Risk-based framework for ship and structural design accounting for maintenance planning

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Abstract

This work develops a risk-based framework for a ship and structural design accounting for maintenance planning. The risk analysed here covers structural failure where, it is deemed as a failure when the structural capacity is less than the subjected loads, reducing the stipulated margin of safety. The risk in this context also includes hazards such as accidental spills, loss of cargo, ship and crew members during the operations stage. For structural failure, time profiles of performance, which will incorporate structural degradation in conjunction with ship hull strength to predict the expected behaviour regarding structural integrity is analysed. The profiles are envisaged to be approximate as they are based on the limited data available during the early design stage. The risk-cantered maintenance methodology is applied for determining the maintenance plan of a ship hull structural system and permits the developed framework to be used in the early stage of design, accounting for different hazard scenarios, specific economic environment and degradation severity along the service life.

Keywords: ship; structural design; risk, cost; maintenance

1 Introduction

Nowadays, two fundamental risk-assessment approaches are employed, qualitative and quantitative ones (Guedes Soares and Teixeira, 2001; Apostolakis, 2004). The qualitative risk approach identifies the risk, employing a pre-defined rating scale. The risk is scored based on the probability or frequency of occurring. A quantitative risk analysis, which is a more advanced approach is employed here to develop a probabilistic analysis accounting for the existing uncertainty.

The approach, presented here, enables the risk mitigation actions in the early ship design stage, accounting for the fact that the ship design and operation are predominantly governed by the ship owner's specification and applicable Regulations and Classification Rules.

The owner's specification covers the ship performance and minimises the capital, CAPEX and operational costs, OPEX and the Regulations and Classification Rules cover the fundamental design, safety, environmental and operational requirements.

The International Maritime Organization, IMO implemented the Formal Safety Assessment, FSA (IMO, 2005, 2006a, b, 2007, 2008, 2013, 2015) to improve the maritime safety and was used to create new rules as shown in (Psaraftis, 2012; Montewka et al., 2014) and designing of ships in the degradation condition in (Papanikolaou et al., 2009). Recently the Formal Safety Assessment was employed (Guia et al., 2016) to perform a sensitivity analysis on the hull girder safety level of a tanker ship and in (Garbatov and Sisci, 2018) for a risk-based conceptual ship design of a multipurpose vessel subjected to shipbuilding constraints, risen due to the limitation of SME shipyard in building new ships as it was discussed in (Garbatov et al., 2017b; Atanasova et al., 2018; Damyanliev et al., 2018).

However, what nowadays is observed is that in the environment of small and medium shipyards, the basic planning and the initial design are done outside of the shipyards and outfitting, and detailed designs are performed in the shipyards. In this perspective, to enhance the capacity of SME shipyard in the design process, the internet environment can be used to enable remote design and information exchange between SMEs and design agents. The implementation of the available software, including in-house developed one may support the development of a low budget integrated design framework for SMEs.

The objective here is to develop a framework, capable to perform ship and structural design accounting for the risk-based life cycle assessment and maintenance in a very early stage of ship design, where limited information is available and at the same time permits to account for a specific measure related to the future maintenance and repair to be considered. The study is performed in three consecutive stages related to conceptual ship design, risk-based structural assessment, and risk-based maintenance as can be seen from Figure 1.

The first stage addresses the risk related to the owner's specification requirements considering aspects including lightweight, dead weight, cargo capacity, freeboard, initial stability, seakeeping etc. Due to a large number of items that need to be considered, a Pareto optimisation algorithm is employed to conclude on the best design choice. The details about this stage were already discussed in (Damyanliev et al., 2017; Garbatov and Sisci, 2018) and here, only a brief description will be presented.

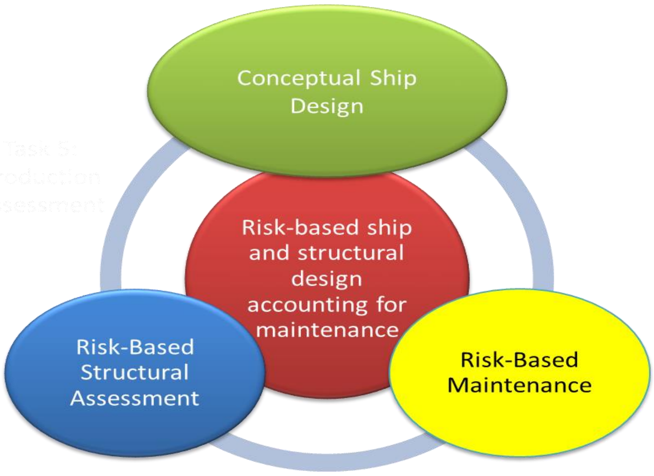

Figure 1 Risk-based ship and structural design

Based on the output from the first stage, the mid-ship section scantlings of an MPS are determined, and a risk-based analysis with emphasis on the lifecycle cost and ultimate strength assessment is carried out. The analysis focuses on the progressive collapse and related probability of structural failure as well as the cost of progressive collapse, structural measures, human life, loss of cargo, accidental spills, where the last two are related to the environmental impact. The output will be a target structural reliability to which the designed structure needs to comply.

In the last stage, the risk-based maintenance planning is performed. The severity of structural degradation is defined in probabilistic terms, and the different hypothesis of structural degradation consequences are studied. The cost of preventive and corrective maintenance is estimated with the aim to optimise the maintenance. The output is a maintenance plan that will aim to reduce the cost of the ship operation. It is noted that the maintenance planning could result in a redesign of the ship structure.

2 Risk analysis of ship hull structural system

The formal safety assessment formulation is applied here, which includes five steps, commonly used in a risk analysis methodology, including the identification of hazard, risk control options, risk analysis, cost-benefit analysis and decision-making and sensitivity analysis.

The risk associated with the ship in operation is estimated based on the probability of failure and the consequences of failure. The scope of the present study includes only the ship hull structural system with the failure that may lead either to the loss of the ship hull structure, loss of cargo, loss of human life or environmental pollution. Therefore, the failure consequence is related to the ship hull structure, cargo, human life loss and environmental pollution. The risk is driven by the failure probabilities, and their consequence and the objective is to estimate the time-dependent probability of failure as a measure of the risk of a ship in operation.

The hazard that reduces the ship hull structural integrity is identified, and the model that defines the global structural performance is based on the progressive collapse of the ship hull structure regarding the midship section of the ship hull girder. The impact of corrosion degradation on the primary structural components is included in the formulations.

2.1 Ship hull structural system

A ship hull structural system is defined as an assembly of structural components, including plates, stiffened panels, platforms, decks, etc., joined to satisfy a specific structural capacity and functionalities of the designed ship.

To define the ultimate limit state of failure, failure rates and consequences, information related to the ship operation, maintenance and repair during the service life needs to be collected. A non-failure state of the ship hull structural system is defined as a state when the ship hull structural system can perform its designed functions by meeting measurable requirements defined by an acceptable reliability or risk level. However, the ship hull structural system may function by only satisfying partially the acceptable level, which is not considered a successful performance.

In this work, a quantitative risk-based life cycle structural integrity assessment of a multipurpose ship in operation is performed. The multipurpose vessel is subjected to the progressive ship hull structural collapse and corrosion degradation during the service life.

The structural system is defined during the conceptual ship design, formulated as a compromise decision support problem with multiple goal constraints given the owner's requirements about the cargo deadweight/containers, speed, range, regulations and data on similar ships to find the main dimensions of the ship.

Two models in the design, related to the ship and voyage descriptions, are involved (Ventura and Guedes Soares, 2015; Damyanliev et al., 2017). The first model includes hull dimensions, hull form generation, hydrostatics, freeboard, hull resistance, propulsion, hull internal layout, hull structure amidships, lightship weight, cargo capacity, stability and capital and operational cost. The voyage model includes port sequence, voyage legs data, port/terminal data, cargo handled/port, round trip time/cost, annual cargo and operational cost. The design solution has to satisfy the system constraints.

The total cost of the ship is derived from the annual operating cost and capital cost, where the first is the sum of the salary of crew members, costs related to the stores and supplies, insurances, port expenses and annual fuel cost, and the second one accounts for all expenses of building the vessel.

The required freight rate has been calculated by dividing the discounted annual average cost of the investment by the annual cargo capacity.

For the present analysis one design solution of a feeder, multi-purpose/container vessel is considered (Figure 2), with main dimensions as a length overall, L_{oa} = 126.08 m, length between the perpendiculars, L_{pp} = 113.75 m, moulded breadth, B = 20.00 m, moulded depth, D = 10.40 m, summer draft, d = 8.29 m, deadweight, DW about 9,800 t, speed: 14 knots and block coefficient, C_b=0.719. The material used in constructing the hull girder is steel of nominal yield strength 235 MPa and higher tensile steel of 315 MPa.

