on SHM data is applied in order to quantify fatigue damage in ship structures. This is performed by recording the strains at the monitored locations and converting those strains to stresses, and by using the appropriate classification guidelines, the fatigue life can be found using Miner's damage accumulation rule (Hess 2007). In this approach, the stresses and the cycle count are used to find the percentage of the consumed life under the vessel operational profile and find the remaining fatigue life. However, these prognosis methods cannot be directly used to study the crack conditions at a damaged location. Additionally, they cannot be used to assess other damage mechanisms such as corrosion or damage due to slamming.

Damage detection techniques based on SHM such as the vibration-based methods are under continuous development for use in ship structures. Vibration-based methods use advanced signal processing techniques such as the empirical mode decomposition and Hilbert-Huang transform to detect the damage by determining the change in the dynamic properties of the structure. This is based on the fact that a change in the mode shapes or frequencies would suggest that a change has occurred to the physical properties of the structure (Salvino and Brady 2008). Due to the inherent randomness associated with the monitoring outcomes, it is necessary to integrate those uncertainties in the damage detection technique (Okasha et al. 2011). Methods such as vector autoregressive modeling can be used for the detection and localization of damage in high-speed naval vessels. In this method, the vibration signal obtained from the structure as a reference signal is modeled and this model is fitted to the measured structural response. The parameters of this model are the damage-sensitive features (Okasha et al. 2011). The model is assumed to provide an accurate prediction of the structural response; thus, an increase in the difference between the model data and the data measured in the future is interpreted as an indication of structural damage. Mattson and Pandit (2006) proposed a vector-based model which allows a signal to be described in terms of its own past values as well as the past values of other sensors.

A measure of the goodness of fit can be used to select the order of the autoregressive model which is a function of the predicted signal and the measured one. An application of such method was conducted by Mattson and Pandit (2006) on an experimental setup. Additionally, the feasibility of applying this model to ships has been tested in Okasha et al. (2011). Although the damage detection using vibration-based statistical methods is found to be a promising approach, more research is still required for verification, validation, and statistical quantification of such models in order to be reliably applied to SHM of ship structures.

Conclusions

This chapter briefly discussed the damage mechanisms affecting steel and aluminum ships with emphasis on time-dependent effects such as fatigue and corrosion. Different damage prediction models for fatigue and corrosion were briefly presented in addition to various sources of uncertainty associated with these deteriorating mechanisms. Additionally, damage identification through NDE methods and SHM was discussed.

The presence of uncertainties associated with the ship loading, operational conditions, and damage prediction models calls for the use of probabilistic performance indicators in the damage prediction process. Such indicators provide rational quantification of the ship performance and safety while considering various sources of randomness. Moreover, those performance indicators can be effectively integrated within the life-cycle management framework to support decision making regarding future inspection and maintenance activities.

Many of the damage evaluation and prediction techniques for marine structures, as well as life-cycle estimation, prediction, and extension, are also used for civil structures such as bridges and buildings (Frangopol and Liu 2007; Frangopol et al. 2008a, b; Frangopol and Okasha 2009; Kwon and Frangopol 2011; Strauss et al. 2008; Soliman et al. 2013; Okasha and Frangopol 2012).

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