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.

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

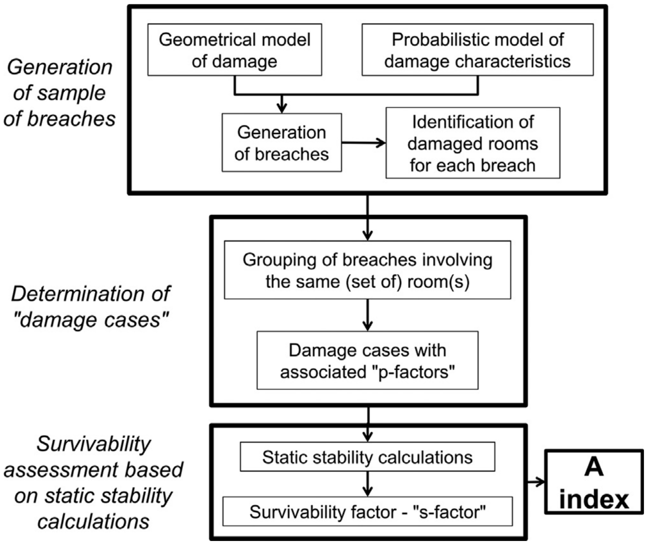

Fig. 1. General logic of the proposed direct non-zonal approach for damaged ship survivability assessment.

grouping in terms of "damage cases" is no longer possible. This latter approach, which was followed in the past by, e.g., Vassalos et al. (2008) (for grounding and collision) and by Spanos & Papanikolaou (2014) (for collision), is, however, much more time consuming, and more challenging to be applied in a regulatory framework. Furthermore, in case of dynamic flooding simulations, probabilistic models of damage characteristics which are specifically intended for such purpose should be used.

It is also worth noticing that, for consistency with SOLAS2009, the attained subdivision index in (1), which is then expected to be compared with a properly defined required subdivision index R, has been defined using three draughts. However, specifying requirements of the type $A \geq R$, provided separately for each draught, would allow removing the well-known arbitrariness in the identification of the limiting $\overline{GM}$ curve. Indeed, specifying requirements of the type $A \geq R$ for each draught, would lead to a unique identification of the limiting $\overline{GM}$ for each ship draught.

In principle, different "p-factors" should be calculated for each of the three draughts (subdivision, partial and light service draught). However, since the generation of the damage cases might be quite time consuming, particularly in case a very large number of hull breaches is to be generated, it was decided at this stage to generate the damage cases and calculate the corresponding "p-factors" only for the deepest subdivision draught d_s, and use the same "p-factors" and damage cases also for the partial subdivision draught d_p and the light service draught d_l. The methodology, however, can also be applied, without any problem, by considering draught dependent "p-factors".

3. Geometrical characterisation of damage

In order to apply the described direct non-zonal approach, it is first necessary to provide a clearly defined, unambiguous geometrical model for the type of damage to be considered. Herein, bottom damages, i.e. damages penetrating the bottom of the vessel in vertical direction, are considered. Such type of damages is conventionally referred to as "type B00". A sketch of this type of damages is shown in Fig. 2, while a detailed representation of the damage geometry, and defining parameters, is shown in Fig. 3. In Fig. 3 and in the following, the ship-fixed coordinate system is assumed to be right handed.

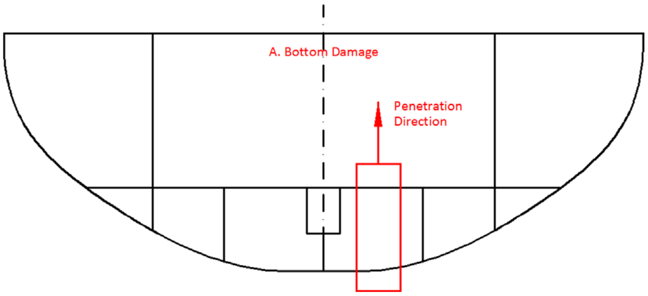

Fig. 2. Sketch of bottom damage.

The damage is assumed to be box-shaped. Moreover, the damage is assumed to be a "potential damage", i.e. a damage which can also partially extend, in some cases, outside the vessel. There are some main reasons for the selection of a box-shaped damage. The first reason is that significantly more complex modelling could not have been supported by the limited available information from accidents. Then, a box-shaped damage has favourable geometrical characteristics from the computational perspective. Finally, a box-shaped damage is more conservative, from the point of view of stability assessment, compared with other possible typical choices, such as, e.g. triangular or parabolic penetrations. With reference to Fig. 3, the defining parameters for a damage of type B00 are:

