Incorporation of Risk and Updating in Inspection of Fatigue-Sensitive Details of Ship Structures

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Abstract:

Fatigue cracks, as a structural deterioration mechanism, may lead to unanticipated out of service of naval ships. Consequently, risk assessment and effective inspection planning of naval ships under fatigue damage are needed to achieve economic and sustainable performance of these structures. This paper presents a probabilistic framework for fatigue risk assessment and updating through inspection events. The computation associated with fatigue damage is performed using fracture mechanics and uncertainties are considered within this process. Furthermore, a quantitative risk assessment model using rating functions is presented to identify inspection priority among multiple fatigue-sensitive details. Bayesian techniques are adopted for reliability and risk updating of both inspected and uninspected fatigue-sensitive details at component and system levels. Additionally, correlation of fatigue damage among different critical details is considered and incorporated within risk assessment and updating. A number of analyses are performed to investigate the fatigue risk ranking assessment and updating. Applications are presented on an existing tanker with multiple fatigue-sensitive details.

Key words: Probabilistic Fracture Mechanics; Risk Ranking; System Reliability; Risk-Informed Inspection; Updating

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1. Introduction

Fatigue crack of ship critical details has always been a main concern associated with ship operation and is one of the deterioration mechanisms that can affect structural performance. Fatigue cracks may propagate and reach critical sizes; ultimately they can lead to unstable crack growth and/or unanticipated out of service. Generally, these cracks are prone to initiate at welded details due to the existence of initial defects, as qualitatively shown in Figure 1(a), caused by several factors such as welding, fatigue loading, and/or environment (SSC 1995; DNV 2010). Traditionally, non-destructive inspections (NDIs) are applied to ship structures periodically without considering the damage level associated with time. Inspection results can be used to update fatigue reliability and risk of investigated structural systems during their remaining service life using Bayes' techniques. Fatigue crack assessment should be performed during service life of ship structures in order to prevent loss of survivability and to achieve economic and reliable performance. This paper aims to develop a probabilistic framework incorporating risk in the inspection of fatigue-sensitive details of ship structures.

The fatigue deterioration process of structural systems is highly uncertain. Therefore, a probabilistic approach is necessary for considering this deterioration process. The assessment of fatigue crack size under uncertainty is qualitatively shown in Figure 1(b). As indicated, the fatigue crack size increases significantly with time and uncertainties are incorporated within the process. The uncertainties are also associated with inspection events. The outcomes of an inspection event are affected by many factors, such as type of inspection method, human factors, and inspection quality. Consequently, uncertainties should be incorporated within the risk-informed decision making and updating. During the past few decades, the field of ship structural reliability assessment has been developed considerably (Cramer and Friis-Hansen 1994; Mansour et al. 1996; Wirsching et al. 1987; Lukic and Cremona 2001a; Ku et al. 2004; Kwon and

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4 Frangopol 2012; Rabiei and Modarres 2013). In its most broad terms, structural reliability is a
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6 measure of the probability of a system's survival given a limit state. Reliability-based structural
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8 performance indicators reflect the uncertainty in load, resistance, and modelling. A risk-based
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10 performance indicator provides means of combining the probability of components or system
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12 failure with consequences of this event (Dong and Frangopol 2015b).
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16 There has been a lack of research that focuses on risk-based performance assessment of ship
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18 structures. The importance of risk as a performance indicator for the inspection planning decision
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20 making is emphasized in this paper. The schematic flowchart of risk-informed inspection
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22 decision making process is shown in Figure 2. The first step associated with the proposed
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24 methodology is to identify structural deterioration, possible hazard scenarios, and structural
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26 details that should be inspected. Subsequently, qualitative and quantitative risk assessment are
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28 conducted for the investigated details. Generally, qualitative risk assessment requires
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30 approximate estimates of failure likelihood and its consequences, while quantitative indicators of
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32 failure likelihood and consequences are needed for quantitative assessment associated with
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34 fatigue-sensitive details under high qualitative risk. To the best knowledge of the authors, there
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36 have been no studies focusing on the risk assessment and updating of multiple fatigue-sensitive
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38 details at system level using inspection information. This paper addresses this issue in detail.
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40 Finally, given the performance threshold associated with risk, the inspection decision can be
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42 made in a probabilistic life-cycle context (Frangopol 2011).
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51 The information on inspected details can be used to update deterioration models of a
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53 structural system to reduce epistemic uncertainty. The fatigue details associated with a given
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55 structural system are correlated due to common parameters associated with materials, design,
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57 fabrication, loading, and operational conditions. Based on these correlations, the inspection
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4 information of one particular detail can be used to update deterioration performance of
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6 othersuninspected details.Probabilistic models have been used to evaluateand update the fatigue
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8 reliability using inspection information. These models can be used to determine the optimal
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10 number of inspected details to make the inspection strategies efficient and economic. Ayala-
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12 Uraga and Moan (2002) and Moan and Song (2000) investigated reliability-based fatigue crack
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14 damage assessment and updating detailsin parallel/series systems; Chen et al. (2011) proposed a
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16 methodology for inspection planning on the basis on Palmgren-Miner's rule and fracture
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18 mechanics; Huang et al. (2013) computed the fatigue reliability index of a complex welded
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20 structure as a series model under multiple cracks;Maljaars and Vrouwenvelder (2014) presented
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22 a reliability-based updating considering multiple critical locations of a bridge.Whileprevious
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24 studies have emphasized on reliability-based decision making process using updating, there is
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26 limited research regarding transferring the information associated with a given inspection event
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28 to risk assessment of other details and/or system performance assessment considering numerous
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30 details. Another novelty of this paper derives from the risk assessment at system level under a
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32 specific system failure event. Based on the system risk, the inspection planning and repair
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34 priority among the investigated fatigue sensitive systems can be identified. In return, the
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36 inspection results can be used to update risk and the timing for the following inspection.
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45 This paper presents a probabilistic framework for fatigue reliability and risk assessment and
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47 updating through inspection events. The flowchart for risk-informed inspection planning for a
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49 structural system under fatigue damage considering updating under multiple fatigue-sensitive
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51 details is shown in Figure 3. The computation associated with fatigue damage is performed using
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53 probabilistic fracture mechanics. Bayesian techniques are adopted for reliability and risk
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55 updating of both inspected and uninspected fatigue-sensitive details. Additionally, correlation of
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fatigue damage among different critical details is considered and incorporated within risk assessment and updating under a large number of fatigue-sensitive details. A number of analyses have been performed to investigate the fatigue risk assessment and updating. A methodology to quantify the risk using rating functions, which have the ability totake different consequence attributes into account, is proposed in this paper. By using rating functions, the consequences with different units can all be transferred into the rating values. Additionally, the decision maker's preference can also be incorporated within the rating assessment process. The optimal inspection plan can be established on the basis of the comparison between the updated risk and target risk. Moreover, the inspection decision makingprocess involves considerationof economic, environmental, and other factors. Applications are made on an existing tanker with multiple fatigue-sensitive details. Overall, this approach can aid in risk-informed decision makingof ship structures under fatigue damage.