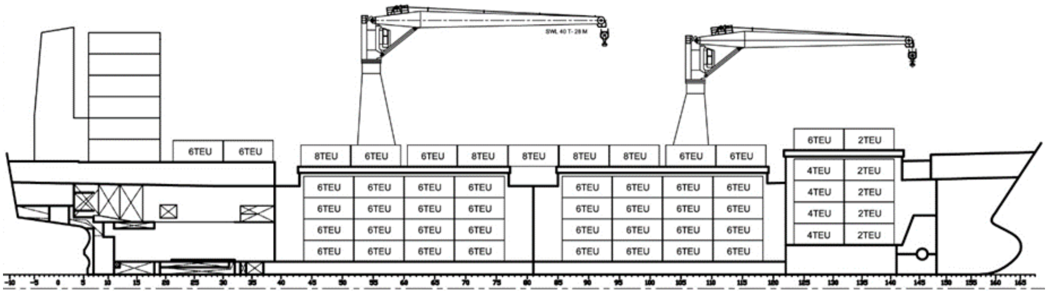

Figure 2 Multi-purpose ship

2.2 Hazard identification

The hazard is identified based on the ship hull structural system, mode of operation, event and effects causing a potential hazard. With this respect, the ship hull´s structural system is exposed to various hazards that undermine the structural integrity during the service life.

The most important hazards experienced by ships operating in open sea include extreme sea wave-induced load, still water load, continuous loading and unloading, corrosion degradation, progressive structural collapse and fatigue cracking. Other hazards result from accidental loads, such as grounding, collision, fire or blast (Guedes Soares and Teixeira, 2001).

Studies in the last decades show that corrosion degradation is one of the most dominant hazards experienced by the ship hull structural system. Corrosion degradation exists in several forms, including general corrosion, pitting and grooving (Caridis, 2001; Garbatov and Guedes Soares, 2015).

In the present study, only general corrosion degradation and the progressive structural collapse of the ship hull structural system subjected to vertical still and wave-induced bending moments are considered.

The corrosion degradation and progressive ship hull structural collapse are identified as initiating events of failure. The risk-based structural integrity assessment transforms these initiating events into a risk measure, where all possible outcomes for the ship hull structural system are evaluated.

Four types of limit states may be considered for the ship hull structural system associated with serviceability limit state, ultimate limit state, fatigue limit state, and accidental limit state. The ultimate limit state, considered in the present analysis, represents the collapse of the structure due to the loss of strength due to buckling and plastic collapse of structural components. The safety of structures may be evaluated by comparing the ultimate strength with the applied loads.

2.3 Risk control options

A structural design modification factor, DMF, is employed as a risk control option here, to allow the structural design to be modified realistically and to identify the effect on the ultimate capacity of the structural system. A change in the ultimate strength is most effectively achieved by modifying the deck structure. Consequently, the chosen DMF modifies the dimensions of the stiffeners and the thicknesses of the deck, while keeping the scantlings of the sides and bottom structure constant (Horte et al., 2007).

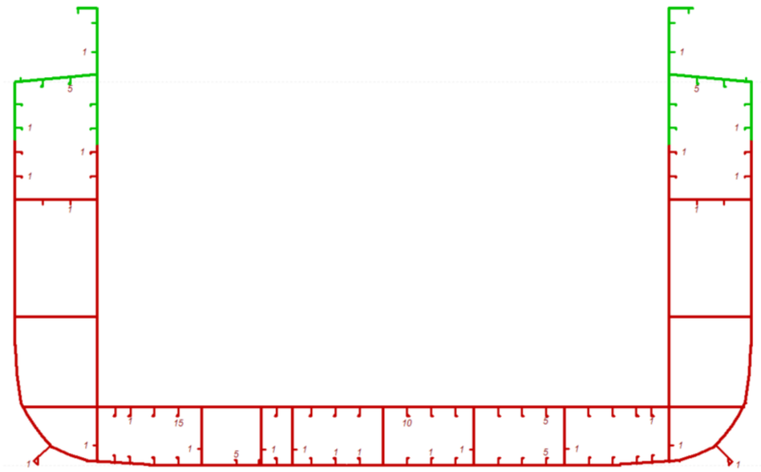

Figure 3 Midship section of multi-purpose ship (green for 315 MPa, red for 235 MPa)

The ship hull structural ultimate capacity is evaluated concerning progressive structural collapse. The thickness of the high tensile steel structural components (shown in green in Figure 3) are modified in a range of $\pm\Delta t$ from the original scantling. The design modifications are represented by design modification factors, which are defined as a relation between the modified midship sectional area and the original one.

The failure analysis associated with the progressive structural collapse as a part of the limit state failure of a plate and its impact on the ship hull structural system are defined as a sequence of events associated to the buckling of the plate, the stiffened panels and the collapse of primary structures ending with the ship hull structural collapse.

The consequences of with the overall hull girder collapse are defined by possible injuries and loss of crew, loss of cargo, contamination with fuel and lubricating oil, which is conditional to the hull structural degradation and failure of primary structural components and associated cost of inspection, maintenance and repair.

2.4 Reliability analysis

2.4.1 Time-dependent profile

The risk profile is defined based on the progressive collapse of the ship hull structural system subjected to corrosion degradation and vertical still water and wave-induced bending moments.

The probability of occurrence of the failure is affected by a time-dependent corrosion degradation mechanism. The failure consequences are also time dependent due to the time-value of money. The expected future failure consequences required an appropriate treatment of the uncertainties of the design variables. Similar considerations are related to the time-dependent value of the human life and environmental pollution.

The limit state is specified based on the definition of the conditions under which the ship hull structural system may not be able to fulfil its function. The load-carrying capacity of the ship hull structural system is evaluated either using simplified design formulations or by using more advanced nonlinear finite element analyses (Garbatov et al., 2017a).

2.4.2 Load

The loads are defined as full, partial and ballast, where the long-term value of the still water and wave-induced bending moments are estimated based on (IACS, 2015). The primary total bending moment load on the ship hull can be decomposed into two components: the still water bending moment M_{SW} and the wave-induced bending moment M_{W}.

Statistical descriptors of the still water bending moment are defined by using regression equations as a function of the length of the ship, L and dead-weight ratio, W= (DWT/Full load) as defined in (Guedes Soares and Moan, 1988) as a function of the still water bending moment, $M_{SW,CS}$ as given by IACS (IACS, 2015) (see Figure 4). The plus sign indicates that the bending moment is in a hogging condition.

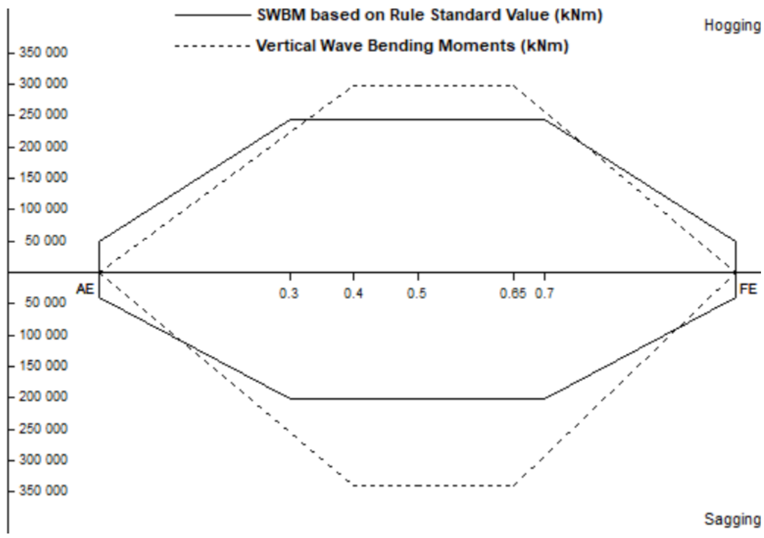

Figure 4 Classification Societies Rules $M_{SW, C S}$ and $M_{W, CS}$ bending moments

The statistical descriptors of the still water bending moment in full, ballast and partial loads are following the Normal probability distribution, N_{FL} (160.8 MN.m, 54.4 MN.m), N_{BL} (295 MN.m, 72.6 MN.m) and N_{PL} (244.9 MN.m, 69.2 MN.m), where the first descriptor defines the mean value and the second one the standard deviation. The still water bending moment is in a hogging condition for the full, ballast and partial loads.

