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Risk-based life-cycle optimal dry-docking inspection of corroding ship hull tankers

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A R T I C L E I N F O

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A B S T R A C T

The performance of the ship hull deteriorates randomly over time under corrosion attacks. To ensure the safe operation of a ship, dry-docking inspections are carried out on a regular basis to inspect, recoat, and renew structural members. The convention “at least two inspections every five years”, implemented in the shipping industry, is empirically determined without much numerical evidence. Considering the expensive cost of dry-docking inspections, it is crucial to study the optimal inspection interval in the presence of uncertainty. This paper proposes a risk-based maintenance decision-making framework for ships to address the optimal dry-docking inspection. The minimum expected cost rule is used to explore the economically optimal inspection interval. Monte Carlo simulations are employed to obtain the probability distribution of the life-cycle cost. The costs considered include the cost of dry-docking and member renewal as well as monetary consequences of hull failure. A ship hull is utilized to illustrate the application of the proposed framework.

1. Introduction

The loss of a ship has significant implications in terms of environmental impact, economic loss, and crew casualties. Metal loss corrosion is a primary concern for the safety of aging ships [1,2]. By decreasing the modulus of the hull cross-section, growing corrosion reduces the ultimate strength against external loadings. To maintain the satisfactory integrity of the hull, ships are dry-docked for inspection at a minimum twice in a 5-year period [3]. During the inspection, the thickness of the structural members of the hull is measured using non-destructive tools (e.g., ultrasound inspection), structural renewal is performed for the critical members and new protective coatings are applied to the hull surface to protect against corrosion [4]. Dry-docking is an expensive process and accounts for the largest maintenance cost throughout the ship service life. The cost of one dry-docking can be as high as \$0.2 M to \$0.7 M [4]. Dry-docking can also adversely affect the flexibility of operational schedules by taking a ship out of service. It is of paramount importance to explore a cost-effective inspection schedule that allows the ship to stay longer in water while guaranteeing an acceptable level of safety.

Determining the optimal inspection is not a simple task. Various uncertainties are associated with the performance of the hull. Specifically, the bending moment induced by still water and sea waves experienced during one voyage is uncertain; the spatial variability of geometric and material properties associated with different structural members, the uncertainty associated with the prediction of bending-resistant capacity, and the stochastic corrosion growth result in the uncertain structural performance of the hull. These uncertainties need to be addressed by using reliability methods. In addition, in-service ships are maintained in compliance with the rule by International Association of Classification Societies (IACS) [5], i.e., the structural members are renewed at dry-docking if corrosion penetration depth reaches the wastage allowance. This condition-based maintenance policy should be considered in the investigation of the optimal dry-docking inspection.

The optimal maintenance strategy for the corroded ship under uncertainty has been investigated [6–8]. Sun and Guede Soares [6] studied the ship inspection schedule with an annual reliability constraint. The structural members were assumed to be renewed if the probability of corrosion depth exceeding the wastage allowance was greater than a certain value. In addition to reliability, Dong and Frangopol [7] investigated the optimal inspection of the corroded hull by incorporating the life-cycle cost, whereas the failure consequence considered only includes the loss of the ship. In the risk-based maintenance framework

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for ships proposed by Garbatov et al. [8], comprehensive aspects of failure outcomes are considered, including the environmental impact, the loss of the cargo and ship, and fatalities, although it was implicitly assumed that structural renewal was age-based, independent of the corroding condition of structural members.

Clearly, there is still a lack of in-depth study on the risk-informed ship maintenance considering the condition-based structural renewal policy that is consistent with realistic practice, while the application of condition-based inspection decision-making has been illustrated for pipeline systems [9–11]. This study attempts to develop a practical condition-based decision-making framework for the optimal risk-informed dry-docking inspection. The structural renewal rule by IACS is incorporated in the analysis. The probability distributions of the life-cycle cost, including the cost of dry-docking (i.e., inspection and re-coating), the cost of structural renewal, and failure consequence, are computed using Monte Carlo simulation. The minimum expected life-cycle cost rule is employed as the decision-making criterion to determine the optimal inspection time interval. The remainder of the paper is structured as follows. Section 2 provides information on the life-cycle cost throughout the service life of ships. Then, the reliability assessment of corroded ships is presented in Section 3. After that, a brief introduction of structural renewal policy is given in Section 4. In Section 5, the optimal inspection schedule of a ship hull is investigated. Conclusions are presented in the last section.

2. Life-cycle costs under uncertainty

2.1. Overview

The optimal inspection planning can be ensured if the lowest life-cycle cost of a structure is achieved. In the presence of uncertain structural performance, however, the life-cycle cost is not deterministic. A common way to address this is to minimize the risk that is often measured by the minimum expected life-cycle cost. This rule reflects the risk-neutral attitudes of decision-makers and is widely employed as a normative model for risk-informed maintenance of structures and infrastructure [10–13].

Mathematically, for a hull inspected with a uniform time interval (τ), the expected life-cycle cost throughout the service life (T) is defined as

$$E[C(\tau,T)] = \sum_{i=1}^{n} c_i(\tau,T)p_i \tag{1}$$

where $E[\bullet]$ is the expectation operation; $c_i(\tau, T)$ is the ith possible outcome in terms of the life-cycle cost; n is the number of possible outcomes; p_i is the probability of the ith possible outcome.

The life-cycle cost of a ship in terms of its service life and the dry-docking interval can be expressed as

$$C(\tau,T) = C_D(\tau,T) + C_R(\tau,T) + C_F(\tau,T) \tag{2}$$

where $C_D(\tau, T)$, $C_R(\tau, T)$, and $C_F(\tau, T)$ are the life-cycle dry-docking cost, the life-cycle cost of renewing structural members, and the life-cycle cost of failure throughout the service life, respectively. For a pre-defined dry-docking schedule, $C_D(\tau, T)$ is deterministic. Due to the uncertainty of hull performance stemming from the variability of corrosion growth, external loadings, and model errors of moment capacity prediction, $C_F(\tau, T)$ is uncertain. The condition-based renewal policy for structural members, combined with the uncertain corrosion growth, produces the uncertainties inherent to $C_R(\tau, T)$.

