

# Cruise Ship Survivability in Waves



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**Abstract** Recent developments in damage stability legislation have drawn from ships with simple internal architecture such as RoPax and cargo ships. However, ships with complex internal architecture, such as cruise ships, have been rather neglected. In a regulatory context, cruise ships are currently grouped with RoPax and other passenger ships and this can be misleading. Moreover, it is well known that cruise ships vary significantly in their behaviour post-flooding incidents in comparison to RoPax ships. This problem has been acknowledged by the Cruise Ship Safety Forum Steering Committee who consequently funded the Joint Industry Project eSAFE to undertake cruise ship-focused research on damage stability. This entails analysis of pertinent simplifications embedded in SOLAS, the development of a methodology to combine consequences from collision and grounding accidents, the establishment of new survival criteria for cruise ships and finally the development of guidelines to use numerical flooding simulation in seaways as an alternative approach to assessing ship damage survivability. The findings of this research are presented in this paper, based on a full set of time-domain numerical simulations along with static calculations for a number of cruise ships. A new s-factor is derived catering specifically for cruise ships that accounts more accurately for survivability in a wave environment. A number of simulations are undertaken on varying size cruise ships with the view to deriving a relationship between the critical significant wave height and the residual stability

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properties of such vessels. The results provide the requisite evidence for comparison between SOLAS 2009 A-Index and the ensuing Damage Survivability Index.

**Keywords** Damage stability · Survivability · s-factor · Safety · Time domain numerical simulations · Cruise ship · Flooding

## 1 Introduction

Damage stability has largely developed as a subject over the past 50 years with most of the scientific advances achieved over the latter half of this period. However, the focus concerning such developments and the ensuing legislation is clearly on ships with simple internal architecture such as RoPax and Cargo ships. Ships with complex internal architecture, on the other hand, such as cruise ships, have been treated as a side line; in essence seldom the focus of scientific research on damage stability. For example, the current SOLAS for probabilistic damage stability is based on cargo ships, irrespective of the fact that RoPax have spearheaded developments over the recent past, following a number of serious accidents. In the regulatory context, cruise ships are currently grouped with RoPax and other passenger ships and this is causing serious problems. Cruise ships have a significantly different behaviour after flooding incidents as opposed to RoPax ships. In particular, cruise ships are usually found not so vulnerable to rapid capsizes as RoPax vessels. Results from numerical time-domain simulations of damage scenarios for both ship types support this fact. More specifically, comparison between results from SOLAS2009 calculations and numerical simulations display a significant difference for cruise ships [19]. This problem has been acknowledged by the Cruise Ship Safety Forum, which has consequently initiated research on this subject in a Joint Industry Project, namely eSAFE. A key objective in this project is to identify and to the degree possible quantify the differences between known and/or expected safety levels as indicated by the results from time-domain flooding simulations of cruise ships and the simplified methodology defined in SOLAS II-1 [11].

This paper delves in this direction through the use of available methods to defining damage stability/survivability of passenger ships, namely the Statistical (SOLAS) and Direct (numerical time-domain simulation) approaches. In this respect, a new s-factor, specifically catering for cruise ships has been devised following the statistical approach based on four sample cruise ships. In addition, a number of numerical simulations in pertinent sea states are performed with the view to gauging survivability in waves, linked to collision and grounding damages for two large cruise ships. On this basis, a comparison is conducted between the statistical and direct approaches results leading to drawing specific conclusions.

## 2 Statistical Approach to Damage Stability (A-Index)

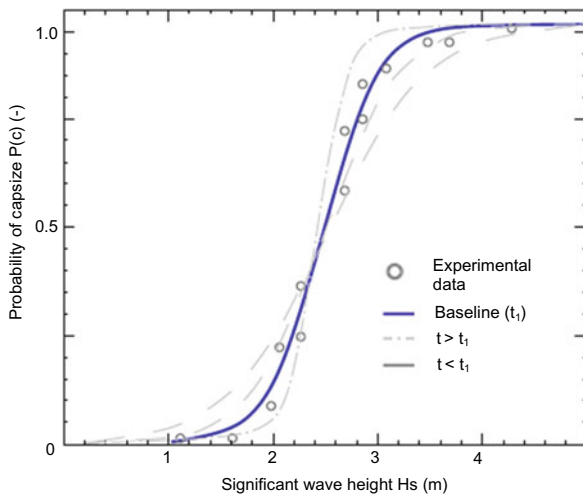
### *Critical significant wave height and capsizes band*

The critical sea state for a specific damage extent and loading condition can be established either with the aid of model tests or by employing time-domain numerical simulations based on first principles. Traditionally, both approaches have been utilised in the past in the course of developing damage stability criteria, including comparisons between the two [7, 8]. Generally, both physical and numerical experiments refer to repeated trials (usually corresponding to 30 min full-scale) in a specific random sea with the view to deriving capsizes rate at a specific significant wave height.