2. Fatigue Reliability Analysis: A Review

Fatigue cracks generally initiate at structural discontinuities such as the welded detail of the intersection of longitudinal and transverse internal supporting members as shown in Figure 1(a). One of the commonly used methods is Paris law which uses linear elastic fracture mechanics to predict the crack growth (Paris and Erdogan 1963). The fatigue crack reliability analysis is related to various factors such as stress range, material property, welding residual stress, loading history, and environmental condition. Generally, all uncertainties involved in loading, material property, crack size and stress intensity factor should be considered in this process. The performance function of an individual structural detail is defined as

$$M_i(t) = a_{ci} - a_i(t) \quad (1)$$

where a_{ci} is the critical crack size and $a_i(t)$ is the crack size of fatigue-sensitive detail i at time t . The critical crack size is often selected as through-thickness crack associated with a plate or weld. It can also depend on the size associated with brittle or ductile failure of details under specified loading effect. Given an initial crack size a_0 , the random crack size after time t can be computed using a crack growth propagation model. The performance function associated with fatigue detail i can be expressed as (Moan and Song 2000)

$$M_i(t) = \int_{a_{0i}}^{a_{ci}} \frac{da}{(\varepsilon_{Yi} \cdot Y(a) \cdot M_k \cdot \sqrt{\pi a})^m} - C_i \cdot \nu_{0i} \cdot t \cdot \varepsilon_{Si}^m \cdot A_i^m \cdot \Gamma(1 + m_i / B_i) \quad (2)$$

where a_{0i} is the initial fatigue crack size associated with detail i ; ν_{0i} is the average zero-crossing rate of stress cycle; ε_S is the modeling uncertainty associated with stress modeling; ε_Y is the modeling uncertainty associated with geometry function; Γ is the Gamma function; a is crack size; C and m are material constants which can be obtained from the experiments on simple specimens; A and B are the parameters associated with Weibull scale and shape, respectively; $Y(a)$ is geometrical correction factor depending on the geometry of cracked detail, nature of load distribution (e.g., bending and membrane), and the crack size with respect to the detail dimension; and M_k is a stress magnification factor which is associated with local weld geometry. The probability that the fatigue crack size exceeds a critical size within the time t is

$$P_i(t) = P(M_i(t) \leq 0) \quad (3)$$

In general, P_i can be computed using Monte Carlo simulation, or by first or second-order reliability methods (Estes and Frangopol 1998). The reliability index β is

$$\beta_i = \Phi^{-1}(1 - P_{f, detail i}) \quad (4)$$

where Φ^{-1} denotes the inverse of the standard normal cumulative distribution function.

The previous studies associated with reliability-based damage analysis of fatigue-sensitive details are reviewed herein. Wirsching et al. (1987) proposed an approach for the reliability-based fatigue analysis based on fracture mechanics considering service life of a detail; Cramer and Friis-Hansen (1994) presented a computational procedure for the optimum design and inspection of a welded fatigue-sensitive component using reliability analysis; Lukic and Cremona (2010a) presented a method for the fatigue reliability assessment of welded joints using probabilistic fracture mechanics; and Kwon and Frangopol (2012) incorporated the component level fatigue reliability analysis in the life-cycle maintenance of aluminum ships. As revealed, the reliability index was used as a performance indicator for the damage assessment of fatigue-sensitive details. Additionally, the reliability index was widely adopted in the inspection planning considering the updating process at the component level. Moan et al. (1997), Moan and Song (2000), and Ayala-Uraga and Moan (2002) developed a series of reliability-based fatigue damage updatings for ships and offshore structures considering different environmental conditions and inspection methods; Ku et al. (2004) developed an inspection plan for a floating structure based on reliability-informed decision and updating; Chen et al. (2011) investigated the inspection planning at component level considering reliability index and fracture mechanics; Berg et al. (2014) investigated the updated fatigue reliability of uninspected joints using the inspection data; and Maljaars and Vrouwenvelder (2014) investigated reliability of multiple fatigue details using Bayesian updating techniques considering different inspection methods. As indicated, risk, as a performance indicator, has not been adopted in these studies for the fatigue damage and updating assessment. The number of studies considering risk-based fatigue assessment and updating is very limited. Goyet et al. (2002) presented an approach for risk-based inspection planning of offshore production using qualitative failure consequence at the component level;

Tammer and Kaminski (2013) presented a general approach associated with the risk-based inspection considering fatigue damage at the component level where the consequences were assessed, without an explicit expression, based on the severity levels; and Lassen (2013) presented a framework for risk-based inspection planning of fatigue cracks in welded steel structures at component level without quantifying the consequences associated with failure. The system level risk assessment and detailed quantification of probability of failure and consequences associated with failure have not been well documented in these studies. Furthermore, to the best knowledge of the authors, there have been no studies focusing on the risk-informed updating of multiple fatigue-sensitive details at system level.

3. Updating Based on Inspection Event

Due to the common variables used in fatigue damage prediction of individual details, correlation among different details exists and correlation among inspected and uninspected details should be established. The results associated with an inspection of a fatigue-sensitive detail can be used in the computation of reliability and risk of inspected or uninspected fatigue-sensitive details.

