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Simulation-based analysis method for damage survivability of passenger ships

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ABSTRACT

A new approach for analysing the level of survivability for a passenger ship in the event of a collision damage is presented. Monte Carlo simulation is used for generating a large number of damage cases. The probability distributions for damage extent and location are based on the current SOLAS regulation. Each case is calculated with time-domain flooding simulation, assuming quasi-static motions and calm sea, thus enabling evaluation of the righting lever curve during the flooding process. The ship survivability is analysed based on requirements for a sufficient reserve stability. The proposed method is demonstrated with a large passenger ship design. Based on the detailed investigation of the results, the effects of various design changes are studied. Furthermore, the impact of waves on the flooding process is studied. The presented method for survivability assessment is robust and especially suitable for comparing design variations, or ships with similar main dimensions.

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KEYWORDS
Damage ship stability; simulation; progressive flooding; Monte Carlo; ship design

1. Background

The safety and survivability of passenger ships has been a top priority in design of new cruise ships for decades, Kulovaara (2015). Given the severe consequences of a major accident for a large passenger ship, King et al. (2016) suggest that a compliance-based safety culture is not sufficient, and first principle tools are needed, especially for damage stability analyses.

Over the years, various analyses on damage stability in waves have been developed. Initially, the focus was on transient flooding and sloshing effects, Zaraphonitis et al. (1997), and accumulation of water on the vehicle deck, Papanikolaou et al. (2000). Some studies have focused on large passenger ship safety in waves, van't Veer et al. (2004) and Vassalos et al. (2004). An overview of this early development is given by Papanikolaou (2007). For large passenger ships in a moderate seaway, the dynamic effects are not important, and the capsizing or sinking is usually caused by loss of residual stability due to progressive flooding, van't Veer et al. (2004). Consequently, some simulation methods have been specially developed to accurate calculate also extensive flooding scenarios, including leaking and collapsing structures, Ruponen (2007) and Dankowski (2013).

Although computational fluid dynamics (CFD) offers advanced methods for detailed analyses of the fluid-structure interaction during flooding, e.g. Cheng et al. (2017), these tools are not suitable for extensive survivability analysis of passenger ships due to the enormous computation times. Therefore, simplified methods, based on hydraulic model for flooding rates, need to be used.

In this paper, a new concept for survivability assessment of large passenger ships is presented, combining the Monte Carlo method and relevant damage statistics with time-domain simulation of progressive flooding and residual stability analysis, using the righting lever curve. This approach allows for an easy investigation of problematic areas in the ship design, and new improved arrangements can quickly be tested.

2. Concept of survivability

In a distress situation on-board a flooding ship, the term survivability is primarily associated with the survivability of the people, and the severity can be analysed and communicated following the Vessel TRIAGE methodology, Nordström et al. (2016). The available time for orderly evacuation and abandonment is an essential parameter that can be estimated with time-domain prediction of progressive flooding and flooding detection on-board, Ruponen et al. (2017). However, during the ship design process, the concept of survivability is related to whether the ship stays afloat with sufficient reserve stability to withstand external moments, e.g. due to wind and waves.

In SOLAS Ch. II-1, the attained subdivision index (A-index) reflects the ship's ability to survive a collision damage that leads to flooding. However, the applied parameter for representing the survivability, the s-factor, is in fact more a design parameter, Vanem et al. (2007), since it can be nullified, e.g.

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due to immersion of a vertical escape hatch or a horizontal evacuation route, even if the ship would eventually reach a stable floating position. Moreover, the simplified treatment of intermediate stages due to non-watertight structures may be unrealistic, as pointed out by Lindroth et al. (2018). Consequently, the A-index can provide a very conservative measure of survivability. Alternative s-factor formulations have been presented by Papanikolaou et al. (2013) and Cichowicz et al. (2016). Still the SOLAS formulae are widely used. Furthermore, Dafermos and Papanikolaou (2016) have presented a more advanced approach, based on calculation of a Survivability Performance Index (SPI). This method combines the regulatory s-factor with a time-to-capsize analysis and quasi-static flooding simulation.