- Longitudinal position of forward end of damage: X_F [m];
- Transversal dimensionless position of centre of measured damage: $\eta_{dam} = Y_{dam}/b(X_F, z^*)$ [−];
- Longitudinal extent of potential damage, i.e. potential damage length: $L_{x,p}$ [m];
- Transversal extent of potential damage, i.e. potential damage width: $L_{y,p}$ [m];
- Vertical extent of potential damage, i.e. potential damage penetration: $L_{z,p}$ [m];
- Vertical position to be used for the transversal positioning of damage: z^* [m];

In the definition of η_{dam}, the quantity Y_{dam} [m] is the dimensional transversal position of the centre of the measured damage (not to be confused with the transversal position of the centre of potential damage, $Y_{dam,p}$ [m]). The quantity $b(X_F, z^*)$ [m] is the breadth of the vessel at a longitudinal position corresponding to the forward end of damage, X_F, and vertical position z^*. For the positioning of the damage, given the characterising variables, it is necessary that the software tool is able to determine the intersection between the section at X_F and a waterplane at $z = z^*$. Defining $y_{SB}(X_F, z^*)$ and $y_{PS}(X_F, z^*)$ as, respectively, the coordinates of the starboard and portside limits of $b(X_F, z^*)$, the quantity Y_{dam} is determined as:

$$\begin{cases} Y_{dam} = y_c(X_F, z^*) + \eta_{dam} \cdot b(X_F, z^*) \\ y_c(X_F, z^*) = \frac{y_{PS}(X_F, z^*) + y_{SB}(X_F, z^*)}{2} \\ b(X_F, z^*) = y_{PS}(X_F, z^*) - y_{SB}(X_F, z^*) \end{cases} \tag{3}$$

On the other hand, the quantity $Y_{dam,p}$ is defined as:

$$\begin{cases} Y_{dam,P} = Y_{dam} + \frac{sign(\delta)}{2} \cdot \max\{(L_{y,p} - L_{y,lim});0\} \\ \text{where} \\ \delta = Y_{dam} - y_c(X_F, z^*) \\ L_{y,lim} = \min\{2 \cdot (y_{PS}(X_F, z^*) - Y_{dam})\ ;2 \cdot (Y_{dam} - y_{SB}(X_F, z^*))\} \\ \text{Note}: \ sign(\delta < 0) = -1\ ;\ sign(\delta = 0) = 0\ ;\ sign(\delta > 0) = 1 \end{cases} \tag{4}$$

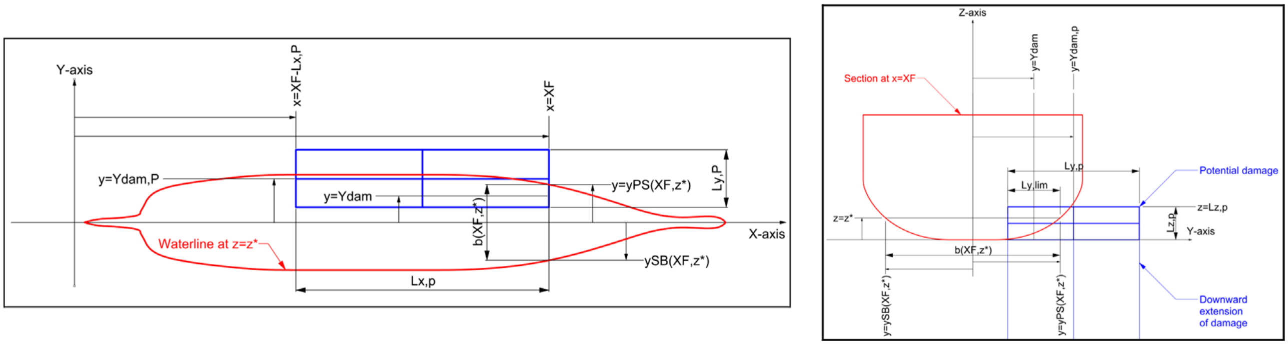

Fig. 3. Geometrical parameters characterising bottom damages (type B00).

If an intersection with the hull at $x=X_F$ and $z=z^*$ is not obtained, as could happen, for instance, for X_F in the very forward or very aft part of the vessel, and for small values of z^*, then $y_{SB}(X_F,z^*)$ and $y_{PS}(X_F,z^*)$ are to be set equal to 0. In case multiple intersections are found, then $y_{PS}(X_F,z^*)$ is set as the maximum y-coordinate among the intersections, and $y_{SB}(X_F,z^*)$ is set as the minimum y-coordinate among the intersections, in such a way that $b(X_F,z^*)$ represents the maximum breadth at $x=X_F$ and $z=z^*$.

The above mentioned geometrical characterisation (in particular the transversal positioning of the damage) has been devised with the intention of reducing the occurrence of "non-contact damages", i.e. generated damages which, eventually, do not get in contact with the hull of the vessel.

4. Probabilistic model of damage characteristics

In order to develop a probabilistic model for the damage, it is necessary to introduce a probabilistic characterisation for the variables, described in the previous section, which are used to specify the generic breach.