3.1 Inspection Modelling

Generally, the probability of detecting a crack depends on crack size and inspection method. Many efforts have been devoted to evaluate the quality of nondestructive inspection methods of fatigue cracks. Among the available nondestructive inspection techniques, liquid penetrant, ultrasonic, magnetic particle (MP), and acoustic emission are commonly employed for fatigue crack detection (Soliman and Frangopol 2014). The probability of detection (PoD) associated with different inspection methods has been indicated in previous studies, including BS-7910 (2013), Moan et al. (1997), and Visser (2002). There are different types of PoD associated with

fatigue cracks. The commonly used exponential form is adopted in this paper (Moan and Song 2000; Chen et al. 2011)

$$PoD(a) = 1 - \exp(-a / \lambda_D) \quad (5)$$

in which λ_D is the mean detectable crack size. This PoD is applicable to several inspection types including close visual and MP inspections. These two inspection methods are adopted herein.

3.2 Reliability Updating

In this paper, the event based inspection updating is adopted based on two inspection results: (a) no crack detected, and (b) crack detected and repaired. If no fatigue crack is detected, the updating can be performed within the original fatigue limit state. If repair actions are conducted, the physical changes need to be considered in the estimation of limit state function. In this paper, it is assumed that once the fatigue crack is detected, it will be immediately repaired. The updated probability of failure of the i th detail under fatigue given inspection event j can be formulated as follows (Moan and Song 2000)

$$P_{i,up} = P[M_i(t) \leq 0 | IE_j(t_{IE})] = \frac{P[(M_i(t) \leq 0) \cap IE_j(t_{IE})]}{P[IE_j(t_{IE})]} \quad (6)$$

where M_i is limit state function associated with detail i ; IE_j is the inspection event j ; and t_{IE} is the inspection time.

Generally, fatigue failure modes associated with individual details of a structural system are correlated due to the common uncertain factors. The initial crack sizes are correlated among all the investigated details due to the common fabrication quality. Additionally, the fatigue failure modes are also partly correlated due to the statistical dependence associated with common material characteristics. The loading effects of these investigated details are also correlated,

leading to the correlation of the stress range associated with the investigated details. Eq. (6) can be applied to the inspected and uninspected fatigue-sensitive details.

The inspection event associated with no fatigue crack detected can be expressed as (Moan and Song 2000)

$$IR_{i,no}(t_{IE}) = a_D - a_i(t_{IE}) = \int_{a_{0i}}^{a_D} \frac{da}{(\varepsilon_{Yi} \cdot Y(a, X) \cdot M_k \cdot \sqrt{\pi a})^m} - C_i v_0 t_{IE} \varepsilon_s^m A_i^m \Gamma(1 + m/B) > 0 \quad (7)$$

where a_D is the detectable crack size and $a_i(t_{IE})$ is the predicted crack size associated with detail i at inspection time t_{IE} . Given the repair actions, the reliability index associated with fatigue crack damages should be recomputed. Then, the limit state associated with repaired details can be established.

The failure modes associated with fatigue cracks of individual details are generally statistically dependent due to common random variables. The initial crack sizes are correlated. The correlation coefficient $\rho(a_{0i}, a_{0j})$ is used to quantify the statistical dependence due to common fabrication among initial fatigue crack sizes associated with different fatigue-sensitive details. The crack growth parameters are also correlated; the correlation coefficient $\rho(\ln C_i, \ln C_j)$ reflects the dependence associated with common material characteristics. Additionally, the scale parameters of the stress ranges are correlated due to common loading effects of individual details. Finally, the modelling uncertainty factors are considered to be correlated among all fatigue-sensitive details. Given correlation coefficients of the common random variables used in fatigue reliability assessment and inspection event (i.e., Eqs. (2) and (7)), the fatigue reliability index of inspected and uninspected fatigue-sensitive details can be updated using Eq. (6). Regarding the inspected detail, the correlation coefficient among the common random variables associated with Eqs. (2) and (7) is 1.0 (e.g., $\rho(\ln C_i, \ln C_j) = \rho(a_{0i}, a_{0j}) = 1.0$).

As there are many structural details with potentially dangerous cracks, the inspection actions are applied to these fatigue-sensitive details simultaneously. It is assumed that among the N_{insp} inspected details, r do not show cracks while fatigue cracks are detected at the remaining $N_{insp} - r = s$ inspected details. Inspections are applied to the N_{insp} fatigue sensitive details simultaneously. The updated reliability of the investigated detail (e.g., inspected, uninspected) under this scenario associated with N_{insp} inspected fatigue-sensitive details can be computed as

$$P_{i,up} = P[M_i(t) \leq 0 | IR_{1,no} \cap IR_{2,no} \cap \dots \cap IR_{r,no} \cap IR_{r+1,yes} \cap IR_{r+2,yes} \cap \dots \cap IR_{r+s,yes}] \quad (8)$$

where $IR_{i,no}$ is the inspection event associated with no fatigue crack detected at fatigue-sensitive detail i and $IR_{i,yes}$ is the inspection event associated with fatigue crack detected.

4. Risk Assessment

Risk-based performance indicators combine the probability of failure with the consequences associated with this particular event. Most of previous studies of ship structure inspection plans have been focused on establishment of target reliability-based values associated with fatigue failure. Although SSC (SSC 2000) proposed an approach for risk-based management of ship structures, the uncertainties associated with consequence evaluation and detailed quantification of probability of failure were not discussed in detail. The risk assessment process depends on various factors such as environmental loading conditions, failure mode, loss of life, environmental pollution and possible economic and social loss (Dong and Frangopol 2015a). For example, the fatigue crack may lead to cargo oil spill. The consequences associated with oil spill are significantly adverse and in turn the fatigue crack detail should be inspected and paid special attention to prevent hazardous consequences. The aim of risk-based management is to develop a management plan that can prevent failures and, consequently, reduce the impact of adverse consequences.

Risk, which combines the probability of occurrence of a specific event with the consequence associated with this event, is a crucial performance indicator for structural systems. A formulation of risk is (Ang and De Leon 2005)

$$R = P \cdot C \quad (9)$$

where P is probability of occurrence of an adverse event and C is the consequence of this event.

4.1 Consequence Evaluation

As mentioned previously, risk is regarded as an important performance indicator within the fields of civil and marine structural engineering. Based on the reliability approach, the failure probability can be computed. The probability of failure associated with fatigue crack can be obtained using Eq. (3). The second key factor to be assessed for risk assessment is consequence. The potential major consequences of failure include economic loss (e.g., loss of vessel), social (e.g., downtime), and environmental impact (e.g., oil spill and pollution). The consequence value can range from low, which is very unlikely to have a significant effect on safety and serviceability, through severe, where the threats to safety and life are significant. Generally, assessing consequence associated with a structural detail failure is a challenging process. Evaluation of the potential consequences may be based on historical data and analyses to define critical details to hull structural integrity (SSC 2000). Consequence assessment is of vital importance in risk ranking of structural details since similar details at two different locations can have significantly different consequences. For example, a crack in the side shell of a cargo oil tank may have much more serious consequences than a similar crack in a deck. This is because the former can cause oil spill and pollution.

