Generic risk models for ship inspection based on readily available information

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ABSTRACT: Inspection and survey provide the lines of defence for eliminating high risk ships from the world fleet. Administration and classification societies are targeting ships for inspection/survey mainly based on parameters that are correlated to the condition of ship, such as ship type, age, size, flag, and related performance monitored in the past. The aim of the EU funded research project SAFEPEC is to improve the targeting process by developing a methodology for identifying ships by means of a risk analysis. For this methodology the following elements are considered:

- Causes for degradation
- Vulnerability of the ship / system to degradation
- Consequences for the ship /system
- Inspection.

The main challenge for this development lies in balancing on the one side the objective of evaluating a larger group of ships, and on the other side the objective of assessing the risk accurately for each ship based on the available information, i.e. using exclusively data that is generally available.

This paper outlines the developed models for the first two elements, causes and vulnerability. In the context of inspection/survey only causes are relevant that could be detected by inspection. Therefore, for the cause model the focus was put on the main time dependent degeneration processes corrosion and fatigue, and, exemplarily for on-board systems, on life-saving appliances. The vulnerability module estimates the effect of these “causes” on the probability of failure, for which representative limit state functions were developed.

KEYWORDS: risk-based inspection; corrosion; fatigue; life-saving appliances

1 INTRODUCTION

Survey and inspection aim at identifying the need for maintenance and repair. In the shipping industry two types of survey and inspection can be distinguished, a) by owner/management in order to achieve high system availability and to keep the ship in compliance with requirements, and b) by Administration/Classification Society for ensuring that ships meet international regulations with respect to safety, security and environment as well as crew members’ living and working conditions, and Class rules. This aims at eliminating the operation of high risk/sub-standard ships.

Inspection/survey of ships is difficult and costly because of their complexity. Therefore all stakeholders are searching for ways to increase the efficiency.

Risk-based inspection (RBI) methodologies have the potential for enhancing the efficiency and therefore are increasingly used to replace traditional empirical based inspection planning in order to focus inspection efforts on the system elements that control the risk.

When developing RBI tools stakeholder related requirements need to be considered. For the owner/management the focus is on selecting the systems/ compartments to be inspected whereas for Administration it is on selecting the “right” ships for inspection.

The aim of the EU research project SAFEPEC is to develop a methodology for identifying ships for inspection and survey by estimating the associated risk, i.e. a risk-based methodology for targeting ships.

1.1 Risk-Based Inspection

The risk-based inspection framework enables operators and inspectors to be more focused and effective, for instance, by identifying structure inspection intervals based on both the structure failure consequence and probability (Ren et al., 2014). RBI methods combine data based on experience with various techniques in order to determine the frequency and purpose of each inspection.

SAFEPEC model utilises readily available information which is limited with respect to ship details, e.g. construction details, inspection results, maintenance, and therefore the models need to be physically-based generic models which are formulated in function of available indicators without detailed knowledge of the ship under consideration.

1.2 Generic Risk Model

The elements of the generic risk model (Cause, Vulnerability, Consequence and Inspection modules) are illustrated in Figure 1.

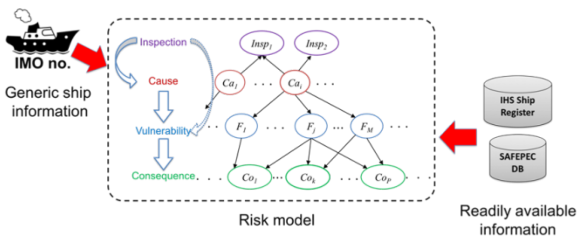

Figure 1. Structure of generic risk model

The quantification of model parameters is based on the ship's IMO number which gives access to ship particulars, e.g. ship type, age, size, and other information like flag State, Class, yard, owner and management. The elements of the risk model are interlinked through the overall risk assessment framework, which can be summarised through the following equation:

$$\text{Risk} = \sum_i \underbrace{\Pr(Ca_i)}_{\text{Cause}} \sum_j \underbrace{\Pr(F_j|Ca_i)}_{\text{Vulnerability}} \sum_k \underbrace{U(Co_k)\,P(Co_k|F_j)}_{\text{Consequence}} \qquad (1)$$