The primary interest of this study is to provide a methodology suitable, in particular, for the survivability assessment of passenger vessels. To this end, herein reference is made to the distribution of bottom damage characteristics as determined in the GOALDS project for the category of non-full vessels (Bulian & Francescutto, 2011; Papanikolaou et al., 2011). Such distributions have been derived from the analysis of the GOALDS database of grounding damage characteristics. It is to be noted that, in case of accidents resulting in multiple breaches, as it is common in case of grounding, the damage characteristics as analysed in GOALDS refer to an "equivalent damage" (Papanikolaou et al., 2011; IMO, 2012). An "equivalent damage" is a single box-shaped breach which is meant to represent, only for the purpose of static stability calculations, the region of the vessel actually damaged by multiple breaches.

The considered distributions are reported analytically in Table 1–5. Graphical representations of the corresponding cumulative distributions are reported in Fig. 4–8. Damages are assumed to be generated such that the forward end of the damage, X_F, is distributed between X_{MIN} and $X_{MAX}=X_{MIN}+L_{ship}$. For application to real vessels, and in order to reduce the fraction of non-contact cases, it is suggested, at this stage, to set X_{MIN} and X_{MAX} at the extremities of the freeboard length of the vessel as specified by the International Convention on Load Lines (IMO, 2014c). For simplicity of notation, in specifying the distribution for X_F (see Table 1), it is assumed that $X_{MIN}=0$. In addition, for simplicity of notation, in specifying the distribution for the damage penetration (see Table 5), the vertical position of the ship bottom is assumed to be at $z_{bottom}=0$. It is also noted that, while in GOALDS the distribution of Y_{dam} (see Table 2) was assumed to be uniform in $[-B/2, B/2]$ (with B the ship breadth), herein the ship breadth B is substituted by the local ship breadth $b(X_F,z^*)$, and Y_{dam} is assumed to be uniformly distributed, according to the local breadth, in $[-b(X_F,z^*)/2, b(X_F,z^*)/2]$. Moreover, in the actual generation of the damages, the vertical position for the transversal positioning of damage, i.e. z^*, is assumed to coincide with the top of the potential damage box, i.e. $z^*=z_{bottom}+L_{z,p}$.

Table 1
Distribution of dimensionless longitudinal position of forward end of damage.

Dimensionless longitudinal position of forward end of damage $\xi_{F,dam}=X_F/L_{ship}$, $\xi_{F,dam}\in[0,1]$	
$CDF(x)$	$\alpha_1\cdot x+(1-\alpha_1)\cdot x^{\alpha_2}$
$PDF(x)$	$\alpha_1+\alpha_2\cdot(1-\alpha_1)\cdot x^{(\alpha_2-1)}$
α_1	0.325
α_2	3.104

Note: Here X_F is intended to be measured starting with $X_F=0$ at X_{MIN}, and $L_{ship}=X_{MAX}-X_{MIN}$.

Table 2
Distribution of dimensionless transversal position of centre of measured damage.

Dimensionless transversal position of centre of measured damage $\eta_{dam}=Y_{dam}/b(X_F,z^*)$, $\eta_{dam}\in[-0.5,0.5]$	
$CDF(x)$	$x+0.5$
$PDF(x)$	1

Note: Ship centreplane is assumed to be at $y=0$

Table 3
Distribution of dimensionless longitudinal extent of potential damage (potential damage length).

Dimensionless potential damage length $\lambda_{x,p}=L_{x,p}/L_{ship}$, $\lambda_{x,p}\in[0,1]$	
$CDF(x)$	$\frac{\alpha_1\cdot x^2+\alpha_2\cdot x}{x+(\alpha_1+\alpha_2-1)}$
$PDF(x)$	$\frac{\alpha_1\cdot x^2+(\alpha_1+\alpha_2-1)\cdot(2\cdot\alpha_1\cdot x+\alpha_2)}{[x+(\alpha_1+\alpha_2-1)]^2}$
α_1	0.231
α_2	0.845

Table 4
Distribution of dimensionless transversal extent of potential damage (potential damage width).

Dimensionless potential damage width $\lambda_{y,p}=L_{y,p}/B$, $\lambda_{y,p}\in[0,1]$	
$CDF(x)$	$\frac{\alpha_1\cdot x^2+\alpha_2\cdot x}{x+(\alpha_1+\alpha_2-1)}$
$PDF(x)$	$\frac{\alpha_1\cdot x^2+(\alpha_1+\alpha_2-1)\cdot(2\cdot\alpha_1\cdot x+\alpha_2)}{[x+(\alpha_1+\alpha_2-1)]^2}$
α_1	0.110
α_2	0.926

Table 5
Distribution of dimensional vertical extent of potential damage (potential damage penetration), measured from baseline. Ship-size-dependent model.