In this respect, one of the main elements, which can be derived from the characteristics of the damaged ship is the capsizes band. This indicates the range of sea states within which a transition from unlikely ( $P_c = 0$ ;  $P_s = 1$ ) to certain capsizes ( $P_c = 1$ ;  $P_s = 0$ ) can be observed, where  $P_c$  is probability of capsizes  $P_s$  probability of survival. Another concept intrinsically linked to the capsizes band is the capsizes rate. The capsizes rate follows always a sigmoid shape distribution. The rate of observed capsizes depends on the time of observation. In this respect, in case of a limiting case of infinite exposure time the capsizes rate distribution will turn into a unit step function as indicated in Fig. 1 for increased simulation times. Indeed, for low capsizes probability, the corresponding significant wave height will remain the same (minor difference) when the time of observation is increased [13]. Hence, a sea state corresponding to a low capsizes rate can be established on the basis of relatively short simulations and would still remain valid for longer observations.

Following previous studies, the concept of the s-factor is linked to the critical significant wave height. Originally, during the EU project HARDER (Tuzcu, 2003b) the s-factor was linked to the critical significant wave height of the sea state at which

**Fig. 1** Indicative capsizes rate transition from baseline curve with increase or decrease of observation time. Where  $t$  represents the simulation observation time and  $t_n$  stands for infinite time. When  $t = t_n$  the sigmoid becomes a vertical line



a ship exposed for half an hour (30 min) to the action of waves would have a 50% chance of capsizing. However, based on subsequent observations in project GOALDS [16], it was found that when the simulation time increases, the capsize band contracts towards its lower boundary, with the capsize probability becoming a step function of  $H_s$ .

**eSAFE—Cruise ship specific s-factor**

In order to account for the complex internal watertight architecture and loss mechanisms of modern passenger ships, a new s-factor derivation has been developed within project eSAFE, catering specifically for cruise ships. Such internal watertight detail can be sufficiently captured with the aid of numerical simulations. To this end, for the first time in the history of development of damage stability criteria, estimation of damage survivability is solely based on numerical time-domain simulation results for four varying size cruise ships using the dynamic numerical time-domain code PROTEUS3 [12].

The new s-factor, does not only account for the variations in cruise ship size but also has been proven robust for different compartment damages, namely (1, 2, 3 and 4-compartment equivalent). Based on regression of the numerical simulation results (94 points in total), a relationship has been derived between the critical significant wave height and residual stability properties, in line with previous work.

A new formula for predicting the critical significant wave height  $H_{s_{crit}}$  has been developed as shown by Eq. (1). Based on statistical analysis of the various data sets, the most accurate regression was achieved with reference to  $GZ_{max}$  and Range properties (as in Project HARDER) but with an additional scaling factor taken into account ( $\lambda$ ) namely EVR as explained further below (similar to Project GOALDS), [6]. The regression has been conducted with consideration of all data points, accounting for critical significant wave heights that span up to 7 m, using global wave statistics [14]. The deviation from SOLAS of using actual wave statistics, rather than wave statistics pertaining to sea states at the time of the incident, is based on the argument that it is essential to estimate the risk of exposing ships to all operating sea states (thus, calculating pertinent risk), and not just those wave characteristics at which accidents have taken place in the past (historical risk). The multiplier in Eq. (1) represents the 99th percentile of the cumulative probability.

$$H_{s_{crit}} = 7 \cdot \left[ \frac{\min(\lambda \cdot Range, T Range)}{T Range} \cdot \frac{\min(\lambda \cdot GZ_{max}, T GZ_{max})}{T GZ_{max}} \right]^{1.05} \quad (1)$$

where,

$T G Z_{max}$  30 cm Target  $GZ_{max}$  value

$T Range$  30° Target range value

$\lambda$  Scaling factor accounting for damage and ship size.

The new s-factor addresses only progressive flooding and is derived on the basis of  $GZ_{max}$  and Range of the un-truncated residual stability curve. This implies that these

values have not been limited to the angle in which unprotected openings are immersed but instead only the angle at which the righting lever vanishes. Such characteristics (openings) relate to local details in ship geometry that cannot be easily captured by global parameters such as properties of the residual stability curve.

In light of the derived results, a disparity was observed, which was attributed to the difference in scale in both the size of each vessel and the volume of accumulated flood-water associated with each of the respective damage cases. To account for this, it was deemed necessary to find an appropriate scaling factor. In this effort, several parameters were investigated including residual freeboard and residual volume. However, the most suitable scaling parameter was found to be the “Effective Volume Ratio” denoted as  $\lambda$ ; a parameter which accounts for both the scale of the damage and that of the vessel. Therefore, the EVR is provided by Eq. (2) as follows,

$$\lambda = \text{Effective Volume Ratio} = \frac{V_{residual}}{V_{flooded}} \tag{2}$$

where, the residual volume  $V_{residual}$  is provided from Eq. (3) below,

$$V_{residual} = V_{WTE} - V_{Displacement} - V_{Flooded} \tag{3}$$

where specifically,

- $V_{WTE}$  Weathertight Envelope is the real weathertight extent and refers to the total volume of all rooms contained in the area spanning from the base line up to and including the deck at which weathertight structure spans vertically. This represents the physical properties of the vessel.
- $V_{Displacement}$  Volume displacement of a given vessel ( $m^3$ )
- $V_{Flooded}$  Volume of the water in the flooded compartments at the final stage of flooding, based on static calculations.