The repair cost C_{rep} is generally computed as percentage of a construction cost C_{cons} . The ratio C_{rep}/C_{cons} is considered to be probabilistic. The repair action considered is replacing the cracked

detail with a new one. The total cost of a repair should include material, labor, dry dock charge, tank cleaning, staging and down time. Consequently, the cost to replace the damaged details is larger than the construction cost. Generally, the repair cost for a ship detail can be computed as (Lukic and Cremona 2001b; Rigterink et al. 2013)

$$C_{rep} = c_{Cons} \cdot W \cdot L \cdot r_{cr} \quad (10)$$

where c_{Cons} is the construction cost per unit area (e.g., USD/m²); L and W are the length (e.g., m) and width (e.g., m) associated with structural detail under investigation, respectively; and r_{cr} is ratio between repair and construction cost.

The consequences are assessed using different units. The repair cost can be established using the monetary value; while the consequence associated with oil spill can be computed in terms of the amount (e.g., tons). A rating system that measures the consequence of failure can be developed. Expert opinion and experience from classification society rules could be adopted as guides in consequences evaluation process. An example of rating system associated with consequences resulting from fatigue crack damage is provided in Table 1. The rating factor associated with oil spill is much larger than that associated with repair cost. Based on this table, different types of consequences can be converted into rating factor. Within the defined boundaries associated with the rating factor, the decision maker should specify the value of this factor. Based on these values, a consistent matrix is developed and the rating factor associated with consequences can be estimated.

Typically, a larger rating factor should be assigned to a larger repair cost. The rating can be defined using linear and exponential functions. The hypothetical value could be adjusted considering the decision maker's value and experienced engineers' input. Rating functions are adopted herein to quantify the consequence associated with fatigue failure; consequently in

return different types of consequences could be transferred into rating factors incorporating the preference of decision maker. For example, an exponential rating function associated with repair cost C can be expressed as follows (Ang and Tang 1984)

$$Rt_c(C) = \left(\alpha_1 + \alpha_2 \exp(\alpha_3 \cdot \frac{C - C_{\min}}{C_{\max} - C_{\min}}) \right) \cdot (Rt_{\max} - Rt_{\min}) + Rt_{\min} \quad (11)$$

where α_1 , α_2 , and α_3 are parameters associated with rating functions; C is the consequence under investigation (e.g., repair cost); $Rt_c(C)$ is the rating factor associated with consequence C ; $Rt_{\min}$ and $Rt_{\max}$ are the minimal and maximal values associated with rating factor, respectively; and $C_{\min}$ and $C_{\max}$ are the minimal and maximal cost values, respectively.

4.2 Expected Risk Ranking

Ship structures have various fatigue-sensitive details. Correlation among the performance function of these details should be considered in the system reliability and risk analyses processes. The uncertainties and correlations among the common random variables used fatigue reliability analysis of different fatigue-sensitive details should be considered in the total risk ranking assessment of a given structural system. The correlation metric associated with the fatigue reliability analysis of different details should also be considered in the risk assessment process. The expected risk ranking associated with failure of a single detail among n details can be computed as

$$R_{rk,1} = P(\overline{E_{D1,S}} E_{D2,S} E_{D3,S} \cdots E_{Dn,S}) \cdot Rt_c(C_{D1,F}) + P(E_{D1,S} \overline{E_{D2,S}} E_{D3,S} \cdots E_{Dn,S}) \cdot Rt_c(C_{D2,F}) \\ + \dots + P(E_{D1,S} E_{D2,S} \overline{E_{D3,S}} \cdots E_{Dn,S}) \cdot Rt_c(C_{Dn,F}) \quad (12)$$

where $C_{Di,F}$ is the consequence considering the fatigue-sensitive detail i failure while all other details survived; Rt_c is the rating factor associated with the repair cost as indicated in Eq. (11); $E_{Di,F}$ and $E_{Di,S}$ are the events of failure and survival of detail i , respectively; and $\overline{E_{Di,S}}$ is the

complement of $E_{Di,S}$. The probability $P(\overline{E_{D1,S}} E_{D2,S} E_{D3,S} \cdots E_{Dn,S})$ associated with one component failure can be computed using a parallel system. The probability of failure of a parallel system can be expressed by the probability of intersections of component failure events

$$P_{PS} = P\left(\bigcap_{i=1}^N \{g_i(\mathbf{X}) \leq 0\}\right) \quad (13)$$

where $g_i(\mathbf{X})$ is the performance function associated with fatigue-sensitive detail i under investigation. The probability of system failure associated with series, parallel, and series-parallel systems can be calculated using first/second order reliability method or simulation methods. The correlation between the random variables used in the fatigue limit state is considered in the reliability computational methods. Due to the common random variables (e.g., $\ln C_i$ and $\ln C_j$) used in the failure modes associated with different fatigue-sensitive details, these failure modes are also correlated. The methodology proposed by Ditlevsen (1979) is employed herein to account for the correlation among the components of a system. The same approach has been adopted by Estes and Frangopol (1998) to compute the system reliability. The probability of system failure can be computed accordingly. Given the adverse consequence associated with the failure event, the risk associated with one component failure can be computed by using Eq. (12)

The risk ranking associated with repair loss due to fatigue sensitive details is emphasized herein. The total expected risk ranking of n fatigue-sensitive details can be computed as

$$R_{RK} = \sum_{D1,i=1}^2 \sum_{D2,i=1}^2 \sum_{D3,i=1}^2 \cdots \sum_{Dn,i=1}^2 P(E_{D1,i} \cap E_{D2,i} \cap E_{D3,i} \cdots \cap E_{Dn,i}) \cdot Rt_c(C_{D1,i;D2,i;\dots;Dn,i}) \quad (14a)$$

$$E_{D1,1} = E_{D1,F} = \overline{E_{D1,S}} \quad (14b)$$

$$E_{D1,2} = E_{D1,S} \quad (14c)$$

where n is the number of fatigue-sensitive details. Given the consequence with respect to the specified system condition, the total expected risk ranking can be computed.