Dimensional potential damage penetration $L_{z,p}$ [m], $L_{z,p} \in \left[0, L_{z,p,\ \max}\right]$	
$CDF(x)$	$\frac{\alpha_1 \cdot x}{x + L_{z,p,\ \max} \cdot (\alpha_1 - 1)}$
$PDF(x)$	$\frac{L_{z,p,\ \max} \cdot \alpha_1 \cdot (\alpha_1 - 1)}{\left[x + L_{z,p,\ \max} \cdot (\alpha_1 - 1)\right]^2}$
Parameters	$\alpha_1 = 1.170; \alpha_B = 0.636$; $k_{MB} = 0.503$; $L_{z,p,\ \max}(B) = \min\{k_{MB} \cdot B^{\alpha_B}, T\}$ with B in $[m]$

Note: This is the distribution of the damage penetration measured from the bottom, fixing the vertical position of the bottom, conventionally, at $z_{bottom} = 0$.

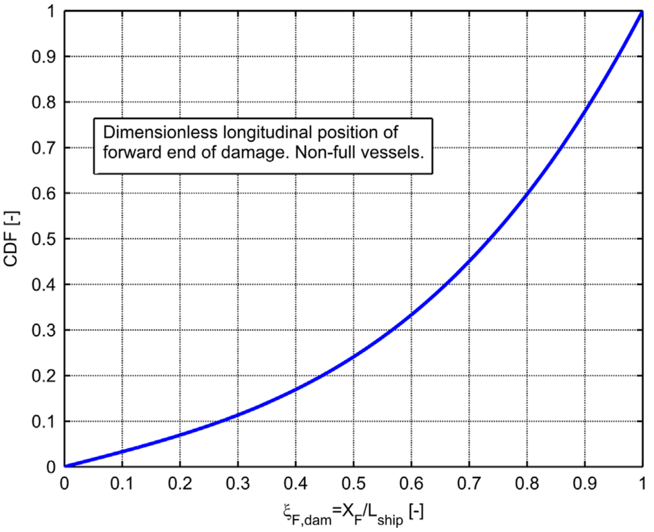

Fig. 4. Plot of cumulative distribution of dimensionless longitudinal position of forward end of damage.

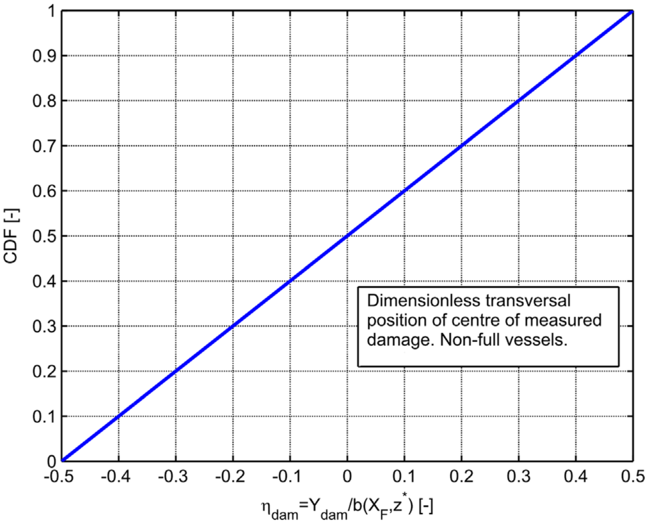

Fig. 5. Plot of cumulative distribution of dimensionless transversal position of centre of measured damage.

All damage characteristics are assumed to be independent random variables. In the framework of a regulatory assessment this is considered to be an acceptable approximation, although it can lead, with low probability, to the occurrence of damage boxes with high aspect ratios. It is however easy to introduce limitations in this respect, if deemed necessary.

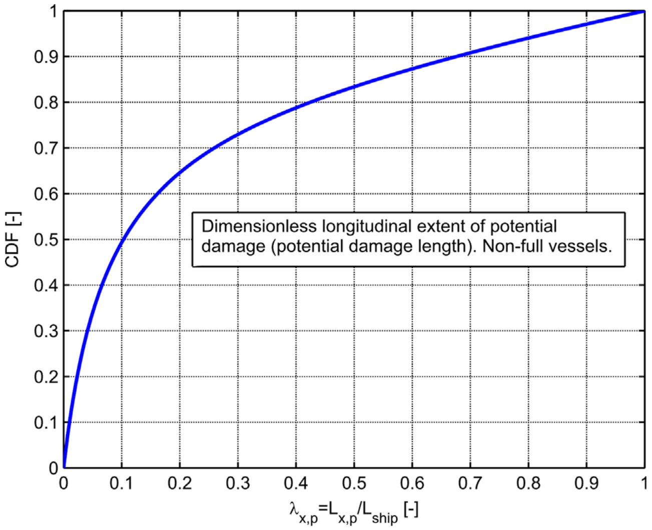

Fig. 6. Plot of cumulative distribution of dimensionless longitudinal extent of potential damage (potential damage length).