Thus, the scaling factor ( $\lambda$ ) is the ratio of Effective Volume Ratios for two cruise ships used as mentioned earlier. This is applied directly to residual stability properties of the GZcurve, namely Range and GZmax as shown in Eq. (1). Given this, a formulation to calculate the s-factor is given by the regressed CDF of wave heights from IACS Global wave statistics. The new s-factor is provided next:

$$s(H_{s_{crit}}) = e^{-e(1.1717-0.9042 \times H_s)} \tag{4}$$

where,

$H_{s_{crit}}$  critical significant wave height [Notably, when  $H_{s_{crit}} = 7$  m,  $s(H_{s_{crit}}) = 1$ ].

### 3 Direct Approach to Survivability Assessment of Cruise Ships

#### Background

The s-factor in SOLAS 2009 is estimated based on the assumption that the ship capsizes within half an hour exposure [17, 18]. This, however, is not applicable for cruise ships since they take minutes to hours due to their intricate internal architecture, hence the need to ascertain the impact of time on cruise ship survivability and to account for this. The Time To Capsize (TTC), is a random variable, thus only known as a distribution determined through probabilistic methods. Moreover, survivability depends on a number of governing parameters (e.g. loading condition, sea state, damage extent) all of which are also stochastic in nature. In this respect, accounting only for the damage case scenarios implicit in SOLAS 2009 (typically over 1000 for a typical passenger ship) and considering the 3 loading conditions, also implicit in these regulations, and some 10 sea states per damage case for estimating capsize rates, it becomes readily obvious that some form of simplification and reduction will be meritorious.

To this end, one of the most efficient ways, entails a process involving Monte Carlo sampling from distributions of pertinent random variables (damage extents, loading conditions, sea states, etc.) to generate damage scenarios and perform numerical time-domain simulations. The latter accounts accurately for the physical phenomena of ship-floodwater-wave interactions as function of time providing robust indication on which of these scenarios would lead to ship capsize/sinking and the TTC. In this manner, any assumptions and approximations inherent in the probabilistic elements of SOLAS 2009 damage stability regulations are diminished/minimised (Fig. 2).

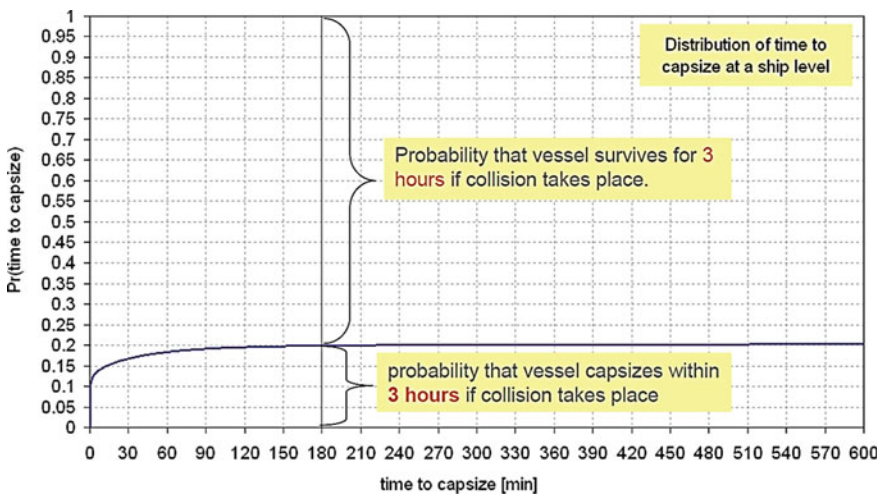


Fig. 2 Cumulative marginal probability for time to capsize [19]

In the comparison of the two sets of results between the direct and statistical approaches, it is to be noted that the Attained subdivision Index (Eq. 5) is an aggregate probability representing the average probability of survival for a set of generated damages. Hence, survivability is calculated for each damage scenario as the “expected” outcome averaged with respect to the distribution of wave heights. On the other hand, the survivability level obtained from numerical simulations (herein denoted as “Survivability Index” indicated by Eq. 6) uses a single significant wave height sampled from pertinent wave statistics and the random outcome (survival or capsized) is then averaged across all damages and loading conditions.

$$Attained\ Index\ (AI) = \sum p \cdot w \cdot \bar{s} \tag{5}$$

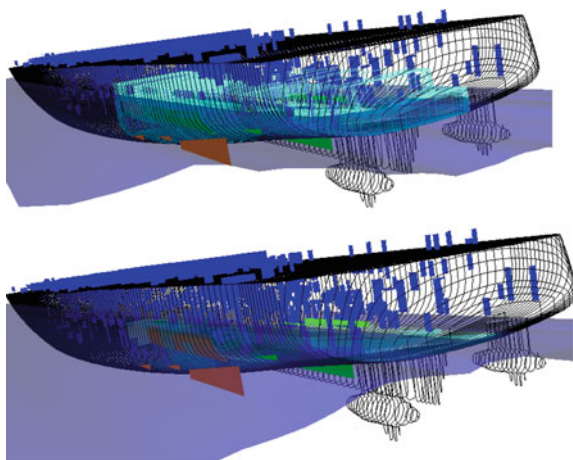
$$Survivability\ Index\ (SI) = \sum p \cdot w \cdot s \tag{6}$$