The stochastic model for defining the vertical wave-induced bending moment, proposed in (Guedes Soares et al., 1996), is employed here. The distribution of the extreme values of the wave-induced bending moment at a random point of time, over a specified period, is assumed to follow the Gumbel distribution, considering that the wave-induced bending moment can be represented as a stationary Gaussian process (short-term analysis), then the wave-induced bending moment, $M_{W, CS}$ as given by the Classification Societies Rules may be modelled as a Weibull distribution.

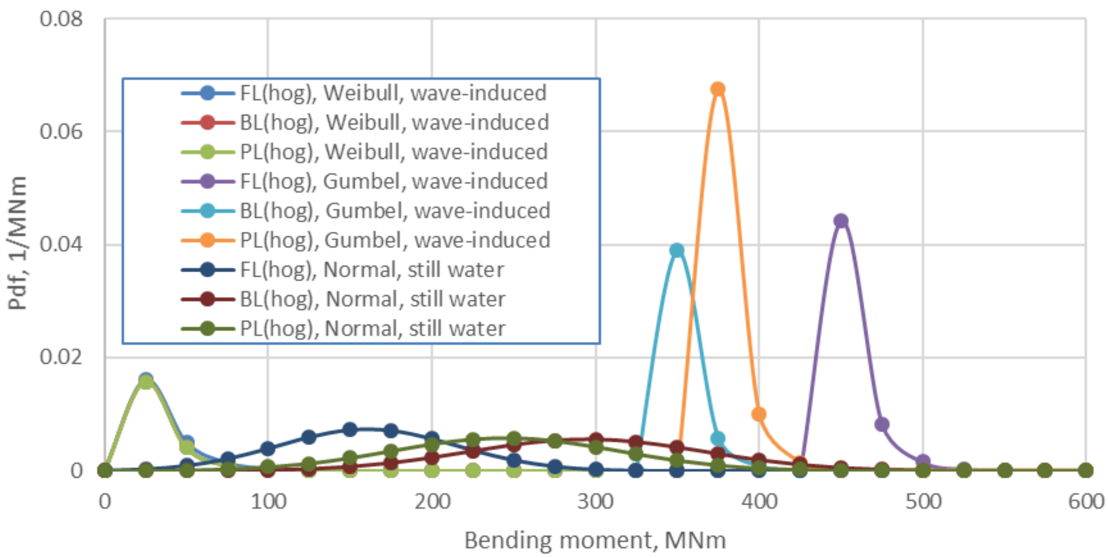

Figure 5 Pdf of still water and wave-induced bending moments

The mean value and standard deviation of the vertical wave-induced bending moment in the full, ballast and partial loading conditions are defined by the Gumbel distribution function as $F_{G,FL}$(443.73 MN.m, 14.84 MN.m), $F_{G,BL}$(341.19 MN.m, 13.15 MN.m), and $F_{G,PL}$(373.32 MN.m, 13.04 MN.m) respectively (see Figure 5).

2.4.3 Corrosion degradation

The effect of corrosion on metal structures is a material thickness reduction, lowering the material's mechanical properties (Garbatov et al., 2014) and making it more vulnerable to the induced load. Failures in the maritime sector over the service life to corrosion and other causes were discussed in (Caridis, 2001).

Very extensive corrosion depth measurement data sets of different structural components in different corrosive environments (Garbatov et al., 2007) were analysed by the Akaike's Information Criterion (Bozdogan, 1987; Burnham and Anderson, 2002) to identify which model is more likely to have generated the data, and how much more likely concluding that the exponential model is more likely to have generated the data respectively in 71% of studied cases.

The exponential model is used in the present corrosion degradation modelling. The mean value, Mean value $[d^{cd}(t)]$ and standard deviation, St Dev $[d^{cd}(t)]$ of the corrosion depth as a function of time are defined as (Garbatov et al., 2007):

$$\text{Mean value } [d^{cd}(t)] = d_{\infty}[1-\exp(-(t-\tau_C)/\tau_t], \ t>\tau_C \quad (1)$$

$$\text{St Dev } [d^{cd}(t)] = a \operatorname{Ln}(t - \tau_C - b) - c], \ t>\tau_C \quad (2)$$

where a, b and c are coefficients.

The analysed ship hull structural system is assumed to be subjected to general corrosion degradation, where the coating life, τ_C = 5 years and transition life, τ_t = 7 for all structural components and the long-term corrosion thickness of any individual structural component are defined based on the corrosion margins as defined by the Classification Society Rules (BV, 2016) and implemented in the BV software (MARS2000, 2011). The effect of the spatial distribution of the corrosion degradation (Garbatov and Guedes Soares, 2017) and material changes due to degradation (Garbatov et al., 2014; Garbatov et al., 2016) are not considered in the present study.

2.4.4 Progressive collapse

Assessing the ship hull structural risk of an ageing multipurpose ship requires the development of an ultimate limit state function concerning the progressive ship hull structural collapse of the primary ship hull structure, where the reference is made to the midship section. The ship hull is considered to behave globally as a beam under transverse load subjected to still water and wave-induced effects.

The midship section scantling and the ultimate capacity is estimated using the progressive collapse method as stipulated by the Classification Society Rules. The 5% confidence level value of the ultimate bending moment, $M_U^{5\%}=M_U^c$ is assumed as a characteristic one, which respects the value estimated by MARS2000 (2011) software and additionally it is assumed that COV equals to 0.08, and it is fitted to the Lognormal probability density function, $f_{LN}(M_U)$ with a mean value, μ_{MU} and standard deviation, σ_{MU} as (Garbatov and Guedes Soares, 2016):

$$f_{LN}(M_U)=1/[M_U\,\sigma_{MU}\sqrt{(2\pi)}]\exp[-[Ln(M_U)-\mu_{MU}]/(2\sigma_{MU}^2)] \quad (3)$$

$$\sigma_{MU=}\sqrt{[\log n(COV^2+1)]} \quad (4)$$

$$\mu_{MU}\rightarrow F_{LN}^{-1}(0.05,\,\mu_{MU,}\,\sigma_{MU})=M_U^{5\%} \quad (5)$$

where F_{LN}^{-1} is the inverted log-normal cumulative distribution function. The probability density function of the ultimate bending moments in the hogging loading condition for both gross, $M_{U,\,gross}$ and net, $M_{U,\,net}$ ship hull scantling for each DMF are presented in Figure 6.

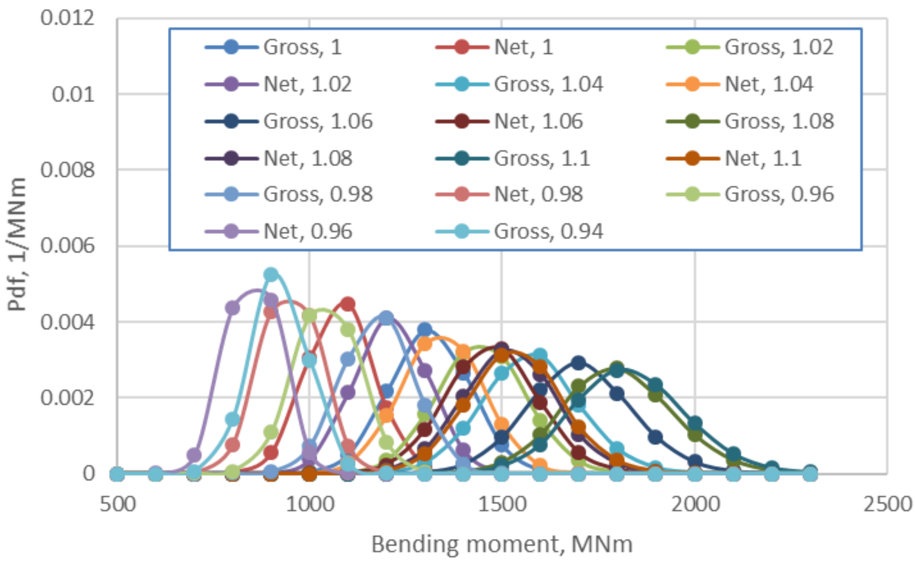

Figure 6 Pdf of gross and net ultimate bending moment as a function of DMF

2.4.5 Reliability estimate

The reliability of a ship hull structural system can be defined as the likelihood of maintaining its ability to fulfil the design purpose for some period. The objective is to estimate the reliability based on its ultimate strength when extreme loads act upon the ship hull structure subjected to corrosion degradation.