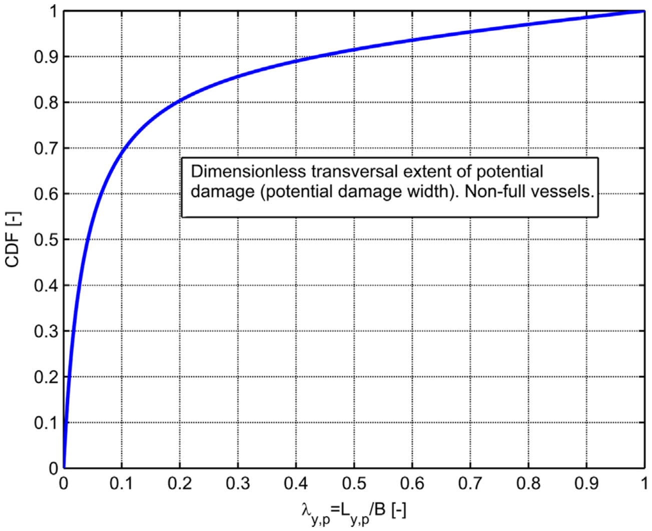

Fig. 7. Plot of cumulative distribution of dimensionless transversal extent of potential damage (potential damage width).

5. Implementation and example results

The described approach has been implemented in a dedicated software tool within the NAPA software environment. A series of successful initial verification cross-checks of the NAPA tool have been carried out regarding the generation of damages and the determination of "p-factors" using an in-house tool available at University of Trieste. The developed tool within the NAPA software environment was designed to be easy to use for practical application purposes, still retaining a sufficient flexibility for research applications. With reference to practical (design) applications, the developed tool allows a user, in a fully automated way, to generate breaches, to determine damage cases and associated "p-factors" and, eventually, to calculate the attained subdivision index. Furthermore, batch processing is possible, in order to more easily handle repeated or multiple calculations. Presently the tool allows to handle bottom damages ("type B00"), as well as side grounding

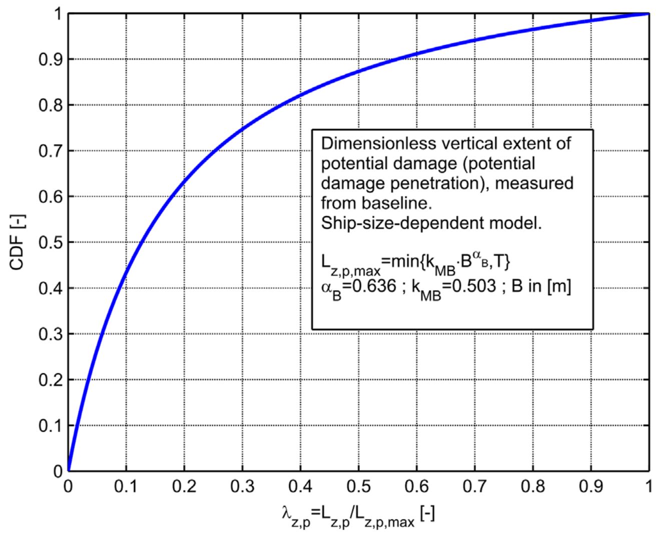

Fig. 8. Plot of cumulative distribution of dimensionless vertical extent of potential damage (potential damage penetration), measured from baseline. Ship-size-dependent model.

Table 6
Main characteristics of the test barge.

Length	100 m	d_s	4.0 m
Breadth	16 m	d_p	3.6 m
Total height	10 m	d_l	3.0 m
Assumed number of passengers	750	Height of double bottom	1.6 m

damages (“type S00”). This latter type of damage is however not discussed in this paper.

Herein the developed approach has been applied through the NAPA tool on a simplified example case. The scope of the example calculations was, firstly, to provide a reference example for comparative purposes, and, secondly, to assess the typical level of dispersion which can be expected for the A-index when applying the described procedure.

To this end, a notional vessel was developed which is simple enough for software verification purposes, and which can be easily and freely reproduced. The considered test vessel is a barge having a box-shaped hull and box-shaped internal compartments. The main characteristics of the barge are reported in Table 6, while a view of the general arrangement is shown in Fig. 9.

