A Framework for Probabilistic Damage Stability Assessment of Passenger Ships Considering Collision, Grounding and Contact Accidents

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Abstract This contribution provides an overview of the framework implemented in the joint industry project "eSAFE—enhanced Stability After a Flooding Event" for probabilistic damage stability assessment of passenger ships. The framework takes into account collision, bottom grounding and side grounding/contact accidents, by providing specific corresponding attained subdivision indices. Damage

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cases and associated flooding probabilities are determined through a common automatic non-zonal approach, while the post-damage survivability metric is based on the SOLAS “s-factor”. The framework is intended for practical application and is generally consistent with existing SOLAS probabilistic damage stability regulations. To support designers in the application of the framework, a specific software functionality has been developed, tested and applied. Some example applications of the framework are reported.

Keywords eSAFE · Damage stability · Non-zonal approach · Collision · Grounding · Contact · SOLAS

1 Introduction

The joint industry project “eSAFE—enhanced Stability After a Flooding Event” [28, 29] ran between 2017 and 2018, with the aim of investigating the survivability of cruise ships in damaged conditions, taking into account the specific design features of such complex type of vessels. As described by Luhmann et al. [28, 29], the project investigated a series of aspects related to the assessment of cruise ships survivability in damaged condition, with a view towards practical implementation of the findings from the project in the actual ship design process. Overall, eSAFE represented a significant step forward to achieve survivability standards beyond current statutory SOLAS damage stability regulations.

One of the key objectives of the eSAFE project was the development of a holistic probabilistic methodology, together with an associated NAPA software functionality to be used in actual design, for assessing post-damage ship survivability combining collision, bottom grounding and side grounding/contact damages, through a sound and consistent generalised approach.

To achieve this target, the activities carried out in eSAFE leveraged on, further developed and expanded relevant outcomes from the preceding EMSA 3 project [11], for which a summary of overall final results and corresponding recommendations for decision making have been provided by Vassalos et al. [44]. The results from EMSA 3 and the applied methodology have also been evaluated by the IMO FSA Experts Group [17].

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 [4, 46]. The method was based on a non-zonal approach where: (a) breaches are directly generated on the basis of a geometrical and probabilistic model for the damage extent through a Monte Carlo approach; (b) “damage cases” are automatically created based on 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. Recently, Bulian et al. [8] have provided a comprehensive description, together with example applications, of the EMSA 3 non-zonal approach, embedding also some improvements stemming from the eSAFE project.

The non-zonal method developed in EMSA 3 for bottom grounding and side grounding/contact has been extended in eSAFE in order to address also collision damages, keeping consistency with present SOLAS [19]. In this context, it was necessary to develop a probabilistic model for the position of the lower edge of damage, as this is missing in the present SOLAS framework [5, 6]. This development, combined with a clear geometrical description 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 in eSAFE for defining safety metrics in order to combine survivability in case of collision, bottom grounding, and side grounding/contact [47]. To this end, reference has been made to statistical analysis of accidents data and to existing risk-models [23, 46]. In this respect, it is worth noting that, in general, risk-based approaches for damage stability are, of course, not new, and have been developed and used already in the past. This can be appreciated, for instance, from the content in Vassalos et al. [43], Papanikolaou [36], Neves et al. [35] and Belenky et al. [2], and from the relevant papers in the review by Bačkalov et al. [1].

Based on the findings from the mentioned eSAFE activities, a new functionality for practical implementation of the non-zonal approach has been made available in NAPA [27], 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 [47].

It is noted that the outcomes from the eSAFE project also represented input for further advancement and development activities within the subsequent FLARE project [12].

Some brief discussion is also worth at this stage regarding the methodological approach used in eSAFE for the results presented herein. In fact, as it will be evident in the following, the reported eSAFE developments are essentially based on a combination of use of historical data and implementation of expert judgement for the risk modelling, when necessary, and on the use of simplified models for the specification of the post-damage survivability metric, essentially the s-factor. The use of historical data is the most common approach, and it has the benefits of being based on evidence and to inherently embed information on design and operation of existing ships. At the same time, historical accident data tend to be generally scarce (in terms of total numbers and details), and this eventually leads to statistical uncertainty in the estimation of frequencies/probabilities. Further uncertainty is introduced when, in absence of sufficient historical data, it is necessary to resort to expert judgement. The analysis by Hamann et al. [13] recognises the benefits as well as the shortcomings of exploiting historical data for the development of risk models, and outlines a framework where the analysis of historical data is combined with first-principle simulation approaches. Such a combined approach has valuable potential, although it should be recognised that the use of first-principle approaches is not free from shortcomings itself. In fact, when first-principle approaches are used, uncertainty may be shifted from the analysis of historical data to the inevitable assumptions implemented in the usage of simulation tools. Nevertheless, the use of first-principle approaches is definitely more flexible, and it allows to carry out more thorough analyses taking into account in more detail ship-specific characteristics. Sensitivity with respect to the used assumptions can also be properly assessed, as deemed necessary. Furthermore, while modelling based on historical data, by its very nature, focuses on "what has happened in the past", the use of first-principle simulation approaches has the potential for trying to foresee what "may happen in the future". A typical, well-known, example of first-principle approach for damage stability assessment is the use of numerical time domain flooding simulation tools (e.g. [22, 40, 41, 45]), that may have the potential for, at least, complementing the use of the SOLAS simplified s-factor. As another interesting example, recently, Conti et al. [9] have shown how first-principle approaches for crashworthiness could be quantitatively embedded into a SOLAS-like flooding assessment framework, in order to give proper credit to differences in the ship structural design. Earlier work on this topic can also be linked to the HARDER project [30]. The approach of Conti et al. [9] clearly shows its potential, but it also shows the necessity of introducing simplifying assumptions. Another example in the direction of a more extensive use of first-principle approaches is provided by Zhang et al. [48], who combined AIS traffic data analysis (see also, e.g., [33]), structural analysis and s-factor-based damage stability analysis, to determine the attained subdivision index. Also the work by Zhang et al. [48] clearly shows the potential of first-principle approaches, but, at the same time, it also shows the associated complexity and the need to introduce working/simplifying assumptions. Therefore, while the use of first-principle approaches shall definitely be pursed for future advancement, still the approach based on historical data, expert judgement and simplified survivability metric as used in eSAFE can be considered fully justified.

