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Probabilistic modelling of the hull girder target safety level of tankers

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ABSTRACT

The paper aims at assessing the probabilistic characteristics of the hull girder target safety level of a Suezmax tanker derived from a cost-benefit analysis. The target safety level is obtained considering as risk control option the change in the cross section scantlings of the tanker and its effect on risk reduction expressed by the total expected cost of the hull girder failure. The approach involves the evaluation of the effect of the risk control option on the hull girder failure probability assessed by means of a structural reliability analysis, and the assessment of the expected cost of hull girder failure in terms of property damage of the ship, pollution due to spillage of oil and loss of life of the ship's crew, as proposed by the International Maritime Organization (IMO). The uncertainties in the costs related to the loss of human life and environmental damages are characterised using available statistics and included into the probabilistic framework. Moreover, a probabilistic model is proposed that explicitly accounts for labour and material costs when evaluating the cost of the risk control option. The hull girder failure probability is calculated using the First-Order Reliability Method, considering the ultimate collapse of the midship cross section under vertical bending moment as the failure event. Uncertainty propagation and sensitivity analyses are conducted for different operational scenarios to assess the contribution of the model parameters on the uncertainty of the target safety level of the tanker with the objective of identifying the range of the variation and the characteristic target safety level of the hull girder that would be adequate for risk-based design and reliability-based code calibration studies.

1. Introduction

Structural reliability methods have been consistently applied in the last decades to assess the safety of ship structures and structural components (e.g. Refs. [1–3]). Most of the applications use structural reliability methods for comparing the safety levels of different ship types [4], ships of the same type [5,6] and different concepts of the same ship type, such as bulk carriers [7] and tankers [8]. Reliability formulations have also been developed for ships in damaged conditions [9] as well as to assess effect of degradation processes such as corrosion on their structural safety [10] and of improved descriptions of the load effects [11,12].

Another and equally important application of the structural reliability methods has been in reliability-based code calibration, which is a well stablished procedure [13–15] that has been used to develop and calibrate several structural code formats and requirements. The code calibration problem can be formulated as a decision problem, being the partial safety factors directly evaluated by means of a cost-benefit analysis [15] or using a two-step procedure, where the desired target safety level is first defined

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and then the partial safety factors are evaluated, which together with the characteristic values of the strength and load variables ensure a certain minimum safety level for the structural components designed according to the code.

The target safety levels to which the partial safety factors are calibrated can be defined based on the systematic assessment of the implicit safety levels of existing structures designed with well-established codes (e.g. Refs. [14,16,17]) combined with engineering judgement [18] or on tabulated values that typically depend on the type of failure and its consequence [19,20]. Target reliability levels can also be developed for relevant limit states of novel structures for which no practical experience exists using a risk based approach [21].

Alternatively, a cost-benefit formulation can also be adopted to derive the target safety level for a given class of civil engineering structures [22] or for FPSO systems, such as mooring lines, using Bayesian Networks to model the failure scenarios and their expected consequences [23,24]. For the hull girder structure, the cost-benefit formulation consists of calculating the target safety level considering the cost of marginally increasing the cross section scantlings and the risk reduction effect this would have in terms of improved safety, environmental and property damages, as suggested by Skjong and Bitner-Gregersen [25]. In this approach, structural reliability methods are used to calculate the hull girder failure probability and the consequences of failure are estimated using the cost-effectiveness criteria for loss of life and environmental impact due to oil spills proposed by the IMO's Formal Safety Assessment (FSA) guidelines [26–28]. The approach thus combines efficient structural reliability methods [29] and risk assessment methods and is in line with the developments that have occurred in the last decades to introduce risk-based approaches in the maritime transportation sector [30–32].