The probability of ship hull structural collapse is estimated here by using the first order reliability method, FORM and formally is defined as:

$$P_f(\mathbf{X})=P[g(\mathbf{X})\leq 0]=\int_{g(\mathbf{X})\leq 0} f_X(\mathbf{X})dx \tag{6}$$

where $f_X(\mathbf{X})$ Is the joint probability density function of the n basic stochastic variables, and $P_f(\mathbf{X})$ denotes the probability of failure. The n-dimensional integral is defined over the failure region.

The FORM methods provide a way of evaluating the probability of ship hull structural failure efficiently with a reasonably good accuracy, which is adequate for practical applications (Hasofer and Lind, 1974; Rackwitz and Fiessler, 1978; Ditlevsen, 1979).

The limit state function is defined as:

$$g(\mathbf{X}|t)=x_u M_u - x_{SW} M_{SW} - x_W x_S M_W \tag{7}$$

where M_U is the ultimate capacity with a model uncertainty factor x_U, which is assumed to be described by a Normal probability density function, N_{xU} (1.05, 0.1). M_W is the vertical wave-induced bending moment. The model uncertainty factor x_W accounts for the uncertainties in the linear response calculation, N_{xW} (1, 0.1) and x_S for the non-linear effects, N_{xS} (1, 0.1). M_{SW} is the still water bending moment with a model uncertainty factor x_{SW}, Nx_{SW} (1, 0.1) (Silva et al., 2014).

The reliability index for the gross and net designs can be related assuming that the gross ship hull structural design respects the non-corroded ship hull structure up to the moment when the corrosion protection fails, and the net design respects the end of the service life when the structure is already corroded, and no maintenance actions took place. The service life of the ship hull structural system is considered as τ_S=25 years, the coating life.

The corrosion degradation is assumed as a non-linear time-dependent process following the time-dependent non-linear corrosion degradation model as developed in (Guedes Soares and Garbatov, 1999) and the time-variant reliability index, where $t\in[0, \tau_S]$ is defined as:

$$\beta(t)= \beta_{gross} -[\beta_{gross} - \beta_{net}][1-[\exp[-[(t-\tau_{C,\,ship})/\tau_{t,\,ship}]]]],\ t>\tau_C, \tag{8}$$

$$\beta(t)= \beta_{gross},\ t<\tau_C \tag{9}$$

then, the time-variant probability of failure, $P_f(t)$ may be estimated, and it is presented as a function of time, conditional to DMFs in Figure 7.

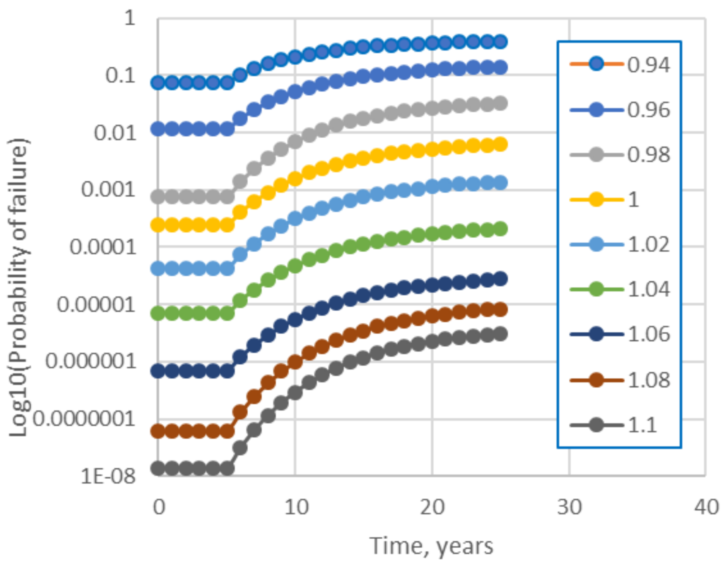

Figure 7 Time-variant probability of failure as a function of time, DMFs

2.5 Risk assessment

The risk analysis accounts for the uncertainties associated with the progressive collapse of the ship hull system subjected to corrosion degradation, and it is defined as the potential for losses resulting from the structural failure.

The risk is based on an identified failure scenario, considered here as a progressive collapse of a ship hull. The risk is measured as a pair of the probability of occurrence of the progressive collapse and the consequences associated with that. The risk is evaluated as a product of the likelihood of the occurrence and the impact of an accident that may happen during a period, which is assumed as the service life of the ship, τ_S:

$$\text{Risk}(\text{Consequence}|\tau_S)=\text{Likelihood}(\text{Event}|\tau_S)\ \text{Impact}(\text{Consequence}|\text{Event}) \quad (10)$$

The likelihood can be expressed as a probability of failure, which is described as a numeric value and the consequences are presented in a monetary value:

$$\text{Risk}(t)=\Sigma_j P_{f,j}(P[g(\mathbf{X}_{1,j}|t)\leq 0])\ C_{f,j}(\mathbf{X}_{2,j}|t) \quad (11)$$

where $P_{f,j}(P[g(\mathbf{X}_{1,j}|t)\leq 0])$ is the probability of failure, $C_{f,j}(\mathbf{X}_2|t)$ is the impact, the consequence cost of failure, $\mathbf{X}_1$ and $\mathbf{X}_2$ are the vectors of parameters involved in the probability of failure and consequence analyses and $t\in[0, \tau_S]$.

The probability of failure is derived based on the assumed limit state, employing the FORM, associated with the progressive collapse of the ship hull structural system subjected to corrosion degradation. The consequence costs included in the present risk analysis cover the design structural measures, loss of cargo, loss of the ship, accidental spill and loss of human life.

The ship's optimal safety level is assessed by performing a cost-benefit analysis, where the objective is to establish an optimal safety and reliability level by using the risk control option in redesigning the initial midship section scantlings.

The cost-benefit analysis of the ship structural system is performed based on the total expected risk, Risk_{total} $(t^n|\text{DMF}, \beta)$, which is a product of the probability of failure and consequence cost, defined as:

$$Risk_{total}(t^n|DMF, \beta)=Risk_{Pf}(t^n|DMF, \beta)+Risk_{me}(DMF, \beta) \quad (12)$$

where $Risk_{Pf}(t^n|DMF, \beta)$ is the risk associated with the ship structural failure and its consequence costs and $Risk_{me}(DMF, \beta)$ is the cost of the implemented ship structural safety measures, which is used here as a risk estimate of the structural safety measure. Both terms of Eqn (28) are defined as a function of the reliability index, β, as this, in return, influences the estimate of the safety target beta reliability level, β_t.

At this stage a decision can be made in defining the part of the entire cost associated with the loss of the ship, cargo, accidental spill and human life related to the minimisation of on the total expected risk, $Risk_{Pf}(t^n|DMF, \beta)$. The multiple cost function is transformed into one, where the single converted cost, $C_W(\mathbf{X})$ is defined as:

$$C_W(\mathbf{X})=\Sigma f_i C_i(\mathbf{X}) \quad (13)$$

where **X** is the vector of the cost descriptors and f_i is the partial factor. The partial factors are defined based on the subjective preferences of the decision maker.

The risk associated with the ship hull structural collapse is estimated over the service life of the ship, accounting for the probability of failure and the discount rate of γ as a function of DMF, β and time as:

$$C_{Pf}(t^n|DMF, \beta)=\Sigma_j^n \{P_f(t_j|DMF, \beta)\ [f_1 C_s(t_j|DMF, \beta) + f_2 C_c+ f_3 C_d+ f_4 C_v]\ e^{-\gamma tj}\} \quad (14)$$

where $P_f(t_j|DMF, \beta)$ is the probability of failure, $C_s(t_j|DMF, \beta)$ is the cost of the ship in the year t_j, C_c is the cost associated with the loss of cargo, C_d is the cost of the accidental spill, C_v is the cost associated with the loss of human life.

The cost of the ship at any time t_j is a function of the initial cost of the ship at $t_o=0$, and the scraping cost at $t_n= \tau_S^{th}$ year, accounting for corrosion degradation, estimated as:

$$C_s(t_j|DMF, \beta)=C_s(t_o|DMF, \beta)-[C_s(t_o|DMF, \beta)-C_s(t_n|DMF, \beta)][1-[\ exp[-[(t_j-\tau_{C, ship})/\tau_{t, ship}]]]],\ t_j>\tau_C \quad (15)$$

$$C_s(t_j|DMF, \beta)=C_s(t_o|DMF, \beta),\ t<\tau_C \quad (16)$$

where $C_s(t_o|DMF, \beta)$ is the initial cost of the ship, $C_s(t_{n|}DMF, \beta)$ is the scrapping value of the ship and t_j is the year of the operation, $t_j \in [0, \tau_S]$.