This contribution is based on Bulian et al. [7] and provides an updated summary overview of the main outcomes of the mentioned activity (see also [28, 29]). In the following, Sect. 2 provides a summary regarding the development of the non-zonal approach for collision. Afterwards, Sect. 3 summarises the different approaches that have been considered for 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, Sect. 6 reports some summarising conclusions.

2 Non-zonal Approach for Collision

The present damage stability framework in SOLAS Ch.II-1 [19] allows determining the probabilities of flooding of a (group of) compartment(s) 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 assumed probability distributions of collision damage characteristics (position, length, penetration and vertical extent above waterline).

It is well known that the basic ideas leading to the present SOLAS originated from the HARDER project (see [30, 31]). Subsequently, some modifications regarding damage distributions have been introduced during the discussion at IMO, leading to the final formulation, as embedded in SOLAS 2009 and eventually in the present SOLAS 2020 regulations.

In the EMSA 3 project a different methodology was proposed for addressing bottom grounding and side grounding/contact [4, 8, 46], 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 idea of exploiting Monte Carlo generation of breaches for determining damage cases and associated probability of flooding was used also by Kehren and Krüger [24], Krüger and Dankowski [25, 26], Valanto and Friesch [42] and Dankowski and Krüger [10] considering ship performance in terms of regulatory damaged ship stability and/or oil outflow following MARPOL [14, 21, 46]. Given the ship model for damage stability calculations, the application logic of the non-zonal approach is illustrated in Fig. 1.

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 [5]. To this end, an explicit definition of the geometrical model for collision damages was provided, and the generation of breaches due to collision damages was based on the distributions for damage characteristics according to SOLAS background.

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 [6, 47]. Shortcomings of the use of “damages of lesser extent” have also been highlighted by Krüger and Dankowski [25]. In order to allow a consistent generation of breaches in the eSAFE non-zonal framework for collision, it was therefore necessary to specifically develop and embed a probabilistic model for the lower limit of vertical extent of damage.

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;

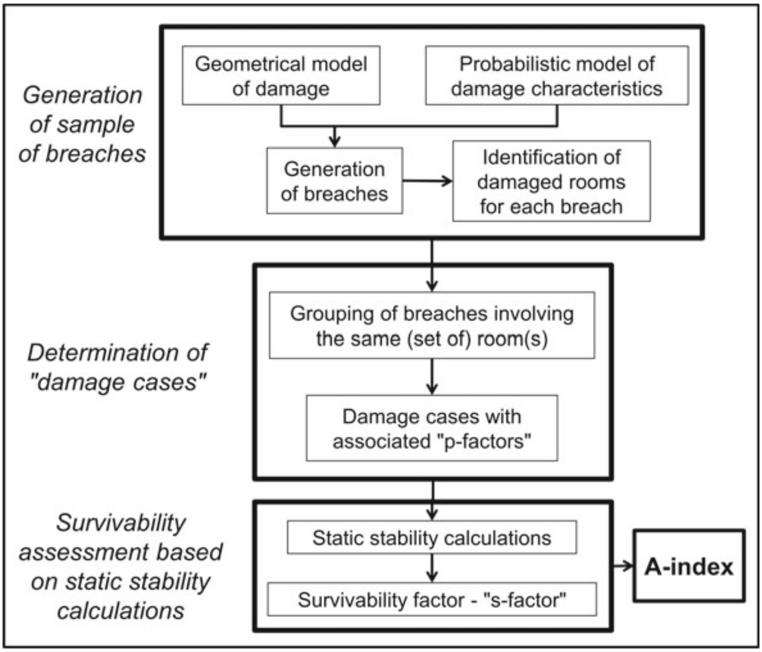


Fig. 1 Application logic of non-zonal approach

- 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 [15, 18], collision damages have been defined to be always crossing the calculation waterline, i.e. 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 damage is defined as a potential damage, this meaning that it can also partially extend outside the vessel. The distributions of all relevant damage characteristics were taken from the analysis of the SOLAS background, with the exception of the distribution for the lower limit of damage that has been newly introduced in eSAFE. In particular [5]:

- 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.

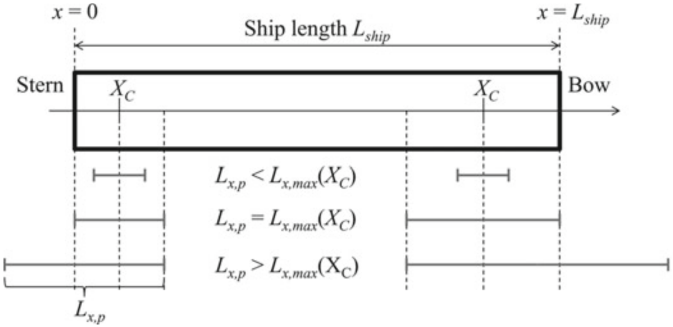
- Longitudinal extent of damage (potential damage length), $L_{x,p}$: bilinear probability density function, with characterising coefficients b_{11}, b_{12}, b_{21} and b_{22} (see [30, 31]) from SOLAS/II-1/B-1/7-1/1.1.
- Transversal extent of damage (potential damage penetration), $L_{y,p}$: truncated trapezoidal distribution depending on potential damage length. The cumulative distribution function, before truncation, corresponds to the function $C(\overline{z})$ reported by Lützen [30, 31].
- Vertical position of upper limit of damage above the waterline, $z_{UL,p} - d$: the cumulative distribution function corresponds to the SOLAS v-factor.

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.

