Considering collision, bottom grounding and side grounding/contact in a common non-zonal framework

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ABSTRACT

One of the objectives of the eSAFE project was to develop a holistic probabilistic methodology, as well as an associated NAPA software functionality, for assessing post-damage ship survivability combining, through a sound and consistent generalised approach, collision, bottom grounding and side grounding/contact damages. This paper provides a summary overview of some main outcomes in this respect, namely: the development of a non-zonal approach for collision starting from, and extending, the SOLAS framework; the development and critical analysis of alternative approaches for considering the different attained indices from collision, bottom grounding and side grounding/contact damages; the practical implementation and testing of the framework.

Keywords: *eSAFE, damage stability, non-zonal approach, collision, grounding, contact, SOLAS.*

1. INTRODUCTION

The key objective of the eSAFE activity overviewed in this paper was to develop a holistic probabilistic methodology, as well as an associated NAPA software functionality, for assessing post-damage ship survivability combining, through a sound and consistent generalised approach, collision, bottom grounding and side grounding/contact damages.

During the EMSA 3 study, a probabilistic method was developed, implemented in a software tool and tested on real designs, for addressing survivability following bottom grounding and side grounding/contact in case of passenger vessels (Zaraphonitis et al., 2015; Bulian et al., 2016). The method was based on a non-zonal approach where: a) breaches are directly generated on the basis of the underlying geometrical and probabilistic model for the damage extent; b) "damage cases" are automatically created from the identification of breached compartments; c) associated probabilities of flooding are estimated by collecting the probability contribution from breaches leading to the same "damage case". Survivability for each damage case can then be determined through the usual s-factor, and attained indices are eventually obtained for each calculation draught and corresponding loading condition.

The non-zonal method developed in EMSA 3 has been extended in eSAFE in order to address also collision damages, keeping consistency with present SOLAS (IMO, 2019a). In this context, it was necessary to develop a probabilistic model for the lower edge of the damage, which is missing in the present SOLAS framework (Bulian et al., 2017, 2018). This development, combined with a clear geometrical description of the geometry of the breach, allowed to develop a non-zonal approach for collision, which could be used alongside those for grounding/contact.

Then, approaches were explored for defining safety metrics in order to combine survivability in case of collision, bottom grounding, and side grounding/contact (Zaraphonitis et al., 2017). To this end, reference has been made to statistical analysis of accidents data and to existing risk-models (Konovessis et al., 2015; Zaraphonitis et al., 2015).

Based on the findings, a new functionality for practical implementation of the non-zonal approach has been made available in NAPA (Lindroth et al., 2017), and the tool has been tested within eSAFE to gain experience and provide feedback.

A procedure for calculation and reporting of results was also envisaged which takes into account the presence of random sampling uncertainty in the application of the non-zonal approach (Zaraphonitis et al., 2017).

This paper provides a summary overview of some main outcomes of the mentioned activity, which is summarised also by (Luhmann et al., 2018a,b). In the following, section 2 provides a summary regarding the development of the non-zonal approach for collision. Afterwards, section 3 summarises the different approaches which have been considered in order to try addressing collision, bottom grounding, and side grounding/contacts in a common framework. Section 4 then provides an overview of the software implementation. Section 5 shows some examples from the testing and application. Finally, section 6 reports some summarising conclusions.

2. NON-ZONAL APPROACH FOR COLLISION

Present damage stability framework in SOLAS Ch.II-1 (IMO, 2019a) allows determining the probabilities of flooding of a compartment (or group of compartments) by using p-, r- and v-factors (SOLAS/II-1/B-1/7-1, SOLAS/II-1/B-1/7-2). In particular, p-factor accounts for transversal subdivision defining so-called “zones”, and this is why the SOLAS approach can be shortly referred to as “zonal”. The analytical formulae for such factors embed the probability distributions of collision damage characteristics (position, length, penetration and vertical extent above waterline) assumed by SOLAS.

It is very well-known that the basic ideas leading to present SOLAS originated from the HARDER project, and are documented in details in HARDER-related documentation (see Lützen (2001, 2002)). Nevertheless, following the HARDER project, some modifications regarding damage distributions have been introduced during the discussion at IMO, leading to the final formulation, as embedded in present SOLAS regulation.

SOLAS, however, does not provide a distribution for the lower limit of vertical extent of damage. Instead, SOLAS uses a “worst-case approach” (often referred to as “damages of lesser extent”), where a systematic variation of the lower limit of damage is carried out in the calculations to find the damage case giving the least s-factor when there are horizontal subdivision boundaries below the waterline (SOLAS/II-1/B-1/7-2/6.2). This approach, by its very nature, is conservative, as it leads to a systematic conservative estimation of the attained subdivision indices (Zaraphonitis et al., 2017; Bulian et al., 2018).

In the EMSA 3 project a different methodology was proposed for addressing bottom grounding and side grounding/contact (Zaraphonitis et al., 2015; Bulian et al., 2016), which was referred to as “non-zonal”. In the “non-zonal” approach, single breaches are generated using a Monte Carlo procedure based on the distributions of damage characteristics. Each individual breach will lead to the flooding of a certain (set of) room(s), which represents what is usually called a “damage case”. Summing up the probabilities associated to all breaches leading to the same damage case, it is possible to estimate the probability of occurrence of each damage case. This can then be directly used in the calculation of A-indices. The logical flow of the non-zonal approach is outlined in Figure 1.