The resale (or scrap) value of the ship, at $t_j=t_n$ is estimated as:

$$C_n(t_n|DMF, \beta)=LW(t_n|DMF, \beta)\ C_{scrap} \quad (17)$$

where LW $(t_n|DMF, \beta)$ is the lightweight of the ship accounting for design modification and corrosion degradation and C_{scrap} is the resale (or scrap) value.

The cost of implementing a safety measure accounts for the redesign of the ship hull structure, including the cost of material and labour. Depending on the level of the design modification, DMF, the cost of the structural redesign, $C_{me}(DMF, \beta)$ may result in a positive or negative value respectively:

$$C_{me}(DMF, \beta)=\Delta W_{steel}(DMF, \beta)\ C_{steel}+ C_{labor}(DMF, \beta) \quad (18)$$

where $\Delta W_{steel}(DMF, \beta) =(DMF-1)\cdot W_{steel}$ is the weight of steel because of the design modifications, tons, DMF is the design modification factor ratio, which is also associated with the reliability level, β, W_{steel} is the weight of the steel related to the ship hull structural design, tons, C_{steel} is the cost of steel and C_{labor} is the labour cost of the constructing a ΔW_{steel} (DMF, β) ton structure.

The cost associated with the loss of cargo, C_c is estimated by considering that a part of the total amount of cargo of the ship, P_{cargo} is lost in the case of ship hull structural failure, defined as:

$$C_c=C_{cargo}\cdot f_{cargo}\cdot P_{cargo} \tag{19}$$

where C_{cargo} is the cost of a ton of cargo and f_{cargo}, is the assumed partial factor of the cargo lost in the case of structural failure.

In the case of ship hull structural failure, a part of the total amount of oil and fuel may be spilt. f_{spill} is the considered partial factor of spill, $P_{s,p}$ is the probability that the oil and fuel reach the shoreline (Sørgard et al., 1999). In the case of an accidental oil spill, the weight of spill that needs to be cleaned up is defined as $f_{spill}\cdot P_{sl}\cdot W_{oil\ and\ fuel,}$ and the cost, C_d associated with that is:

$$C_d=f_{spill}\cdot P_{sl}\cdot CATS\cdot W_{oil\ and\ fuel} \tag{20}$$

where CATS·is the cost of one ton accidentally spilt oil and fuel that needs to be cleaned.

The implied cost of averting the fatality, ICAF, used in the risk model is obtained from the average of OCDE countries (OCDE, 2014). The loss of human life is accounted for by including the ICAF as used in a study performed in (Horte et al., 2007):

$$C_v=n_{crew}\cdot f_{crew}\cdot ICAF \tag{21}$$

where n_{crew} is the number of crew members, f_{crew} is the probability of loss of the life of a crew member.

2.6 Benefit decision making

The risk management of ship hull structural system requires the optimisation of the available capacity in supporting the design functionality of the ship subjected to corrosion degradation. It also requires a definition of the acceptable risk level and alternative options for decision making. The objective is to reduce the risk to an acceptable level.

The risk of ship hull structural collapse and design structural safety measure is estimated as a function of the structural DMF. The target risk or reliability levels are used for developing design procedures for ship structures. The selected reliability level determines the probability of failure of ship hull structural system and the cost consequences of that. Three methods are normally used to select the target reliability level: (1) agreeing upon a reasonable level in the case of a novel structural system without prior history; (2) calibrating the beta reliability level implied in currently successfully used design codes; (3) choosing the target reliability level that minimizes a total consequence cost over the service life of the structural system in the case of design in which the failure results in economic losses and consequences.

The range of target beta reliability index, β_t at the $t^n = \tau_S{}^{th}$ year of the service life of the ship hull structural system may vary between 1.5 and 5. The target beta reliability index is estimated by minimising the total risk associated with the probability of failure and consequence cost, defined as a function of the beta reliability index. The optimum/target reliability index is shown in Figure 8, where β_t = 4.296, corresponding to the minimum of the curve of the total risk, $Risk_{total}(t^n|DMF, \beta)$.

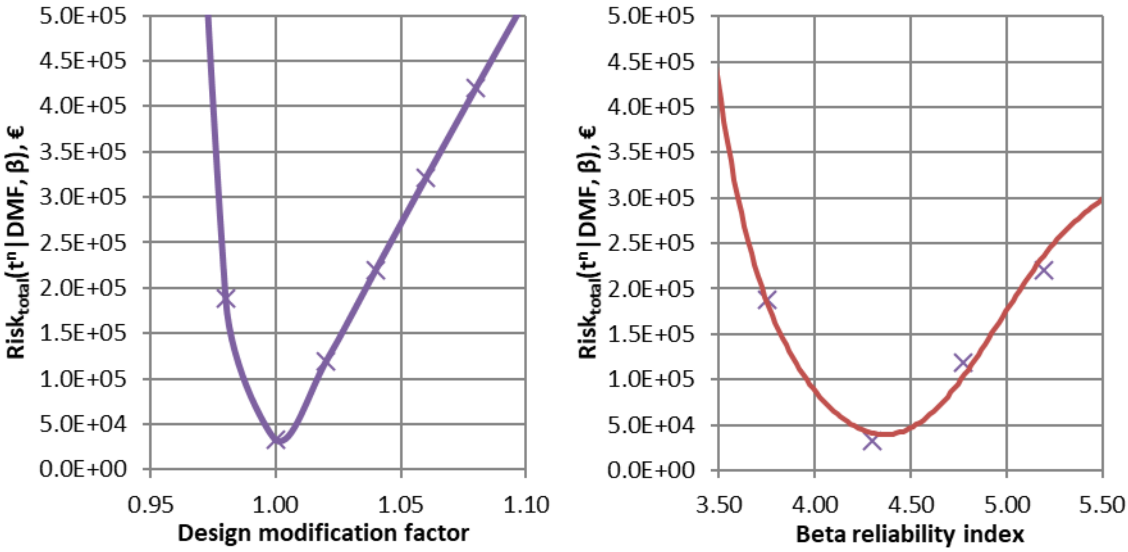

Figure 8 Estimation of target structural reliability index

The impact of structural degradation with age, namely corrosion degradation is reflected by increasing the probability of failure as a function of time.

A sensitivity analysis using a risk-based framework for the conceptual ship design of a multi-purpose vessel, evaluating the impact of three types of design modification factors related to ship design, structural scantling and cost descriptors (Garbatov and Sisci, 2018) demonstrated that the structural redesign, the length and the block coefficient of the ship have the most significative impact on the reliability and structural collapse consequence cost.

Partial safety factors can be used in the preliminary ship design, conditioned by the imposed target reliability index, which represents an acceptable risk level and minimum cost (Garbatov and Sisci, 2018). The time-dependent reliability and risk may be a base to set up a maintenance and inspection plan conditional on the acceptable reliability and risk levels (Garbatov and Guedes Soares, 1998).

2.7 Risk-centred maintenance

Planning of ship hull structural maintenance in the past has been done based on structural reliability approaches (Guedes Soares and Garbatov, 1998) involving models that represent the time deterioration as proposed in (Garbatov et al., 2007).

It is evident that operations and maintenance, represent a high-cost item in ship hull structural system during the service life. The approach employed here uses a probabilistic model of time to fail, which is used as a basis for maintenance decisions. The failure of the ship hull structural system is defined by the Weibull probabilistic model, which represents the failure rates in operation as described in (Moubray, 1997; Rausand, 1998)

The analysis is used to address important issues of the condition-based maintenance action and structural repair. This approach covers the analysis of the severity of structural degradation, the costs of preventive and corrective maintenance, optimal replacement interval, optimal replacement age as has been reported in (Garbatov and Guedes Soares, 2001, 2009)

2.7.1 Degradation tolerance

The acceptable risk levels depend on different factors as reported in (Moan, 1998) and the failure cause and mode may result in redundant structures in $P_{f,l}$=4.17 10^{-5} (β_l=3.93) for a low degradation tolerance, $P_{f,m}$=1.02 10^{-4} (β_m =3.71) for a moderate degradation tolerance, $P_{f,h}$=1.92 10^{-4} (β_h =3.55) for a high degradation tolerance and $P_{f,e}$=3.14 10^{-4} (β_e =3.42) for an extreme degradation tolerance (see Figure 9). Using these acceptable beta reliability levels, the analysed ship hull structural system, subjected to buckling and corrosion degradation has a mean time of failure, $MTTF_i$, of 8, 12, 16 and 20 years.