**Monte Carlo numerical simulation methodology**

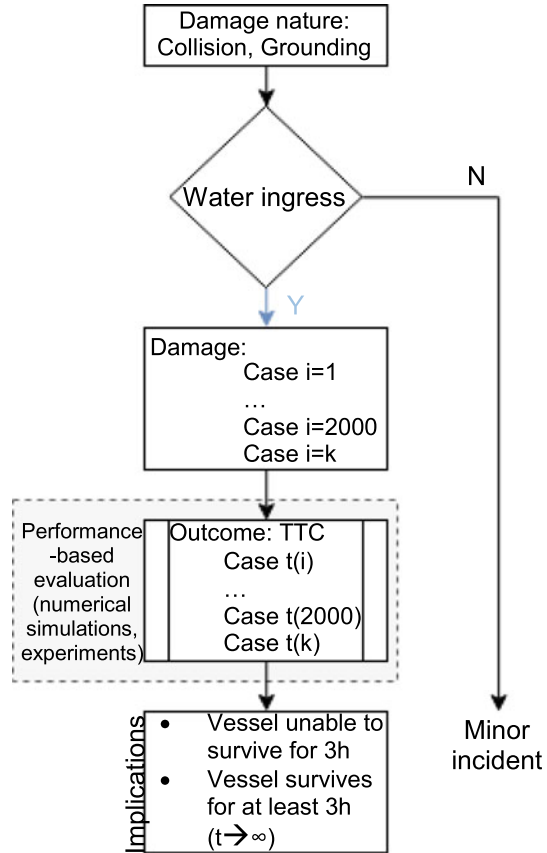
Survivability can be assessed with use of time-domain simulations for a group of damages. This allows for derivation of an estimate of the expected probability of survival for a given group of damages characterised by random locations, damage extent and sea states. The Time To Capsize (TTC) can be defined through an automated process using Monte Carlo sampling (see Fig. 4) and dynamic flooding simulations with the time-domain numerical simulation code PROTEUS3 as shown in Fig. 3 for a 3 compartment damage [12].

Two large cruise ships ranging in overall length ( $290 \leq L_{OA} \leq 325$ ) have been subjected to a number of Monte Carlo simulations for a single loading condition, namely the deepest subdivision draft. Significant wave heights are randomly sampled from the distribution of global wave statistics as presented in [14], which is provided

**Fig. 3** 3-compartment aft damage in PROTEUS3



**Fig. 4** Monte Carlo simulation set-up



in Fig. 5. In the case of collision scenarios, time-domain simulations were also performed in calm water, in order to ascertain impact of waves and ship dynamics on survivability.

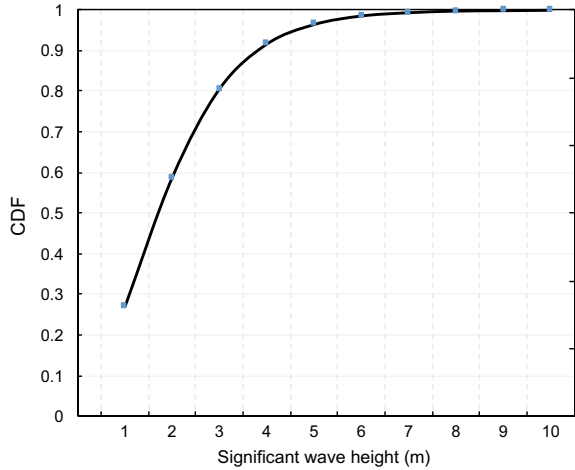
The total time for each simulation run is 1820s (30 min) and they are initiated after 20 s in order to allow for any transients to settle. This means that the damage openings are activated after 20 s of simulation time. Survivability is assessed not only on the basis of physical/actual capsizes (ship turns over,  $\theta_{\text{heel}} > 90$  deg) but also on the basis of the following three capsizes criteria:

- ITTC capsizes criteria [9] when the instantaneous roll angle exceeds 30 degrees or the 3-min average heel angle exceeds 20°.
- Criterion for insufficient capability of evacuation, assessing the effect of heeling angle when the angle of heel is higher or equal to 15° SOLAS CH. II-1 [10].

The maximum final flooding rate of mass per hour for each damage case. The three aforementioned criteria are applied in a parallel fashion during filtering process of the numerical simulation results.



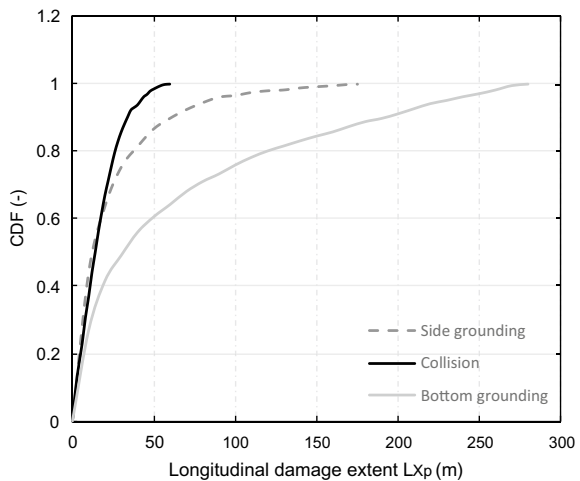
**Fig. 5** Cumulative distribution of the significant wave heights in the case of global wave statistics [15]



Figures 6, 7, 8 and 9 present the damage distributions with respect to their longitudinal and transverse damage extents for each of the two vessels. The damages are sampled based on distributions, which have been derived from work presented in Refs. [2–5, 20]. There, a probabilistic framework has been devised to account for bottom, side groundings and collisions. This overcomes the dichotomy present in SOLAS where survivability in case of collision is addressed in a probabilistic framework while the issue of grounding is addressed in a deterministic manner. The developed approach is compatible with the SOLAS2009 conceptual framework for collision.