Furthermore, 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 [30, 31, 39], it was necessary to pay particular attention to the proper positioning of the damage, given X_C and $L_{x,p}$. 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 [3, 16]. The procedure for the longitudinal positioning of the damage is reported in Fig. 2, where, for simplicity of notation, the aft and the forward end of the ship length are assumed to correspond to $x = 0$ and $x = L_{ship}$, respectively. In the figure, $L_{x,max}$ is the maximum damage length with centre in X_C that can be within the ship length L_{ship}, while $x_{min,p}$ and $x_{\max,p}$ are the longitudinal coordinates for the aft end and forward end of potential damage, respectively.

A further 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 $C(\overline{z})$ reported by Lützen [30, 31], 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 [3, 16, 30, 31, 39]. One possibility to generate damage penetrations consistently with the maximum limit embedded in SOLAS, is to initially generate a potential damage penetration according to the distribution associated with $C(\overline{z})$, then, in case the generated penetration exceeds the maximum value $L_{y,p,\max} = (15 \cdot B/L_S) \cdot L_{x,p}$, the penetration is limited to $L_{y,p,\max}$, otherwise the generated penetration is kept. It is noted that, since $L_{y,p,\max}$ depends on $L_{x,p}$, in this generation approach $L_{x,p}$ has to be generated before $L_{y,p}$.

It is worth mentioning that Krüger and Dankowski [25, 26] addressed SOLAS probabilistic damage stability assessment using a Monte Carlo approach sharing the fundamental logic of the non-zonal approach, and they highlighted some implementation problems related to the treatment of extremities and the treatment of penetration consistently with SOLAS. Such consistency problems are actually resolved by the



When $X_C \le \dfrac{L_{ship}}{2}$:

$$\begin{cases} L_{x,max} = 2 \cdot X_C \\ x_{max,p} = X_C + \dfrac{\min\left(L_{x,p}, L_{x,\max}\right)}{2} \\ x_{min,p} = x_{max,p} - L_{x,p} \end{cases}$$

When $X_C > \dfrac{L_{ship}}{2}$:

$$\begin{cases} L_{x,max} = 2 \cdot \left(L_{ship} - X_C\right) \\ x_{min,p} = X_C - \dfrac{\min\left(L_{x,p}, L_{x,\max}\right)}{2} \\ x_{max,p} = x_{min,p} + L_{x,p} \end{cases}$$

Fig. 2 Graphical representation of longitudinal positioning of collision damage with corresponding analytical formulae for the determination of longitudinal coordinates for aft end ($x_{min,p}$) and forward end ($x_{max,p}$) of potential damage

damage positioning procedure reported in Fig. 2 and by the described procedure for the generation of penetration, as used in eSAFE.

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 was based on the analysis of historical accident data, using data from the HARDER accidents database as updated in the GOALDS project [3, 16, 32]. Collision damages were considered to be always crossing the waterline, i.e. with upper limit above the waterline and lower limit below the waterline. 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 [5, 27]. Eventually, one of the two models was selected for describing the vertical position of lower limit of potential damage from the ship bottom, $z_{LL,p}$. This model considers $z_{LL,p}$ to be statistically independent of the other damage characteristics, and to have the following cumulative distribution [5, 6]:

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

where d is the actual calculation draught. This model is used for describing, and hence generating, $z_{LL,p}$ in the non-zonal approach. Details of the derivation of this model are given by Bulian et al. [5, 6].

It is noted that the finally selected probabilistic model for the lower limit of damage also allows to easily define a “u-factor” which can be directly embedded in the existing SOLAS zonal framework (see [5, 6] for details).

3 Safety Metrics for the Combined Impact of Collision, Grounding and Contact Accidents

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 A_{CL} for collision, A_{GR-B} for bottom grounding, and A_{GR-S} for side grounding/contact.

The three mentioned A-indices represent ship survivability, separately, for each type of accident. Depending on the application, these indices are either partial indices, i.e. indices associated with a specific loading condition, or global indices, i.e. indices obtained after averaging across different draughts as in SOLAS.

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 in eSAFE:

- 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 accidents.

The metrics defined by the two approaches are both represented by weighted combinations of individual A-indices corresponding to different types of accidents. Relevant detailed information, in the framework of eSAFE, have been provided by Zaraphonitis et al. [47] and Luhmann et al. [28, 29].

3.1 Risk-Based Safety Metric—SM

The risk-based safety metric SM is directly related to societal risk from collision, bottom grounding and side grounding/contact damages. The fundamental ideas and assumptions behind the developed risk-based safety metric have been anticipated in the EMSA 3 project [23, 44, 46], and can be summarised 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.

The approach has then been applied within eSAFE [28, 29, 47], as described in the following.

The analysis started from existing risk models. Specifically, the reference risk models that have been used in the derivation are those developed in the EMSA 3 study [23, 46] that are relevant for cruise ships. In particular, see Sect. 10.2.5 and Figs. 10–22 in Konovessis et al. [23] for the collision risk model, and Sect. 8.9.2 and Fig. 52 in Zaraphonitis et al. [46] for the grounding and contact risk model.

On the basis of the available risk models, the potential loss of life (*PLL*) associated with each type of accident can be determined, in general, as follows:

$$\begin{cases} PLL_j = POB \cdot c_j \cdot \left(1 - A_j\right) \\ j = CL,\ GR-B,\ GR-S \end{cases} \tag{2}$$

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. In fact, following the branches of the event tree of the relevant risk model (collision, bottom grounding, side grounding/contact), *PLL* can be expressed explicitly as a function of products of initial frequency, conditional probabilities, assumed percentages of fatalities, $1 - A$, and *POB*. Therefore, each coefficient c_{CL}, c_{GR-B} and c_{GR-S}, can be determined as the proportionality factor between *PLL* and $POB \cdot (1 - A)$ for each type of accident, and each coefficient reflects the whole underlying relevant risk model.