4.3 Decision Making Criteria and Optimal Inspection

Most of the previous studies emphasized on the reliability-based inspection planning for marine structures without considering correlation among the inspected and uninspected details and failure consequences (Kim et al. 2011; Soliman et al. 2013). Risk is a better structural performance indicator than reliability. The risk associated with repair loss of fatigue-sensitive details at both component and system levels is emphasized herein.

Risk is selected as the main performance indicator to be included in the decision making process due to the fact that it contains information regarding both the probability of failure and its associated consequences. Threshold values for classifying the risk levels at the fatigue-sensitive details have to be set. Generally, acceptable risk levels for fatigue critical details must be determined using expert opinion, engineering judgment, vessel cost, and classification rules. The fatigue reliability and risk ranking are updated using Bayesian approach, and then the time interval to the subsequent inspection action can be obtained. Risk ranking assessment and relevant management strategies associated with different risk performance threshold are indicated in ABS (2003). A structural detail with a high-risk priority rating has high risk associated with it, implying a high expected loss when it fails. A risk-based management strategy implies that these decisions are based on the risk ranking associated with each fatigue-sensitive detail. The risk-based priority ranking can be used to determine how the various fatigue-sensitive details should be maintained. According to SSC(2000), the low, moderate, high, and extreme risk levels are associated with the rating intervals $0 < R_{RK} \leq 10$, $10 < R_{RK} \leq 1000$, $1000 < R_{RK} \leq 10000$, and $R_{RK} > 10000$, respectively. The low, moderate, high, and extreme risk are associated with maintenance

strategies that should give the lowest, moderate, high, and the highest priority for maintenance, respectively.

The risk assessment and decision making process at the system level are also investigated herein. In order to quantify the risk associated with a system composed of multiple fatigue-sensitive details, the system failure mode should be identified firstly. A system of n fatigue-sensitive details is assumed to fail if m adjacent details fail. The configuration of the series-parallel system is shown in Figure 4. The event associated with system failure can be expressed as follows:

$$E_{SysF} = (E_{D1,F} \cap E_{D2,F} \cdots \cap E_{Dm,F}) \cup (E_{D2,F} \cap E_{D3,F} \cdots \cap E_{Dm+1,F}) \cup \cdots \cup (E_{Dn-m+1,F} \cap E_{Dn-m+2,F} \cdots \cap E_{Dn,F}) \quad (15)$$

where E_{SysF} is the event associated with system failure and m is the number of adjacent details.

The probability of system failure $P(E_{SysF})$ can be determined by using simulation and/or first/second order reliability analysis. Due to the correlation among the random variables used in fatigue assessment associated with different fatigue-sensitive details and the fact that the same variables are presented in failure modes of parallel sub-systems in Figure 4, the events in Eq. (15) are also correlated. Given the consequence associated with system failure, the risk can be computed as the product of the probability of occurrence of failure and its associated consequence. Based on this risk, the inspection priority and planning can be obtained. Most of the previous studies considered one detail at a time, while a structure would have multiple fatigue-sensitive details. Due to the similar geometry and loading, the inspection information could be used to update the fatigue reliability and risk associated with multiple potential crack locations at system level.

5. Illustrative Example

The proposed approach is illustrated on fatigue-sensitive details of an existing tanker. The investigated fatigue prone details are located at deck, bottom, and side shell. Generally, fatigue cracks are concentrated at the welded details (ABS 2003; DNV 2010). The location and dimensions of the investigated stiffeners are as follows (Chen et al. 2011): (a) Deck (web: 400mm x 30mm); (b) Bottom (web: 550mm x 14.5mm, flange: 180mm x 22mm); and (c) Side Shell (web: 540mm x 12mm; flange 120mm x 18 mm). The fatigue reliability and risk ranking of the fatigue details are investigated considering uncertainties. The updating is also conducted in the illustrative example. Subsequently, the risk-informed optimal inspection is obtained by using the updating results.

5.1 Probabilistic Fatigue Crack Growth and Risk Ranking Assessment

In this section, the reliability index and risk ranking of the fatigue-sensitive detail located at the deck of the investigated tanker are computed. The time interval is assumed to be 30 years. According to Chen et al. 2011, the mean values of $\ln A$ and $1/B$ for deck fatigue-sensitive detail are 2.05 and 2.17, and their coefficients of variation are 13.8% and 10%, respectively. The probability of fatigue failure of the deck $P_{f,Deck}$ is computed using Eqs. (2) and (3). The parameters involved in these equations are shown in Table 2. An equivalent initial flaw size distribution is adopted in the fatigue crack assessment and assumed to follow the Weibull distribution (Moan and Song 2000; Soliman et al. 2014). The geometrical correction factor Y is a function associated with crack size as well as other geometric parameters, such as the crack half-length and flange thickness. The stress magnification factor M_k depends on the crack depth and other geometric parameters, such as flange thickness, weld height, and weld angle. The values of Y and M_k are based on Newman and Raju (1981) and have been widely used in the previous studies for the

fatigue damage assessment process. Given the random variables associated with geometric and fatigue crack growth, Y and M_k can be generated using Monte Carlo simulation (Lukic and Cremona 2001b; Maljaars and Vrouwenvelder 2014). Given all the parameters involved in fatigue reliability analysis, the probabilistic fatigue damage of the investigated deck fatigue-sensitive detail is obtained. The reliability index of this detail is computed using Eq. (4). The time-variant probability of fatigue failure and its associated reliability index are both shown in Figure 5. As indicated, the reliability index of the deck fatigue-sensitive detail decreases significantly with time.

The repair cost is computed using Eq. (10). Then based on Eq. (11), the rating factor is obtained. The parameters used in Eqs. (10) and (11) are shown in Table 2. The uncertainties associated with the unit construction cost and repair cost ratio are considered in risk assessment process as indicated in this table. Herein, the boundary values $R_{t_{min}}$ and $R_{t_{max}}$ are 5,000 and 15,000, respectively. The risk ranking is computed as a product of probability of fatigue failure and the consequence rating factor associated with repair cost. Based on the results shown in Figure 5(a) and using Eq. (9), the risk ranking of the given detail is shown in Figure 6(a). As indicated, the ranking increases dramatically with time as no repair action is applied to the deck fatigue-sensitive detail. The mean, mean plus and minus one standard deviation of risk ranking are also shown in this figure. The probability density functions (PDFs) of risk ranking at $t = 10$ and 20 years are revealed in Figure 6(b) and their expected values are 125 and 496, respectively. As indicated, the dispersion of risk ranking increases significantly with time.