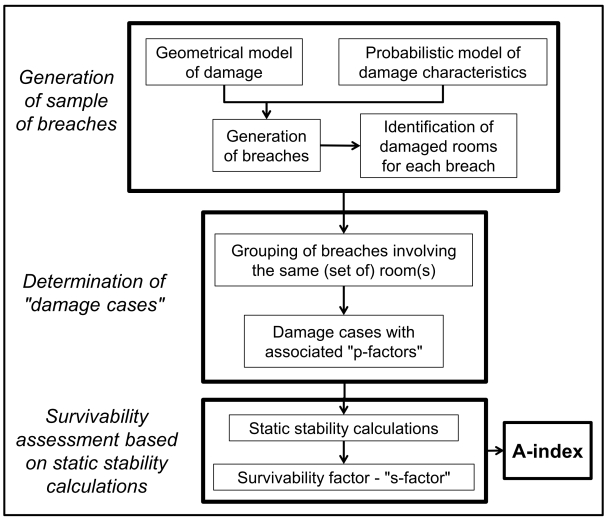


Figure 1: Logic of non-zonal approach.

A schematic graphical representation of the principle of the non-zonal approach is shown in Figure 2. The figure shows different breaches, and different colours identify the (set of) breach(es) leading to the same damage case.

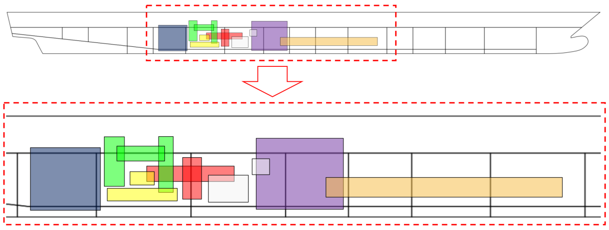


Figure 2: Schematic graphical representation of the principle of non-zonal approach. Top: full longitudinal view. Bottom: zoom of the region where example breaches are shown.

During eSAFE, the EMSA 3 non-zonal approach was extended to cover also collision damages, keeping, as main target, the highest possible consistency with existing SOLAS framework.

To this end, the following main aspects were addressed (Bulian et al., 2017):

- Explicit definition of the geometrical model for collision damages;
- Generation of collision damages using the distributions for damage characteristics according to SOLAS background;
- Development of a probabilistic model for the lower limit of vertical extent of damage, not available from SOLAS.

The geometrical model for collision damage (conventionally referred to as damage of type “C00” in eSAFE) was defined according to the following characteristics:

- The damage penetration is measured orthogonally to the ship’s centre plane;
- The longitudinal extent of damage (damage length) is measured parallel to the ship’s longitudinal axis;
- The vertical damage extent is measured along the vertical direction;
- The horizontal section (profile) of the damage follows the waterline at the actual calculation draught. As a result, the damage, in general, is not box shaped.

In addition, for consistency with SOLAS (IMO, 20018, 2017), collision damages have been defined to be always crossing the calculation waterline. This means that the upper limit of damage is always above the waterline, and the lower limit of damage is always below the waterline, for each calculation draught.

The distributions of all relevant damage characteristics were taken from the analysis of the SOLAS background, with the exception of the lower limit of damage. In particular (Bulian et al., 2017):

- Damage side: 50% probability on each side, unless the damage side is specified in the calculations.
- Longitudinal position of centre of the extent of damage within the limits of the ship length, X_C: uniformly distributed along the ship length.
- Longitudinal extent of damage (potential damage length), $L_{x,p}$: bilinear probability density function, with characterising coefficients b_{11}, b_{12}, b_{21} and b_{22} (see Lützen (2001, 2002)) from SOLAS/II-1/B-1/7-1/1.1.
- Transversal extent of damage (potential damage penetration), $L_{y,p}$: truncated trapezoidal distribution depending on potential damage length. The cumulative distribution function, before truncation, corresponds to the function $C\left(\bar{z}\right)$ reported by Lützen (2001, 2002).

- Vertical position of upper limit of damage above the waterline, $z_{UL,p} - d$: the cumulative distribution function corresponds to the SOLAS v-factor.

The damage is defined as a potential damage, this meaning that it can also partially extends outside of the vessel.

For consistency reasons, the “ship length” to be considered in the calculations has been taken as the subdivision length of the ship according to SOLAS.

Two points required particular attention in order to derive a methodology consistent with existing SOLAS.

The first point concerned the proper positioning of the damage, given X_C and $L_{x,p}$, in order to be consistent with the analytical and theoretical formulation of zonal SOLAS p-factors for compartments at the extremities of the ship length (Lützen, 2001, 2002; Pawłowski, 2004). When the damage is fully contained within the ship length, the longitudinal coordinate X_C corresponds to the centre of damage. However, if the potential damage partially extends outside the vessel, this is no longer the case, and the longitudinal coordinate of the midpoint of the potential damage differs from X_C (Bulian and Francescutto, 2010; IMO, 2012). The procedure for the longitudinal positioning of the damage is graphically reported in Figure 3.

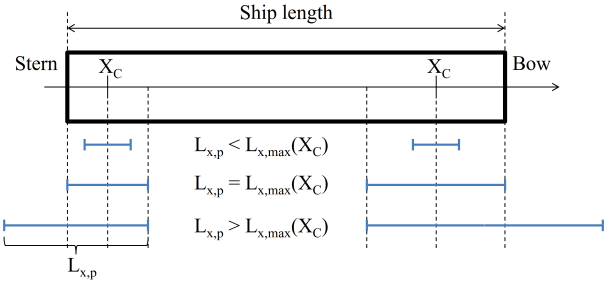


Figure 3: Graphical representation of longitudinal positioning of collision damage.