The 'Cause module' describes the sequences leading to causes as well as their probability. The 'Vulnerability module' evaluates the failure probabilities with various failure modes conditional on the causes. The different failure modes of a ship can lead to a multitude of consequences which are quantified by the 'Consequence module'. The 'Inspection module' takes into account the information obtained from inspections to update the probability of cause and eventually the risk of a ship by Bayesian updating.

The 'Cause module' and the 'Vulnerability module' are explained in more detail in the following.

2 CAUSE MODULE

The 'Cause module' considers the basic time dependent structural deterioration by corrosion and fatigue related fracture, and elements of life-saving appliances (lifeboat, liferaft) exemplary for on-board equipment.

2.1 Corrosion

Corrosion of ship structure is influenced by many parameters, e.g. coating type and quality (application, surface preparation), corrosivity of the product (cargo, fuel …), inspection and maintenance strategies and environmental conditions.

The basic idea is to develop a model that estimates the corrosion depth for a location on a vessel using only readily data available, e.g in public data bases. To meet this target three elements are required:

I. Coating lifetime model
II. Corrosion model
III. Parameters influencing the coating lifetime and the corrosion process

The model distinguishes two parts: coating life and corrosion rate.

Coating life is an important factor when estimating corrosion material wastage. Coating condition and extent of damaged coating is in focus of inspection and survey. For instance, the frequency of visual inspection depends on coating condition. The 'Cause module' considers both effects, i.e. estimating the area with coating breakdown and coating life, using readily available models for estimating degradation process for coating and corrosion.

For areal coating degradation a simple exponential function is specified based on the work published by Melchers and Jiang (2006):

$$A_{DamCoating}(t) = a_{CT} \cdot e^{b_{CT} \cdot t} \qquad (2)$$

The parameters a_{CT} and b_{CT} were determined by means of publically available information on coating life and corrosion and assuming that coating life is equivalent to 10% of areal loss of coating. Figure 2 shows the time dependent process of coating degradation estimated with this model for inner bottom and bulkhead of water ballast tank.

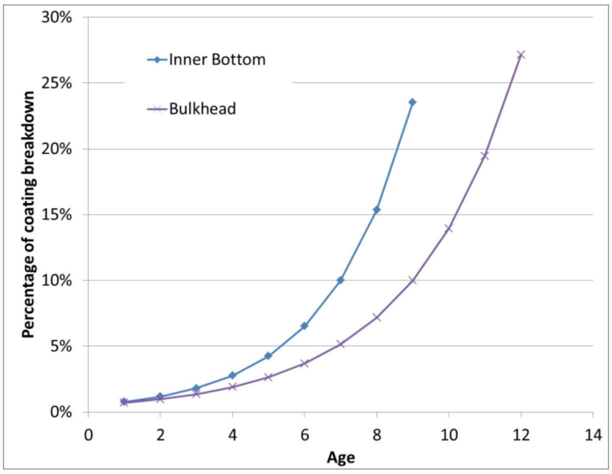

Figure 2. Estimation of coating breakdown area for structural areas in water ballast tank

The authors like to point out that the available coating life data is unsatisfactory because no direct measurement data on coating life and extent of coating breakdown is available, but only recursively determined data from corrosion thickness measurements (e.g. Sone et al., 2003; Yamamoto & Ikegami, 1998).

As a consequence of this lack of data coating life for different structural areas was estimated on the basis of published information on measurements (e.g. Sone et al., 2003) and expert judgement considering information on corrosion allowance and coating requirements in current rules as well as inspection/survey requirements. This approach is deemed appropriate considering the objectives of SAFEPEC.

Coating life is estimated based on this process for different structural areas/surfaces as specified in Figure 3. For instance, the ship side shell has two surfaces exterior and interior with different coating life. Additionally, effects that increase or reduce coating life were considered via parameters like operational area of vessel, cargo (abrasive/non-abrasive).