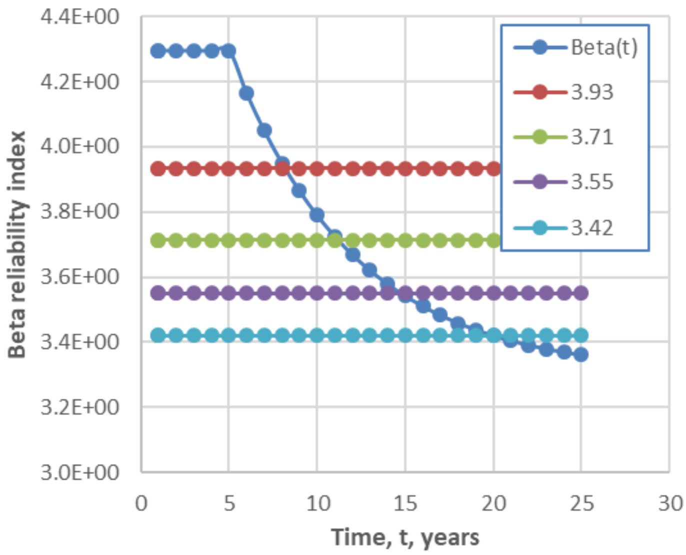

Figure 9 Time-dependent reliability and degradation tolerance levels

The probability of failure of ship hull structural system is modelled by a Weibull probability function, where the three-parameter Weibull distribution is defined by the shape parameter, β_W, location parameter γ_W and scale parameter, η_W where β_W and η_W are greater than 0.

The reliability estimates for the different levels of degradation tolerance levels defined here as low, moderate, high and extreme degradation tolerance is given in Figure 10, where β_{low}=2.16, η_{low}=6.21 years, γ_{low}=5 years, $\beta_{moderate}$=2.16, $\eta_{moderate}$=7.9 years, $\gamma_{moderate}$=5years, β_{high}=2.16, η_{high}=11.29 years, γ_{high}=5years, $\beta_{extreme}$=2.16, $\eta_{extreme}$=20.33 years, $\gamma_{extreme}$=5years in the case of DMF=1 (see Figure 10).

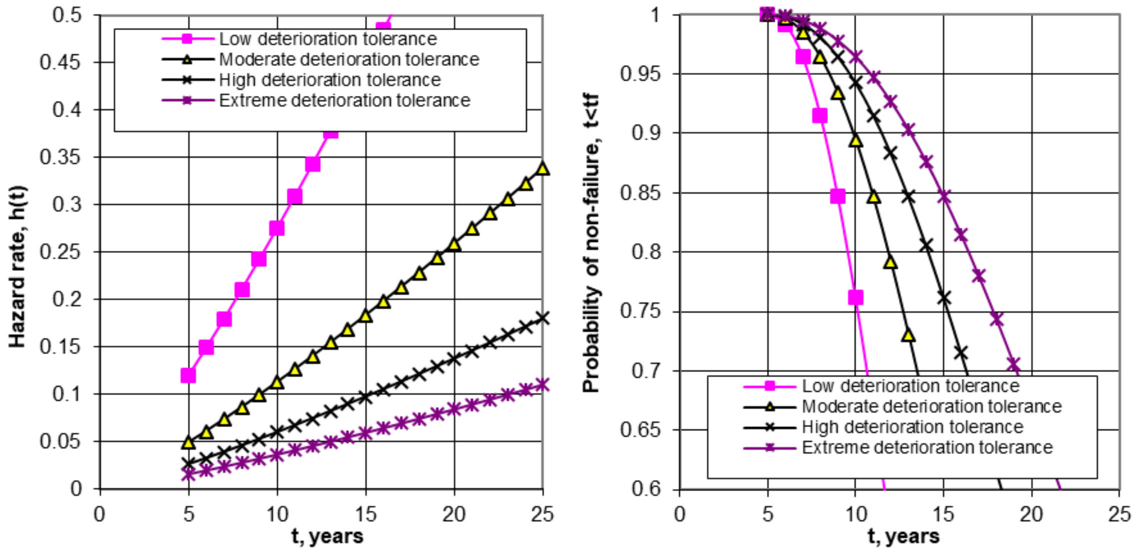

Figure 10 Hazard rate, left and reliability (right) of ship hull structural system as a function of degradation tolerance levels

2.7.2 Cost of maintenance

A major part of the operating expenditures are the maintenance costs during the vessel's lifecycle. In general, this cost contributes to 25%-35% of the total operating expenditures, OPEX (Turan et al., 2009). It depends on many factors, including the quality of the work delivered by the shipyard, the geographical location of the vessel, its access to periodic maintenance, operational profile, etc.

It is important to create a procedure for analysing the potential failure by classifying the severity of the effect of failures on the structure, which is widely used in many industries during various phases of the service life (DoD, 1984; Kececioglu, 1991; Langford, 1995). A failure mode may be defined as how failure is observed, and it generally describes how the failure occurs. Tools used in the design stage for identifying failures and determining their consequences are risk priority numbers, occurrence/severity matrix, risk ranking tables and criticality analysis.

For the current work, these methods are adapted to identify the age of the structure of the first repair and the interval of preventive repairs. The input is the cost of a preventive repair, C_p and the cost of a repair after failure, C_f, which are assumed here for four hypothetical levels: low, moderate, high and extreme repair consequences as an example as can be seen in Figure 11.

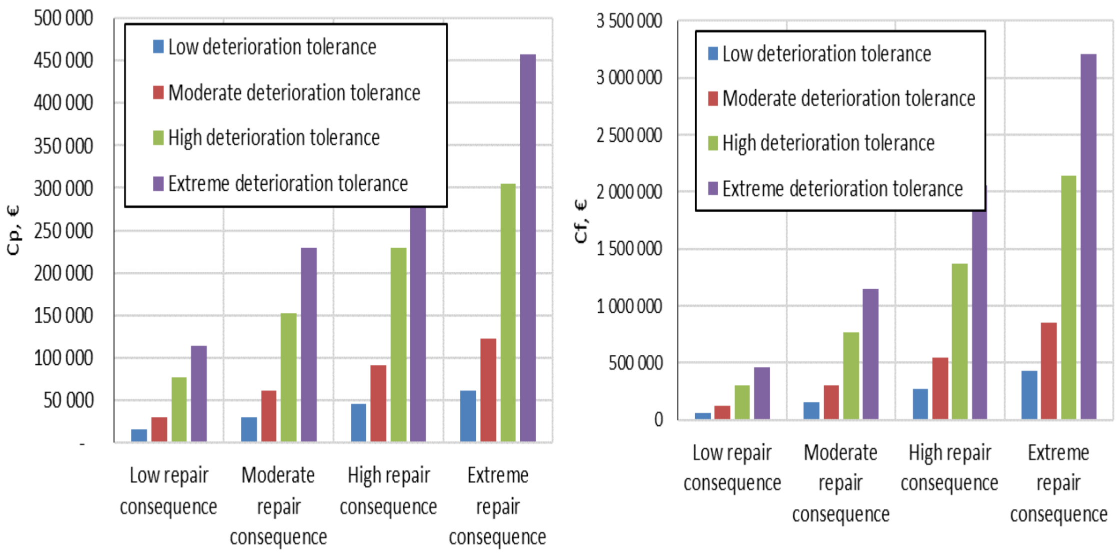

Figure 11 Cost of preventive repair, C_p (left) and failure repair, C_f (right)

2.7.3 Repair interval

Ship hull structural systems are subjected to corrosion degradation and buckling, and when a failure occurs, the structural system needs to be repaired. Since the failure is not expected, then it may be assumed that the failure repair is costlier than the one in an earlier repair. To reduce the failure consequences, repair can be scheduled to occur at specified intervals. However, a balance is required between the amount spent on the repair and their resulting benefits.

The repair policy is such so that preventive repair occurs at fixed intervals of time and repair due failure occurs whenever is necessary. The objective is to determine an optimal interval between the preventive repairs and to minimise the total expected cost of repairing the ship hull structural system per unit time.

The total cost of a repair before failure is defined as C_p, while C_{fi} is the total cost of repair due to failure and f(t) is the probability density function of the ship hull structural system failure as a function of time. The repair policy is to perform the repair at constant intervals of time, t_p, years, irrespective of the age of the ship hull structural system, and repair due to failure as many times as required in the interval $t \in (0, t_p)$.

To determine the optimal interval between the preventive repair, the total expected repair cost per unit time is minimised. The total expected cost per unit time for the preventive repair at the intervals of a length, t_p, years, denoted $C_{RI}(t_p)$ equals the total expected cost in the interval $(0, t_p)$ divided by the length of the time interval, t_p (Garbatov and Guedes Soares, 2009):

$$C(t_p)=[C_p+C_fH(t_p)]/t_p \qquad (22)$$

where $H(t_p)$ is the expected number of failures in the interval $t \in (0, t_p)$. To determine $H(t_p)$, the renewal theory approach is to be applied. The optimal preventive repair intervals are defined as the minimum of $C(t_p)$, as shown in Figure 12.