The second point of attention concerned the proper generation of the potential damage penetration $L_{y,p}$, in order to be consistent with the zonal SOLAS r-factor. The absolute maximum damage penetration according to SOLAS is B/2, where B is the ship breadth, and this limit is directly embedded in the function $C\left(\bar{z}\right)$ reported by Lützen (2001, 2002), and already mentioned before. However, in addition, the SOLAS framework also implicitly assumes that the ratio between the dimensionless damage penetration and the dimensionless damage length cannot exceed 15 (Lützen, 2001, 2002; Pawłowski, 2004; Bulian and Francescutto, 2010; IMO, 2012). Different equivalent approaches can be used to generate the penetration of damages consistently with the truncation embedded in SOLAS. The following algorithm is an example:

1) Firstly, the potential damage length $L_{x,p}$ is generated.
2) The corresponding maximum potential damage penetration $L_{y,p,\max}$ is then determined as $L_{y,p,\max} = \left(15 \cdot B / L_S\right) \cdot L_{x,p}$, where B is the ship breadth and L_S is the ship length.
3) Then, a “raw” potential damage penetration $L_{y,p,raw}$ is generated according to the non-truncated trapezoidal distribution associated with $C\left(\bar{z}\right)$.
4) Finally, if $L_{y,p,raw} < L_{y,p,\max}$ the potential damage penetration $L_{y,p}$ is taken as $L_{y,p} = L_{y,p,raw}$, otherwise $L_{y,p}$ is taken as $L_{y,p} = L_{y,p,\max}$.

As SOLAS does not provide a probabilistic model for the extent of damage below the waterline, it was necessary to specifically develop one to be embedded in the non-zonal approach. The development of a probabilistic model for the lower limit of vertical extent of damage was based on the analysis of historical accident data. To this end, use has been made of data from the HARDER accidents database as updated in the GOALDS project (Mains, 2010; Bulian and Francescutto, 2010; IMO, 2012). As the underlying distributions of collision damage characteristics in SOLAS is common to passenger and cargo vessels, historical accidents data from both passenger and cargo ships were considered in the analysis. Data from the database were filtered in three stages. Firstly, data were filtered consistently with the HARDER approach, as done in GOALDS (Bulian and Francescutto, 2010; IMO, 2012), by extracting damages due to ship-ship collisions where the damaged vessel is the struck one. After this, a subsequent filtering was applied, in order to remove some few cases which appeared as having inconsistent data. Then, for consistency with SOLAS (IMO, 2008), the final set of data was extracted by retaining only those cases with sufficient information to unambiguously identify damages crossing the waterline. The final filtered dataset which was eventually used for the analysis comprised a total of 152 samples. More information on the filtering have been reported by Bulian et al. (2017, 2018).

Two probabilistic models for the lower limit of damage below waterline with different levels of complexity were developed, discussed, implemented in the non-zonal approach, and compared (Bulian et al., 2017; Lindroth et al., 2017). One of the two models was eventually selected for describing the vertical position of lower limit of potential damage from the ship bottom, $z_{LL,p}$. The model considers $z_{LL,p}$ to be statistically independent of the other damage characteristics, and to have the following cumulative distribution (Bulian et al., 2017, 2018):

$$\begin{cases} CDF\left(z_{LL,p}\right) = 1.4 \cdot \frac{z_{LL,p}}{d} - 0.4 \cdot \left(\frac{z_{LL,p}}{d}\right)^2 \\ z_{LL,p} \in \left[0, d\right] \end{cases} \quad (1)$$

where d is the actual calculation draught. This model can then be used for describing, and hence generating $z_{LL,p}$ in the non-zonal approach.

It is noted that this probabilistic model also allows to easily define a “u-factor” which can be directly embedded in the existing SOLAS zonal framework (see Bulian et al. (2017, 2018) for details).

The developed non-zonal approach was implemented in a NAPA software functionality, and it was successfully verified through comparisons with SOLAS zonal calculations (Bulian et al., 2017; Lindroth et al., 2017; and see section 5).

3. SAFETY METRICS FOR THE COMBINED IMPACT OF COLLISION, BOTTOM GROUNDING AND SIDE GROUNDING/CONTACT

For each type of accident (collision, bottom grounding, side grounding/contact), a corresponding attained subdivision index (A-index) can be obtained from damage stability calculations, namely:

- For collision: A_{CL};
- For bottom grounding: A_{GR-B};
- For side grounding/contact: A_{GR-S}.

The three mentioned A-indices represent ship survivability, separately, in case of specific types of accidents. However, a measure is needed in order to provide a combined quantification of the ship safety. To this end, two different methods to derive a measure of ship survivability, covering all three accident types, have been considered:

- A risk-based safety metric, directly related to societal risk;
- A probability-/survivability-based safety metric, based on the relative frequencies of different types of accident.

The metrics defined by the two approaches share the characteristic that they can be determined as weighted combinations of individual A-indices corresponding to different types of accidents.

Risk-based safety metric - SM

The fundamental ideas and assumptions behind the developed risk-based safety metric have been anticipated in the EMSA 3 project (Konovessis et al., 2015; Vassalos et al., 2015; Zaraphonitis et al., 2015), and are as follows:

- With reference to consequences from flooding accidents, the total societal risk which is accounted for is given by the sum of the risk due to collision, the risk due to bottom grounding, and the risk due to side grounding/contact;
- The risk is measured through the "Potential Loss of Life (*PLL*)", i.e. the expected number of fatalities per ship-year (which, if needed, can be transformed to ship-life);
- The reference risk models which have been used are those developed in the EMSA 3

study and which are relevant for cruise ships.