The rating factor associated with the failure consequence depends on the severity of this consequence as shown in Table 1. In order to demonstrate the advantage of using quantitative risk as a performance indicator, the risk rankings of two fatigue-sensitive details are evaluated.

Detail A refers to the deck fatigue-sensitive detail investigated previously. The load parameters $\ln A$ and $1/B$ of detail B are 1.85 and 1.16, respectively. All other parameters involved in fatigue reliability analysis of detail B are the same as those associated with detail A. Following the same process of fatigue reliability of detail A, the results of detail B are obtained and shown in Figure 7(a). As indicated, the reliability index of detail B is much larger than that of detail A during the investigated time interval. The detail A is more critical than detail B considering only the reliability index. The consequence of detail B fatigue failure can result in a high damage intensity associated with oil spill. The expected rating factor associated with detail B fatigue failure is 1,000,000 as indicated in Table 1. In order to compare the inspection priority of these two details using risk ranking, the quantitative risks are computed for details A and B and are shown in Figure 7(b). As indicated, although the reliability index of detail A is always smaller than that of detail B, the risk ranking of detail B is larger than that of detail A after $t = 10$ years. Consequently, different inspection priorities of these two details can be obtained using the reliability and quantitative risk-informed performance threshold after 10 years. The PDFs of risk ranking of details A and B at $t = 12$ years are indicated in Figure 8. The dispersion of risk ranking of detail B is larger than that of detail A.

5.2 Fatigue Reliability and Risk Ranking Updating

The fatigue reliability and risk ranking of the fatigue-sensitive detail considering updating are investigated in this section. The detectable fatigue crack size follows the exponential distribution (Moan and Song 2000; Chen et al. 2011). Mean values of detectable crack size a_d associated with close visual and MPI methods are 2 and 0.89 mm, respectively. The inspection is performed at $t = 4$ years; it is assumed that no fatigue crack is detected. The conditional updated reliability index associated with the inspected deck fatigue-sensitive detail

given no crack detected is computed using Eq. (6) and shown in Figure 9(a). As expected, the reliability index increases significantly giving no crack is detected using MPI. The effect of inspection methods on the reliability updating is also investigated herein. As indicated in Eq. (7), the detectable crack associated with given inspection method affects the probability of detecting a crack within a fatigue-sensitive detail. This would affect the updated probability of failure of the investigated detail using Eq. (6). For a more advanced inspection method (e.g., MPI), the increase of reliability index is much larger than that associated with a less advanced method (e.g., visual inspection) given no crack is detected. The updated reliability index at $t = 4$ years using MPI is larger than the initial value at $t = 1$ year due to the fact that the detail has a significant amount of fatigue capacity remaining. Additionally, the updated expected risk ranking of the inspected detail located at the deck under different inspection methods is shown in Figure 9(b). As indicated, there is a huge difference between the expected risk rankings of the inspected detail using different inspection methods.

The fatigue failure modes of individual detail of a structural system are correlated due to common uncertainties. The correlation coefficients for slight, moderate, and strong correlation among random variables in different fatigue-sensitive details are assumed 0.3, 0.5, and 0.8, respectively. Due to the common random variables used in the computational process of safety margins (e.g., Eq. (2)) and inspection events (e.g., Eq. (7)), the information obtained from inspection is used to update the fatigue performance of inspected and uninspected details systematically. As indicated previously, the initial crack sizes (i.e., a_0 associated with fatigue details i and j) are correlated among all investigated details. Additionally, material characteristics (e.g., $\ln C_i$ and $\ln C_j$ associated with fatigue-sensitive details i and j) are correlated among the fatigue details in the investigated tanker. The loading characteristics of investigated details are also

correlated, leading to the correlation of random variables associated with stress range (e.g., $\ln A_i$ and $\ln A_j$). The modeling error ε_S and geometry error ε_Y factors of various fatigue-sensitive details are correlated. The results obtained are based on a correlation model suggested by Moan and Song (2000) and Schneider et al. (2013). The inspection is applied to the deck fatigue-sensitive detail at $t = 4$ years assuming that no crack is detected using MPI. The updated probability of failure of the uninspected deck fatigue-sensitive detail is computed using Eq. (6) and is shown in Figure 10. As indicated, the updated reliability index of the uninspected detail at $t = 4$ years increases given the inspection event compared to the value without updating. Additionally, the reliability index increases as the correlation coefficient among the random variables becomes larger. When $\rho = 0.3$, the updated reliability index of the uninspected reliability index is close to that associated with the case without updating.

The scenario associated with fatigue crack detected at the deck fatigue-sensitive detail is also investigated herein. It is assumed that once the fatigue crack is detected, the repair action is applied to the detected detail. The new material variables (e.g., a_{0r} , C_r and m_r) associated with the repaired detail are modelled using the same original properties (e.g., a_0 , C and m), but these random variables are statistically independent (e.g., $\rho(C_r, C) = 0$) (Moan and Song 2000). At $t = 4$ years, if a crack is detected using MPI, the updated reliability of the inspected detail is shown in Figure 11(a). Given no repair action, the reliability index decreases significantly due to the existence of the detected crack. When the repair action is applied to the detected fatigue-sensitive detail at 4 years, the reliability index of the detail increases as indicated in Figure 11(a). Shortly after the repair, the reliability index decreases more significantly than that associated with the case without repair. This specific conclusion is based on the parameters adopted in the illustrative example. The expected risk ranking for different correlation cases is shown in Figure 11(b).

The effects of the number of inspected details on updated reliability index associated with an uninspected fatigue-sensitive detail are also investigated. It is assumed that no crack is found on the inspected deck fatigue details at $t = 4$ years and the correlation coefficients among the random variables are 0.5. The updated reliability index is computed using Eq. (8). As shown in Figure 12(a), the reliability index of the uninspected detail increases with the number of inspected details N_{insp} . The risk ranking associated with the uninspected detail under fatigue damage is also computed. As shown in Figure 12(b), the difference between the expected risk rankings is decreasing with N_{insp} . Given the risk threshold associated with fatigue damage, the timing of the following inspection can be obtained accordingly as shown in Figure 12(b). Herein risk replaces reliability as a performance indicator for the inspection decision making process. The relevant results for 1, 10, 20, 30, 40, and 50 inspected details are shown in Figure 13(a). The effects of N_{insp} on the risk ranking of the inspected detail are also conducted. The relevant results are shown in Figure 13(b). The updated risk ranking of the inspected detail is slightly lower than that in the case of the uninspected detail given no fatigue crack detected at year 4.