It is noted that, according to Eq. (2), the same value of the attained index A leads, in general, to different *PLL* for given *POB*, because coefficients c_{CL}, c_{GR-B} and c_{GR-S} are, in general, different. This is a direct consequence of the differences among the relevant risk models, in terms of structure of the model, initial frequencies, conditional probabilities and modelling of consequences.

The total *PLL* can then be determined by summing up the contribution to risk from the three accidents, which provides the means for defining the safety metric SM, as follows:

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

The safety metric SM can then be obtained, in general, from its definition in Eq. (3) and from the relations in Eq. (2), as follows:

$$\begin{cases} SM = k_{CL} \cdot A_{CL} + k_{GR-B} \cdot A_{GR-B} + k_{GR-S} \cdot A_{GR-S} \\ k_j = c_j / c_T \quad \text{with } j = CL, GR - B, GR - S \end{cases} \tag{4}$$

and the following result has been obtained in eSAFE, on the basis of the background information:

$$SM = 0.11 \cdot A_{CL} + 0.17 \cdot A_{GR-B} + 0.72 \cdot A_{GR-S} \tag{5}$$

The weighting coefficients of the attained indices in Eq. (5) represent the relative contribution to societal risk stemming from the different types of accidents on the basis of the risk models from EMSA 3, in a hypothetical condition where the attained index is the same for all types of accidents.

It can be noted that the weighting coefficient for side grounding/contact in Eq. (5) is significantly larger than the other two coefficients, and this makes the attained index A_{GR-S} playing a dominant role in the quantification of the safety metric SM. This is a direct natural consequence of the background information used in the development. At the same time, this outcome raised a discussion within the eSAFE project, and some relevant considerations are reported hereinafter in Sect. 3.3.

3.2 *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:

$$A = Pr_{CL} \cdot A_{CL} + Pr_{GR-B} \cdot A_{GR-B} + Pr_{GR-S} \cdot A_{GR-S} \tag{6}$$

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} can be determined from the analysis of historical data. To this end, the accidents data analysis in eSAFE relied on the accidents database developed in the EMSA 3 project [23].

Also this approach has been followed in eSAFE [28, 29, 47]. It is noted that the size of available accidents sample, after the filtering, was rather limited, corresponding to 16 accidents in total (collisions: 4, bottom grounding: 3, side grounding/contact: 9). 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. In fact, according to the available data, the conditional probabilities with associated 95% confidence intervals have been estimated as $Pr_{CL} = 25\%\ [7\%\ , 52\%\ ]$, $Pr_{GR-B} = 19\%\ [4\%\ , 46\%\ ]$ and $Pr_{GR-S} = 56\%\ [30\%\ , 80\%\ ]$. Therefore, from the analysis of data, the following Combined Attained Subdivision Index, A, was eventually derived (see also [28, 29, 47]):

$$A = 0.25 \cdot A_{CL} + 0.19 \cdot A_{GR-B} + 0.56 \cdot A_{GR-S} \tag{7}$$

It can be noted from Eq. (7) that also in case of the combined A-index, the side grounding/contact accidents are associated with the largest weighting coefficient, which reflects the highest relative fraction of observed accidents. The outcomes from the analysis have been subject to extensive discussion within the eSAFE project, and some relevant considerations are reported in the following Sect. 3.3.

3.3 Discussion on Selection and Use of the Safety Metric

Two safety metrics have been defined in eSAFE which share the characteristic that they can both be represented by weighted combinations of individual A-indices corresponding to different types of accidents, namely the risk-based safety metric SM (see Eq. (5)) and the Combined Attained Subdivision Index A (see Eq. (7)).

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.

Comparing Eqs. (5) and (7), 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. 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. 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. As a result, this topic has been left as an important topic to be addressed in future research activities.

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 by the sensitivity analysis in EMSA 3 [23] and by the details of the underlying accident statistics, the number of accidents in the various branches of the event trees of the risk models is small. This, as already highlighted, increases the uncertainty in the weighting coefficients of 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, and respectively the consequences. Hence, the application of the safety metric SM in its current form, which to a great 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 has been recommended, in order to achieve a more reliable measure for the risk due to flooding [28, 29, 47].

4 Software Implementation for Practical Application

In industrially oriented projects like eSAFE, 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.

By utilizing and extending the technology and a tool developed in the EMSA 3 project [46], a new functionality was originally developed in eSAFE for generating bottom grounding, side grounding/contact and also collision damages, on the basis of the non-zonal approach stemming from eSAFE. This functionality was initially made available in a modified test version of NAPA software, for evaluation use in the project.

The tool in NAPA was first extended to cover collision damages which, as described in Sect. 2, are consistent with current SOLAS with the addition of a probabilistic model for the extent of damage below the waterline. 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.

The tool was then tested through pilot applications by the developers of the methodology and by the designers [27]. Results from the pilot usage were eventually used to provide insight to the newly developed approach and to guide subsequent calculations within the project. Systematic tests have also shown the usability and robustness of the tool.

The successful pilot testing led to the interest in continuing exploring the potentials and benefits of the developed approach and associated tool. As a result, the original eSAFE test tool has recently been further refined and implemented as a new feature in NAPA software [34]. This recent evolution basically brings the eSAFE approach from the research and development stage, to a new level with potential for generalised practical application.

The tool allows the application of the non-zonal approach considering bottom grounding (B00 damages) and side grounding/contact (S00 damages) according to EMSA 3 modelling [8, 46] and collision (C00 damages) according to the approach developed in eSAFE, which is in line with, and extends, SOLAS (see Sect. 2).

It is also noted that breaches for each damage type are generated separately for each calculation draught. As a result, the calculation of flooding probability for each damage case is also draught dependent for each type of accident. This represents an improvement of the EMSA 3 approach, where, for reasons related to computational time, damage cases and corresponding flooding probabilities were calculated only at the deepest draught and then were kept the same for the other calculation draughts [4, 46]. This updated capability is used in the application examples in the following Sect. 5, and it has also been used by Bulian et al. [8].

