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Efficient response modelling for performance characterisation and risk assessment of ship-iceberg collisions

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ABSTRACT

Unique features of the Arctic region, such as sub-zero temperatures and glacial activities, pose serious risk to ships. The potential for ship accidents requires tailored guidelines for ship-ice interactions which justify the need for a suitable performance and risk assessment model for ships navigating in the Arctic waters. Research on the development of such model is currently limited. In this paper, a conceptual framework is proposed for performance characterisation and quantitative risk assessment of ships in iceberg collisions. The framework focusses on the components required for asset risk computation, such as probabilistic performance measures and ship-iceberg collision probability. The computationally intensive ship-iceberg collision models are captured by efficient surrogate models in performance estimation, while the basic events are linked by a fault tree representation to identify collision probability. The interaction between a double-hull oil tanker and a spherical iceberg is chosen as the reference collision scenario to demonstrate the applicability of the framework. The crushable foam plasticity model for the iceberg material is validated and the response computations are performed using the non-linear finite element software Abaqus®. The presented computation model underlines the significance of different risk components, providing valuable guidance for improving risk-based ship designs.

1. Introduction

The regions of the Arctic are attracting the interest of multinational organisations due to the opening of new ship passages and the availability of large reservoirs of oil and gas. Exploration and exploitation of these regions will not come easy as the environment is characterised by sub-zero temperature and glacial activities, leading to ice formations. The combination of these factors have the potential to cause an increase in accidents such as ship collisions [1]. Due to this reason, ship designers are taking proactive steps to design ship structures that are capable of withstanding ice loads. These steps require new guidelines for risk-based ship design that would assess potential ship impacts in icy waters.

Two major factors identified as critical during Arctic operations are lack of information on ice conditions and the corresponding inability to predict ice loading on the ship hull [2]. These types of uncertainties can have significant effect on the ship structural response during ice impacts as they influence the response computations. Some typical examples of these parameters are the mass and local geometry of ice bodies, ship displacement, relative velocity and collision angle between the ship and ice formation [2–4]. Hence, uncertainties in ship-ice impact response need to be efficiently characterised for the purpose of quantifying the performance of ship structures and the associated collision risks. According to the probabilistic Formal Safety Assessment (FSA) procedure recommended by the International Maritime Organisation (IMO), possible collision scenarios need to be identified for the quantitative assessment of collision risk to allow for the estimation of the probability of collision scenarios and the associated consequences [5]. In general, risk is evaluated as:

$$Risk = \sum_{i=1}^{n} P_i\left(Damage\right) \times Consequence_i, \tag{1}$$

where $P\left(Damage\right)$ is the probability of damage that considers all potential accident sequences. In the context of a ship collision event:

$$P\left(Damage\right) = P\left(Damage|Collision\right) \times P\left(Collision\right), \tag{2}$$

where $P\left(Damage|Collision\right)$ is the probability of damage given a collision and $P\left(Collision\right)$ is the probability of a collision. The consequences could be considered in terms of structural, economical,

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environmental and social effects. The collision probability can be estimated from the construction of logical diagrams, such as fault trees, event trees and Bayesian networks, which involve the relationship of basic events leading to the undesired event. Reddy et al. [6] developed a fault tree, with the associated iceberg quantities as basic events, to estimate the probability of iceberg impacts with offshore structures using a Monte Carlo simulation approach. Korsnes [7] presented the probability of iceberg impact on an offshore structure by estimating the mean annual iceberg production, using an improved iceberg melting and breakdown model. Khan et al. [8] developed a framework for risk assessment of ship transport in the Arctic by constructing a Bayesian network that relates the probability of ship collision with the oil spill consequence. However, the evaluation of the consequence did not relate the loss from oil spill with ship structural damage.

The shared-energy design principle is often employed for the determination of ship structural strength and assessment of related consequences; this means that the results of ship-iceberg collision analysis include significant deformation of both the ship structure and the iceberg [9]. The material of ice has both solid and fluid features that determine its response during loading, such as load-displacement and load-fluid velocity relationships [10,11]. The consideration of these two models for response characterisation makes ice a highly complicated material thereby making it difficult to accurately capture its deformation mechanism. A simplified approach is usually applied which involves the consideration of short-term, quasi-static loading for ice material behaviour hence, fluid response in ice can be neglected for the assessment [12–15]. If the pressure-area relationship outcome from the approach is verified to be reasonable when utilised under strength design (that is ice deforms only), then the ice material model is also considered sufficient to capture ice behaviour under shared-energy design [13]. The characterisation of structural performance by stochastic modelling has been extensively applied to the case of ship-ship collisions [16–19]. The approach is transferable to ship-iceberg collision analysis, however specific guidance on computationally efficient performance and risk quantification is not available in the literature. Liu et al. [20] performed probabilistic ship-iceberg collision assessment using Bayesian networks by linearising idealised stages of the energy-displacement curve to evaluate the objective function. However, the linearisation procedure may not always represent the energy displacement relation accurately, especially for complex collision cases.