Corrosion starts after coating life expires. Generalised models exist for predicting material wastage without addressing particular form of corrosion, for instance by Southwell et al. (1979), Yamamoto (1997), Melchers & Ahammed (1998), Soares & Garbatov (1999). All these models have their pros and cons with respect to approximating corrosion for selected ship types and locations. Here the model by Yamamoto (1997) was chosen, which was also used when developing IACS CSR[1]

$$z(\tau) = a_{Corr} \cdot \tau^{b_{Corr}} \qquad (3)$$

with z the wear in terms of mm of plate thickness, a_{Corr} a constant governing the characteristics of corrosion growth, b_{Corr} a constant characterising the slope of the function z and time τ, i.e. age of the vessel minus coating life.

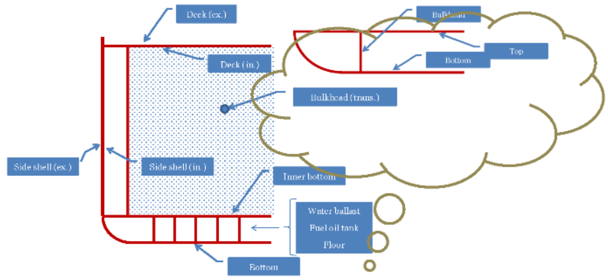

Figure 3. Generic cross section of cargo ship with nomenclature for structural element surfaces

Model parameters were quantified by the following procedure:

- b_{Corr} is set equal to 2/3 as suggested by Guo et al. (2008) for "mean" corrosion growth rate in cargo oil tanks and ballast tanks.
- Quantitative analysis of measurement data for bulk carrier and semi general cargo and container ships published by Yamaoto & Ikegami (1998), Paik et al (1998) and Samudro et al. (2000).
- Verification and adjustment by comparison with the statistical data, e.g. by Sone et al. (2003) and Guo et al. (2008).
- Discussion with experts.

Coating life as well as the corrosion growth rate are influenced by the quality of initial coating, maintenance/repair, the ship's operational profile and operational area, cargo type and handling and survey/inspection. Generally, detailed information on these parameters is not readily available; indicators were determined to consider these influences and are used to estimate influencing parameters for a particular ship, e.g. maintenance by indicators owner/management, Flag, class, number of owner changes, operational area and number of ports called per year.

Additionally, cargo ships coating life and corrosion growth rate highly depend on corrosivity, abrasivity and temperature of cargo, cargo handling and cargo frequency. Corrosion growth rate in water ballast tanks depends on time ship operates in ballast (moisture, abrasive elements in water), respectively number of times ballast water is changed (provision of oxygen).

The basic structure for the coating part of the degradation model with some major parameters is shown in Figure 4.

The selected parameters have been investigated with regard to their availability and quantified according to their significance for the corrosion

[1] CSR: Common Structural Rules

process. A first quantification has been performed based on information from literature and experts. However, these parameters will be further adjusted in the project by means of test cases.

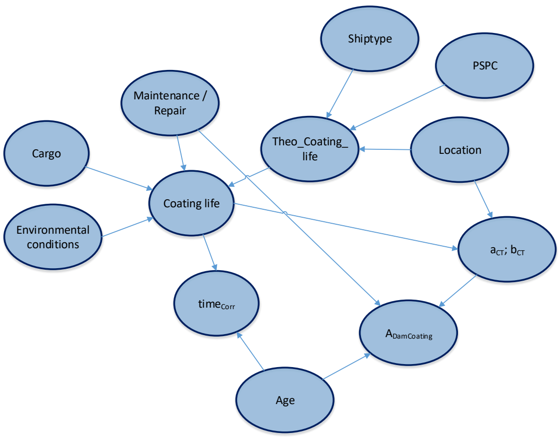

Figure 4. Graphical representation of coating model

2.2 Fatigue

Fatigue is a phenomenon that causes weakening of structures under fluctuating loading. This happens in ships due to wave loading and loads due to the loading and unloading of cargo. Fatigue damage might lead to a crack in the structure that can grow and in the worst case cause total collapse of the structure. In order to plan efficient inspections for fatigue damage it is important to understand where and how it occurs for which it is necessary to understand the causes of fatigue.