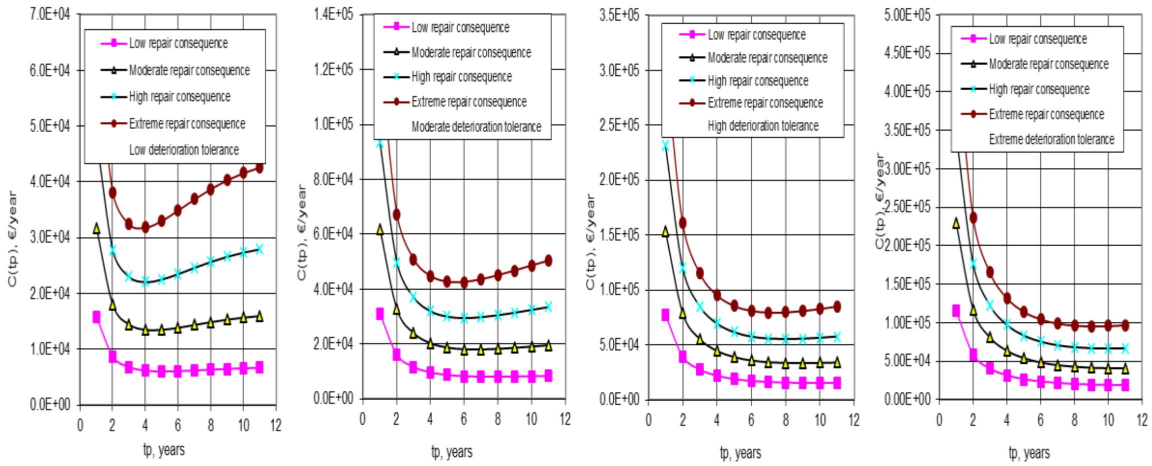

Figure 12 Optimal preventive repair interval, t_p, years

2.7.4 Repair age

This problem is similar to the one presented before, except that instead of repairing at fixed intervals, with the possibility of performing a repair shortly after the repair due to failure, the time at which the repair occurs depends on the age of the structure. When a failure occurs, repair is made. When this happens, the clock time is reset to zero, and the next repair occurs only when the structure has been in use for a specified period.

The problem is to balance the cost of the repair against the benefits, and this is done by determining the optimal repair age to minimise the total expected cost due to repair per unit time.

The repair policy is to perform a preventive repair when the structure has reached a specified age, T_p, and repair due to failure when necessary. The objective is to determine the optimal repair age, T_p to minimise the total expected repair cost per unit time.

There are two possible cycles of operation: one cycle being determined by the ship hull structural system reaching its planned repair age, T_p, and other being determined by the ship hull structural system ceasing to operate due to a failure occurring before the planned time for repair.

The total expected cost of repair per unit time is defined as $C(t_p)$ (Garbatov and Guedes Soares, 2009). The total expected repair cost per cycle equals the cost of a cycle before failure, C_p times the probability of a cycle, $R(t_p)$ plus the cost of a failure cycle, C_f times the probability of failure cycle, $[1-R(t_p)]$ divided to the expected length of the cycle, T_p. The mean time to failure is defined as $M(t)=\int t_f(t)/[1-R(t_p)]dt$ and therefore, the total cost results in:

$$C(t_p)=[C_pR(t_p)+C_f[1-R(t_p)]]/[t_p\, R(t_p)+ \int t\, f(t)dt] \tag{23}$$

where $R(t)=1-F(t)$, $F(t)$ is the cumulative distribution function of the ship hull structural system failure.

The optimal preventive repair age is defined as $T_p=t_p(C_{min})+\gamma$, and the expected cost of repair per unit time as a function of t_p is shown in Figure 13, and the positioning factor, which is associated with the coating life is assumed here as γ=5years.

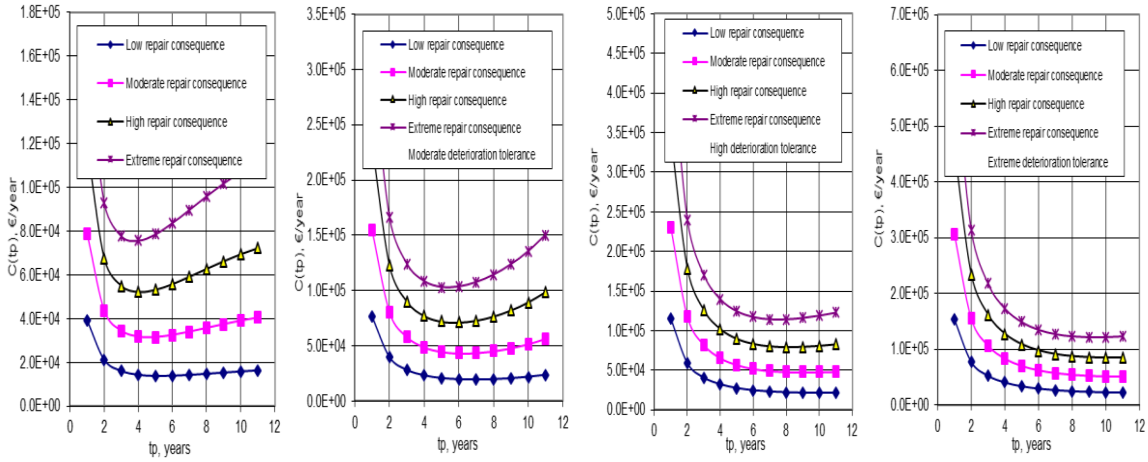

Figure 13 Optimal preventive repair age, $T_p=t_p(C_{min})+\gamma$, years

In some cases, due to difficulties in financing or the desire to get maximum throughput or utilisation of ship hull structural system, the repair policy applied may be one that minimizes the total downtime per unit time or, equivalently, maximizes availability (Garbatov and Guedes Soares, 2009).

3 Maintenance decision

The decision making is performed defining $C_{ij}(\mathbf{X})$ related to the cost associated with the low, moderate, high and extreme degradation tolerances conditional to the level of repair consequences. The weight sum method converts the multiple degradation tolerances into a single cost function for any repair consequence level, $C_{W,j}$ defined as:

$$C_{W,j}(\mathbf{X})=\Sigma_i w_{ij} C_{ij}(\mathbf{X}) \tag{24}$$

where $\mathbf{X}$ is the vector of the repair cost descriptors, and w_{ij} are the weighting factors, $\Sigma_i w_{ij}=1$ and $w_{ij}\in[0, 1]$. The weighting factors may be defined based on the subjective preferences of the decision maker, and here they are assumed to be estimated as $w_{ij}=(MTTF_i-MTTF_{i-1})/\Sigma MTTF_i$ where $MTTF_i$ represents the mean time to failure in the case of the low, moderate, high and extreme degradation tolerance respectively.

The goal is to define the optimal ship hull structural system age for repair, T_p (see Figure 14, left) and preventive repair interval, t_p (see Figure 14, right) by minimising the converted repair cost of the ship hull structural system conditional of the repair consequence level.

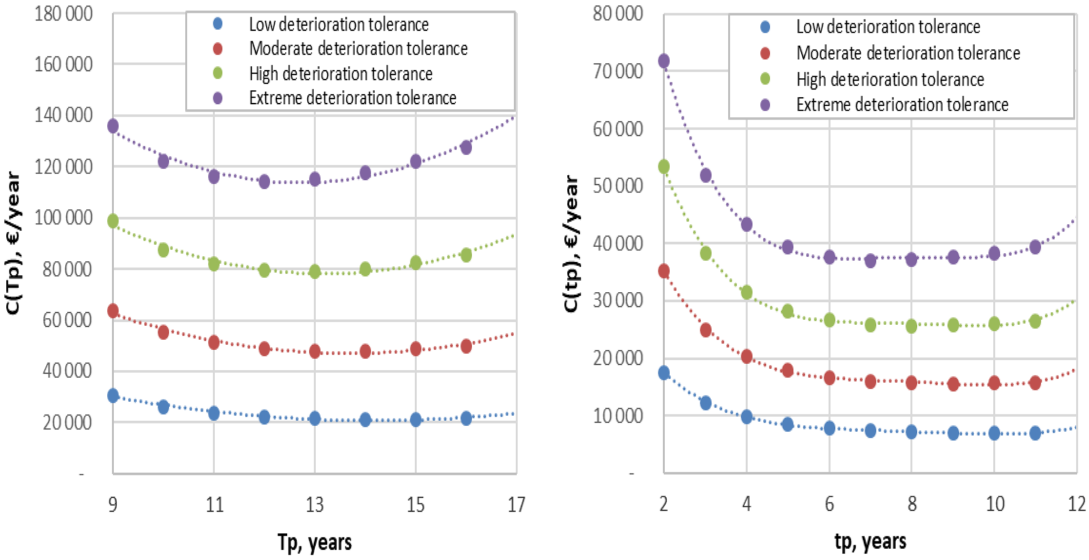

Figure 14 Preventive repair age (left) and repair interval (right)

The preventive repair age and repair interval for the studied repair consequence levels are presented in Table 1.