Monte Carlo simulation has been used for damages scenarios with static stability analysis, Santos and Guedes Soares (2005), as well as for simulation of the intermediate flooding stages, Dankowski and Krüger (2013). Furthermore, the Monte Carlo method has also been used by Spanos and Papanikolaou (2012) for studying the survivability in a single damage scenario for a RoPax vessel with a random sea state and loading condition. Spanos and Papanikolaou (2014) extended the analysis to include probability distributions for the breach size and location, considering both RoPax and passenger ships. These studies focused on damaged ship motions in waves, and, e.g. the effects of internal structures and progressive flooding were not considered. Also, Vassalos (2016) has proposed to use dynamic flooding simulation in waves for assessment of survivability, together with a Monte Carlo method for damage characteristics. However, proper use of this approach requires that each damage scenario is simulated several times in order to determine the probability of exceeding the applied angle of capsize. Moreover, the ability to withstand external heeling moments, such as wind or passenger crowding, during the flooding is not accounted for.

For RoPax ships, the accumulation of water on the vehicle deck can cause a rapid capsize, and the effect of the waves on the flooding may be very significant, Santos and Guedes Soares (2009). However, pure passenger ships have a dense non-watertight subdivision on the bulkhead deck. Consequently, capsizing is usually caused by extensive progressive flooding and insufficient residual stability. Therefore, the use of quasi-static methods is justified.

It is also worth noticing that due to the large superstructure, residual strength is not considered as a primary parameter for survivability of large passenger ships, Iversen et al. (2006). Consequently, in this study, the term survivability means that the ship will have a sufficient reserve stability for at least three hours after the damage.

3. Framework

3.1. General

Collision and grounding are the most likely reasons for flooding. Based on the analysis by Eliopoulou et al. (2016), these incident types are almost equally likely for passenger cruise ships. However, the available statistics are not very comprehensive since accidents are fortunately rare. Pioneering work on grounding damages was carried out in the GOALDS, Papanikolaou et al. (2013), and EMSA III projects, EMSA (2015). Since the SOLAS framework and the underlying probabilities are well established, the present study is limited to collision damages. However, the same methodology can be used for any damage type if representative probability distributions are available. The applied procedure for assessing the survivability level and testing the effects of design improvements is illustrated in Figure 1.

3.2. Damage generation

The damages are generated with Monte Carlo simulation. This approach requires cumulative density functions (CDF) for the damage location and extent. SOLAS Ch. II-1 provides the probabilities for damage location, longitudinal extent, penetration and vertical upper limit. The corresponding probability distributions are provided in Bulian and Zaraphonitis (2017). However, SOLAS framework treats the lower vertical limit with a conservative approach, where the case giving the smallest s-factor from the different lower vertical limits is used in the summation of the attained subdivision index. However, a proper survivability assessment requires probabilities, and thus an equivalent distribution for the lower boundary of the damage, given by Bulian et al. (2018), is applied in this study.

Another problem with the SOLAS probabilities for damage extents is that they are based on non-dimensional parameters. For example, the damage length is proportional to the length of the struck ship, whereas in reality this is mainly governed by the characteristics of the striking ship, Pedersen and Zhang (2000). However, this is not a major problem when comparing design variations with roughly the same main dimensions.

3.3. Survivability assessment

In general, the flooding process can be divided into three separate stages with different characteristics:

- *Transient flooding*, usually involving complex dynamics and fluid-structure interaction, lasting