The items of the life-cycle cost in Eq. (2) can be expressed as follows:

$$C_D(\tau,T) = \sum_{i=1}^{n_{in}} \frac{C_p}{(1+v_0)^{\tau i}} \tag{3a}$$

$$C_R(\tau,T) = \sum_{i=1}^{n_{in}} \frac{C_{r,i}}{(1+v_0)^{\tau i}} \tag{3b}$$

$$C_F(\tau,T) = \sum_{l=1}^{n_f} \frac{C_f}{(1+v_0)^{\tau l}} \tag{3c}$$

where C_f and C_P are the cost of failure and the cost of one dry-docking, respectively; $C_{r,i}$ is the renewal cost incurred in the ith dry-docking; n_{in} and n_f are the total number of dry-docking inspections and failure events, respectively; v_0 denotes the discount rate of money. Estimating the dry-docking cost is not easy. For example, the rental fees of docking, the cost of cleaning and coating, and the cost of setting up scaffolding all vary. In this paper, parametric analysis is carried out to consider the dry-docking cost.

2.2. Structural renewal cost

The cost of renewing a structural member is caused by the inserted material, welding, electricity consumptions, fabrication of stiffeners, intersections of structural members, and preparation of brackets and joints [14]. Rahman and Caldwell [15] developed an empirical method for estimating the cost of renewing a panel consisting of several longitudinally stiffened plates. The average cost of replacing a single stiffened plate is approximated as the cost of a panel divided by the number of longitudinal stiffeners. The cost of renewing a panel plate is [15]

$$C_{panel} = C_{mp} + C_{mlt} + C_{wlt} + C_{int} + C_{ele} \tag{4}$$

where C_{mp} and C_{mlt} are the material cost of plates and stiffeners, respectively; C_{wlt} is the cost of welding the stiffeners; C_{int} is the cost of the intersection between longitudinal stiffeners and transverse webs, and preparation of brackets and joints; C_{ele} is the cost of electricity, electrodes, and fabrication of stiffeners. C_{mp}, C_{mlt}, C_{wlt}, C_{int}, and C_{ele} are expressed, respectively, as [15]

$$C_{mp} = W_p C_p \tag{5a}$$

$$C_{mlt} = (W_l I_l + W_t I_t) C_p \tag{5b}$$

$$C_{wlt} = (N_l L T_l + N_t B T_t) C_w \tag{5c}$$

$$C_{int} = N_l N_t (T_c + T_w) C_w \tag{5d}$$

$$C_{ele} = (N_l L + N_t B)(T_{ee} + T_f) C_w \tag{5e}$$

where W_p is the plate weight; C_p is the material price per unit weight; W_l and W_t are the weight of longitudinal stiffeners and transverse frames, respectively; I_l and I_t are the coefficients of cost increase for longitudinal stiffeners and transverse frames, respectively; N_l and N_t are the numbers of longitudinal and transverse stiffeners of the re-constructed panel, respectively, L and B are length and breadth of the panel, and T_l and T_t are the labor times per unit length spent on welding longitudinal and transverse stiffeners, respectively; C_w is the cost of labor per unit time; T_c is the labor time needed to fix stiffeners to transverse frames; T_w is the labor time needed to weld stiffeners to transverse frames; T_{ee} is the labor time required for electricity and electrodes and T_f is the labor time for fabrication of stiffeners and frames. The values of the parameters in Eq. (5) are provided in [14].

2.3. Failure cost

Hull failure can result in the accidental oil spill, ship loss, and crew fatalities. Guia et al. [16] presented a quantitative estimate of monetary failure consequence. This estimate is adapted herein to estimate the cost of hull failure from the perspective of the ship owner. The cost of failure includes the averted cost of crew fatalities, the cleaning-up cost of the oil drifting to the shoreline, and the property loss of a ship and oil cargo it contains. The total failure cost conditioned on the collapse of the hull girder is [16]

$$C_f = C_l + C_c + C_{lc} + C_0 \tag{6}$$

where C_l = cost of human life; C_c = cost of oil cleaning-up; C_{lc} = cost of oil cargo loss; C_O = initial ship construction cost.

$$C_l = n_{cr} P_{cr} I_C \tag{7a}$$

$$C_c = P_s P_{sl} D_w C_{acr} \tag{7b}$$

$$C_{lc} = C_{cr} P_s D_w \tag{7c}$$

where n_{cr} is the total number of crew members; P_{cr} is the probability of life loss of a crew member; I_C is the implied cost of averting a fatality; P_s is the percentage of spilled oil cargo; P_{sl} is the probability of spilled oil drifting to the shoreline; D_w is the deadweight of a ship; C_{cr} is the cost of oil per ton; and C_{acr} is the cleaning-up cost of spilled oil per ton.

3. Reliability analysis

It is widely recognized that the dominant failure of the hull girder under still water and sea waves is ultimate collapse of the cross section due to either crack-rated fatigue or corrosion-induced reduction in section modulus [6–8,16–18]. The collapse is mainly caused by the external vertical bending moment. The contributions of horizontal bending, shear, torsion, and lateral pressure to this failure can be neglected [5]. The performance function associated with the hull girder at mid-span is [18]

$$G = \xi_u M_u - \xi_{sw} M_{sw} - \xi_w \xi_{w,n} M_{we} \tag{8}$$

where M_u is the ultimate vertical bending capacity of the hull girder; M_{sw} is the maximum still water induced moment at mid-span during one voyage; M_{we} is the annual maximum wave-induced bending moment; ξ_u and ξ_{sw} are the model errors of predicting the ultimate bending capacity and still water moment, respectively; ξ_w and $\xi_{w,n}$ are the model error associated with wave-induced moment predictions. Note that ξ_w specifically accounts for the uncertainty of linear response prediction and $\xi_{w,n}$ is a correction factor considering the nonlinearity of responses due to hull flare and large ship motion amplitude [18]. ξ_u, ξ_{sw}, ξ_w, and $\xi_{w,n}$ follow normal distribution with unit mean value. The coefficient of variation of ξ_u is 0.15 [17] and the coefficients of variation of ξ_{sw}, ξ_w, and $\xi_{w,n}$ are 0.10 [18,19]. The linear superposition of the moments by still water and sea waves in Eq. (8) reflects one of the Turkstra's load combination rules, and this combination dominates the ship failure probability [19].