Starting from the risk models developed in the EMSA 3 study (Konovessis et al., 2015; Zaraphonitis et al., 2015), the potential loss of life (*PLL*) associated with each type of accident can be determined as follows:

$$\begin{cases} PLL_{CL} = POB \cdot c_{CL} \cdot \left(1 - A_{CL}\right) \\ PLL_{GR-B} = POB \cdot c_{GR-B} \cdot \left(1 - A_{GR-B}\right) \\ PLL_{GR-S} = POB \cdot c_{GR-S} \cdot \left(1 - A_{GR-S}\right) \end{cases} \tag{2}$$

where *POB* is the number of persons on board (crew and passengers, considering assumptions with respect to occupancy). The coefficients c_{CL}, c_{GR-B} and c_{GR-S} depend on, and can be directly calculated from, the assumed reference risk models.

More specifically, each coefficient c_{CL}, c_{GR-B} and c_{GR-S}, can be readily determined according to the following procedure. At first, the relevant risk model is selected for each type of accident (collision, bottom grounding, side grounding/contact). Then, by following the various branches of the event tree, *PLL* is expressed explicitly as a function of products of initial frequency, conditional probabilities, assumed percentages of fatalities, $1-A$, and *POB*. In fact, *A* and *POB* are the ship-specific parameters to be provided for the determination of *PLL* in each of the background risk models. Finally, each coefficient c_{CL}, c_{GR-B} and c_{GR-S}, as appropriate, is determined as the proportionality factor between *PLL* and $POB \cdot \left(1-A\right)$ for each type of accident, as stemming from the described procedure.

The total *PLL* can then be determined by summing up the contribution to risk from the three accidents, as follows:

$$\begin{cases} PLL_{TOT} = PLL_{CL} + PLL_{GR-B} + PLL_{GR-S} \\ \qquad\quad = POB \cdot c_{T} \cdot \left(1 - SM\right) \\ \text{with } c_{T} = c_{CL} + c_{GR-B} + c_{GR-S} \end{cases} \tag{3}$$

The safety metric SM can then be obtained, with a weighting of the attained indices based on the relative contribution to risk from different types of accidents and calculated using the risk models from the EMSA 3 study:

$$\begin{aligned} SM = \; & 0.11 \cdot A_{CL} + \\ & + 0.17 \cdot A_{GR-B} + \\ & + 0.72 \cdot A_{GR-S} \end{aligned} \tag{4}$$

With reference to the obtained weighting coefficients in (4), and considering risk investigations performed in GOALDS and EMSA 3, the topic of quantification of uncertainty was discussed, but not fully explored during eSAFE. This is due to complexity of the matter combined with the limited time frame. In fact, risk models embed different sources of uncertainty. Part of the uncertainty comes from the limited size of the sample of available data, which can be efficiently estimated. However, additional uncertainty, which is more difficult to quantify, stems from the subjective expert judgement used in quantification of the underlying risk models. As a result, this topic has been left as an important topic to be addressed in future research activities.

Combined Attained Subdivision Index - A

An alternative way for the derivation of a safety metric considering all three types of accidents is through the definition of a Combined Attained Subdivision Index, using appropriate weighting factors for the three individual A-indices, based on the relative frequencies (conditional probabilities) of the corresponding accidents, as follows:

$$\begin{aligned} A = \; & Pr_{CL} \cdot A_{CL} + \\ & + Pr_{GR-B} \cdot A_{GR-B} + \\ & + Pr_{GR-S} \cdot A_{GR-S} \end{aligned} \tag{5}$$

The combined A-index, therefore, represents a measure of the probability of survival conditional to the occurrence of a flooding accident, hence not considering differences in the consequences for the different accident categories. The relative frequencies (conditional probabilities) Pr_{CL}, Pr_{GR-B} and Pr_{GR-S} were determined from the analysis of historical data. The accidents database which was used for the accidents data analysis is the same as the one developed and used within the EMSA 3 project (Konovessis et al., 2015). The sampling plan and filtering of data was chosen in order to be relevant for the scope of the project.

It is noted that the size of available accidents sample, after the filtering, was rather limited, corresponding to 16 accidents in total. Although this is a good outcome from a safety perspective, it leads to a large uncertainty in the estimated relative fractions of different types of accidents, i.e. in the weighting coefficients of different A-indices. This is evident from the results in Table 1, where Pr_{CL}, Pr_{GR-B} and Pr_{GR-S} estimated from the available data are reported, together with corresponding 95% confidence intervals.

Table 1: Weighting factors for combined A-index.

Type of accident	**Number of accidents**	***Pr_i*** **(i = CL, GR-S, GR-B) with 95% confidence interval**
CL	4	25% [7% , 52%]
GR-B	3	19% [4% , 46%]
GR-S	9	56% [30% , 80%]

From the analysis of data, the following Combined Attained Subdivision Index, *A*, was eventually derived:

$$\begin{aligned} A = \; & 0.25 \cdot A_{CL} + \\ & + 0.19 \cdot A_{GR-B} + \\ & + 0.56 \cdot A_{GR-S} \end{aligned} \tag{6}$$

Discussion on selection and use of the safety metric

Two safety metrics have been defined which share the characteristic that they can both be determined as weighted combinations of individual A-indices corresponding to different types of accidents.