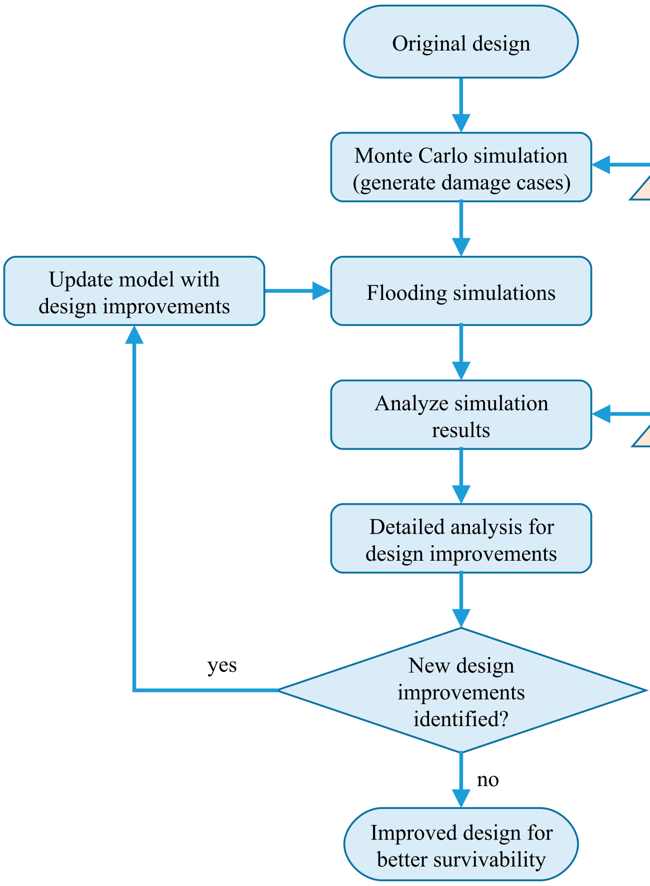

Figure 1. Flow chart for improved survivability using flooding simulations.

only a couple of roll cycles (about a minute), Manderbacka and Ruponen (2016).

- *Progressive flooding* through internal openings to other rooms. This process can last from a couple of minutes to several days, depending on the damage case. Especially the non-watertight doors inside the watertight (WT) compartments have a significant effect on this, Ruponen (2017).
- *Steady state*, or a quasi-steady condition if flooding takes place in waves. Floodwater does not progress to new rooms through openings.

Naturally, the later stages can only occur if the ship survives the previous stage without capsizing or sinking. Different criteria for survivability need to be applied for the transient flooding stage since momentary large roll angle does not lead to capsize, whereas the same heeling during the progressive flooding stage is not survived. In this study, the time limit for the transient stage is set to 30 s. In addition, the maximum simulation time is limited to 3 h. If a final equilibrium is not found within this time, the steady-state criteria for survivability level is applied to the last calculated time step.

The recommended limit of capsizing by the International Towing Tank Conference is 30°, ITTC (2017). Additionally, if the 3-minute average exceeds 20°, the ship is considered as capsized. Since the progressive flooding and steady-state stages can be long, it is also important to ensure that the ship can withstand external moments, e.g. due to wind, without capsizing. In this study, a constant wind velocity of 14 m/s is considered, as in the wind moment for s-factor calculation in SOLAS. The wind direction is selected so that it is increasing the steady heeling angle. If heeling due to wind moment exceeds 20°, the risk of capsizing is notable, and hence the s-factor for the case is nullified.

The time-domain flooding simulation in the NAPA software is used. This method is based on implicit time integration with a pressure-correction algorithm, Ruponen (2007, 2014), which has proven to be an efficient and accurate approach for damage scenarios with extensive progressive flooding to several compartments. The method has been validated against both model tests, Ruponen et al. (2007), and full-scale experiments, Ruponen et al. (2010). An adaptive time step between 1.0 and 4.0 s is used, based on a previous study, Ruponen (2014).

Constant volume of floodwater in each flooded room is applied in the calculation of the righting lever (GZ) curve, Ruponen et al. (2018). The GZ curve characteristics (*range* and GZ_{max}) for reserve stability analysis are calculated without the effect of external moments. The range of stability is limited to the immersion angle of critical points, placed on top of the buoyant hull. These parameters are illustrated in Figure 2.