The barge has a total length of 100 m (starting from $x = -4$ m up to $x = 96$ m), a breadth of 16 m and a total height of 10 m. The barge has a double bottom with height equal to 1.6 m. A horizontal deck (the bulkhead deck) is positioned 6 m above the ship bottom. The deepest subdivision draught is set to 4 m, while the light draught is set to 3 m, this leading to a partial subdivision draught according to SOLAS of 3.6 m. A series of transversal bulkheads are fitted, which extend from the ship bottom up to the bulkhead deck. The transversal bulkheads are uniformly spaced at a distance of 10 m from each other, leading to a total of 10 zones. With the exception of the extreme aft and forward zones, the double bottom is longitudinally subdivided, leading to central compartments of 6 m in width and wing compartments of 5 m in width on each side. In the extreme aft and forward zones the double bottom extends from side to side. Eventually, this leads to a total of 26 rooms in the double bottom, 10 rooms immediately above the double bottom and a single room above the deck up to the maximum height, summing up to a total of 37 rooms. In this example case the permeability of all rooms has been taken as 0.95.

Each room in the double bottom is associated with an unprotected opening, which becomes relevant in the s-factor calculation whenever the associated compartment belong to the considered damage case. Such openings are meant to represent overflow vents, and are modelled in NAPA as one-way connections from the associated double bottom room to the uppermost room. Unprotected openings are all vertically positioned at 7.5 m above the ship bottom, and longitudinally positioned at the centre of the associated room. For the central double bottom rooms, and for double bottom rooms extending from side to side, the opening is also transversally positioned at the centre of the room, which coincides with the ship centreline. On the other hand, for wing compartments, the openings are positioned at 0.5 m from the ship side, i.e. at $y = 7.5$ m or $y = -7.5$ m, for port or starboard side double bottom wing compartments, respectively. Unprotected openings are reported in Fig. 9 as small square marks. It is worth recalling that unprotected openings have an effect on the attained subdivision index, through the s-factor, since the $\overline{GZ}$ curve contributes in the s-factor calculation until the relevant openings (if any) are immersed.

For the considered test vessel, the attained subdivision index $A_{GR,B}$ has been calculated according to (1). Damages have been generated considering a length of the ship equal to the overall length of the barge ($X_{MIN} = -4$ m, $X_{MAX} = 96$ m, $L_{ship} = 100$ m-See Table 1 and Table 3). An increasing number of generated breaches have been considered, namely: 10^3, 10^4 and 10^5. For each case, a series of 20 different repetitions have been run, and for each repetition the index $A_{GR,B}$ has been determined.

In the determination of $A_{GR,B}$, the “s-factor” has been calculated according to SOLAS Regulation 7–2 (IMO, 2014a), considering only the final stage of flooding. Only the final stage of flooding has been considered because the test vessel has a layout of compartments which is characterised by unrestricted spaces not limiting the flooding, which can therefore be considered as instantaneous. Furthermore, this also simplifies possible comparisons with the calculations reported herein. Heeling moments due to passengers on one side (750 passengers, of 75 kg each, at 7.2 m from centreline) and due to wind (according to SOLAS) have been considered in the determination of the “s-factor”, whereas the moment due to the launching of survival craft has been neglected. For the sake of the present testing, the same metacentric height, $\overline{GM} = 2.0$ m, has been used for all three calculation draughts.

Results from the described example calculations are shown in Fig. 10. Black squares represent the attained subdivision index $A_{GR,B}$ as obtained from each single repetition, for the different numbers of generated breaches. Superimposed, the curve of the average index among the available repetitions is also reported. Around the average index, an approximate simplified Gaussian confidence band is shown, which extend for $\pm 2\sigma_A$, with σ_A being the standard deviation of $A_{GR,B}$ as estimated from the available repetitions, for each number of breaches. This band is to be interpreted as a simplified approximate region within which the outcome from a single run will lie, with approximately 95% probability. If the A-index is averaged among different repetitions, the confidence band for the averaged index decreases by the square root of the number of repetitions.

From a practical point of view, the results in Fig. 10 provide indications regarding the number of breaches to be used in order to obtain a given accuracy for $A_{GR,B}$. Alternatively, they provide information regarding the confidence in the estimated A-index. For instance, when 10^4 breaches are used for the example case, σ_A is estimated as $1.65 \cdot 10^{-3}$. This means that, if a single repetition is considered, then, with approximately 95% confidence, the true attained index is in an interval of $\pm 3.30 \cdot 10^{-3}$ around the obtained $A_{GR,B}$. In case the index is obtained by averaging, e.g., five repetitions, then the expected 95% confidence interval around the