The vertical bending strength is predicted using simple analytical expressions [20]. This method assumes that the hull girder cross-section fails by overall plastic collapse when the tensile flange yields and the compression flange reaches the ultimate buckling strength. With the assumed longitudinal stress distribution over the cross-section, the ultimate bending strength of the hull girder in sagging (M_{us}) and hogging (M_{uh}) conditions are [20]

$$\begin{aligned} M_{us} = & -A_D(D-g)\sigma_{uD} - \frac{A_s}{D}(D-H)(D+H-2g)\sigma_{uS} - A_B \\ & g\sigma_{yB} + \frac{A_B^{'}}{H}(g-D_B)[D_B\sigma_{uS} - (H-D_B)\sigma_{yS}] - \frac{A_S H}{3D} \\ & [(2H-3g)\sigma_{uS} - (H-3g)\sigma_{yS}] \end{aligned} \tag{9a}$$

$$\begin{aligned} M_{uh} \\ = & A_D g\sigma_{yD} + A_B(D-g)\sigma_{uB} + A_B^{'}(D-g-D_B)\sigma_{uB}^{'} + \frac{A_S H}{3D} \\ & [(2H-3g)\sigma_{uS} - (H-3g)\sigma_{yS}] + \frac{A_S}{D}(D-H)(D+H-2g)\sigma_{uS} \end{aligned} \tag{9b}$$

where D is the total hull girder depth; D_B is the height of the double bottom; A_B, $A_B^{'}$, A_D, and A_S are the total sectional areas of the outer bottom, inner bottom, deck, and half-sectional area of the side, respectively; g denotes the neural axis position; H is the depth of the hull section in linear elastic the state; σ_{yB}, σ_{yS}, and σ_{yD} are the yield strength of the bottom, side, and deck, respectively; σ_{uB}, $\sigma_{uB}^{'}$, σ_{uD}, and σ_{uS} are the ultimate compression strength of the bottom, inner bottom, deck, and side, respectively. The detailed calculation of g and H is provided in [20]. Note that A_B, $A_B^{'}$, A_D, and A_S are implicit functions of time. The flange and side of the ship hull girder are stiffened panels with spaced flat, angle or T-bars. A stiffened panel consists of stiffened plate elements with stiffeners of various sizes. The strength of stiffeners is typically higher than that of plates. The ultimate strength of the flange and side is approximated as the equivalent value strength of stiffened plate elements. Similarly, the yield strength of a stiffened plate element equals the equivalent yield strength of the plate and its stiffener. The ultimate compression strength, σ_u, of a stiffened plate is evaluated as follows [21]:

$$\sigma_u/\sigma_y = (0.995 + 0.936\lambda^2 + 0.17\beta^2 + 0.188\lambda^2\beta^2 - 0.067\lambda^4)^{-0.5} \tag{10}$$

$$\text{where } \lambda = \frac{l}{\pi r}\sqrt{\frac{\sigma_y}{E}} \tag{11}$$

$$\text{and } \beta = \frac{b}{wt}\sqrt{\frac{\sigma_y}{E}} \tag{12}$$

σ_y is the steel yield strength; l is the longitudinal stiffened plate length between transverse webs; r is the gyration radius of the stiffened plate; E is Young's modulus; b is the breadth of the plate between longitudinal stiffeners; and wt is the wall thickness of the plate.

Still water bending moment is caused by the difference in the distribution between the ship weight and buoyancy force along the longitudinal direction. In the ship loading manual [5], it is recommended that the maximum bending moment is calculated as

(a) for sagging condition

$$M_{sw,max} = -0.05185 C_{wv} L^2 B (C_b + 0.7)\,\text{KNm} \tag{13a}$$

(b) for hogging condition

$$M_{sw,max} = 0.01 C_{wv} L^2 B (11.97 - 1.9 C_b)\,\text{KNm} \tag{13b}$$

where B is the ship breadth; C_b is the ship block coefficient; L is the ship length; C_{wv} is the wave coefficient given as [5]

$$C_{wv} = \begin{cases} 10.75 - [(300-L)/100]^{1.5} & \text{for } 150\ \text{m} \le L \le 300\,\text{m} \\ 10.75 & \text{for } 300\ \text{m} < L \le 350\,\text{m} \\ 10.75 - [(L-350)/150]^{1.5} & \text{for } 350\ \text{m} < L \le 500\,\text{m} \end{cases} \tag{14}$$

In addition to the ship size, still water moment is also dependent on the ship type and load condition. During one voyage, the maximum still water moment can be different because of the fuel consumption and load redistribution. There exist uncertainties associated with the maximum still water moment. Statistical analysis of various types of ships on a number of voyages found that the maximum bending moment during one voyage can be described by a normal distribution with the mean and standard deviation given, respectively, as $\mu_{sw} = \gamma_1 M_{sw,\max}$ and $\sigma_{sw} = \gamma_2 M_{sw,\max}$, where $\gamma_1 = 0.70$; $\gamma_2 = 0.20$ [18].

The wave-induced moment is the result of hull girder hydrodynamic response under the dynamic distribution of buoyancy forces. By assuming the wave in the short period as a stationary Gaussian process, the response can be predicted using the stochastic spectrum analysis with the peak moment response at a random time point approximated as a Rayleigh distribution [22]. In a long duration, a ship experiences a variety of different sea states. To account for this, the Rayleigh distribution is weighted proportionally to the time the ship spent in different sea states [22]. Statistical analysis based on the sea wave condition given in the IACS North Atlantic scatter diagram shows that the weighted Rayleigh distribution can be approximated by the Weibull distribution [23]:

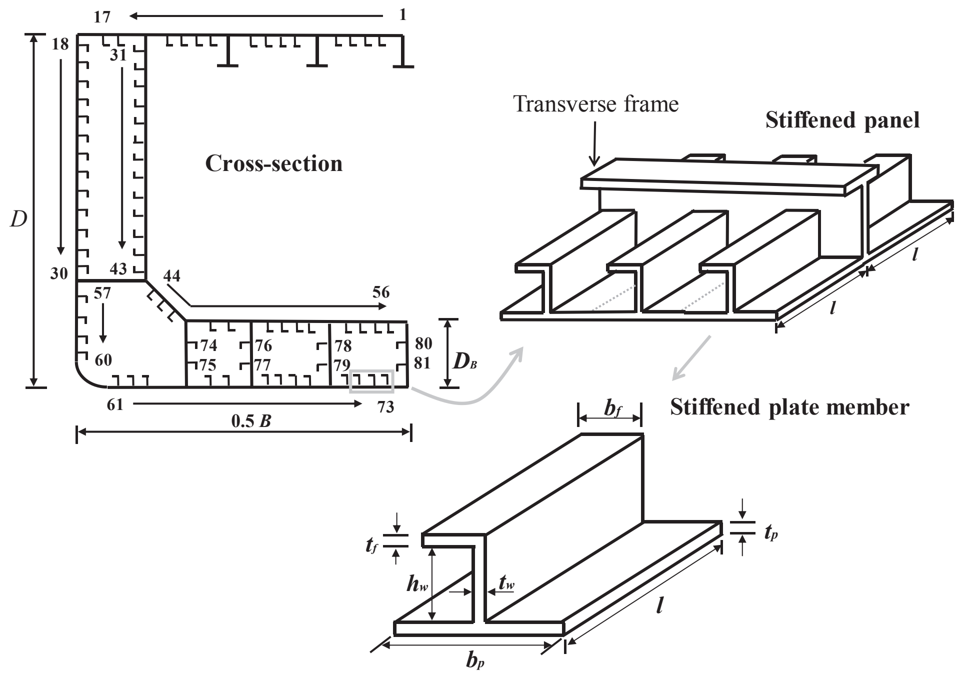

Fig. 1. Mid-ship cross-section of the tanker (adapted from [26]).

$$F_{M_e}(m_e) = 1 - \exp\left[-\left(\frac{m_e}{w}\right)^k\right] \tag{15}$$

where $k = 1$; $w = -M_{w,\max}/\ln 10^{-8}$; $M_{w,\max}$ is the maximum wave-induced bending moment in the ship loading manual [5], which is given as:

(a) for sagging condition

$$M_{w,max} = -0.11C_{wv}L^2B(C_b + 0.7)\text{KNm} \tag{16a}$$

(b) for hogging condition

$$M_{w,max} = 0.19C_{wv}L^2BC_b\text{KNm} \tag{16b}$$

For a period of one year, in-service ships experience many peak cycles. It follows that the annual maximum wave-induced bending moment is described by Gumbel distribution

$$F_{M_{we}}(m_{we}) = \exp\left[-\exp\left(-\frac{m_{we} - \lambda_0}{\theta_0}\right)\right] \tag{17}$$

where λ_0 and θ_0 are the characteristic value and scale parameter of Gumbel distribution, respectively. The parameters of Gumbel distribution are [23]

$$\lambda_0 = w\left[\ln(\frac{a_c T_r}{T_w})\right]^{k^{-1}} \text{and } \theta_0 = \frac{w}{k}\left(\ln(\frac{a_c T_r}{T_w})\right)^{\frac{1-k}{k}} \tag{18}$$

where T_r is the considered reference time, i.e., $T_r = 1$ year; T_w is the average wave period, i.e., $T_w = 7.0$ s; a_c is a factor accounting for the time fraction of a load condition, e.g., $a_c = 0.35$ for a full load condition.

4. Ship structural renewal policy

In the analysis of optimal dry-docking schedules, the realistic maintenance practices of corroded ship hulls are implemented. In the dry-docking inspection, a ship is taken out of service and transported to a dry dock such that the entire hull can be exposed, cleaned, and recoated; the net thickness of the ship's steel plates is measured by using ultrasonic tools and examined for structural renewal. Structural members (i.e., stiffened plates) meeting the renewal criterion are replaced with new inserted materials that have greater material strength and plate thickness than the as-built ones. New coatings on the hull surface prevent corrosion from growing for a certain time of period. The condition of a renewed member is as good as the as-built, and corrosion starts to grow only after the failure of coatings. The condition of the entire ship may be not restored to the pristine state because of the difference in corrosion penetration depth and corrosion allowance corresponding to different structural members.

The most common type of corrosion considered for ships is general corrosion [24]. It uniformly decreases the thickness of steel elements. The renewal criterion for uniform corrosion specified in [5] is

$$t_m < t_{as-built} - t_{was} \tag{19}$$

where $t_{as\text{-}built}$ is the as-built thickness; t_m is the measured average thickness; t_{was} is the double side waste allowance, rounded up the nearest 0.5 mm. The as-built thickness is the sum of the structural design thickness plus corrosion addition. The corrosion addition for general corrosion equals t_{was} + 0.5 mm [5]. Note that there also exits other forms of corrosion on the hull, such as pitting [25]. However, for simplicity of analysis but without the loss of generality, they are not considered herein since general corrosion is the most relevant [24].

5. Illustrative example

5.1. Overview

Consider the double tanker adapted from [26], with its mid-ship section of the double hull girder and structural members shown in Fig. 1. The numbers (1–81) indicate structural members of stiffened plates. The nominal values of the geometric dimension of these members are presented in Table 1. The ship is assumed to have a length (L) of 168 m, a breadth (B) of 28 m, a depth (D) of 16 m, a height (D_B) of the double bottom of 3.3 m. The distance (l) between the transverse webs is 3925 mm. It is further assumed that the ship has a deadweight (D_w) of 40,000 tons [27]. Based on this deadweight, the construction cost is estimated to be C_O = \$43 M [28]. The probabilistic characteristics of the resistance of the hull are presented in Table 2. The geometric and

Table 1
Nominal values of geometric properties of structural members in Fig. 1 (adopted from [26]).