5 Application Examples

The developed non-zonal approach has been extensively applied throughout the eSAFE project. At first, a series of calculations were carried out to verify the correct implementation of the non-zonal approach for collision [5, 27]. In this context, among other checks, an example verification was carried out for a barge [27] with and without double bottom, and without any additional horizontal subdivision boundary below the waterline.

The barge configuration with double bottom is depicted in Fig. 3. The subdivision of the configuration without double bottom is exactly the same as that shown in Fig. 3, but without the inner bottom. The overall length of the barge, which corresponds to the subdivision length [19], is 170.25 m, while the length between perpendicular, which is taken as ICLL length [20], is 165 m. The breadth of the barge is 28 m and its total height is 16 m, with a double bottom height of 2 m and a bulkhead deck positioned at 10 m above the bottom. The barge does not have any longitudinal bulkhead, all compartments extend from side to side, and Fig. 3 reports the longitudinal coordinates of the transversal bulkheads.

The loading conditions used in the calculations correspond to a light service draught d_l of 6.2 m, a partial subdivision draught d_p of 6.8 m and a deepest subdivision draught d_s of 7.2 m, all with zero trim. The same metacentric height, $\overline{GM} = 2$ m, was used for all calculation draughts.

Since the focus of this analysis was the relative comparison between non-zonal and zonal approach, and not the assessment of A-indices in absolute sense, all calculations have been carried out using a permeability $\mu = 1.00$ for all compartments, without considering any connection between rooms, without considering any opening, without considering any applied moment, and considering only s_{final}. The s-factor was calculated following SOLAS 2009 according to SOLAS/II-1/B-1/7-2, assuming that the vessel is a passenger ship.

For the case of the barge without double bottom, the SOLAS zonal approach provides exact results in terms of A-indices, because, for that configuration, the "worst-case approach" adopted by SOLAS to deal with horizontal subdivision boundaries below the waterline has no impact on the results. Therefore, the non-zonal approach could be directly compared with SOLAS for such configuration [27]. Instead, in case of the 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 [6]. 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" [6]. 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 Fig. 4. The figure reports partial and global A-indices from standard SOLAS zonal approach, from SOLAS zonal approach supplemented by "u-factor", and from non-zonal approach for collision. To increase the accuracy of non-zonal calculations, a total of 12 repetitions with 10^5 breaches for each repetition were carried out, and non-zonal data in Fig. 4 correspond to the average A-indices across repetitions, together with 95% confidence interval (which are so small that they are hardly visible). The observed very small differences in Fig. 4 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.

A number of practical design-oriented applications have then been carried out throughout the project to assess the developed approach. Among them, a series of calculations have been carried out, as a pilot application, for a cruise ship with overall

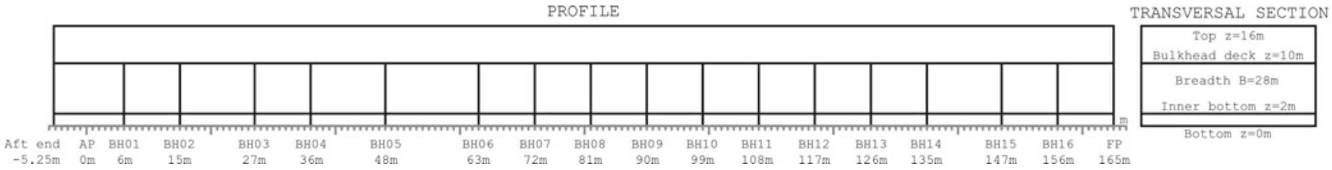


Fig. 3 Barge used for testing. Configuration with double bottom

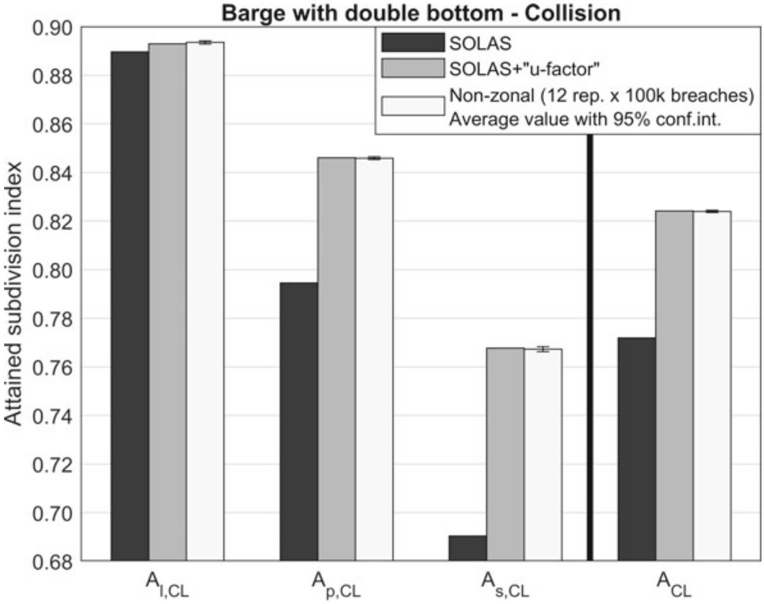


Fig. 4 Barge with double bottom. Comparison of partial and global A-indices obtained by standard SOLAS zonal approach, SOLAS zonal approach supplemented by "u-factor", and non-zonal approach (average values with 95% confidence interval)

length of about 240 m carrying more than 2000 persons onboard, using loading conditions providing marginal compliance with SOLAS 2009 damage stability requirements [27]. An example result of this application of the non-zonal approach for collision is shown in Fig. 5. This figure compares the attained subdivision indices calculated according to standard SOLAS zonal approach, SOLAS zonal approach supplemented by the "u-factor", and non-zonal approach for collision (average index across repetitions, with 95% confidence interval).