Fatigue is caused by alternating loads on a structure below the yield strength of the material. Typically, two forms of fatigue failure are distinguished: high and low cycle fatigue. High cycle fatigue relates to a high number (10^4-10^8 cycles) of low amplitude loads, such as by wave loads, whereas low cycle fatigue relates to high amplitudes and low number. For the SAFEPEC model focus is put on high cycle fatigue.

Fatigue occurs in different locations of the ship hull e.g. weld joints, typically ends of welds, bolt joints, locations of high stress and locations with repeated stress. The likelihood of fatigue is increased by geometrical imperfections (e.g., construction misalignment), poor detail design against fatigue, and substandard materials (e.g., steel and welding materials). A very important factor is also the skill of the construction personnel in the ship yard since many initial flaws increasing fatigue in ships operation can be avoided by good workmanship.

An initial crack, typically in a weld, is needed to start crack growth due to fatigue. This microscopic crack starts to grow due to repeated loading below the yield strength of the material.

The purpose of the fatigue cause module is to provide probabilities of cracks in ships. For this an approach is developed using statistical information combined from various sources. The model considers pure statistical probability values as well as factors based on statistics that are used to adjust the probabilities, e.g. from Port State Control (Paris MoU) data. Some of these factors are further adjusted by expert opinion.

The model is realised in the form of a Bayesian network that calculates probabilities for crack occurrence and crack size related to the ship. Figure 5 shows the different elements of the Bayesian network model.

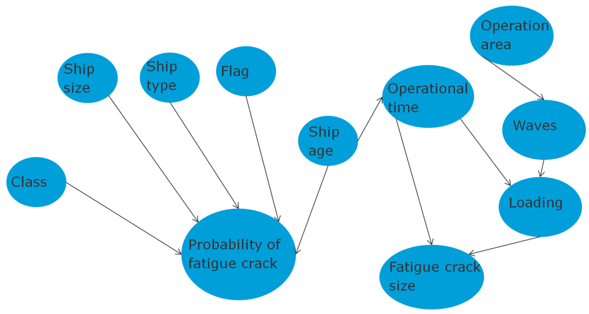

Figure 5. Fatigue causes module Bayesian Network structure

Parameters affecting probability of fatigue cracks in statistical data are the age, type and size of the vessel. The data are arranged for each ship type, age category and size category to calculate the probability of having a crack for three generic locations.

To provide information on the location of the possible crack, the general information described above needs to be divided into more specific information for each ship type. IACS instructions for surveyors (see e.g. IACS, 1999) were used to identify typical crack locations. Adjustment factors based on expert opinion are used to change the probability for cracks in a generic hull location into the probability for a detailed location.

The probability of fatigue cracks is greatly affected by operational conditions. Wave loading varies between sea areas and with ship type and size. These influences are considered and the model allows to compare relative crack growth between ships of different characteristics and trade.

The crack growth model applied on a weld detail on the deck structure is used to estimate crack growth during a given period of operation. The model considers ship's trade route, time spent on the trade and the information on the wave condition. Encountered wave loading is adjusted for the trade route by scaling the design fatigue loading from DNV GL Rules (2016) to get representative loading. Encountered maximum wave height and the number of load cycles are adjusted based on the load information for trade routes and for the time the ship has spent on them.

The representative crack used in the model is located in the block joint weld of the mid-ship region. Only hull girder loading due to wave loading is considered.

The crack growth is estimated using the Paris law (Paris & Erdogan, 1963)

$$\frac{da}{dN} = C(\Delta K)^m \quad (4)$$

where N is the number of load cycles, a is the crack length, ΔK is the stress intensity factor range and C and m are the material constants.