Element member	Plating		Stiffener			
	$b_{p,n}$ (mm)	$t_{p,n}$ (mm)	$h_{w,n}$ (mm)	$t_{w,n}$ (mm)	$b_{f,n}$ (mm)	$t_{f,n}$ (mm)
1, 6, 11	800	15	1050	10.5	300	15
2–5, 7–10	800	12.5	350	9	90	13
12–15	800	14	300	10.5	100	15
16–17	800	14	200	9	90	12
18–43	750	12.5	300	10.5	120	16
44–56	750	13.5	350	10.5	120	18
57–60	750	12.5	350	10.5	120	16
61–73	750	14	350	10.5	120	16
74–81	1100	14	350	10.5	120	18

Table 2
Probabilistic characteristics of parameters of the hull resistance [7,29].

Notation	Distribution	Mean	Coefficient of variation (%)
b_p	Deterministic	$b_{p,n}$	–
h_w	Deterministic	$h_{w,n}$	–
b_f	Deterministic	$b_{f,n}$	–
t_p	Normal	$t_{p,n}$	5
t_w	Normal	$t_{w,n}$	5
t_f	Normal	$t_{f,n}$	5
σ_y	Lognormal	269 MPa	8
E	Lognormal	206,000 N/mm^2	3

material properties associated with different stiffened plate members are assumed to be fully correlated. It is considered that ξ_u, ξ_{sw}, ξ_w, and $\xi_{w,n}$ are independent and the variable representing the same parameter is time-independent.

A linear model [17] is adopted for the corrosion growth on the surface of the plating and stiffeners. The probabilistic characteristics of growth rates are provided in Table 3. The growth rate of corrosion associated with the plating and stiffener of the same structural member is assumed to be fully correlated. The corrosion growth rates in the same location category (i.e., deck, side, and double bottom) are assumed fully correlated and those in different location categories are assumed independent. It is further assumed that the coating life for the deck, side, and the bottom are 11, 3, and 3 years, respectively, based on the results of statistical analysis [2]. The corrosion allowance at different locations of the mid-ship cross-section is shown in Fig. 2. The average cost of renewing a member of stiffened plates with the length l is calculated as \$1,538, using Eqs. (4) and (5). The values of parameters of estimating the failure costs are n_{cr} = 25, P_{cr} = 25%, I_C = \$3.85 M, P_s = 20%, P_{sl} = 10%, C_{cr} = \$108 per ton, and C_{acr} = \$60,000 [30]. It follows that the failure cost equals C_f = \$115.9 M. Note that although the oil price is very volatile, the cost of oil cargo losses accounts for only 0.7% of the total failure cost. Therefore, the variability of oil price is neglected herein.

The expected life-cycle cost is calculated and used to select the optimal inspection interval, among a set of alternatives with the uncertain performance of the corroded hull. These uncertainties are evaluated using Monte Carlo simulations with one million samples. To

Table 3
Probabilistic characteristics of annual corrosion growth rates of plates and stiffeners (mm/year) [17].

Location	Distribution	Mean	COV
Deck	Weibull	0.065	0.5
Side	Weibull	0.03	0.1
Double bottom	Weibull	0.17	0.5

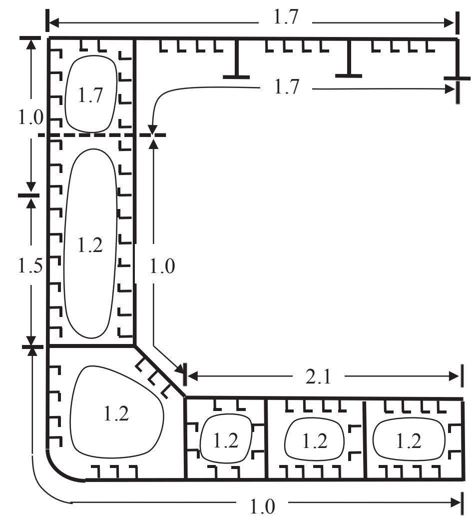

Fig. 2. Wastage allowance, t_{was}, at different ship locations (mm) (adapted from IACS [5]).

investigate the effects of the dry-docking cost, the time discount rate, and the corrosion distribution along the hull longitudinal direction on the optimal dry-docking interval, a baseline example is created with the dry-docking cost C_P = \$0.2 M, the discount rate v_O = 5%, the design life T = 25 years, and the corrosion distribution in the longitudinal direction being assumed to be within a distance l. Parametric analysis is carried out by varying the values of these parameters. In the following sections, if a value is not specified for a parameter, it is implicitly the same as that in the baseline example.

5.2. Results

Fig. 3 shows the expected value of the life-cycle cost ($C(\tau, T)$), the failure cost ($C_F(\tau, T)$), and the maintenance cost ($C_D(\tau, T) + C_R(\tau, T)$) for the baseline example as a function of dry-docking interval using an increment of one year. It is shown that $E[C_D(\tau, T) + C_R(\tau, T)]$ decreases as the inspection interval increases, while $E[C_F(\tau, T)]$ is increased. This is expected because a longer inspection interval results in an increase in the probability of failure, despite the reduction in the maintenance cost. When the ship is frequently docked for inspection (e.g., $\tau \le 5$ years), the contribution of $E[C_D(\tau, T) + C_R(\tau, T)]$ to $E[C(\tau, T)]$ is higher than that of $E[C_F(\tau, T)]$, and $E[C(\tau, T)]$ is very sensitive to the inspection interval. However, for $\tau \ge 6$ years, $E[C_F(\tau, T)]$ is greater than $E[C_D(\tau, T) + C_R(\tau, T)]$ and dominates $E[C(\tau, T)]$. The optimal interval corresponding to the minimum value of $E[C(\tau, T)]$ is 10 years. The slope of E

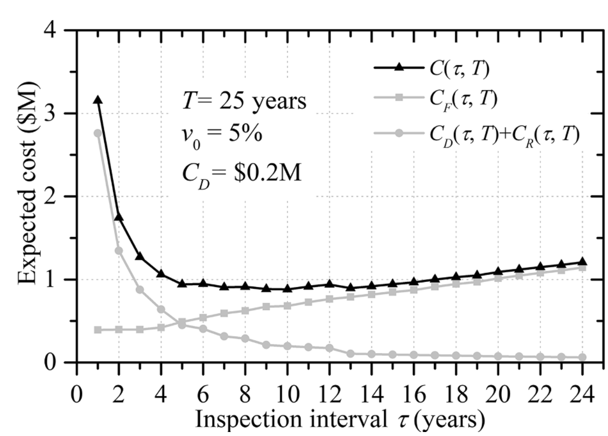

Fig. 3. Expected cost versus the inspection interval of dry-docking for the baseline example.