A more general scenario that involves inspection results associated with fatigue crack detected and not detected is investigated using Eq. (8). The updated reliability index of the uninspected detail under different inspection outcomes is shown in Figure 14(a). It is assumed that among the 5 inspected details (i.e., $N_{insp} = 5$), six outcomes associated with inspection at $t = 4$ years are considered. These outcomes correspond to $r = 0, r = 1, r = 2, r = 3, r = 4$, and $r = 5$ details out of the 5 inspected fatigue-sensitive detail do not show damage and fatigue cracks are detected at the remaining details $s = 5, s = 4, s = 3, s = 2, s = 1$, and $s = 0$, respectively, where $s + r = 5$. As more fatigue-sensitive details are detected with crack (i.e., s increases), the reliability

index of the uninspected fatigue detail drops significantly. If more than 2 out of the 5 details are detected with crack (i.e., $s > 2$), the reliability index of the uninspected detail is generally smaller than that without updating. The results associated with 10 fatigue-sensitive details inspected are also computed and shown in Figure 14(b). Finally, the updated expected risk rankings of the uninspected detail under different inspection outcomes of 5 inspected details at year 4 are indicated in Figure 15.

5.3 Risk-Informed Inspection Decision Making

The risk associated with the three fatigue details of the tanker (i.e., deck, bottom, and side shell) is investigated herein. According to Chen et al. 2011, the mean values of $\ln A$ and $1/B$ for Deck, Bottom, and Side Shell are 2.05 and 2.17, 2.26 and 1.29, 1.22 and 1.16, respectively; and the coefficients of variation of $\ln A$ and $1/B$ are 13.8% and 10%, respectively. For tankers, the side shell plates can protect cargo oil and, therefore, are considered as having a high failure consequence. As shown in Table 1, the damage intensity associated with side shell detail failure is high. The repair loss for the fatigue-sensitive details located at bottom and deck corresponds to moderated damage intensity. As expected, the risk associated with the side shell is much larger than that of the other two details as shown in Figure 16(a). Given the risk threshold, the details at the side shell should be treated as the priority detail for the inspection.

If multiple fatigue-sensitive details are investigated in a ship structure, it is of vital importance to take the correlation among the random variables involved in fatigue damage assessment and inspection into account for fatigue risk assessment. The total expected risk of two fatigue-sensitive details located at the deck considering correlation coefficients 0.1, 0.5, 0.8, and 1.0 among the random variables are computed using Eqs. (12) and (14). The expected risk ranking of the two deck fatigue-sensitive details given one or two details failure is shown in

Figure 16(b). When the correlation is considered in risk ranking for the case with one detail failure, the expected risk ranking decreases as the correlation increases. The opposite conclusion is drawn for the case associated with failure of two details. The results associated with $n = 10, 20, 50$, and 100 deck, bottom, and side shell fatigue-sensitive details are presented in Table 3 at $t = 4$ years. Two scenarios are investigated herein: (a) risk associated with one fatigue-sensitive detail failure, and (b) failure of two details among 10, 20, 50, and 100 details, respectively. Although the consequence associated with two details failure is much larger than that involving one detail failure, the risk ranking associated with failure of one detail is generally larger than that associated with failure of two details. As indicated, the expected risk ranking of a system depends on many factors, such as the number of fatigue-sensitive details, the correlation coefficients, and the fatigue failure scenarios.

Given a risk ranking threshold associated with a fatigue-sensitive detail failure, the timing for inspection can be obtained. Considering 10 as the minimum acceptable risk ranking per fatigue-sensitive detail, the first inspection is required at $t = 4$ years for the details located at the deck and bottom as shown in Figures 11 and 15(a). As indicated in Figure 12, the required time interval between inspections increases as more details are inspected simultaneously. Given that 1 out of 10, 20, 50, and 100 inspected fatigue-sensitive details at the deck is detected with damage at $t = 4$ years, the next inspection associated with an uninspected detail at the deck is at $t = 8, 10, 13$, and 14 years, respectively.

Based on the system failure event defined in Eq. (15), the probability of system failure can be computed. Then, given the consequence associated with system failure, the risk ranking is obtained. The reliability analysis is performed using the computer program RELSYS (Estes and Frangopol 1998). The risk ranking associated with a system composed of 10 deck fatigue-

sensitive details is shown in Figure 17. The failure modes associated with fatigue-sensitive details are generally statistically dependent due to common random variables. Herein, the correlation coefficient among the random variables (e.g., $\rho(\ln C_i, \ln C_j)$, $\rho(a_{0i}, a_{0j})$, $\rho(A_i, A_j)$) is 0.5. The effect of the number of adjacent fatigue-sensitive details considered to fail in parallel m on the system reliability is shown in Figure 17(a). In this figure, the system failure is defined as the failure of $m = 2, 3$, and 4 adjacent fatigue-sensitive details. As indicated, m has significant effect on the system fatigue reliability. The scenario associated with $m = 2$ reveals the largest probability of system failure during the investigated time interval. The risk ranking of these failure modes is also computed. As more details fail, the consequence associated with system failure becomes larger. For example, oil spill could arise from system failure that defined as more adjacent fatigue-sensitive details fail. The consequences associated with system failure when $m = 2, 3$, and 4 are assumed 10,000, 100,000, and 1,000,000, respectively for illustrative purposes. The risk ranking is shown in Figure 17(b). The risk ranking associated with $m = 4$ is much larger than that associated with $m = 2$ and 3 after about 8 years. Accordingly, the inspection priority could be different when reliability and risk indicators are used. The system failure modes and consequence evaluation have significant effects on the risk ranking assessment. Additionally, the effects of inspection on the system reliability are investigated. Assuming $m = 3$ and $n = 10$, the updated system reliability at $t = 4$ years detection and no detection of cracks at all 3 fatigue-sensitive details is shown in Figure 17(c).

