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Review of risk-based design for ice-class ships

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ABSTRACT

The growing interest for Arctic and Antarctic shipping activities due to the decreasing ice cover will also increase the risks of accidents on these waters. The design of ships for ice has traditionally been based on the practical experience without a clear link to the physics of the ship-ice interaction. The rules are, however, getting more towards the goal based approach, which require good knowledge of all the various element important for design. Risk based ship design (RBSD) is also widely applied e.g. for the passengers ships. Therefore, the scope of this paper is the review of the knowledge necessary for RBSD for Arctic conditions. The main focus is on ice loads and ship structures. Accident prevention and environmental consequences of oil spills are also discussed, but more briefly. In risk analysis, there is a recent focus on the treatment of uncertainty, or conversely, the strength of knowledge underlying the risk quantification. In light of this, the review is performed with specific focus on the strength of evidence of the different fields of knowledge needed to perform RBSD in ice conditions. The results indicate that the risk based design for Arctic operations is challenging as the ice environment, together with all the possible ship-ice contact scenarios, are complicated to define properly, especially on proper probabilistic terms. The main challenges are still related how to describe the ship-ice interaction parameters such as ship-ice contact characteristics, pressure distributions, and load levels in all the various ice conditions. In addition, the possible environmental consequences of the accidents need further research. Finally, human factors need to be incorporated in risk analysis techniques.

1. Introduction

Activity in the Arctic occurs in remote regions where there is typically lack of infrastructure, sometimes insufficient basic information, such as bathymetry, and generally harsh environmental conditions, such as ice cover and low temperatures. Furthermore, the ice cover is highly variable and dynamic, characteristics that are anticipated to increase in the future due to the effects of climate change. These characteristics complicate Arctic operations. The remoteness of the Arctic areas implies that in case of an accident, the search and rescue (SAR) capability is low. Fairways are not marked very extensively and especially the soundings taken for charting are relatively scarce. These Arctic conditions are compounded by the fact that the rate of recovery of the natural environment in the Arctic nature is slow, i.e. the consequences of shipping accidents in the Arctic are potentially very serious for the vulnerable ecosystem.

Conventional rule-based ship design follows a design spiral - a graphical representation that captures the basic tenets of widely accepted ship design approaches [1,2]. This design spiral consists of three main phases, namely, concept, preliminary and detail design. Safety rules are often treated as design constraints in this design paradigm. Although rule or prescriptive-based design

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approaches are easy to follow and implement, they may cause over-conservative design problems and do not drive innovative changes for performance improvement [3]. Safety level is often uncertain or unknown in design rules and rules do not always reflect experience. Therefore, a move towards a goal or performance-based approach to ship design would be preferable over the conventional approaches. A risk-based design approach is one way forward in this direction. This new design paradigm treats safety as a design objective rather than constraint [4]. This implies that a risk-based design can help to meet safety expectations in cost-effective ways.

Risk assessment has for many years been considered to be a useful tool in many application areas [5], and has also been adopted as a basis for risk-based ship design [4,6]. The underlying rationale of such a proactive approach to safe ship design is in line with the philosophy adopted by the International Maritime Organization (IMO) to apply goal-based (opposed to rule-based) ship design standards [130]. The focus on risk-based approaches in international maritime regulatory decision-making is also clear from the Formal Safety Assessment (FSA) framework adopted by the IMO [131] and the implementation of several research projects focusing on risk-based design approaches for the maritime industry [7–9]. For the marine industry risk assessment is nothing new. Classification societies have published general guidelines on risk assessment and its applications to ship design and operations (e.g., [10,11]). These guidelines have laid a reasonably good knowledge basis for the adoption of the risk-based approach by the marine industry [12].

In general, a risk-based ship design approach helps to translate estimated risk values into design parameters. To obtain such model, we need to answer four questions:

(1) How to identify the key hazards and associated parameters?
(2) How to measure risk consistently through a formalized procedure?
(3) How to integrate the risk assessment procedure into the design process?
(4) How to trade off among system performance, cost and risk reduction?

Bergström et al. [13] have studied in detail the assessment of the applicability of goal- and risk-based design on Arctic sea transport systems. The focus in the system level approach and how to define a holistic design process considering operational and regulatory requirements, cost-efficiency, and design robustness. The proposed method makes use of system thinking and discrete event simulation based Monte Carlo simulations [14]. Bergström et al. [13] also defined the difference between goal and risk based design, stating that goal based design approach is for deterministic functional requirements for the performance parameters and risk based design require probabilistic functional requirements. This means that in risk based design, the basic tools developed as part of risk analysis framework will be applied and used in design e.g. to define the target safety level or individual risks of the product under consideration. So risk analysis are needed to determine probability of the various studied scenarios and their consequences and risk based design aims to design the ships and other systems so that a proper risk level is achieved.

The scope of this paper is the review of the knowledge necessary for risk based ship design (RBSD) for ice conditions, especially Arctic conditions. Following a scenario-based approach to quantitative risk analysis, RBSD requires at minimum to cover the following topics: definition of hazard scenarios, their occurrence probabilities, and consequences, see Fig. 1. This is in line with the well-known risk triplet “What can happen?”, “How likely is it that will happen?” and “If it does happen, what are the consequences” [16]. The minimum knowledge requirements to apply RBSD for Artic operations is an understanding of the behaviour of the sea ice cover, ship-ice interaction and structural response, and the possible consequences of failures. The paper includes both ship accidents and any local ship hull damages as possible scenarios, however, the focus is on the local design of ship hull and related consequences such as local dents which have been traditionally used a design scenarios for ice-strengthened ship hulls.

In risk analysis, there is a recent focus on the treatment of uncertainty, or conversely, the strength of knowledge underlying the risk quantification [17]. In maritime risk analysis applications and FSA, uncertainties are often not elaborated on. As a step towards improving current practices, the review is performed with specific focus on the strength of evidence of the different fields of knowledge needed to perform RBSD in Arctic ice conditions. Such an evaluation of uncertainties also serves as a research agenda, where priorities for reducing the uncertainties can be set.

The remainder of this paper is organised as follows. In Section 2, a brief background about the treatment of uncertainty in risk analysis is provided. In addition, the methodology for assessing the strength of evidence is outlined. In section 3, current approaches to ship hull design in Arctic conditions are briefly reviewed and after that, in Section 4, first an overview of Arctic activities and a history of ship accidents is described, and thereafter the various elements of a proper risk based ship design approach, as illustrated in Fig. 1, are reviewed and discussed. For the available data and models, different quality characteristics are finally considered and judged, from which a rating for their evidential strength is derived in Section 5.

2. Uncertainty in risk analysis: background, concept and method

2.1. Background

In the scientific risk research community, there is a recent focus on foundational issues, where concerted efforts are called for to strengthen the scientific basis for risk analysis applications and to improve current practices [18,19]. One of the issues raised is the appropriate characterization, representation and interpretation of uncertainty in risk analysis and management [17]. Whereas uncertainty treatment has been argued to be a validity criterion for risk analysis [20] and is explicitly mentioned in IMO's FSA guidelines [131], current practices show that uncertainties are often not considered in actual maritime risk analysis applications [21].