Differently from the case of the barge (see Fig. 4), for the cruise ship (see Fig. 5) the zonal SOLAS+"u-factor" approach is an approximate one, because the cruise ship 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 shown in Fig. 5. 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. Further investigations would be useful to better understand the general level of discrepancy between the application of the approximate SOLAS+"u-factor" approach and 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" approach and

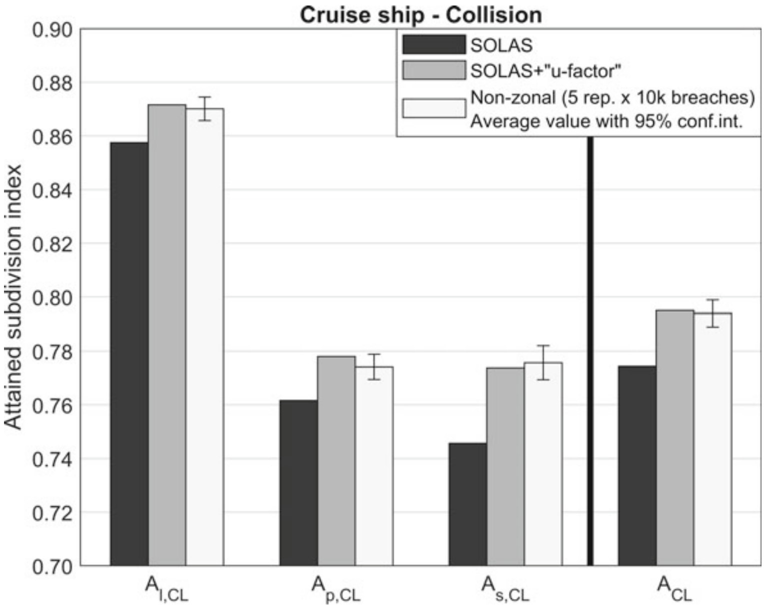


Fig. 5 Example cruise ship. Comparison of partial and global A-indices obtained by standard SOLAS zonal approach, SOLAS zonal approach supplemented by "u-factor", and non-zonal approach (average values with 95% confidence interval)

non-zonal approach) provides, as expected, an increase of the calculated attained subdivision indices (see Bulian et al. [6] for more details on this topic).

Further example outcomes from practical application on the same cruise ship are reported in Fig. 6, which shows partial and global A-indices obtained from the non-zonal approach for the three considered types of accidents: collision (CL), bottom grounding (GR-B), side grounding/contact (GR-S). In all cases, the global indices are obtained by averaging the partial indices for the three calculation draughts using standard SOLAS weighting factors, i.e. 0.2 for light service draught d_l, 0.4 for partial subdivision draught d_p, and 0.4 for deepest subdivision draught 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 [37, 38].

6 Conclusions

This contribution has provided an overview of the development and implementation of a common framework for probabilistic damage ship stability assessment of

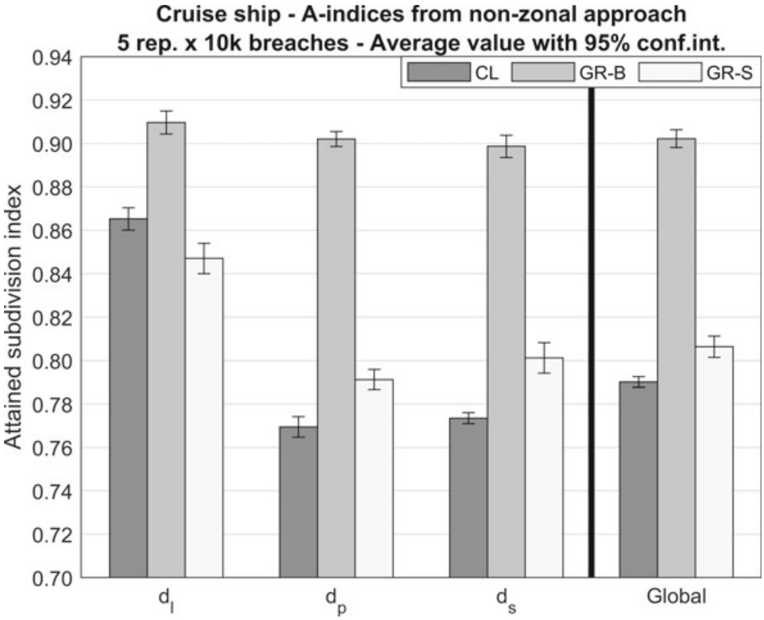


Fig. 6 Example cruise ship. Partial and global A-indices from non-zonal approach for collision (CL), bottom grounding (GR-B) and side grounding/contact (GR-S). Average values with 95% confidence interval

passenger ships, considering damages due to collision, bottom grounding and side grounding/contact accidents, as carried out during the eSAFE project.

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 has been demonstrated. Moreover, the lack of a probabilistic description for the lower limit of collision damage in the present SOLAS zonal approach has also been overcome with the development of a specific model based on historical accidents data. This allows a more consistent assessment of the effect of horizontal subdivision boundaries below the waterline and, eventually, of the ship survivability in case of collision accidents.

A software functionality has been developed in NAPA software 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. Consequently, the developed approach has a potential generalised practical applicability beyond the research and development level.

Different alternatives have been considered in eSAFE 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 associated discussion were carried out within eSAFE regarding the different alternatives. Eventually, it has been recommended by eSAFE to actively use the new tools and first gain experience on the impact of design changes on the survivability following a collision, bottom grounding and side grounding/contact accident, by using the respective attained subdivision indices separately, for the time being. In addition, a regular review and update of the risk models has been recommended, to achieve a more reliable measure for the risk due to flooding. In this respect, it can also be added that a more complete collection of accident details, resulting in additional and higher quality data, would definitely be important to achieve the goal of improving the risk models through the review and update process. It is noted that advances with respect to revision and update of the risk models are being pursued by the recent FLARE project.