Both options for a combined measure of survivability after a flooding event have been thoroughly discussed during the eSAFE project, and it was concluded that the risk-based approach is to be the preferred one.

The risk-based safety metric SM (see (4)) is a risk-based approach directly related to societal risk (*PLL*) from collision, bottom grounding and side grounding/contact damages. It is based on the EMSA 3 risk models for collision and grounding/contact accidents relevant to cruise ships, which were developed in the EMSA 3 project and the applied methodology has been evaluated by the IMO FSA Experts Group (IMO, 2015). Weighting coefficients in the risk-based safety metric represent the relative contribution to societal risk stemming from different types of accidents, on the basis of the assumed risk models, in a hypothetical condition where the attained index is the same for all types of accidents.

The combined attained subdivision index *A* (see (6)), represents a measure of the probability of survival conditional to the occurrence of a flooding accident. The weighting coefficients of the combined A-index are obtained from the direct analysis of accidents data, and the weighting coefficients correspond to the relative frequencies of different types of accidents. If the objective of watertight subdivision and damaged stability analysis is to maximize the probability of a ship to survive an accident and remain afloat, then the combined index *A* appears to be the natural choice. However, it is not possible to reflect the risk-level of the vessel directly from this index, and therefore the combined A-index is not a direct risk-based safety metric.

Comparing (4) and (6), it can be seen that the weighting coefficients for the three attained indices in the two metrics are different. This is a consequence of the fact that the two metrics provide measures associated with two different quantities: societal risk on the basis of the assumed risk models in case of SM, and probability of ship survival conditional to the occurrence of a flooding accident in case of the combined A-index. Accordingly, on the one hand, the weighting coefficients in the combined A-index only accounts for relative frequencies of different types of accidents (see Table 1). On the other hand, the weighting coefficients in SM also embed the relative effect of consequences from different types of accidents, on the basis of the assumed risk models.

The estimated weighting coefficients for both metrics are affected by uncertainty due to the limited sample size coming from accidents data. In addition, the risk-based safety metric SM also embeds a certain level of uncertainty coming from the subjective expert judgement related to the structure of the underlying risk models and to the specification of probabilities of some events.

Considering the main characteristics and inherent limitations of the two alternatives, it was agreed within eSAFE to use the risk-based safety metric SM.

However, as shown in the sensitivity analysis in EMSA 3, as well as when going into the details of the underlying accident statistics, the number of accidents in the various branches of the event tree of the risk models is small, which, as already highlighted, leads to uncertainty in the coefficients for SM.

In addition, the calculated weighting coefficients show that side grounding/contact seems to be the dominating risk for flooding. This result raised some concerns during the discussions, because it is based on past casualty reports, and it may not reflect the actual situation of cruise ships. Modern technical features and improved operational procedures may have changed the probability for grounding and contact events, respectively the consequences. Hence, the application of the safety metric SM in its current form, which to a larger degree is based on historical accident data, may not lead to the proper focus during the design of cruise ships. Thus, even if the combined evaluation of different types of damages is regarded as favourable, these aspects require further investigations.

Therefore, it has been decided to use the attained indices separately for collision, bottom grounding and side grounding/contact, for the time being.

In addition, a regular review and update of the risk models is recommended to achieve a more robust measure for the risk due to flooding. It is also worth mentioning that research&development in this respect is expected to be carried out in the framework of the forthcoming Horizon 2020 "FLooding Accident REsponse (FLARE)" project, with a review of the recent risk model for side and bottom damages.

4. SOFTWARE IMPLEMENTATION IN VIEW OF PRACTICAL APPLICATION

General

In industrially oriented projects, the implementation of scientific and technical advances into practically applicable tools is of utmost importance in order to quantify and maximize the impact and benefit of the fundamental developments. Accordingly, practical implementation was one of the drivers in eSAFE, where project partners representing different stakeholders of the cruise industry, together strived to develop, test and put into practice innovative methodologies related to ship safety. In this context, the developments related to the combined non-zonal approach for collision, bottom grounding and side grounding/contact have been implemented in a design-oriented, practically applicable, NAPA software functionality.

A testing tool implemented in NAPA

By utilizing and extending the technology and a tool developed in the EMSA 3 project (Zaraphonitis et al., 2015), a new functionality was developed for generating also collision damages, on the basis of the non-zonal approach stemming from eSAFE. This functionality was made available in a modified test version of NAPA, for evaluation use in the project.

The tool in NAPA was first extended to cover collision damages which, as described in section 2, are consistent with current SOLAS with the addition of a probabilistic model for the extent of damage below water. In addition, the tool embedded an update of the EMSA 3 approach for addressing bottom grounding and side grounding/contact damages, with the aim of harmonizing some aspects of the calculation methods among different types of damages. Similarly to the original EMSA 3 tool, the results from the calculation (A-indices) are finally listed separately for each damage type (collision, bottom grounding, side grounding/contact) and for each calculation draught.

The tool was then tested through pilot applications by the developers of the methodology and by the designers (Lindroth et al., 2017). Results from the pilot usage were eventually used to provide insight to the newly developed approach and to guide subsequent calculations within the project.

A number of systematic tests have also shown the usability and robustness of the tool, so that it can be used in daily design work.

The tool allows the application of the non-zonal approach considering three types of breaches, namely:

- Bottom grounding (B00 damages), according to EMSA 3 modelling (Zaraphonitis et al., 2015);
- Side grounding/contact (S00 damages), according to EMSA 3 modelling (Zaraphonitis et al., 2015);

- Collision (C00 damages), according to the approach developed in eSAFE, which is in line with, and extends, SOLAS (see section 2).

