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Probabilistic assessment of damaged ship survivability in case of grounding: development and testing of a direct non-zonal approach

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ABSTRACT

This paper presents the results of ongoing research efforts aimed at the theoretical development and practical implementation of a probabilistic framework for regulatory assessment of ship survivability following grounding accidents, with particular attention to passenger vessels. In the envisioned framework, the probabilities of flooding of a compartment, or a group of compartments, i.e. the so-called "p-factors", are determined using a flexible and easily updatable direct non-zonal approach. The assessment of the conditional ship survivability, on the other hand, is based on the SOLAS "s-factor". The general framework is described, together with implementation details in the specific case of bottom grounding. Testing results, carried out using a specifically developed software tool, are also reported.
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1. Introduction

Past and more recent accidents have shown that grounding can potentially have catastrophic consequences. This is particularly true when speaking of passenger vessels, for which the risk to be accounted for is the potential loss of lives. Express Samina in 2000, Sea Diamond in 2007 and Costa Concordia in 2012, are some examples of such accidents.

From a regulatory point of view, present SOLAS damage stability regulations for passenger and (dry) cargo vessels (IMO, 2014a) address ship survivability following a flooding due to collision in a probabilistic framework, with some additional deterministic requirement on top of the basic probabilistic ones. The underlying distributions of damage characteristics were originally developed in the framework of the EU-funded HARDER project (Lützen, 2002), and have then been adapted as a result of discussion at IMO (IMO, 2003a, 2003b, 2004a, 2005; 2006).

On the other hand, SOLAS regulations for passenger and cargo ships do not specifically address the case of grounding damages within the probabilistic framework. Safety with respect to bottom grounding is instead addressed deterministically through Chapter II-1-Regulation 9 "Double bottoms in passenger ships and cargo ships other than tankers". Regulation 9 (IMO, 2014a), which was developed using historical data of grounding damages (IMO, 2004b), sets minimum double bottom requirements and specifies deterministic bottom grounding damage characteristics to be used for survivability assessment in case of vessels with unusual bottom arrangements. An analysis of the effectiveness of the deterministic requirements in Reg.9 in light of the statistics of grounding damage characteristics collected in the GOALDS project can be found in (IMO, 2012; Papanikolaou et al., 2011).

It should also be reminded that SOLAS Reg.9 only deals with grounding damages assumed to penetrate the vessel vertically, from the ship bottom (i.e. bottom grounding damages). However, as both historical data and more recent accidents show, grounding damages can also result in breaches on the side of the vessel, extending partially or totally above the double bottom. Side damages can also be the result of the contact with fixed or floating objects. However, such type of damages is presently not considered by Reg.9.

Therefore, a lack of harmonisation exists in present SOLAS regulations, between the applied probabilistic framework for collision-related survivability, and the applied deterministic framework for bottom grounding-related survivability. Such situation could benefit from a harmonisation towards a fully probabilistic framework for both collision and grounding damages. Indeed, with particular reference to stability-related regulations, the present evolution of knowledge and practice regarding rule-development, taking into account risk-assessment, indicates that the more rational way to address the problem of survivability following an accident is by trying to develop a regulatory framework based on probabilistic concepts. Probabilistic frameworks, in addition of being more strictly related with reality, also allow more design

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flexibility, which, instead, is in some cases impaired by deterministic prescriptions. Moreover, in the grounding framework, it would also be necessary to introduce damages occurring on the side of the vessel, in addition to bottom damages.

In order to develop a probabilistic framework for survivability assessment in damaged condition, two elements are needed. Firstly, it is necessary to specify an appropriate geometrical and probabilistic model for the damage shape, position and extent. Secondly, it is necessary to have at disposal a means for assessing the conditional ship survivability following a damage. With a view towards a harmonization with existing SOLAS damage stability regulations dealing with collision accidents, these two elements can be used to determine, respectively, the so-called "p-factors" (i.e. the probability of flooding a compartment, or group of compartments) and the consequent "s-factors".

In present SOLAS regulations, "p-factors" for collision damages can be calculated by means of analytical formulae which have been derived starting from the underlying distributions of damage characteristics (Lützen, 2002). Following the "zonification" process, such formulae are applied to ships having compartments of generic shape. However, this is just an approximation, and the formulae are strictly valid only for box-shaped vessels having box-shaped compartments.

Studies carried out within the GOALDS project (Bulian & Francescutto, 2010) indicated that, in case of bottom grounding, the development of analytical, or semi-analytical, "p-factors", although it was technically possible, would have been hardly applicable to realistic ships and subdivision layouts. To overcome this difficulty, it was therefore suggested to address the determination of "p-factors" using a direct approach, based Monte Carlo generation of breaches, starting from the underlying probabilistic model.