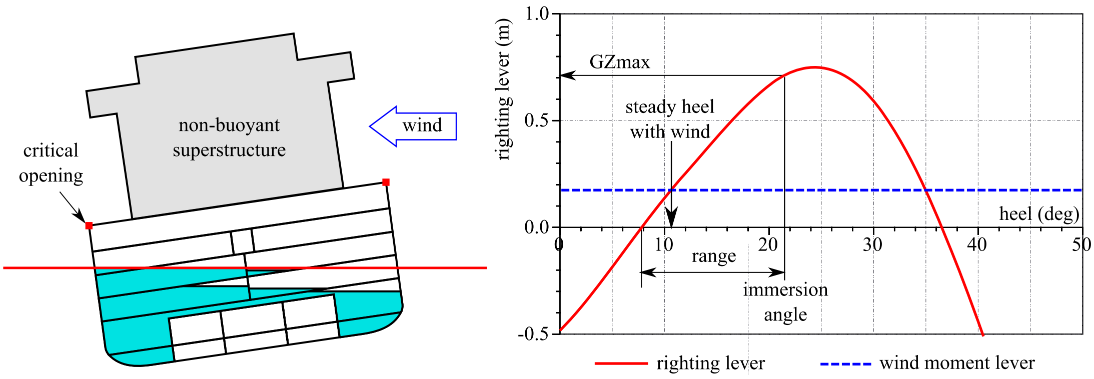

Figure 2. Schematic illustration of the parameters affecting the survivability analysis.

The applied criteria for evaluation of the survivability s_i for each case i, using flooding simulation results, are presented in Table 1. Based on these results, a survivability index for the ship is defined as:

$$SI = \frac{\sum s_i}{N} \tag{1}$$

where N is the number of calculated damage cases.

4. Modelling principles

4.1. Compartment 3D model

A complete 3D model of the ship is needed for the flooding simulations. In principle, all rooms divided by steel bulkheads should be modelled, but small adjacent rooms can be combined in order to simplify the modelling and to speed up the calculations.

In reality, also the superstructure provides some additional reserve buoyancy, but for practical reasons, the buoyant part of the hull should be limited vertically, e.g. at three deck heights above the bulkhead deck level. In general, the same assumptions as in normal intact stability calculations should be used. More simplifications in the modelling can be applied on the upper decks, since the ship is practically already lost when these decks are flooded.

4.2. Internal openings

In principle, all doors and openings between the modelled rooms need to be defined. Leakage and collapse characteristics of closed non-watertight doors are modelled following the guidelines developed in the EU FP7 project FLOODSTAND, and summarised in Jalonen et al. (2017). These simplified models are based on full-scale tests and dedicated finite element analyses that were performed for a range of typical doors in modern passenger ships. The industry standard discharge coefficient, $C_d = 0.6$, can be used for all internal openings, excluding possible cross-flooding ducts and pipes, Ruponen et al. (2012).

Previous research has shown that the status (open/closed) of non-watertight doors can have a significant effect on the flooding progression, and especially on the time-to-capsize, Ruponen (2017). Therefore, it is essential that the applied door statuses are carefully considered based on the normal operation of the ship. For example, the cold room doors are normally closed but the doors along service corridor are usually open.

Table 1. Applied criteria in survivability level analysis.

Flooding stage	Description	Criterion	Survivability level
transient ($t < 30$ s)	capsize	heel > 30°	$s = 0$
progressive	capsize	heel due to wind > 20°	$s = 0$
	reserve stability	s-intermediate without heel	$s = \left(\frac{GZ_{max}}{0.05} \cdot \frac{range}{7}\right)^{\frac{1}{4}}$
steady state (or $t = 3$ h)	capsize	heel due to wind > 20°	$s = 0$
	reserve stability	s-final without heel	$s = \left(\frac{GZ_{max}}{0.12} \cdot \frac{range}{16}\right)^{\frac{1}{4}}$

4.3. Breaches

The breaches, caused by a penetrating box, with extensions obtained from the Monte Carlo simulation, are modelled as openings. For simplicity, a box-shaped penetration is assumed, Figure 3. Each modelled breach opening connects the damaged room directly to the sea. If the room is not bounded by the hull surface, this approach results in a slightly overestimated inflow rate, especially in the very beginning of flooding.