It is noted that in the eSAFE application, breaches for each damage type are generated separately for each calculation draught. As a result, the calculation of probabilities for each damage case is also draught dependent for each type of damage. This represents an improvement compared to the EMSA 3 approach. In fact, in the EMSA 3 non-zonal calculations for bottom grounding and side grounding/contact, damage cases and corresponding probabilities were calculated only at the deepest draught, and remained the same for the other calculation draughts (Zaraphonitis et al., 2015; Bulian et al., 2016). This approximation was introduced for reasons related to computational time. In eSAFE, instead, this limitation has been overcome.

As the ship length considered for bottom grounding and side grounding/contact is the ICLL length (IMO, 2019b), whereas the ship length for collision calculations is the SOLAS subdivision length (IMO, 2019a), the tool consequently offers separate relevant input.

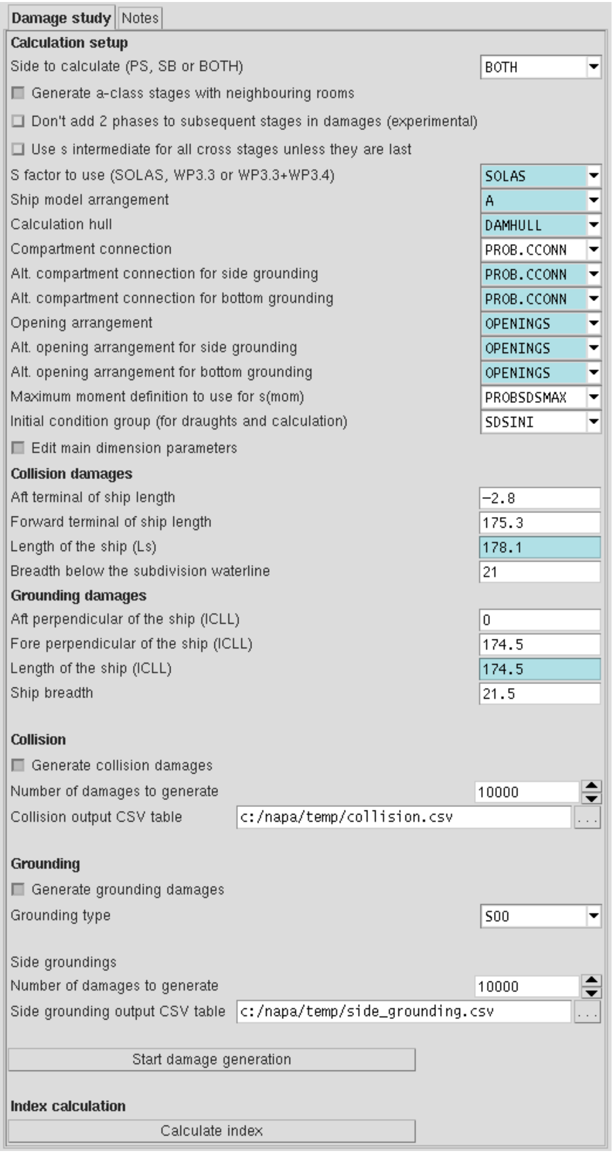
A representative view of the NAPA tool interface is shown in Figure 4, where the user can control the generation and calculation parameters. Ship modelling and other needed preparation work are not addressed by this interface, as they are part of the ship model preparation for the statutory damage stability analysis in NAPA. As a result, the non-zonal calculations (Monte Carlo generation of breaches and subsequent determination of A-indices) are quick to set up and easy to perform through the dedicated interface.

Notably, as the impact on flooding by bottom or side damages is slightly different, the designer might need to use different opening definitions and compartment connections for the different damage types. The tool, therefore, offers this flexibility.

For larger calculation sets or repetitions the tool also allows the preparation and automatic execution of multiple runs in batch. In such case, the input required for the different runs is provided by the user through a dedicated table.

In addition to generating breaches and calculating A-indices using the s-factor from SOLAS, the tool also offers alternatives for the generation and for the survivability assessment. Some of these options stem from objectives and activities within the eSAFE project, while other originate from external sources, e.g., regulatory interpretations.

Additionally to the successful pilot testing of the tool performed in the eSAFE project, there is an interest in continuing to explore the potentials and benefits of the developed approach and associated tool. Therefore, implementation and further development of the tool as a new and supported NAPA feature is planned.



Calculation setup

Side to calculate (PS, SB or BOTH)	BOTH
☐ Generate a-class stages with neighbouring rooms	
☐ Don't add 2 phases to subsequent stages in damages (experimental)	
☐ Use s intermediate for all cross stages unless they are last	
S factor to use (SOLAS, WP3.3 or WP3.3+WP3.4)	SOLAS
Ship model arrangement	A
Calculation hull	DAMHULL
Compartment connection	PROB.CCONN
Alt. compartment connection for side grounding	PROB.CCONN
Alt. compartment connection for bottom grounding	PROB.CCONN
Opening arrangement	OPENINGS
Alt. opening arrangement for side grounding	OPENINGS
Alt. opening arrangement for bottom grounding	OPENINGS
Maximum moment definition to use for s(mom)	PROBSDSMAX
Initial condition group (for draughts and calculation)	SDSINI
☐ Edit main dimension parameters	
Collision damages	
Aft terminal of ship length	-2.8
Forward terminal of ship length	175.3
Length of the ship (Ls)	178.1
Breadth below the subdivision waterline	21
Grounding damages	
Aft perpendicular of the ship (ICLL)	0
Fore perpendicular of the ship (ICLL)	174.5
Length of the ship (ICLL)	174.5
Ship breadth	21.5
Collision	
☐ Generate collision damages	
Number of damages to generate	10000
Collision output CSV table	c:/napa/temp/collision.csv
Grounding	
☐ Generate grounding damages	
Grounding type	S00
Side groundings	
Number of damages to generate	10000
Side grounding output CSV table	c:/napa/temp/side_grounding.csv
Index calculation	

Figure 4: Representative view of the NAPA tool interface for the application of the non-zonal approach.