A total of 6000 damages are investigated through the time domain simulations relating to 2000 breaches for collision, side and bottom grounding, respectively for

**Fig. 6** Cumulative distribution of the longitudinal damage extent (length)  $L_{x,p}$  for ship A



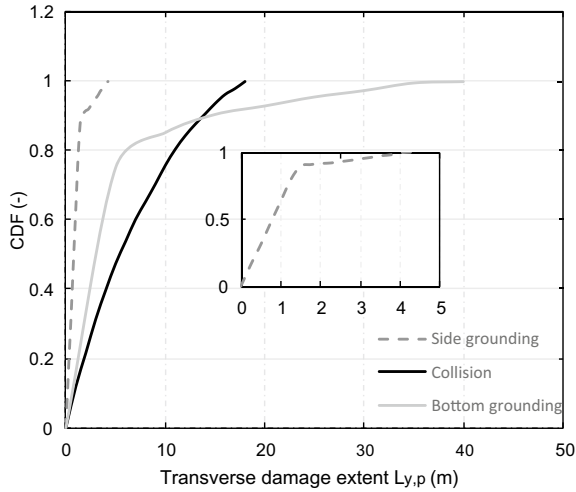


Fig. 7 Cumulative distribution of the transverse damage extent (length)  $L_{y,p}$  for ship A

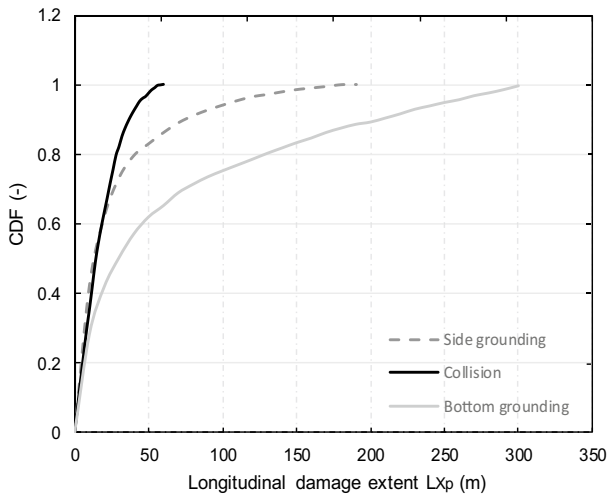
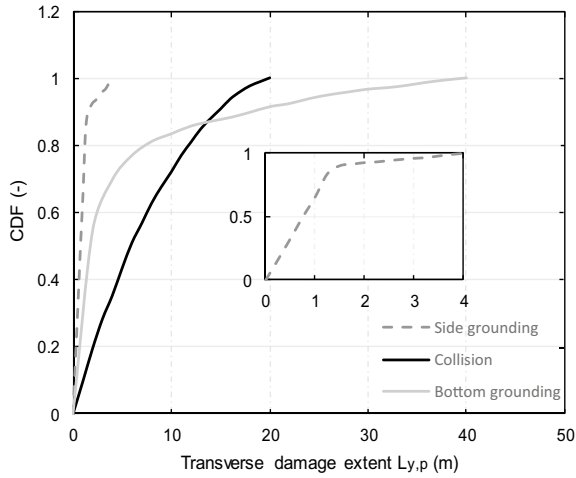


Fig. 8 Cumulative distribution of the longitudinal damage extent (length)  $L_{x,p}$  for ship C

each vessel. The calm-water runs for the case of collisions were repeated for all damage case scenarios.

**Numerical simulation results**

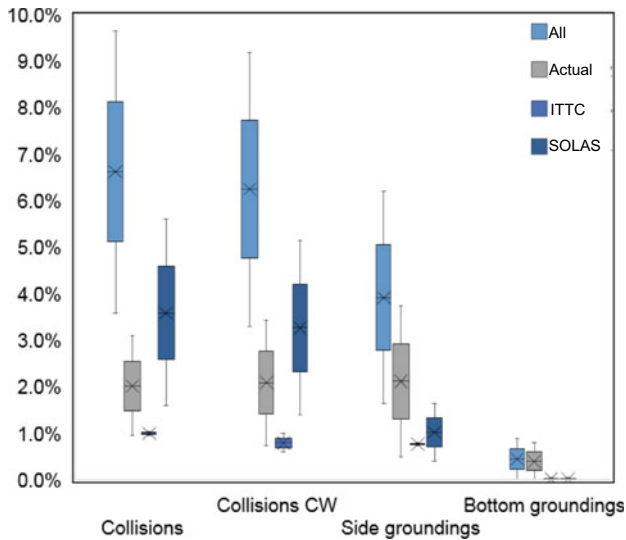
The numerical simulation results are presented with indications linking these to the aforementioned failure criteria for each ship in Fig. 10. In particular, ship A results in 72 capsizes due to collision damages, of which 19 cases are actual capsizes