Table 1 Maintenance descriptors

	Repair consequence			
	Low	Moderate	High	Extreme
Repair age, years	14	13	13	12
Repair interval, years	11	9	8	7

The minimal repair can be performed as minor maintenance that returns the structural system to the same structural capacity state that it was just before the minor maintenance. The general repair improves the structural system state, and the renewal repair completely returns the structural system to the statistically as-good-as-new condition. The concept of virtual age is introduced to model the structural system maintenance.

The real age (run-time) of the structural system is presented on the vertical axis, and the virtual age is on the horizontal axis in Figure 15. At the first repair, when the structural system age is 16 years, in the case of a low repair consequence, the structural system becomes of age 14 years, after the maintenance action. Once the structural system has operated for a further period of 11 years to bring its running age for 14 + 11 years, another maintenance action occurs that brings the structural system in a virtual age to 25 years, etc. The acceptable operational regime and the boundary of the preventive repair for different levels of deterioration tolerance are also shown in Figure 15.

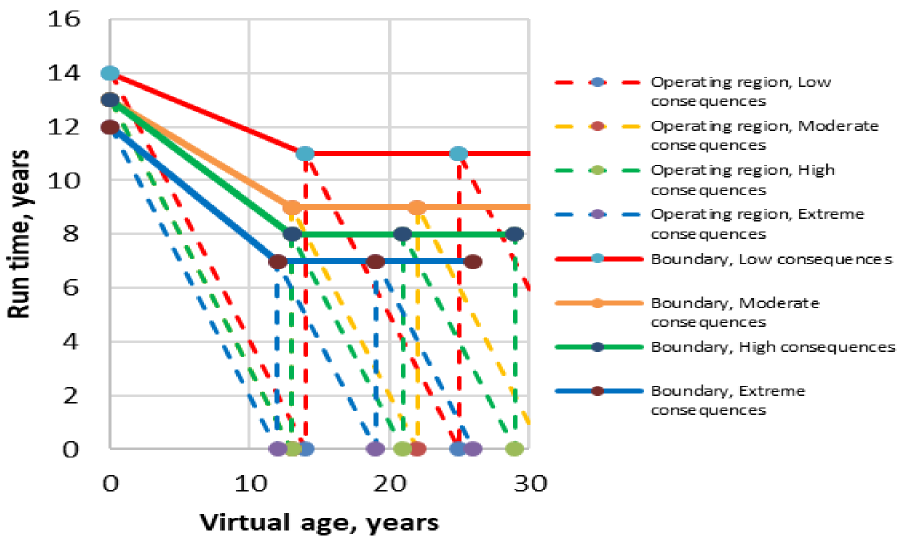

Figure 15 Operating regions and boundaries of preventive repair

The issue addressed here is to be taken into consideration when there is a need for a maintenance intervention and to define what kind of repair action should be taken: minimal repair, general repair or complete renewal. To address this issue, the repair limit concept through the cost is employed.

If the cost estimate of the preventive maintenance is between zero and the limit of 10% of the residual cost of steel structural system, then a minimal repair is made. If the cost is between 10% and the cost boundary, then a general repair is made. The boundary cost is assumed to be the cost of the residual steel structural system at the moment of the maintenance action (see Figure 16, right).

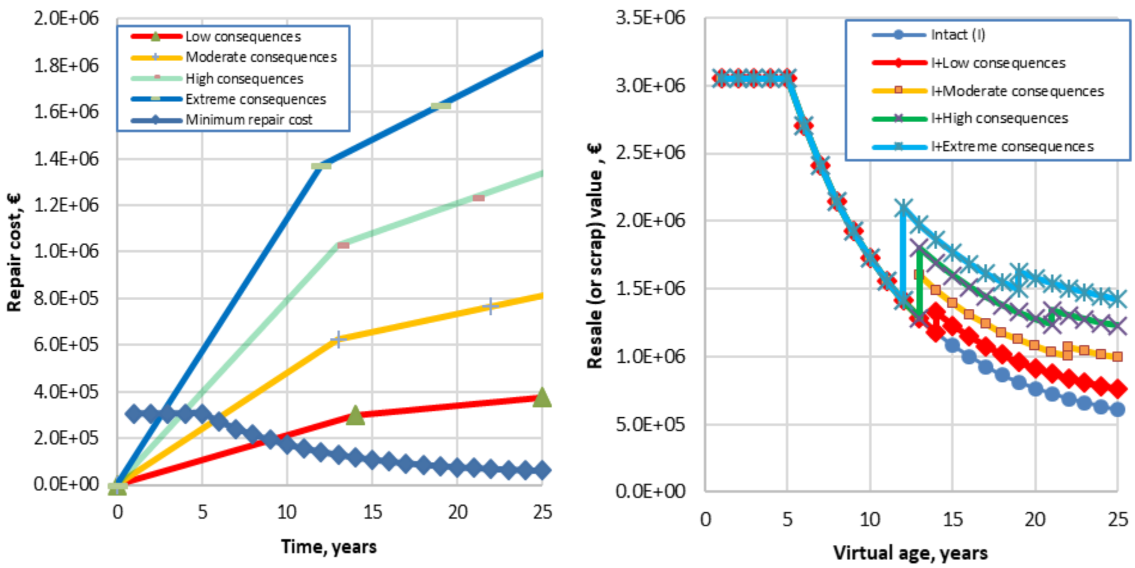

Figure 16 Cumulative repair cost (left) and resale (or scrap) value (right)

The cost associated with the first maintenance intervention at the 14th year, is more than 10% of the resale (or scrap) value, in the case of a low repair consequence, so a general repair instead of a minimal repair should be made, and consequently, the structural system capacity is improved when compared to its condition prior to repair commencing.

The cost associated with the planned preventive maintenance actions are shown in Figure 16, left, and how the residual (scrapping) cost of steel structural system is distributed during the service time, accounting for the maintenance planning is given in Figure 16, right.

It can be seen from Figure 16 that the repair cost, keeping the capacity of the structural system on the same level, in the case of lower repair consequence, is invested later and with less frequency than the other repair consequence levels. In the case of the lower repair consequence, the scrapping cost will be less at the end-of-service-life, which can be explained by the less resting weight of steel.

The output of this analysis provides information that can be used by the designer for decision making leading to redesign of the initial solution in optimising the repair cost needed to be invested during the service life of the ship.

It has to be pointed out that the present analysis is performed based on the assumption that the structural steel system, ship hull, will start the service life in the condition of the gross design and will arrive to the end of the service life at the net design, where the structural components will be degraded according to the corrosion adds as prescribed by CSR and the coating life is assumed to be 5 years and the transition life of 7 years. However, a much more severe corrosion environment may be seen during the service life, and the developed risk-based framework of the ship and structural design is capable of accounting for it.

4 Conclusions

This work developed a risk-based framework for the ship and structural design to be used in the conceptual ship design stage accounting for maintenance planning, where different approaches are being applied to address the early design stage of ship and ship structures. Risk covered here is associated with the ship hull structural failure, accidental spills, loss of cargo, loss of ship and crew members during the service life. The structural failure accounted for structural corrosion degradation in conjunction with the ship hull strength. Some of the employed methods are envisaged to be approximate as they are based on the limited data available during the early design stage. The risk-cantered maintenance methodology was applied in determining the maintenance planning of a ship hull structural system in its operating context for four hypothetical repair consequences. The concept of the virtual age was introduced to model the ship hull structural system maintenance, where the boundary of the preventive repair on different deterioration tolerance levels is established. The boundary cost of performing a general repair or renewable repair is established based on the resale (or scrap) value of steel structural system. The developed risk-based framework for the ship and ship structural design is capable of analysing different types of ships operating in different environmental conditions. The present risk-based framework is developed to be used in the early stage of ship design where limited data is available and at the same time permits to project a specific maintenance planning allowing a measure related to the future maintenance and repair to be considered making the design solution more economical leading to a less operational cost and satisfying the existing requirements for a safety transportation.

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