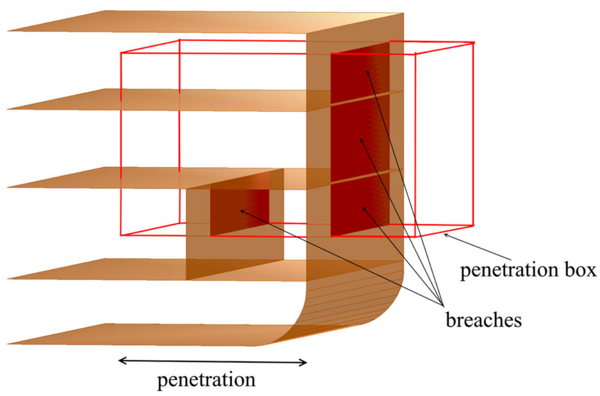

Figure 3. Modelling of breach openings from the damage extensions.

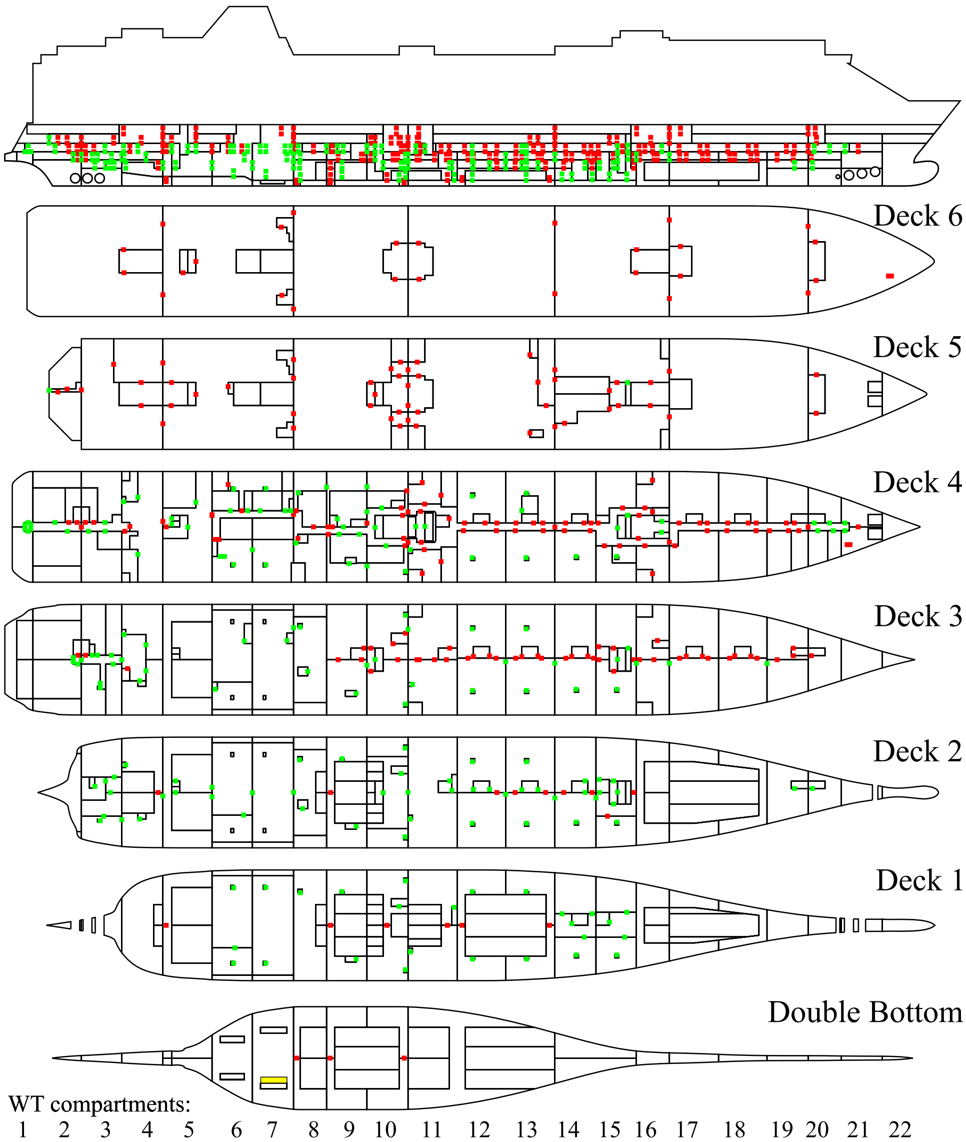

Figure 4. Modelled rooms and openings in the studied ship design.