Material and thus material factors depend on the ship size. Same initial crack size distribution is used for all vessels. Crack growth parameters are selected for air and non-corrosive environment conditions. The crack growth calculation method is based on the procedure presented in DNV GL (2015). The modelling of the crack growth is performed in probabilistic manner using DNV GL software called “Profast” that is part of the DNV GL’s “Sesam GeniE” package.

The model provides a probability distribution of crack size in the considered structural detail. Both crack growth through the thickness of the plate and through the plate field are considered.

The probability of having cracks and the probability of their size provides information for the Vulnerability, Consequence and Inspection modules. Inspection findings play an important role for the adjustment of the fatigue crack size probability distribution. An interface in the Causes module will allow the inspection finding information to be taken into account.

2.3 Life-Saving Appliances

Components of life-saving appliances (LSA) have changed through the decades always aiming at the reduction of the risk of injury or death in the event of a marine accident by meeting simultaneously different requirements: demands for larger lifeboat capacities and ease of operation. These changes were driven mainly by serious marine accidents in which many human lives were lost. The main variable that affects the safe operation and the overall condition of LSA is maintenance. As a result, inspections ensure the safe operation of an LSA either in a case of an actual evacuation or during a drill.

In SAFEPEC the LSA module focuses on the calculation of the probability of different types of failures for specific life-saving appliances (i.e. davit launched life boats, free-fall lifeboats etc.) which are deployed on the ship types addressed in the project, i.e. general cargo vessels, containerships and passenger ships.

The aim of the analysis is to identify all causes which may lead to a failure of the specific group appliance (e.g. lifeboats). Following this rationale and by taking also into account the international literature (e.g. Ross, 2006) and the feedback from different LSA manufacturers, the most important (mechanical) components of each type of LSA - which may lead to the failure of the safe launching of the LSA - have been specified. Furthermore, correlations have been established between these main components and the degradation mechanisms (i.e. corrosion and cracking). The performed analysis is focused on LSA for ship types under consideration:

- Davit launched lifeboats;
- Free-fall lifeboats;
- Davit launched liferafts; and
- Marine Evacuation System (MES)

Of these MES was not considered for the time being because of the structure, operation and maintenance. Figure 6 depicts the developed fault tree (FT) for the calculation of the probability of failure for davit launched lifeboats.

As shown in Figure 6, the key components for the safe operation of davit launched lifeboats are the following:

- Davits;
- Release mechanism;
- Winch;
- Falls, sheaves & blocks;
- Tricing & bowsing;
- Lifeboat; and
- Fall wires.

Some of the components are further divided into subcomponents in order to reflect in a comprehensive way the complex of the LSA.

The quantification of the developed models requires data, which can be derived from inspection reports. Data was available from Port State Control (Paris MoU) as well as reports and claims from a number of LSA manufacturers that volunteered to support this effort. The final detailed data set comprises 5143 records: 4021 inspection reports from Paris MoU and 1122 reports and claims from manufacturing companies with the kind contribution from “Norsafe Water craft Hellas A.E.”. The relative distribution of deficiencies with respect to ship types is shown in Figure 7; based on the examined dataset, the predominance of deficiencies (in absolute numbers) of General Cargo ships is rather clear.