6. Conclusions

This paper provides a probabilistic framework for risk-informed decision making of ship structures under fatigue damage incorporating inspection information. The uncertainties and correlations among the random variables involved in fatigue damage assessment and inspection

are incorporated within the framework. The results of inspection are utilized for reliability and risk ranking updating associated with inspected and uninspected fatigue-sensitive details. The total expected risk ranking of structural systems associated with multiple fatigue-sensitive details is also investigated. The proposed framework is applied to an existing tanker with multiple fatigue-sensitive details. The following conclusions are obtained.

1. The inspection methods and associated mean detectable crack sizes have considerable effects on reliability and risk updating. Additionally, correlation among the random variables used in fatigue reliability and inspection should be considered in the fatigue damage and risk assessment. Given no fatigue crack detected, the inspection interval of uninspected fatigue-sensitive details increases if correlations are considered. Neglecting correlation can significantly affect the reliability and risk ranking of fatigue-sensitive details.
2. Given no crack detected, the updated reliability of a fatigue-sensitive detail increases as the number of inspected details becomes larger. Bayesian updating shows the effect of inspections on the reliability and risk ranking assessment of structures considering fatigue failure. The updating information has to be incorporated within the decision making process associated with inspection priority and planning.
3. It should be noted that the inspection priority among fatigue-sensitive details considering risk ranking is sensitive to consequence evaluation associated with failure of details. The parameters and uncertainties associated with consequence rating factor should be evaluated and investigated.
4. An approach for computing the reliability and risk of a system composed of multiple fatigue-sensitive details is proposed. The system failure event and consequence

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4 evaluation can significantly affect the system reliability and risk. Given the system
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6 reliability and risk thresholds, the inspection priority and planning can be obtained and
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8 updated using inspection information.
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11 5. Future research is needed to include nonlinear fracture mechanics in the damage
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13 assessment of fatigue-sensitive details. Additionally, the effects of multiple fatigue cracks
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15 on the structural capacity have to be taken into account in future studies for the risk
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17 assessment of fatigue-sensitive structures.
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21 6. The information associated with inspection can be used to update the deterioration
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23 models to reduce the epistemic uncertainty. If no fatigue crack is detected, the reliability
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25 of the detail after inspection would increase. Overall, Bayesian approach can be adopted
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27 to update the reliability and risk ranking associated with inspected and uninspected
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29 fatigue-sensitive details. The presented approach could be adopted as a risk-based
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31 decision making tool in the industry area considering specific loading and inspection
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33 methods.
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41 **Acknowledgments**

42
43 The support from the U.S. Office of Naval Research (contracts N 00014-08-1-0188 and N
44
45 00014-12-1-0023, Structural Reliability Program, Director Dr. Paul E. Hess III, ONR, Code 331)
46
47 is gratefully acknowledged. The opinions and conclusions presented in this paper are those of the
48
49 authors and do not necessarily reflect the views of the sponsoring organization.
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Table 1. Consequences rating factors for structural detail failure associated with fatigue damage

Damage intensity	Rating factor	Consequences (SSC 2000)
Low	$[5 \times 10^2; 15 \times 10^2]$	Temporary repair, and/or no immediate repair
Moderate	$[5 \times 10^3; 15 \times 10^3]$	Unscheduled repair and/or reduction of serviceability
High	$[5 \times 10^5; 15 \times 10^5]$	Minor oil spill, major structural failure, cargo loss, loss of serviceability and/or salvage
Extreme	$[5 \times 10^7; 15 \times 10^7]$	Loss of ship, cargo, lives, and/or major oil spill involving cargo tanks

Note: lower and upper bounds are provided in square brackets

Table 2. Random variables associated with fatigue crack limit state and consequence assessment

Random variables	Distribution type	Mean	COV
Initial crack size, a_0 (mm) ¹	Exponential	0.11	1
Detectable crack size, a_d (mm) ¹	Exponential	0.89	1
Average stress cycle rate, v_0	Normal	1×10^6	0.07
Material parameter, m ¹	DNA	3.1	DNA
Material parameter, $\ln C$ ¹	Normal	-29.97	0.017
Stress modeling error, ε_S ²	Lognormal	1	0.1
Stress geometry error, ε_Y ²	Lognormal	1	0.1
Repair cost ratio, r_{cr} ³	Lognormal	2.5	0.2
Unit construction cost, c_{cons} ⁴	Lognormal	447	0.2
Minimal cost value, C_{min}	DNA	200	DNA
Maximal cost value, C_{max}	DNA	2000	DNA
Structural dimension, W (m)	DNA	0.6	DNA
Structural dimension, L (m)	DNA	2.0	DNA

COV: coefficient of variation; DNA: does not apply;

¹: Moan and Song (2000); ²: JCCS (2000); ³: Lukic and Cremona (2001b);

⁴: Maljaars and Vrouwenvelder (2014)

Table 3. Risk ranking of deck, bottom, and side shell with different number of fatigue-sensitive details and correlation coefficients at $t = 4$ years

Number of details, n	Detail	One detail failure			Failure of two details		
		$\rho = 0$	$\rho = 0.5$	$\rho = 0.8$	$\rho = 0$	$\rho = 0.5$	$\rho = 0.8$
10	<i>Deck</i>	126.2	68.9	24.5	1.3	27.7	20.6
10	<i>Bottom</i>	109.6	57.3	22.4	0.8	23.8	17.7
10	<i>Side shell</i>	4615.7	2479.7	923.4	50.0	1067.5	660.6
20	<i>Deck</i>	250.2	92.8	30.4	9.8	52.7	22.5
20	<i>Bottom</i>	220.5	84.7	25.9	7.2	39.0	17.0
20	<i>Side shell</i>	9345.5	3641.9	1086.3	212.1	1779.7	909.2
50	<i>Deck</i>	611.4	138.5	33.8	29.3	98.3	20.5
50	<i>Bottom</i>	530.9	122.6	28.9	18.4	87.1	14.3
50	<i>Side shell</i>	22745.0	5457.2	1298.1	1247.5	3242.8	873.8
100	<i>Deck</i>	1140.5	178.3	39.5	187.2	140.3	23.5
100	<i>Bottom</i>	1005.2	163.4	33.2	82.5	70.8	28.6
100	<i>Side shell</i>	42314.0	7121.8	1664.6	2519.9	4535.8	1511.9

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17