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

References

1. Bačkalov I, Bulian G, Cichowicz J, Eliopoulou E, Konovessis D, Leguen J-F, Rosén A, Themelis N (2016) Ship stability, dynamics and safety: Status and perspectives from a review of recent STAB conferences and ISSW events. Ocean Eng 116:312–349. https://doi.org/10.1016/j.oceaneng.2016.02.016
2. Belenky VL, Spyrou KJ, van Walree F, Neves MAS, Umeda N (eds) (2019) Contemporary ideas on ship stability—risk of capsizing. Springer. https://doi.org/10.1007/978-3-030-00516-0
3. Bulian G, Francescutto A (2010) Exploratory data analysis of ship-ship collision data from the updated GOALDS database. Project GOALDS (GOAL based Damage Stability), 30 August
4. Bulian G, Lindroth D, Ruponen P, Zaraphonitis G (2016) Probabilistic assessment of damaged ship survivability in case of grounding: development and testing of a direct non-zonal approach. Ocean Eng 120:331–338. https://doi.org/10.1016/j.oceaneng.2016.02.018

5. Bulian G, Zaraphonitis G, Francescutto A, Ruponen P (2017) eSAFE-D2.1.1—Description of geometrical and probabilistic model for collision damage. Joint Industry Project "eSAFE—enhanced Stability After a Flooding Event—A joint industry project on Damage Stability for Cruise Ships", 03 May (Rev.1)
6. Bulian G, Cardinale M, Francescutto A, Zaraphonitis G (2019) Complementing SOLAS damage ship stability framework with a probabilistic description for the extent of collision damage below the waterline. Ocean Eng 186(106073):1–11. https://doi.org/10.1016/j.oceaneng.2019.05.055
7. Bulian G, Cardinale M, Dafermos G, Eliopoulou E, Francescutto A, Hamann R, Lindroth D, Luhmann H, Ruponen R, Zaraphonitis G (2019) Considering collision, bottom grounding and side grounding/contact in a common non-zonal framework. In: Proceedings of 7th international ship stability workshop (ISSW2019), 10–12 June, Helsinki, Finland, pp 245–257
8. Bulian G, Cardinale M, Dafermos G, Lindroth D, Ruponen P, Zaraphonitis G (2020) Probabilistic assessment of damaged survivability of passenger ships in case of grounding or contact. Ocean Eng 218(107396):1–27. https://doi.org/10.1016/j.oceaneng.2020.107396
9. Conti F, Le Sourne H, Vassalos D, Kujala P, Lindroth D, Kim SJ, Hirdaris S (2021) A comparative method for scaling SOLAS collision damage distributions based on ship crashworthiness—application to probabilistic damage stability analysis of a passenger ship. Ships Offshore Struct. https://doi.org/10.1080/17445302.2021.1932023
10. Dankowski H, Krüger S (2011) On the safety level of the SOLAS 2009 damage stability rules for RoPax vessels. Marine Syst Ocean Technol 6:87–96. https://doi.org/10.1007/BF03449296
11. EMSA (2020) Study assessing the acceptable and practicable risk level of passenger ships related to damage stability. http://www.emsa.europa.eu/damage-stability-study.html. Last accessed 14 Aug 2020
12. FLARE (2021) FLooding Accident REsponse (FLARE) Project. https://flare-project.eu/
13. Hamann R, Eliopoulou E, Zaraphonitis G (2019) Deliverable 2.5—Revised event tree and recommendations for improvements. Project "FLooding Accident REsponse (FLARE)", 30 November (V01). Available from https://flare-project.eu/
14. IMO (2003) Resolution MEPC.110(49)—Revised interim guidelines for the approval of alternative methods of design and construction of oil tankers under regulation 13F(5) of Annex I of MARPOL 73/78. 18 July (see also corrigenda issued through IMO Document MEPC 49/22/Add.2/Corr.1 on 3 February 2006)
15. IMO (2008) Resolution MSC.281(85)—Explanatory notes to the SOLAS Chapter II-1 Subdivision and damage stability regulations, 4 Dec
16. IMO (2012) SLF 55/INF.7—The GOAL based Damage Stability project (GOALDS)—Derivation of updated probability distributions of collision and grounding damage characteristics for passenger ships. Submitted by Denmark and the United Kingdom, 14 Dec
17. IMO (2015) SDC 3/3/4—Report of the intersessional meeting of the Experts Group on Formal Safety Assessment (FSA). Submitted by the Chairman of the FSA Experts Group, 12 Nov
18. IMO (2017) Resolution MSC.429(98)—Revised explanatory notes to the SOLAS Chapter II-1 Subdivision and damage stability regulations, 9 June
19. IMO (2020) International Convention for the Safety of Life at Sea (SOLAS). Consolidated edition
20. IMO (2020) International Convention on Load Lines, 1966, as amended by the 1988 Protocol by Res. MSC.143(77) in 2003. Consolidated edition
21. IMO (2020) International Convention for the Prevention of Pollution from Ships. Consolidated edition
22. Jasionowski A (2001) An integrated approach to damage ship survivability assessment. PhD Thesis, University of Strathclyde
23. Konovessis D, Hamann R, Eliopoulou E, Luhmann H, Cardinale M, Routi A-L, Kujanpaa J, Bertin R, Harper G, Pang E, Papanikolaou A (2015) Risk acceptance criteria and risk based damage stability, Final Report, part 2: Formal Safety Assessment. DNVGL Report No.: 2015-0166 Rev.3, Project EMSA/OP/10/2013, European Maritime Safety Agency, 29 June. Available from http://www.emsa.europa.eu/damage-stability-study.html