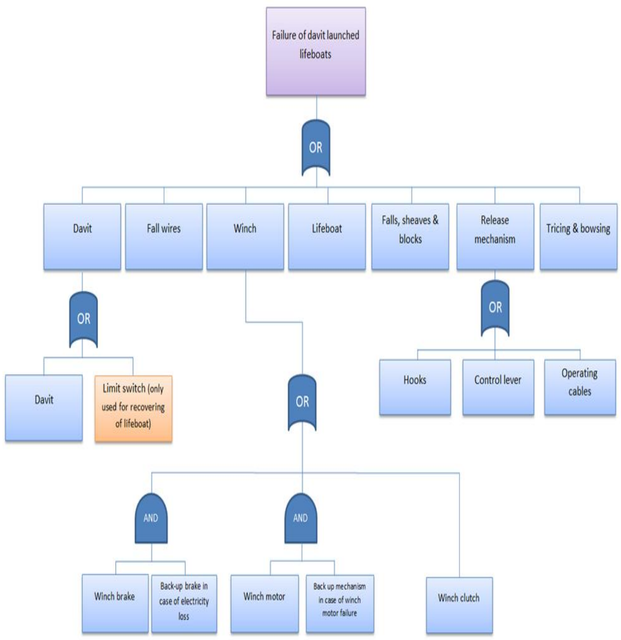

Figure 6. Developed FT for the calculation of the probability of failure for davit launched lifeboats.

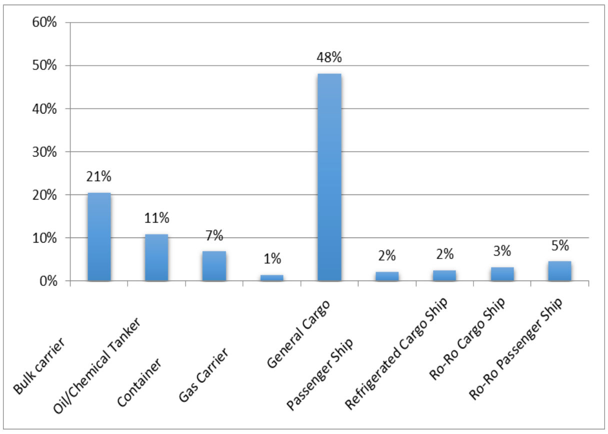

Figure 7. Percentage of deficiencies per ship type (2011-2013).

Further elaboration of the statistical data highlights the main defective item categories for different ship types: 22.1% of the records have been classified as deficiencies of lifeboats, rescue boats and liferafts on general cargo ships. Moreover, these three LSA types provide 25% of all the deficiencies onboard passenger ships. These initial results support the examination with respect to the selected types of LSA for general cargo and passenger ships.

The failure probability for the selected types of LSA will be estimated by processing inspection data from the PSC and LSA manufacturing companies from 2011 to 2016. The elaboration of these data is still ongoing.

3 VULNERABILITY MODULE

The 'Vulnerability module' considers relevant failure modes and calculates associated failure probabilities. In this paper, the assessment of flexural failure of hull-girder sections due to corrosion diminution is outlined. The model is summarised by the Bayesian Network (BN) of Figure 8. Each node corresponds to a random variable or parameter, and the arrows reflect their dependences. This model estimates the probability distribution of the bending moment capacity and the loads based on limited ship information, which include ship type, length, breadth, draft, displacement.

To be aligned with the generic risk model, the ship properties are represented by a few indicators. This approach assumes that most ships of the same type are designed with similar utilisation factor. Different ships of the same type and with the same indicators are likely to have similar properties, such as plate thicknesses, placement of stiffeners, and moment capacity. For bending capacity, container ships can be characterised by TEU (Twenty Foot Equivalent Unit) while general cargo ships can be characterised by breadth and length. The spatial distribution of corrosion loss is also simplified, following the definition in the 'Cause module'.

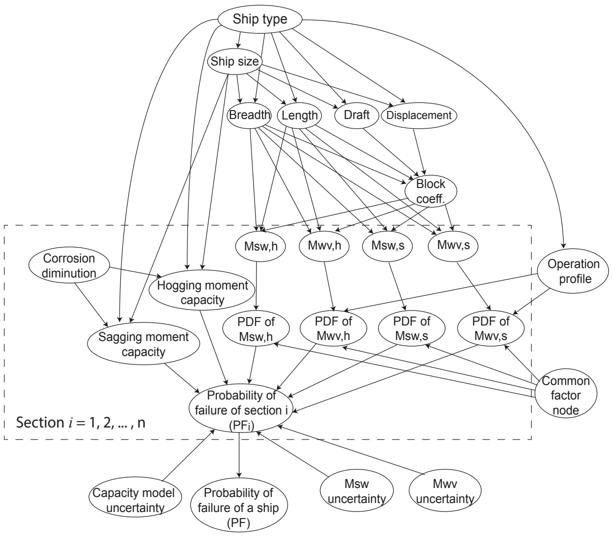

Figure 8. Bayesian network model of bending failure

This relationship between the indicators and the ultimate moment capacity is described by means of a response surface. A full quadratic function is taken to express the response surface as follows:

$$M_u = \beta_0 + \sum_{i=1}^{K} \beta_i X_i + \sum\sum_{i<j} \beta_{ij} X_i X_j + \sum_{i=1}^{K} \beta_{ii} X_i^2 \qquad (5)$$

where X_i is each indicator considered, K is the total number of variables, β is the regression coefficient.

The regression coefficients are obtained from the calculation of a sufficient number ultimate moment capacities for ships with varying designs, based on Poseidon, the in-house software of DNV GL. The calculation is based on incremental-iterative method. The regression coefficients β are identified by Maximum Likelihood Estimation as follows:

$$\beta = (X^T X)^{-1} X^T M \tag{6}$$

In this way, the response surfaces for different ship types are identified in advance, and then used in the BN model to estimate ultimate moment capacity efficiently.

This approach is verified with three container ships whose indicators are 5000, 9200 and 14000 TEU. Accordingly the response surface has 6 variables, which correspond to the ship indicator and values of corrosion diminutions at five locations from the cause module (Figure 9).

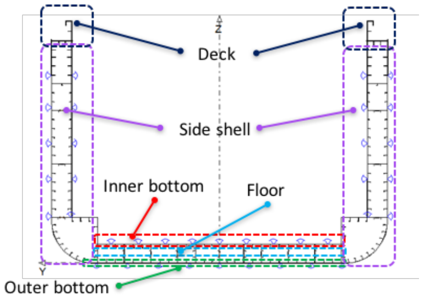

Figure 9. Five corrosion groups

To populate ship models under various corrosion states, 100 samples of corrosion diminutions are randomly generated. In order to take supporting points at the boundary of the considered domain, 31 samples are manually selected.

In this way, 393 models are generated representing various circumstances of corrosion diminutions and varying ship indicators. These models are analysed with Poseidon to calculate ultimate hogging and sagging moment capacities. Then the results are used to fit the response surface.

The average error from the response surface is found to be in the order of 3% to 4%. Relatively larger error values, about 10%, are observed at smaller capacity, but they are acceptable since absolute discrepancies are not significant (0.28 GNm for hogging, 0.54 GNm for sagging).

The identified response surface describes the effect of corrosion diminution and the ship indicator in terms of the ultimate moment capacity. Then it is combined with a stochastic load model, which also utilizes readily available ship information, to compute the probability of failure. The results allow a comparison of the probability of failure at different sections in the ship as well as comparison of different ships in terms of their risk.

4 SUMMARY AND CONCLUSION

The objective of the EU research project SAFEPEC is to develop a tool for targeting ships for inspection/survey by means of risk-based methods. The tool can be used for identifying ships for inspection/survey by flag State and Class but also by shipowners operating larger fleets. The risk-based inspection model developed in SAFEPEC considers modules for estimating the probability of occurrence of degradation effects, the vulnerability of the structure to these degradation and the consequences associated with failures of the structure.

The presented model is using readily available information directly or via influence parameters quantified by statistical analysis. So far the SAFEPEC risk-based inspection tool considers degradation of ship structure by corrosion and fatigue, and of life-saving systems (lifeboat and liferaft). The influence of inspection on the probability of different causes will be taken into consideration.

It is expected that this model will improve the targeting of ships for inspection/survey by better approximating degradation of structure as well as in systems (e.g. LSA), and quantifying ship's condition in terms of risk.

At the present stage, such a targeting tool needs to use high-level models because of limited access to detailed information and to ensure an acceptable effort for model development.

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