5. EXAMPLE OUTCOMES

The developed non-zonal approach has been extensively applied throughout the eSAFE project.

At first, a series of calculations were carried out in order to verify the correct implementation of the non-zonal approach for collision (Bulian et al., 2017; Lindroth et al., 2017). In this context, among other verification checks, an example verification was carried out for a barge (Lindroth et al., 2017) with and without double bottom, and without any additional horizontal subdivision boundary below the waterline. The barge configuration with double bottom is depicted in Figure 5. The subdivision of the configuration without double bottom is exactly the same as that shown in Figure 5, but without the inner bottom. The barge does not have any longitudinal bulkhead, and all compartments extend from side to side.

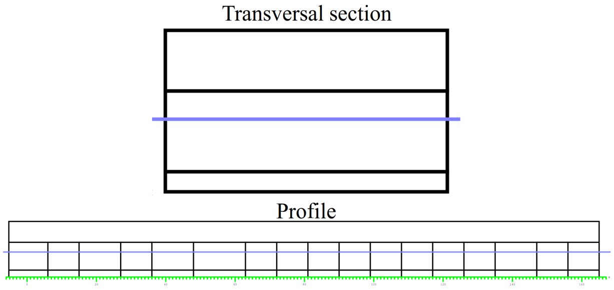
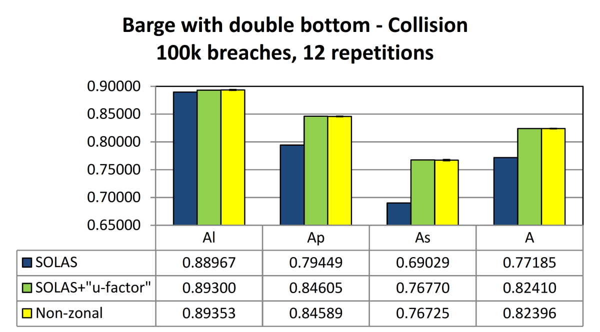


Figure 5: Barge used for testing. Configuration with double bottom.

For the case of the barge without double bottom, the SOLAS zonal approach provides exact results in terms of A-indices. Therefore, the non-zonal approach could be directly compared with SOLAS for such configuration. Instead, in case of barge with double bottom, the standard SOLAS zonal approach cannot be directly compared with the non-zonal approach due to the use of the “worst-case approach” in SOLAS/II-1/B-1/7-2/6.2 (Bulian et al., 2018). Therefore, for the barge configuration with double bottom, the outcomes from the non-zonal approach have been compared with those from the SOLAS zonal approach supplemented by the use of the “u-factor” (Bulian et al., 2018). The verification was successful in both cases, confirming the proper implementation of the non-zonal approach for collision in a way which is consistent with SOLAS. As an example, a comparison of A-indices for the barge with double bottom is shown in Figure 6. The figure reports A-indices from the non-zonal approach, from SOLAS zonal approach supplemented by “u-factor”, and from standard SOLAS. In order to increase the accuracy of non-zonal calculations, a total of 12 repetitions with 10^5 breaches for each repetition were carried out, and the non-zonal data in Figure 6 correspond to the average A-indices across repetitions, together with 95% confidence interval (which are indeed so small that they are hardly visible in the graphs). The observed very small differences in Figure 6 between SOLAS+“u-factor” and non-zonal results, are associated with random sampling uncertainty. Instead, the differences with respect to standard SOLAS are due to the use of the “worst-case approach” in the standard SOLAS zonal approach.



	Al	Ap	As	A
🟦 SOLAS	0.88967	0.79449	0.69029	0.77185
🟩 SOLAS+"u-factor"	0.89300	0.84605	0.76770	0.82410
🟨 Non-zonal	0.89353	0.84589	0.76725	0.82396

Figure 6: Barge with double bottom. Comparison between non-zonal approach (average with 95% confidence interval) and SOLAS zonal approach supplemented by u-factor.

An example practical application of the non-zonal approach for collision on a cruise ship is shown in Figure 7. The figure compares the attained subdivision indices for the considered cruise vessel, calculated according to the standard SOLAS zonal approach, the SOLAS zonal approach supplemented by the “u-factor”, and the non-zonal approach for collision (average index across repetitions, with 95% confidence interval).

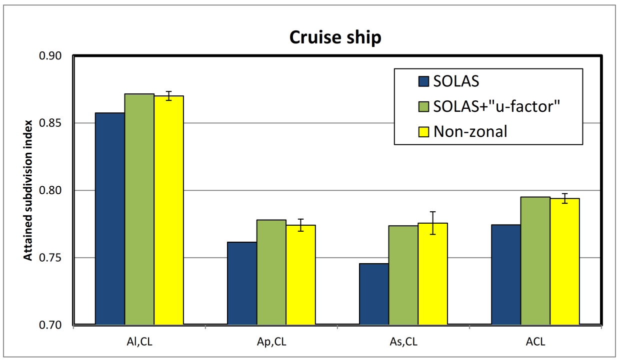


Figure 7: Example cruise ship. Comparison between SOLAS zonal approach, SOLAS zonal approach supplemented by u-factor, and non-zonal approach (average with 95% confidence interval from 5 repetitions with 10^4 breaches each).