An example of how the cost-effectiveness criteria can be tied together with the probability of failure in a risk-based framework using a cost-benefit analysis may be found in MSC 81/INF.6 [33]. The same approach has also been applied to damaged ships due to collisions by Hørte et al. [34] and, more recently, by Teixeira et al. [35] to assess the effect of different environmental criteria on the target hull girder safety level of a Suezmax. In particular, the volume dependent environmental criterion adopted in the latest FSA guidelines [28] and the ones proposed by other authors, such as [36–38]; as well as the cost of averting a tonne of oil spilt (CATS) environmental criterion proposed by Ref. [39]; have been considered by Teixeira et al. [35]. This study has shown that all volume dependent approaches proposed to estimate the total cost associated to an oil spill lead the similar target safety levels (reliability indices β ranging from 3.14 to 3.18) and that the target hull girder reliability index only increases (to $\beta = 3.52$) when the CATS criterion of 60,000 USD per ton of oil is adopted, which attributes a higher value per ton for spills larger than 2 ton compared to any of the other volume dependent approaches.

Later Guia et al. [40], have performed a sensitivity analysis on the optimum safety level of the Suezmax tanker with the objective of identifying the most important variables of the cost-benefit model. The results obtained for a baseline scenario similar to that adopted in Ref. [33] indicated that the most important input parameter is the cost of steelwork per ton, followed by the initial cost of the ship and the variables that characterize the environmental consequences due to the accidental oil spill. As expected, the study indicated that when the probability of loss of life increases, the importance of the variables related to loss of life increases, whereas the significance of variables related to the environmental consequences of the hull girder failure decreases. Although, the sensitivity analysis conducted by Guia et al. [40] have considered some uncertainty in the input parameters, the stochastic models adopted have not reflected their actual probabilistic characteristics and, therefore, the calculated sensitivities have not provided a proper indication on the relative contribution of each variable to the total uncertainty of the target safety level of the tanker.

The objective of this paper is to conduct an uncertainty propagation analysis of the target hull girder safety level of a Suezmax tanker derived by a cost-benefit model, as done by Skjong and Bitner-Gregersen [25] and Teixeira et al. [35]; with improved descriptions of the probabilistic characteristics of the model parameters. Overall, eleven input variables are considered, for which the sources of uncertainty are quantified and probabilistic models are developed. The model uncertainties are propagated through Monte Carlo simulation and sensitivity analyses are conducted to assess the contribution of each variable to the total uncertainty of the target hull girder safety levels in different operational scenarios.

The focus is on the uncertainties in the costs components associated to oil spills and loss of human life, the later calculated using the Net Cost of Averting a Fatality (NCAF) acceptance criterion, as proposed by IMO [28]. In particular, the formulation proposed by IMO [28] is adopted to calculate the total spill costs and probabilistic models are derived for specified volume intervals from a consolidated database of reported spill costs submitted by Germany, Japan and the United States to IMO [41].

A probabilistic model is constructed to describe the uncertainty in the NCAF acceptance criterion based on updated information on life expectancy at birth and gross domestic product (GDP) per capita of the 35 countries with the highest shares of flag registrations in the world.

Regarding the cost of the RCO, while Teixeira et al. [35] and Guia et al. [40] have adopted a single input variable that incorporates all costs associated to the increase of the hull girder cross section scantlings, following the approach suggested by Ref. [33]; this paper considers separately material and labour cost components to estimate the cost of the RCO. Labour costs are estimated using the regression model proposed by Ref. [42] to calculate the number of man-hours, and data on man-hour unit costs compiled by Ref. [43]. Moreover, a model is suggested to more adequately estimate the marginal cost of increasing the ship's cross section scantlings that differentiates between the labour required to increase the hull girder strength by increasing the scantlings of the cross section and by increasing the number of its structural elements.

The effect of these uncertainties on the target hull girder safety level of a Suezmax tanker is assessed by means of Monte Carlo simulation and a sensitivity analysis is performed for different operational scenarios to identify the contribution of the uncertainty of each parameter of the cost-benefit model on the total uncertainty of the target safety levels.