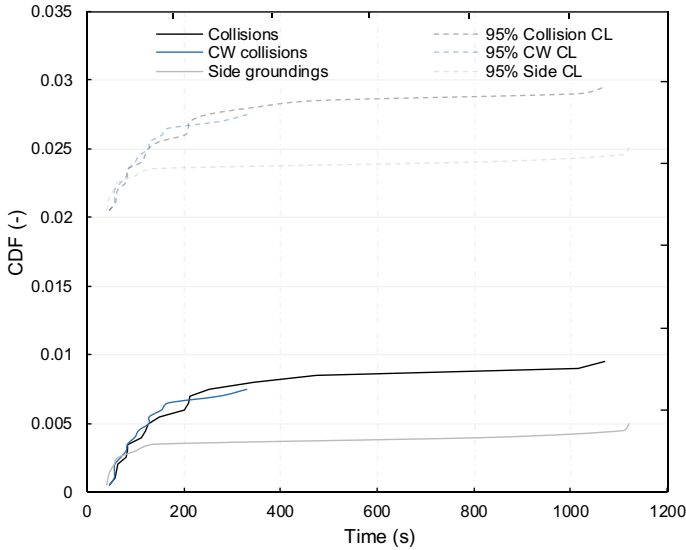
**Fig. 9** Cumulative distribution of the transverse damage extent (length)  $L_{y,p}$  for ship C

(26%). The time required to perform the numerical simulations is depended on the significant wave height used and total size of damage which in turn defines the floodwater accumulation mass. Indicatively, on average, simulations varied between 30 min and 1.2 h.

The cumulative distribution function for Time To Capsize in case of collision damages, based on actual capsizes, shows that the majority of capsizes occurred



**Fig. 10** Quartiles of capsizes for both cruise ships



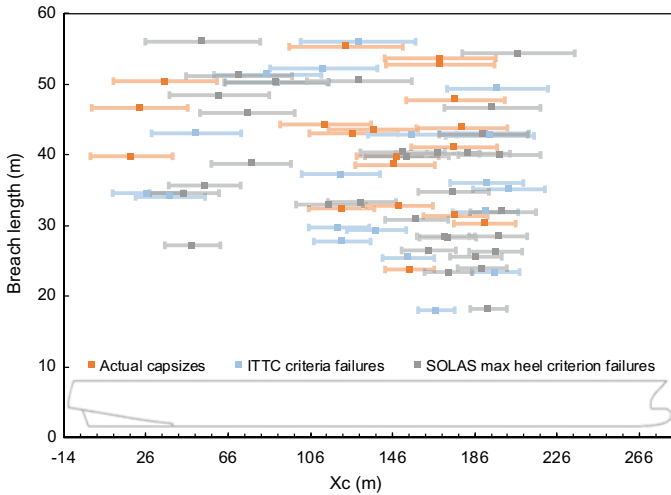
**Fig. 11** Cumulative probability distribution of Time To Capsize for collisions—actual capsizes (ship A) including Calm Water (CW) collisions

within the early stage of the simulations (under 5 min) with no cases beyond 18 min duration, as shown in Fig. 11.

Based on these findings [1], the expected probability of survival as expressed by the Survivability Index lies between 0.97 and 1 with 95% confidence. However, the CDF for TTC calculated for all capsizes (i.e., actual and those violating the ITTC and SOLAS maximum heel criteria) does not stagnate, indicating that some further capsizes would be observed for longer simulation times. Nevertheless, considering the estimates based on half-an-hour runs, the average probability of surviving at least 30 min can be estimated to fall between 0.94 and 0.98 with 95% confidence.

The calm-water runs (CW) resulted in fewer capsizes (63 cases) when compared to collisions in waves. Specifically, three of the calm-water capsizes represent a “shift” towards more conservative failure criteria (i.e. from actual capsizes to ITTC, and from ITTC to SOLAS max heel). This denotes the impact of waves on survivability assessment.

In the case of side groundings, the results indicate 2% of capsizes (33 capsizes) of which 30% represent actual capsizes. Hence, the expected probability of survival corresponds to an equivalent Attained-Index (Survivability Index) of 98.3%. The simulations of Ship A for bottom groundings did not result in any capsizes or violations of the aforementioned survivability criteria. This is likely to be the result of insufficient duration of the simulations, given the slow up-flooding process. In fact, analysis of the final 3-min of the simulations reveals that 52 cases show significant rate of change of heel (over 2 deg/h), 2 show a rate of change of trim in excess of 1 deg/h and 39 indicate sinking at a rate of 2 m/h. Finally, in 62 cases the net



**Fig. 12** Distribution of critical collision damages along the length of ship A with indication of actual capsizes and cases that failed the ITTC and SOLAS criteria

floodwater inflow rate exceeded 1000 t/h. The damage extents and location of the highlighted cases are shown in Fig. 12.