The assumption of a large rectangular breach is not realistic. Instead, the petalling of the steel structures will significantly affect the inflow rate, as described by Li et al. (2014). A simple approach to account for this effect is to apply a smaller discharge coefficient, $C_d = 0.3$, for the breach openings.

4.4. Loading condition

In principle, the applied initial conditions for a survivability analysis can be based on the real operational profile of the ship. For ship types with notable variation in the draft, trim and metacentric height, such as cargo ships, this is essential. However, recent research has confirmed that for passenger ships the changes in the draft are usually quite small, Paterson et al. (2018). In addition, the draft affects the damage generation, and therefore, the assumption of a single representative initial condition notably simplifies the survivability analysis. In practice, the partial loading condition (DP) in SOLAS Ch. II-1 calculations is considered as a typical initial condition for passenger ships.

The conventional damage stability calculations in SOLAS are done for a dry ship, so that the tanks are empty and can be flooded, although the mass of the liquid loads is included in the initial condition. The same approach can be used for survivability analysis, however, it should be noted that the results are somewhat conservative, especially in the cases where an asymmetric tank arrangement is damaged.

5. Case study

5.1. Description of the ship design

A large passenger ship design, Kujanpää and Routi (2009), is used for demonstration of the developed survivability assessment method. The initial design that was developed in the EU FP7 project FLOODSTAND, has been modified to better represent the current design practices, and, e.g. a double skin arrangement has been added to the engine room compartments. The modelled rooms and openings are illustrated in Figure 4, and the applied probability distributions are shown in Figure 5.