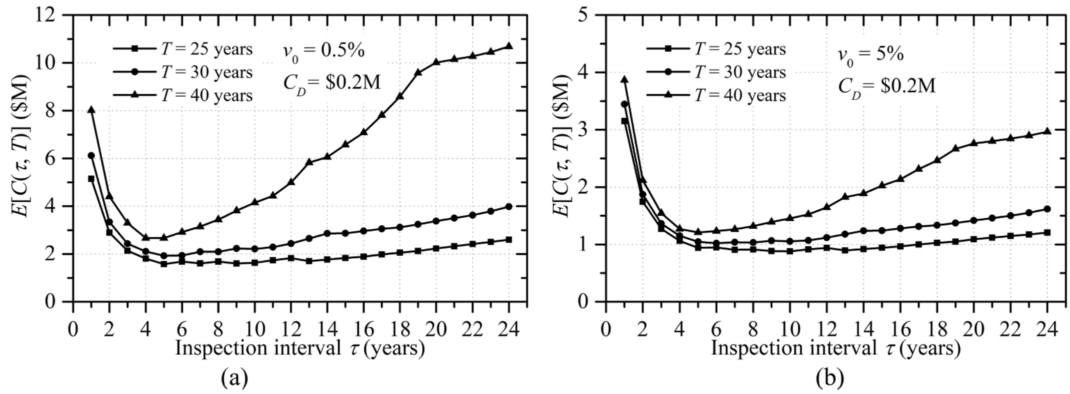

Fig. 4. Expected life-cycle cost versus the inspection interval of dry-docking for T = 25, 30, and 40 years: (a) ν_0 = 0.5%; (b) ν_0 = 5%.

$[C(\tau, T)]$ is quite flat near the optimal solution. This result indicates that there exit several near-optimal solutions with the values of $E[C(\tau, T)]$ close to the minimum. τ = 1 year is associated with the maximum value of $E[C(\tau, T)]$, indicating that very frequent annual inspection is less preferred than even a single inspection at the very end of service life.

The actual service life of a ship can exceed its design life T = 25 years. To investigate the impact of this possible extended life on the optimal inspection interval, the analysis generating the results in Fig. 3 are repeated considering T = 25, 30, and 40 years. The obtained expected life-cycle cost as a function of inspection interval τ, for three service life values of T = 25, 30, and 40 years is shown in Fig. 4a for ν_0 = 0.5% and Fig. 4b for ν_0 = 5%. It is observed that the curves of $E[C(\tau, T)]$ corresponding to T = 25 and 30 years have similar trend and this trend is not significantly influenced by the discount rate of money, while T = 25 years is associated with a smaller value of $E[C(\tau, T)]$ because of fewer inspections performed during the service life. In contrast to the flatness of the curve of $E[C(\tau, T)]$ for T = 25 and 30 years when $\tau \geq$ 5 years, $E[C(\tau, T)]$ associated with T = 40 years becomes very sensitive to both short and long inspection interval except when $E[C(\tau, T)]$ is close to its minimum value. Comparison of results in Fig. 4a and b indicates the increase of the discount rate from ν_0 = 0.5% to 5% significantly reduces the value and the sensitivity of $E[C(\tau, T)]$ to the inspection interval.

The impact of inspection interval on the total expected cost of member renewal, $E[C_R(\tau, T)]$, is illustrated in Fig. 5a for ν_0 = 0.5% and Fig. 5b for ν_0 = 5%, when T = 25 years. $l_0 = l$ = 3925 mm, 15 l, and 30 l are considered for each case. The values of $E[C_R(\tau, T)]$ are not provided for $\tau \leq$ 5 years because frequent inspection and recoating of the hull well arrest corrosion growth and, therefore, the number of structural members satisfying the renewal criterion is very limited. As expected, a wider distribution of corrosion along the longitudinal direction is shown to result in a higher value of $E[C_R(\tau, T)]$. By comparing $E[C_R(\tau, T)]$ with $E[C(\tau, T)]$ for T = 25 years in Fig. 4, it is observed that the cost of member renewal accounts for a negligible portion of the life-cycle cost irrespective of the inspection interval, even if l_0 = 30 l equivalent to 70% of the ship length. The probability of structural members reaching corrosion allowance within the design life T = 25 years is very low. This observation is also valid for the cases when T = 30 and 40 years. Therefore, it can be inferred that the optimal inspection interval, based on minimizing the expected life-cycle, is not significantly affected by the corrosion distribution in the longitudinal direction. On the other hand, the result also illustrates that assuming $l_0 = l$ in the evaluation of the life-cycle cost is reasonable due to the trivial contribution of renewal cost. Furthermore, $E[C_R(\tau, T)]$ does not monotonically increase as the inspection interval increases. The values of $E[C_R(\tau, T)]$ drop at τ = 13 years. While more structural members are expected to be renewed due to corrosion growth if inspection interval is increased, the annual probability of ship failure also increases. In simulation analysis, the cases satisfying the renewal rule but are associated with ship failure are excluded in computing $E[C_R(\tau, T)]$. This explains why a longer inspection interval does not necessarily lead to a higher value of $E[C_R(\tau, T)]$.