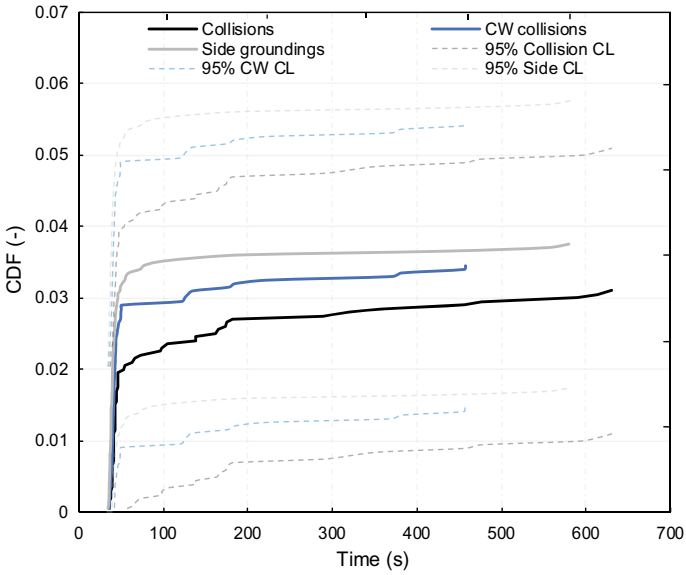
For the second ship, the results demonstrate that the probability of survival (1-A) for collisions corresponds to a Survivability Index of 90.35%, as indicated in Fig. 13. Notably, the calm-water runs resulted in fewer capsizes (181 cases) when compared to in-waves simulations (193 cases). The damage extents and location of the highlighted cases are shown in Fig. 14.

Finally, the CDF of TTC for side groundings yields a Survivability Index of 93.7. In the case of bottom groundings, the simulations result in approximately 2% of capsizes cases, of which 89% represent actual capsizes. In this case the cumulative probability distribution of Time To Capsize provides an indication of Survivability Index as high as 99.1%.

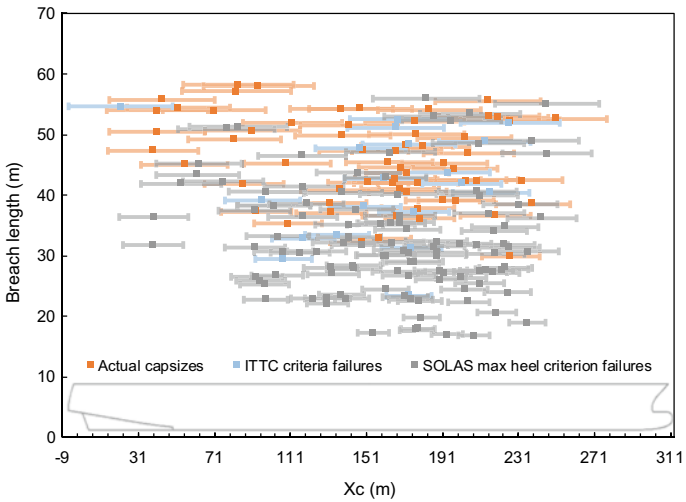
The calm-water runs provide an interesting insight on the impact of waves showing that a significant number of capsizes were either missed in the calm water (herein denoted as CW) runs or would fail only the more conservative criteria. One of the main implications of this is that the impact of waves should be explored in more detail, which could be achieved by testing individual damages in a range of wave heights, preferably with multiple repetitions per wave height. Such approach would be an extension to the methodology employed for deriving the s-factor (based on capsizes band).

***Comparison between Direct and Statistical approaches***

In light of the numerical results, a comparison is conducted between the static calculations linked to the statistical approach and numerical simulations as shown in Figs. 15 and 16, respectively, linked to the Direct Method, for both cruise vessels.



**Fig. 13** Cumulative distribution function of TTC—actual capsizes in collision damages (ship C)

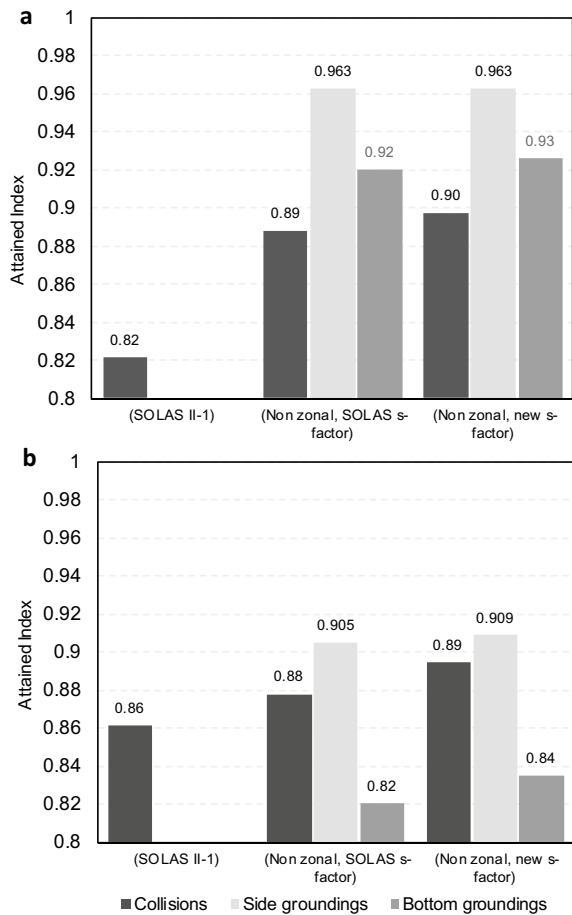


**Fig. 14** Distribution of critical collision damages along the length of ship C with indication of actual capsizes and cases that failed the ITTC and SOLAS criteria