24. Kehren F-I, Krüger S (2007) Development of a probabilistic methodology for damage stability regarding bottom damages. In: Proceedings of 10th international symposium on practical design of ships and other floating structures (PRADS2007), Houston, Texas, USA
25. Krüger S, Dankowski H (2009) On the evaluation of the safety level of the Stockholm Agreement. In: Proceedings of 10th International Marine Design Conference (IMDC2009), Trondheim, Norway, 26–29 May
26. Krüger S, Dankowski H (2019) A Monte Carlo based simulation method for damage stability problems. In: Proceedings of ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2019), June 9–14, Glasgow, Scotland, UK
27. Lindroth D, Bulian G, Dafermos G, Zaraphonitis G, Cardinale M, Luhmann H, Ruponen P (2017) eSAFE-D2.3.1—Final report of "WP2.3—Development of a software tool for the application of the combined methodology". Joint Industry Project "eSAFE—enhanced Stability After a Flooding Event—A joint industry project on Damage Stability for Cruise Ships", 09 Aug (Rev.1)
28. Luhmann H, Olufsen O, Atzampos G, Bulian G (2018) eSAFE-D4.3.1—Summary report. Joint Industry Project "eSAFE—enhanced Stability After a Flooding Event—A joint industry project on Damage Stability for Cruise Ships", 24 Oct (Rev.4)
29. Luhmann H, Bulian G, Vassalos D, Olufsen O, Seglem I, Pöttgen J (2018) eSAFE-D4.3.2—Executive summary. Joint Industry Project "eSAFE - enhanced Stability After a Flooding Event—A joint industry project on Damage Stability for Cruise Ships", 24 October (Rev.3). Available from https://cssf.cruising.org/projects
30. Lützen M (2001) Ship collision damages. PhD Thesis, Department of Mechanical Engineering, Technical University of Denmark, Lyngby, Denmark, December
31. Lützen M (2002) Damage distributions. Document 2-22-D-2001-01-4, Project HARDER (Harmonisation of Rules and Design Rationale), 29 Jul
32. Mains C (2010) WP3 Database of damage characteristics—File: GOALDS-database-rev3.xls. Project GOALDS (GOAL based Damage Stability)
33. Montewka J, Hinz T, Kujala P, Matusiak J (2010) Probability modelling of vessel collisions. Reliab Eng Syst Saf 95:573–589. https://doi.org/10.1016/j.ress.2010.01.009
34. NAPA (2020) NAPA for Design Manuals 2020.1—Damage Stability (DAM)—Non-Zonal Analysis (DAM)
35. Neves MAS, Belenky VL, de Kat JO, Spyrou K, Umeda N (eds) (2011) Contemporary ideas on ship stability and capsizing in waves. Springer. https://doi.org/10.1007/978-94-007-1482-3
36. Papanikoalou A (ed) (2009) Risk-based ship design—Methods, tools and applications. Springer. https://doi.org/10.1007/978-3-540-89042-3
37. Paterson D, Atzampos G, Vassalos D, Boulougouris E (2017) eSAFE-D1.2.1—Analysis of onboard data with regards to probabilities of initial draughts. Joint Industry Project "eSAFE—enhanced Stability After a Flooding Event—A joint industry project on Damage Stability for Cruise Ships", 01 Mar (Rev.5)
38. Paterson D, Vassalos D, Atzampos G, Boulougouris E, Luhmann H (2019) Impact of drafts on the damage survivability of cruise ships. Ocean Eng 187(106136):1–8. https://doi.org/10.1016/j.oceaneng.2019.106136
39. Pawłowski M (2004) Subdivision and damage stability of ships. Euro-MTEC book series, Foundation for the Promotion of Maritime Industry, Gdansk, Poland, Poland, ISBN 83-919488-6-2, 311p
40. Ruponen P, Lindroth D, Routi A-L, Aartovaara M (2019) Simulation-based analysis method for damage survivability of passenger ships. Ship Technology Research 66:180–192. https://doi.org/10.1080/09377255.2019.1598629
41. Spanos D, Papanikolaou A (2014) On the time for the abandonment of flooded passenger ships due to collision damages. J Mar Sci Technol 19:327–337. https://doi.org/10.1007/s00773-013-0251-0
42. Valanto P, Friesch J (2009) HSVA Report No. 1669—Research for the parameters of the damage stability rules including the calculation of water on deck of Ro-Ro passenger vessels, for the amendment of the directives 2003/25/EC and 98/18/EC—Final report Part I. 22 Jul

43. Vassalos D, Hamamoto M, Papanikolaou A, Molyneux D (eds), Spyrou K, Umeda N, de Kat JO (co-eds) (2000) Contemporary ideas on ship stability. Elsevier
44. Vassalos D, Hamann R, Zaraphonitis G, Luhmann H, Kuusisto T, Lietzen J (2016) Combined assessment of cost-effectiveness of previous parts, FSA compilation and recommendations for decision making. DNVGL Report No.: 2015–0404 Rev.1, Project EMSA/OP/10/2013, European Maritime Safety Agency, 12 Jan. Available from http://www.emsa.europa.eu/damage-stability-study.html
45. Vassalos D (2022) The role of damaged ship dynamics in addressing the risk of flooding. Ships Offshore Struct 17(2):279-303. https://doi.org/10.1080/17445302.2020.1827639
46. Zaraphonitis G, Bulian G, Lindroth D, Hamann R, Luhmann H, Cardinale M, Routi A-L, Bertin R, Harper G, Papanikolaou A, Francescutto A, Ruponen P (2015) Evaluation of risk from raking damages due to grounding, Final report. DNV GL Report No.: 2015-0168 Rev.2, Project EMSA/OP/10/2013, European Maritime Safety Agency, 17 Jun. Available from http://www.emsa.europa.eu/damage-stability-study.html
47. Zaraphonitis G, Bulian G, Hamman R, Eliopoulou E, Cardinale M, Luhmann H (2017) eSAFE-D2.2.1—Description of methodology. Joint Industry Project "eSAFE—enhanced Stability After a Flooding Event—A joint industry project on Damage Stability for Cruise Ships", 29 Mar (Rev.2)
48. Zhang M, Conti F, Le Sourne H, Vassalos D, Kujala P, Lindroth D, Hirdaris S (2021) A method for the direct assessment of ship collision damage and flooding risk in real conditions. Ocean Eng 237(109605):1–20. https://doi.org/10.1016/j.oceaneng.2021.109605