In order to address these limitations, the present study combines the evaluation of the probability of collision scenarios and characterisation of the associated consequences to propose a conceptual framework for the risk assessment of ship-iceberg collisions, as shown in Fig. 1 (discussed further in Section 1.2). The study proves the transferability of the framework proposed for ship-ship collisions to other collision variants such as ship-iceberg, ship-bridge, and ship-platform (see [21]). Appropriate probabilistic characteristics of underlying uncertain parameters are identified from the literature. Samples of the variables required for response characterisation are generated using the Latin Hypercube sampling (LHS) apporach. The study also illustrates the characterisation of the plasticity stage of the iceberg material in the nonlinear finite element software, Abaqus®, using the crushable foam model and the result is calibrated against recommended practice. The novelty of the framework relates to the evaluation of efficient response models that characterise ship-iceberg collisions, estimation of the probability of ship structural damage and the evaluation of the causation probability for risk computation. The path relating to the 'Response Surface Modelling Module' of the framework is taken in the present study.

To show the functionality of the framework, a reference collision scenario involving two moving deformable bodies is analysed. These bodies are an iceberg and a double-hull crude oil tanker. Ice formations that may interact with ships vary in terms of production stage and categories. It may be unrealistic to develop tailored ice material models that are peculiar to all types of ice condition. Also, icebergs are known to be highly hazardous due to detection difficulties during navigation [22–24]. Therefore, the scope of the present study focuses on iceberg modelling and interaction with ships. The consequence considered is defined as the rupture of the asset which could lead to flooding of the damaged compartment, and ultimately impeding on the asset intact stability. The focus of the present study is the assessment of the primary consequence to support decisions on the design process of ship structures in risk-based designs. The consequence is assessed in terms of the internal energy dissipated by the ship structure during collision using the non-linear finite element software, Abaqus®.

Kriging response surface model is used to formulate a generic mathematical relationship between the input random variables and the response. The development of ship response function using Kriging model is done using MATLAB®. For the purpose of assessing the risk to the reference ship structure, structural reliability analysis is performed by using the evaluated Kriging model in the First and Second Order Reliability Methods (FORM/SORM) to estimate $P(Damage|Collision)$. The collision probability [$P(Collision)$] is evaluated by considering the logical relationship between possible basic events leading to the accident using fault tree analysis (FTA). For the present study, the number of possible ship-iceberg collisions is calculated from the iceberg impact analysis presented by Eik and Gudmestad [25] for the Shtokman region. The focus of the present study is for risk computation in terms of structural consequences only.

The modules used for the categorisation of elements of the proposed framework are discussed in Section 1.2. Before going into the assessment of the reference collision scenario, a detailed description and validation of the iceberg material model is given in Section 2. Section 3 discusses the numerical evaluation of the structural consequence and capacity of the reference double-hull oil tanker in a collision scenario involving an iceberg. Hence, structural response that is vital for asset risk computation is identified in this section. The probabilistic characteristics of the input random variables identified for the ship-iceberg collision scenario are described in Section 4. In Section 5, the Kriging surrogate model of the non-linear finite element analysis models is developed for response characterisation. The application of the Kriging model for the evaluation of $P(Damage|Collision)$ along with collision probability computation are discussed in Section 6. Finally, the asset risk computations associated with the studied ship-iceberg collision scenario are demonstrated in Section 6.

1.1. Proposed framework for ship performance and risk computation in iceberg collisions

The developed framework can be categorised into four main modules (Fig. 1); ship mechanics module, uncertainty characterisation module, response surface modelling module and performance and risk computation module. The basis for the ship mechanics module is to define the reference ship-iceberg collision scenario and to set the performance targets expected of ship structures to achieve when involved in collisions. These performance targets can be linked with ship responses to develop the failure criteria to which ship structural performance can be assessed.

The objective or performance function of the ship-iceberg collision analysis can then be formulated from either simplified analytical models (SAM) or response surface modelling. The former applies to the analysis of the structural mechanism of the reference collision scenario response by categorising the response in stages with respect to structural member contributions to the total