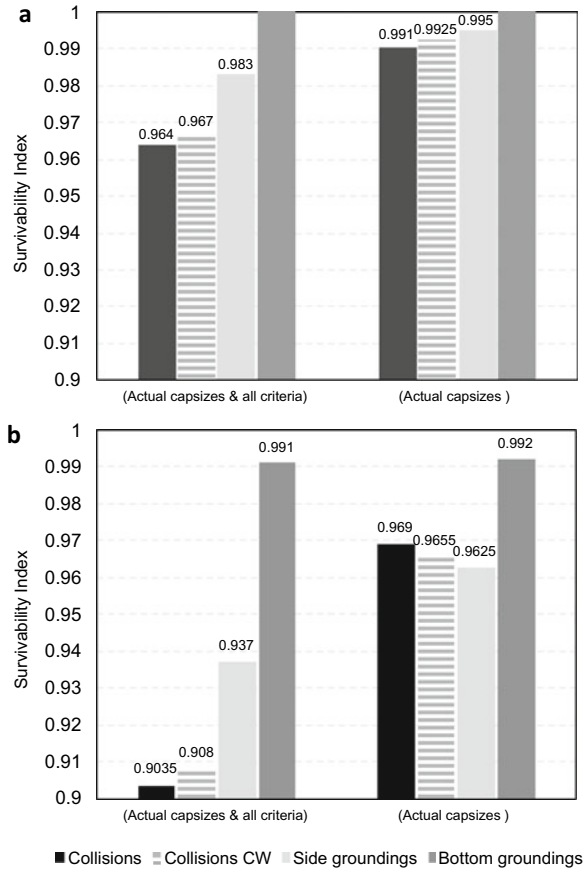
Figure 15 demonstrates the impact on the Attained Subdivision Index using three different formulations namely, the current SOLAS s-factor, the non-zonal average survivability model with the current s-factor and finally the non-zonal average survivability model with the new eSAFE s-factor. In addition, Fig. 16 presents the obtained survivability levels through dynamic simulations in two ways; conditionally through employing all criteria and solely actual capsizes.

On the basis of the foregoing, the newly developed survivability factor is found to underestimate survivability of cruise ships in collision damages. Cruise ships have demonstrated resistance to capsize in waves higher than 5 m (Maximum 8 m) and the prevailing s-factor does not reflect this. Numerical simulation results are consistent with the static calculations. In particular, both methods identify the same vulnerable locations along the ship. However, the numerical simulation results indicate higher survivability than the static calculations. The discrepancies in expected survivability levels are particularly large in grounding scenarios. This is likely due

**Fig. 15** Comparison of survivability based on static calculations for: **a** Ship A, **b** Ship C



**Fig. 16** Comparison of survivability based on simulations for ship for: **a** Ship A, **b** Ship C



to relatively short simulation durations given the slowly developing up-flooding. In general, it is understood that the time-domain simulations of flooding within complex geometries require significantly longer simulation runs. Notwithstanding this, the gap between the simulation results and static calculations has been significantly reduced, in comparison to earlier results.

Generally, the results represent significant steps forward in understanding flooding events, although, the differences between SOLAS Attained subdivision Index and expected survivability levels (Survivability Index), based on simulations, cannot yet be fully explained and further work is needed in this direction.



## 4 Concluding Remarks

On the basis of the aforementioned work, a new  $s$ -factor is being proposed specifically for cruise ships and a critical  $H_s$  formulation applicable to ships in service worldwide. In addition, a comparison has been conducted between Statistical (SOLAS) and Direct (numerical time-domain simulations) approaches on survivability through time-domain numerical simulations, on the basis of which the following conclusions can be drawn:

- The results demonstrate that survivability does depend on sea state and a relationship that is cruise-ship specific has been derived, linking  $H_s$ -critical to characteristics of the residual GZ curve, namely Range and  $GZ_{\max}$ .
- Similarly to project GOALDS, where the residual intact volume following flooding was used as a parameter within the  $s$ -factor formulation, results also indicate that ship size and amount of floodwater are linked to survivability, meaning that survivability in cruise ships is affected by scale. As such, a suitable scaling factor depending on both floodwater volume and residual volume has been derived.
- A new  $s$ -factor that caters for pertinent geometry characteristics of cruise ships and captures their flooding mechanism has been devised which addresses progressive flooding and is derived on the basis of  $GZ_{\max}$  and Range of the un-truncated residual stability curve.
- Dynamic time-domain flooding simulations provide an effective means for screening flooding scenarios, likely to lead to vessel loss. At the same time, they offer additional information to address the ensuing potential risk at a forensic level not afforded by static calculations.
- The numerical simulation results indicate higher survivability than the static calculations. The discrepancies in expected survivability levels are particularly large in grounding scenarios. This is likely due to relatively short simulation durations given the slowly developing up-flooding.
- Overall, the gap between the simulation results and static calculations has been significantly reduced. In this respect, the results obtained in the eSAFE project represent significant steps forward in understanding flooding events.
- Through this work, it has been understood that the survivability level of cruise ships is considerably higher than that postulated by rules and there is now clearer understanding why this is the case.

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**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.

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