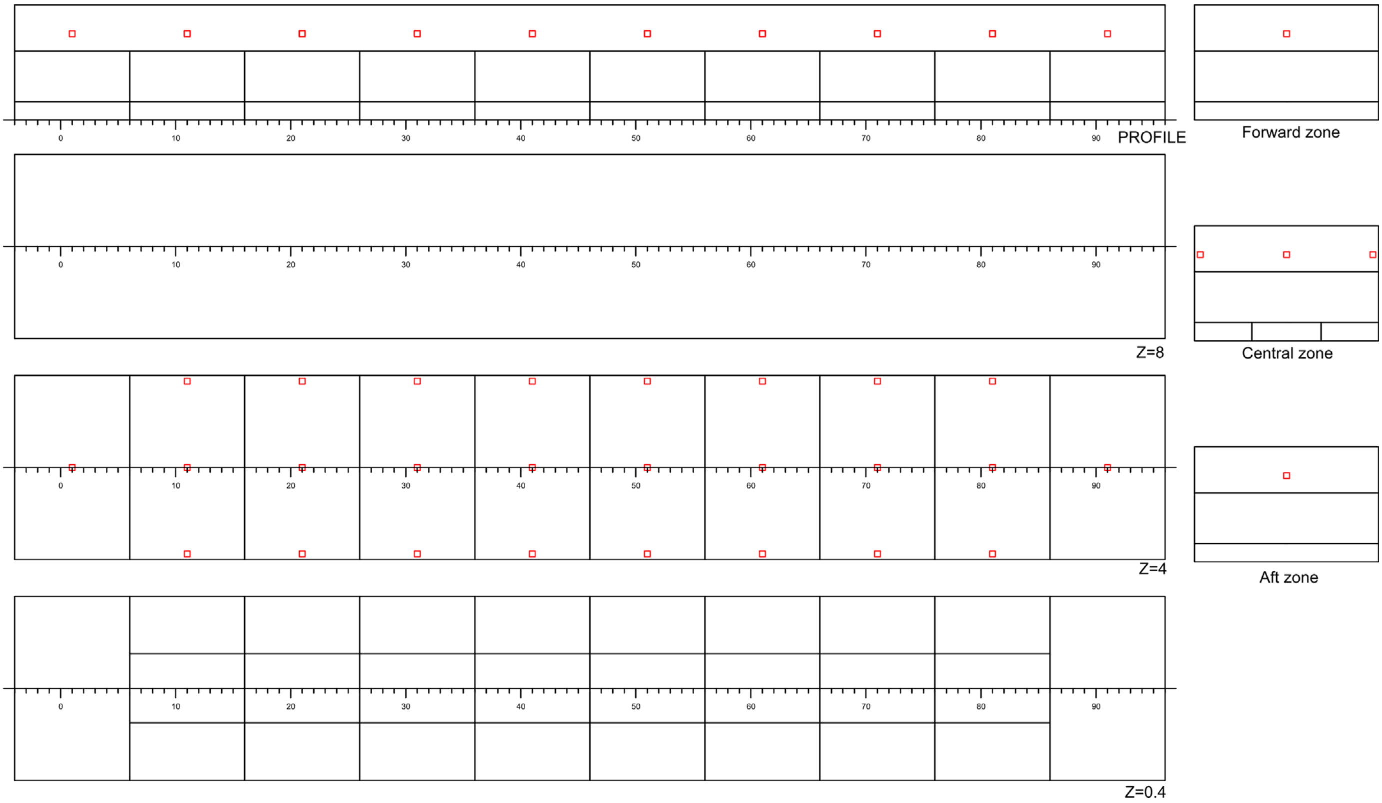

Fig. 9. Layout of the test barge. Small squares mark the positions of one way unprotected openings.

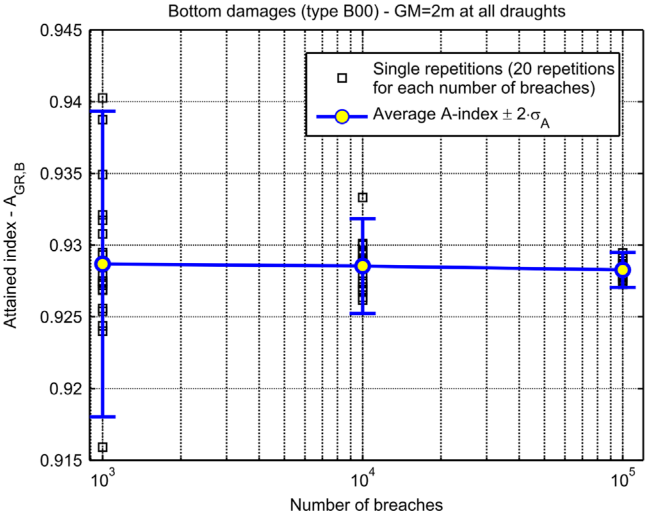

Fig. 10. Example calculations for $A_{GR,B}$.

Table 7
A-index and partial A-indices.

Number of breaches: 10^5 Number of repetitions: 20	$A_{GR,B}$	$A_{GR,B,l}$	$A_{GR,B,p}$	$A_{GR,B,s}$
Average A-index	0.92830	0.91098	0.93155	0.93370
Estimated standard deviation σ_A	0.00061	0.00074	0.00059	0.00059

obtained average reduces to $\pm 3.30 \cdot 10^{-3}/\sqrt{5} = \pm 1.48 \cdot 10^{-3}$. From the perspective of practical applications, the obtained results indicate that calculations based on the generation of 10^4 breaches can be considered to provide an acceptable level of accuracy, particularly when using multiple repetitions. It can therefore be preliminary suggested to carry out a series of five repetitions, with 10^4 breaches for each repetition.