To study the influence of the dry-docking cost (i.e., inspection and recoating), the analysis that generates results for Fig. 4 is repeated considering C_D = \$0.2 M, \$0.4 M, and \$0.6 M, respectively. These values of C_D are representative of actual dry-docking costs [4,31]. The computed results are presented in Fig. 6. Similar to the results in Figs. 3 and 4, $E[C(\tau, T)]$ is very sensitive to the shorter inspection interval and insensitive to the long inspection interval for all cases analyzed. In addition, it is observed that a higher value of C_D increases the values of $E[C(\tau, T)]$, whereas this impact of C_D decreases when the inspection interval is increased and eventually becomes negligible when τ is greater than a certain value. This value depends on the discount rate and the service life considered. For example, when ν_0 = 0.5% and

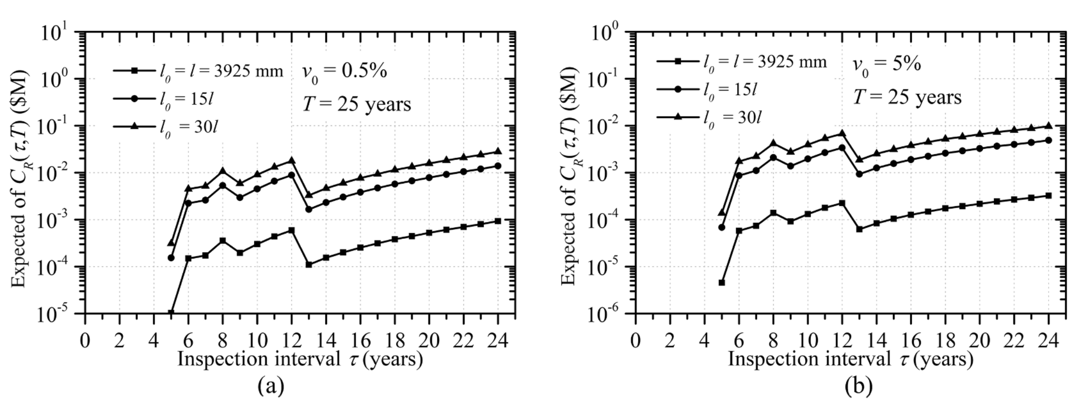

Fig. 5. Expected cost of structural renewal versus the inspection interval of dry-docking for T = 25 years. $l_0 = l$ = 3925 mm, 15l, and 30l are considered for each case: (a) ν_0 = 0.5%; (b) ν_0 = 5%.

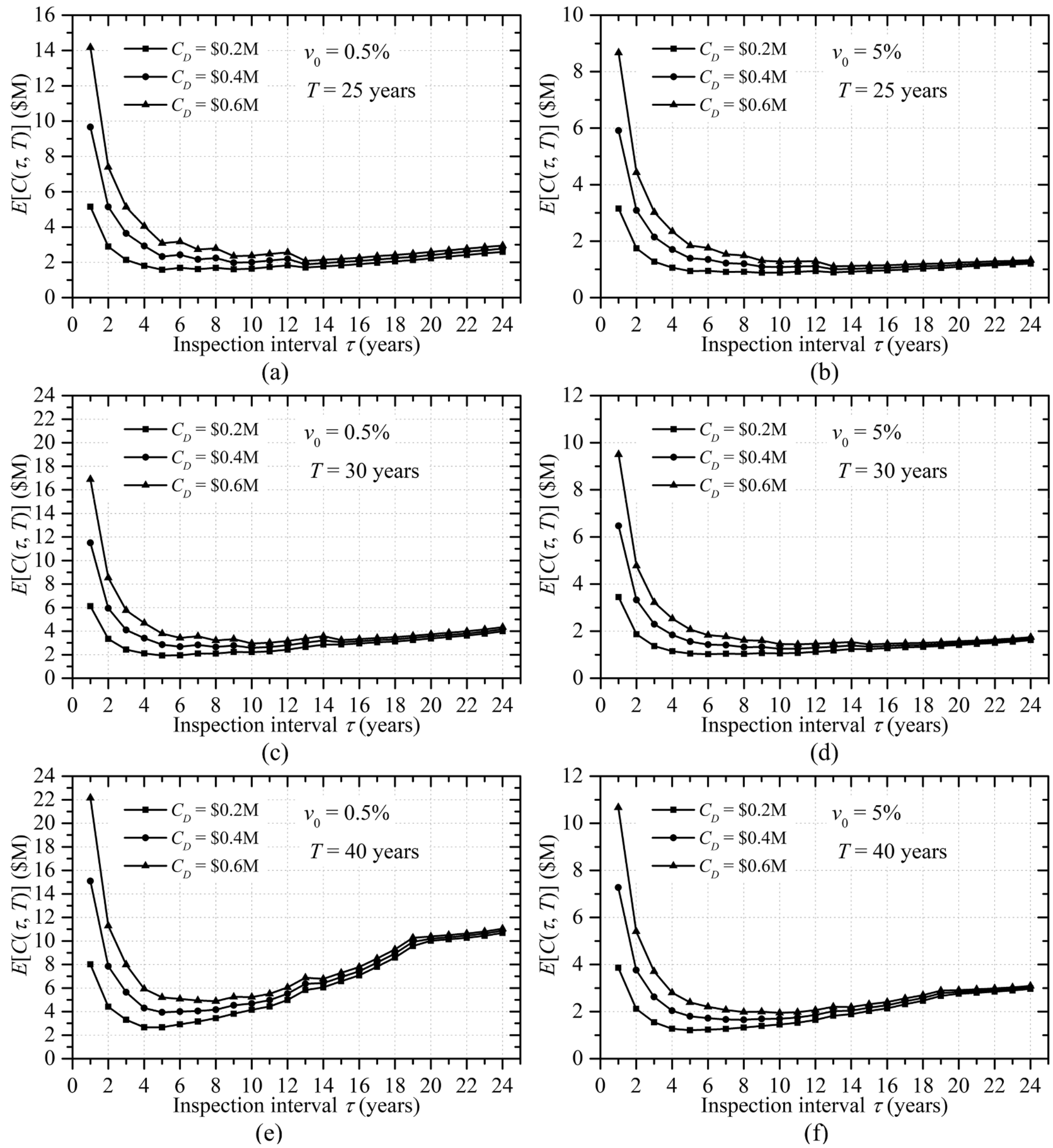

Fig. 6. Expected life-cycle cost versus the inspection interval of dry-docking for T = 25, 30, and 40 years, for different values of the life-cycle dry-docking cost C_D = $0.2M, $0.4M, and $0.6M: (a), (c), (e) v_0 = 0.5%; (b), (d), (f) v_0 = 5%.