Differently from the case of the barge in Figure 6, in case of the cruise ship in Figure 7 the zonal SOLAS+"u-factor" approach is an approximate one, because the vessel is not box-shaped and the compartments are, in general, not box-shaped as well. Therefore, in this case, results from the non-zonal approach are to be considered as the "exact" ones, bearing in mind the random sampling uncertainty which is reflected by the confidence intervals in Figure 7. It is therefore expected that results from the non-zonal approach and the SOLAS+"u-factor" approach do not perfectly match. Nevertheless, it can be seen that the zonal SOLAS+"u-factor" provides a very good approximation of the results obtained from the non-zonal approach. It can also be noticed that the introduction of a probabilistic model for the lower limit of damage below the waterline (SOLAS+"u-factor" and non-zonal approaches) provides, as expected, an increase of calculated attained subdivision indices (see Bulian et al. (2018) for more details on this topic).

Further example outcomes from practical application on the considered cruise ship are shown in Figure 8. The figure shows A-indices from the non-zonal approach for the three considered types of damages: collision (CL), bottom grounding (GR-B), side grounding/contact (GR-S). The reported indices are global ones, i.e. indices averaged for the three calculation draughts using standard SOLAS weighting factors (i.e. 0.2 for d_l, 0.4 for d_p, and 0.4 for d_s). In this respect, it is worth noting that the eSAFE project also investigated the suitability of SOLAS assumptions regarding the relative frequency of different draughts in the specific case of cruise vessels, showing that the actual operational profile of cruise vessels would call for the use of weighting factors different from the standard ones (Paterson et al, 2017, 2018).

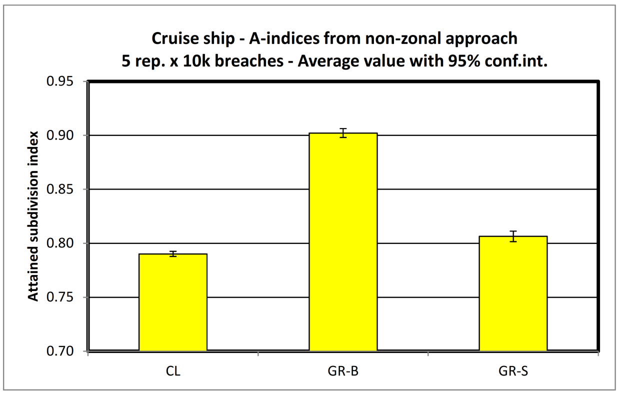


Figure 8: Example cruise ship. A-indices from non-zonal approach for collision (CL), bottom grounding (GR-B) and side grounding/contact (GR-S). Average with 95% confidence interval from 5 repetitions with 10^4 breaches each.

6. CONCLUSIONS

The paper provided an overview of some main outcomes from the eSAFE project, regarding, specifically, the development and implementation of a common framework for probabilistic damage ship stability assessment, considering collision, bottom grounding and side grounding/contact damages.

In this respect, the non-zonal approach, originally developed in the EMSA 3 project for bottom grounding and side grounding/contact has been extended in eSAFE to the case of collision.

Consistency with present SOLAS has been taken as a key objective, and it was verified during testing. Moreover, the lack of a probabilistic description for the lower limit of collision damage in present SOLAS zonal approach has also been overcome.

A software functionality has been developed in a test version of NAPA for the application of the common non-zonal methodology for collision, bottom grounding and side grounding/contact. A number of systematic tests have shown the usability and robustness of the tool, so that it can be used in daily design work.

Different alternatives have been considered for dealing with the attained subdivision indices from different types of damages: a risk-based safety metric, a combined attained subdivision index, and the separate use of attained indices from different types of damages. An extensive analysis and discussion was carried out within eSAFE regarding the different alternatives. Eventually, it has been recommended by eSAFE to actively use the new tools and gain experience in what effects design changes might have on the survivability from collision, bottom grounding and side grounding/contact, by using the attained indices separately for collision, bottom grounding and side grounding/contact, for the time being. In addition, a regular review and update of the risk models has been recommended to achieve a more robust measure for the risk due to flooding. In this respect, it can also be added that a more complete collection of accident details, with collection of additional and higher quality data, would definitely be important to achieve the goal of improving the risk models through the review and update process.

The non-zonal approach provides now the basis for a holistic assessment of survivability after flooding considering collision, bottom grounding and side grounding/contact. The experience gained during eSAFE also shows that the approach can be of practical application in the actual design activity.

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A number of the achievements from eSAFE reported in this paper build upon and extend some of the outcomes from the EMSA 3 project "Study assessing the acceptable and practicable risk level of passenger ships related to damage stability" (EMSA/OP/10/2013 - www.emsa.europa.eu/damage-stability-study.html). The original funding of EMSA 3 project from the European Maritime Safety Agency (EMSA), as well as the encouragement to continue the research&development activity in the framework of the eSAFE project, are highly acknowledged.

DISCLAIMER

The information and views as reported in this paper are those from the authors and do not necessarily reflect the views of the eSAFE Consortium.

The views as reported in this paper are those of the authors and do not necessarily reflect the views of the respective organizations.

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