As an additional information, Table 7 provides numerical values for the average value and for the standard deviation of the attained index for the case with the smaller dispersion, i.e. the case with 10^5 generated breaches. The values of the partial indices are also reported, from which it can be noticed that, in the considered case and under the considered assumptions for the loading conditions, the partial index increases with the draught. The average value of the estimated A-index is 0.92830, and this value is partially dictated by the presence of the assumed unprotected openings. As a comparison, in the same calculation conditions, the average estimated A-index is 0.96759 and the standard deviation of the A-index is 0.00036 when unprotected openings are not taken into account.

6. Final remarks

In this paper, a probabilistic approach has been presented for the regulatory assessment of damaged ship survivability following a grounding accident. The presented approach is flexible and easily updatable. Furthermore, the essence of the described approach was designed to be in line with existing SOLAS2009 probabilistic regulations dealing with survivability following a collision. As a result, this potentially allows for a harmonization within the existing SOLAS framework.

The main difference between the described approach and present SOLAS2009 regulations resides in the way the “p-factors” are determined.

Indeed, SOLAS2009 uses analytical expressions for the determination of “p-factors”. Such expressions have been developed, and are strictly valid, only in case of box-shaped vessels with orthogonal subdivision, which is clearly not the case for most real vessels. Their practical application to real vessels is hence approximate, and it requires, in addition, the so-called "zonification" of the vessel, combined with explanatory notes aimed at specifying how to address compartments having complex (non-box-shaped) layouts. Furthermore, the analytical expressions for the determination of "p-factors" are strongly tied with the underlying distributions for the assumed damage characteristics, which do not appear explicitly in the regulations. As a result, although the "zonal approach" is fast and practical, it is inherently approximate and difficult to update. While its application in case of collision has been considered sufficiently accurate, the same cannot be said in case of damages due to grounding.

To take a step forward with respect to the present situation, the approach presented herein is based on the idea of determining the "p-factors" using a direct non-zonal approach. In such an approach, as a first step, the geometrical model of the damage is clearly described. Then, appropriate distributions are specified for the damage characteristics. These two elements lead to a fully characterised, transparent and easily updatable probabilistic model for the position and extent of the damage. This explicit model is then used to generate a sufficiently large number of breaches on the vessel. Collecting breaches leading to the same set of damaged compartments allow to automatically determine what are commonly called "damage cases" together with their associated "p-factors" (probability of occurrence). The occurrence of non-contact cases is addressed by proper renormalization of "p-factors". Combining the obtained "p-factors" with the "s-factor" calculated, for instance, according to SOLAS, for each "damage case", and for each calculation draught, it is eventually possible to arrive at an attained survivability index. This index is intended to represent the survivability of the vessel following a grounding accident. The number of generated breaches needs to be large enough to achieve sufficient convergence of the attained index.

Once the geometrical model of the damage is clearly and properly described, hopefully limited explanatory notes regarding the application of the methodology are necessary, and the methodology is able to handle any compartment shape. Moreover, this approach can be easily updated in terms of underlying geometrical damage model and associated probability distributions, since no explicit analytical expressions, which in the general case cannot be obtained without essential simplifications, are to be developed for the determination of "p-factors". When new, or better, probabilistic damage models, or new, or better, probability distributions for the characteristics of existing damage types become available, they can simply substitute the existing ones in the calculation code, together with the generation procedure for the breaches (if this needs to be modified). The software tool and its underlying logic (which is actually very simple) remain exactly the same. Such flexibility and ease of update can be exploited in a number of ways: periodic update of the regulations, alternative design assessment taking into account structural effects, ship-specific damage models, model tuning based on direct structural calculations, specific damage models for implementation into dynamic flooding simulations, just to mention a few possibilities.

In this paper, an example has been reported for the case of bottom grounding damages. However, the same procedure and software tool can be used, and have been developed, also for the case of grounding damages to the side of the vessel, extending partially or totally above the double bottom. In addition, the same procedure and software tool could be applied also to the case of collision, provided some updates are introduced in the current SOLAS framework. It is also important to note that this procedure is not totally new for the IMO regulatory framework. In fact, a procedure very close to the one reported herein, is already at the basis of the alternative assessment of accidental oil outflow performance or of double hull and double bottom requirements within MARPOL. As a result, almost the same software tool and logic could be applied also to such cases.

Preliminary testing of the described framework have shown that the number of breaches to be generated in order to achieve a sufficient convergence of the attained subdivision index is reasonable enough to render the approach practical for engineering purposes.

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