T = 30 years, the curves of $E[C(\tau, T)]$ corresponding to C_D = $0.2 M, $0.4 M, and $0.6 M are almost identical when $\tau \geq 15$ years. If the service life is extended to T = 40 years, the threshold of inspection interval without causing significant impact is approximately 20 years.

The optimal inspection interval that results in the minimum expected life-cycle cost for each case in Fig. 6 is summarized in Table 4. Comparison of the results highlights that the optimal inspection interval is affected by the service life and the values of C_D and v_0, though to a different extent. For a given service life, the increase in C_D and/or v_0 increases the optimal interval. As the service life increases, a shorter inspection interval is required to achieve the minimum life-cycle cost. The minimum optimal inspection interval is 4 years, which is an extended period compared with the enforced two dry-dockings every 5 years. This implies that, for the considered ship, the convention of the dry-docking frequency is not cost-effective. By extending the inspection interval from 2 years to 4 years, around 40% reduction in the life-cycle cost can be achieved for the case of v_0 = 0.5%, C_D = $0.2 M, and T = 40 years. It is also seen that the optimal interval is even up to 13 years when v_0 = 0.5%, C_D = $0.6 M, and T = 25 years. In this case, the life-cycle cost curve is not sensitive to the inspection interval (see

Table 4
Optimal interval of dry-docking using the minimum life-cycle cost rule (years).

T(years)	v_0 = 0.5%			v_0 = 5%		
	C_D = $0.2 M	C_D = $0.4 M	C_D = $0.6 M	C_D = $0.2 M	C_D = $0.4 M	C_D = $0.6 M
25	5	13	13	10	13	13
30	5	10	10	6	10	11
40	4	5	8	5	8	10

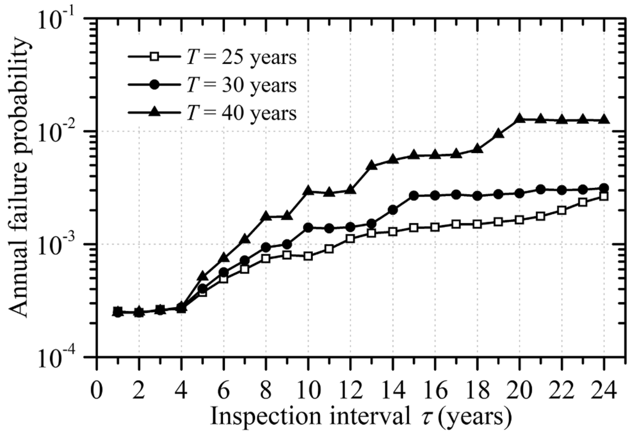

Fig. 7. Maximum annual failure probability throughout the ship service life T = 25, 30, and 40 years.

Fig. 6a), and the constraint on maximum annual reliability commonly implied by regulators may govern the selection of optimal interval in lieu of the minimum life-cycle cost.

The annual maximum failure probabilities for T = 25, 30, and 40 years as a function of the inspection interval are presented in Fig. 7. Overall, the maximum annual failure probabilities increase as the inspection interval increases. For τ < 5 years, the maximum annual failure probabilities for all three cases are very similar, around 1.7×10^{-4}. This is due to the fact that with frequent dry-docking recoating, no significant corrosion is generated and, therefore, the performance of the ship does not substantially deteriorate over time. However, for $\tau \geq$ 5 years, the failure probabilities corresponding to T = 40 years are significantly higher than those corresponding to T = 20 years. This is reasonable since the corroded structural members that do not reach the wastage allowance will continue to deteriorate, which may cause ship failure in the future. The result reveals that to satisfy a consistent reliability target, the hull, which is expected to be in service for a longer time, needs a shorter inspection interval. If an annual probability constraint of 10^{-3} is requested, the inspection interval should be no longer than 11, 8, and 6 years for T = 25, 30, and 40 years, respectively. On the other hand, it can be inferred that it is quite safe for the considered ship to extend the dry-docking period to 4 years, since the increase in the annual failure probability, resulting from this extension, is very small.

6. Conclusions

This paper introduces a risk-based framework for the optimal dry-docking inspection interval of corroded ship hull tankers under uncertainty. The minimum life-cycle cost rule is employed to select the optimal dry-docking time interval, where both the cost of periodic inspection and structural renewal, and the cost of hull failure are incorporated. A condition-based renewal policy of structural members, which is consistent with the inspection practice required in [5], is considered. Monte Carlo simulations are employed to deal with the uncertainty of ship performance. The developed framework is demonstrated on a ship hull, and parametric analysis is conducted to study the impact of dry-docking costs, renewal costs, discount rates of money, corrosion distribution along the ship length, and the service life on the optimal inspection interval. The developed framework is useful in facilitating the risk-based dry-docking management of the corroded hull tankers.

The following conclusions are drawn. The life-cycle cost is very sensitive to the inspection time interval ($\tau \leq$ 5 years) when the ship is in service for an extended service time, T = 40 years. This sensitivity is greatly reduced for long inspection time intervals (τ > 10 years) when T = 25 and 30 years; in this case the slope of the life-cycle cost is quite flat near the optimal inspection time interval, indicating that decision-makers can prescribe a set of near-optimal inspection time intervals. The cost of structural renewal contributes a negligible part of the life-cycle cost regardless of the corrosion length in the ship longitudinal direction. The minimum value of the life-cycle cost when T = 40 years corresponds to a shorter inspection interval, compared with those associated with T = 25 and 30 years. This finding highlights the importance of performing more frequent inspections if the ship is expected to have a longer service time. A higher discount rate of money leads to a longer optimal dry-docking inspection interval, which is consistent with the finding regarding the optimal pipeline inspection in [9]. A higher value of dry-docking cost significantly increases the life-cycle cost when the inspection interval is short and tends to increase the optimal interval. For the considered ship, the requirement of a dry-docking twice every 5 years leads to a high ship annual reliability and is not cost-effective from the point of view of the life-cycle cost. It is important to note that the life-cycle cost and the optimal inspection are obtained based on the assumptions regarding the cost estimates of maintenance and failure consequence. To obtain improved results, a refined cost modeling is necessary.

Declaration of Competing Interest

None.

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