In the past, a direct approach for the determination of "p-factors", in case of collision damages, was also explored by Koelman (2005). In this study, a methodology based on direct deterministic integration of the underlying probability density functions of damage characteristics was used. Moreover, a direct, non-analytical determination of the probability of flooding of (group of) compartments, starting from the underlying distributions of damage characteristics, is implicit in the alternative assessment of accidental oil outflow performance or of double hull and double bottom requirements within MARPOL (IMO, 2003c, 2014b). For MARPOL oil outflow assessment, a direct approach of the Monte Carlo type was used by Kehren & Krüger (2007) for the determination of the probabilities of damaging a compartment (or group of compartments) following bottom damages. Furthermore, Kehren & Krüger (2007) also correctly pointed out that the same philosophy could have been used also for survivability assessment.

It is therefore the scope of this paper to present the results of ongoing research efforts aimed at the theoretical development and practical implementation of a probabilistic framework for regulatory assessment of ship survivability following grounding accidents, with particular attention to the case of passenger vessels. In the envisioned framework, "p-factors" are determined using a flexible and easily updatable direct non-zonal approach, while the assessment of the conditional ship survivability is based on the SOLAS "s-factor". In the following, the general framework is described. Although the framework has been developed for both bottom and side grounding damages, and it could be extended to collision damages (and also to, e.g., accidental oil outflow performance), herein implementation details are given only for the specific case of bottom grounding. An example testing application, carried out using a specifically developed software tool, is also reported.

2. Outline of the approach

Scope of the assessment is to determine an attained subdivision index, which is meant to be representative of the survivability of the vessel following a bottom grounding accident leading to hull breach. Furthermore, in order to allow a possible harmonization with existing regulations, the approach is designed to be formally in line with present SOLAS probabilistic assessment of survivability following a collision accident (hereinafter, briefly, SOLAS2009).

Considering bottom grounding damages, an attained subdivision index $A_{GR,B}$ is defined in line with SOLAS2009, considering three calculation draughts d_s (deepest subdivision draught), d_p (partial subdivision draught) and d_l (light service draught), as follows:

$$A_{GR,B} = 0.4A_{GR,B,s} + 0.4A_{GR,B,p} + 0.2A_{GR,B,l} \tag{1}$$

Each partial index is given by the summation of contributions from all damage cases taken into consideration:

$$A_{GR,B,c} = \sum_{i_c} p_{i_c} \cdot s_{i_c} \text{ with } c = s, p, l \tag{2}$$

where i_c represents each compartment or group of compartments under consideration, p_{i_c} accounts for the probability that only the compartment or group of compartments under consideration may be flooded, and s_{i_c} accounts for the probability of survival after flooding the compartment or group of compartments under consideration.

In the considered methodology, the "s-factors" are assumed to be determined in accordance with the *GZ*-based methodology in SOLAS2009. On the other hand, factors p_{i_c} are determined by means of a direct, non-zonal approach. In this approach, on the basis of the probabilistic model for the damage characteristics, a sufficiently large number of breaches, each one with an associated probability of occurrence, are generated by a Monte Carlo procedure. For each breach, the corresponding compartments which become open to the sea are identified. Then, all breaches leading to the flooding of the same compartment, or group of compartments, are grouped into what are commonly referred to as "damage cases", and the probability contributions of each breach in each "damage case" are summed up to obtain estimates of p_{i_c}. "Non-contact cases" are disregarded and the remaining "p-factors" are renormalized in such a way that they sum up to unity. This renormalization is assumed to be acceptable as long as the fraction of generated non-contact breaches is small enough, which is achievable by a careful definition of the geometrical and probabilistic model of the considered damage (Bulian & Francescutto, 2012).

It is to be noted that the described direct procedure leads to an automatic determination of damage cases. Also, this fully automatic procedure does not need the preliminary "zonification" process, which is instead required when using analytical "p-factors", as in case of SOLAS2009. For such reason, this procedure can be referred to as "non-zonal". Furthermore, this procedure does not have any limitation regarding the actual shape of the compartments. Since the outcome from this procedure is affected by sampling uncertainty, the number of generated breaches must be large enough to achieve an acceptable convergence of the attained subdivision index. The general logic of the proposed direct non-zonal approach is shown in Fig. 1.

It should be highlighted that the proposed approach is a simplified one, intended to be in line with the SOLAS2009 framework. In particular, the approach is simplified in terms of survivability assessment ("s-factors"), which is assumed to be performed on the basis of a *GZ*-based static stability assessment. In case survivability is to be assessed by means of more advanced tools, such as time domain dynamic flooding simulations, then a survivability assessment should be carried out for each individual breach, and

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