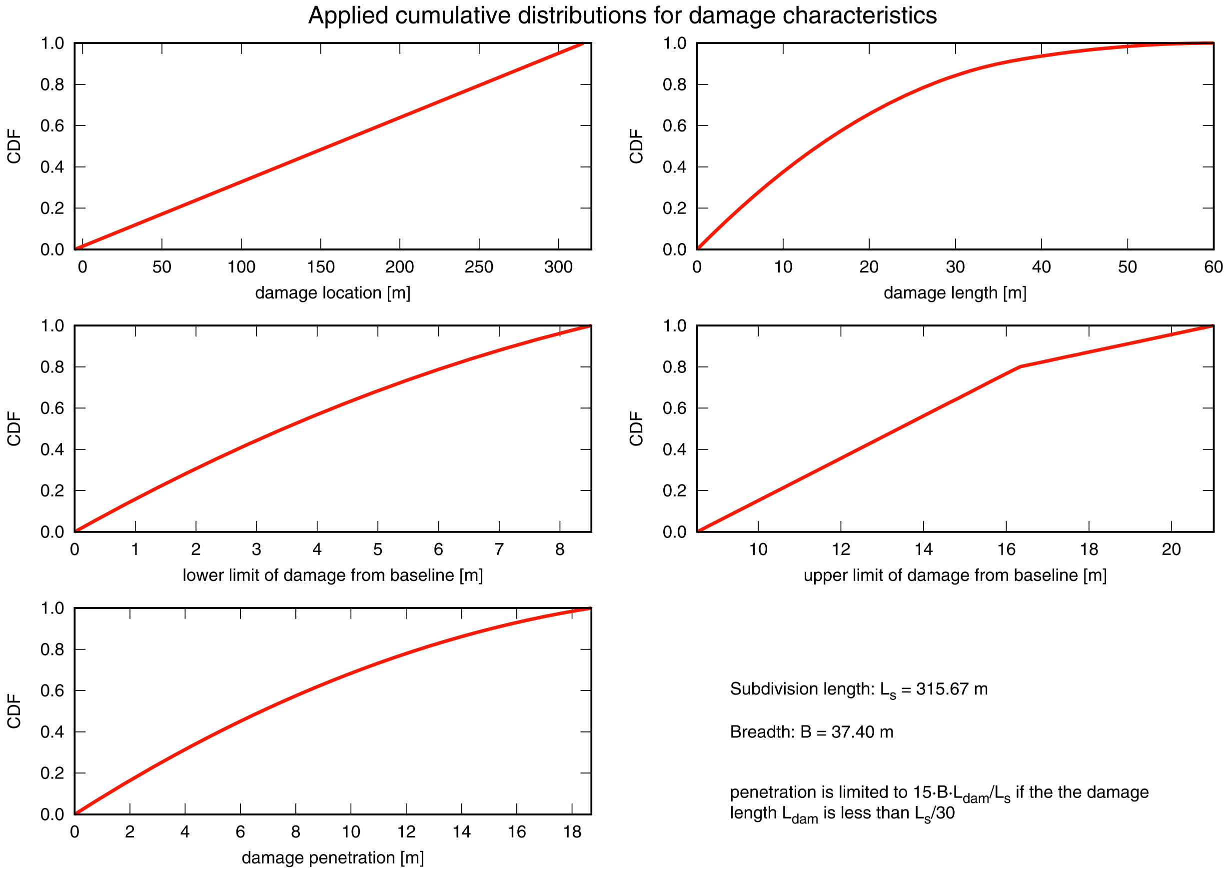

Figure 5. Applied cumulative probability distributions for the collision damage characteristics.

Cross-flooding openings are modelled at the centreline. However, the large U-shaped voids in the main engine room compartments and the large double bottom void amidships are equipped with efficient cross-flooding devices and ventilation ducts. Consequently, each of these voids is modelled as a single room for the simulations.

The partial loading condition DP according to SOLAS Ch. II-1 is used. Consequently, the intact draft is 8.52 m and metacentric height is 2.25 m. The original design meets the SOLAS2009 requirements. The WT doors are closed, and the applied status (open/closed) of the A-class doors depends on the type and location of the door. For example, the cold room doors are closed, but the fire doors in the service corridor are open.

5.2. Results for the original design

Ten batches of 1000 random collision damages were calculated. The results of the Monte Carlo simulation for damage length versus damage location are shown in Figure 6. In addition to the average survivability index, Equation (1), also 95% confidence limits were evaluated based on normal distribution (Figure 7).

The average index as a function of the number of batches is shown in Figure 8. Based on these results, at least five batches are needed to get a reasonably accurate estimate of the survivability level. On the other hand, a single batch of 1000 damages can already provide valuable insight into the damage stability characteristics, and the results can be utilised in improving the design. Therefore, the first batch (B-1) was chosen for a more detailed analysis.

5.3. Design improvements

Based on a detailed analysis of the simulation results, some problematic areas in the original design can be identified. Figure 9 visualises the results for the 1000 damage cases in the Batch 1. There are several damages

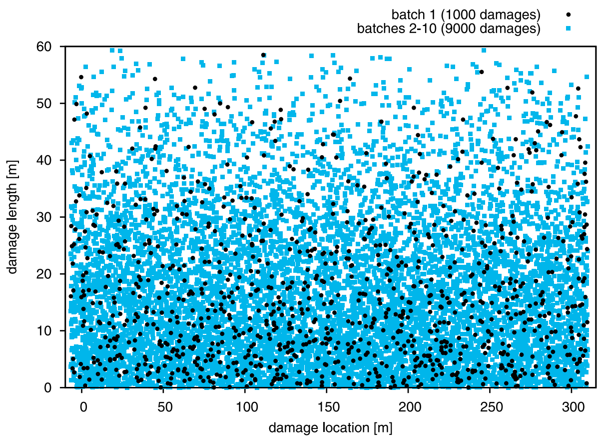

Figure 6. Damage length versus damage location.

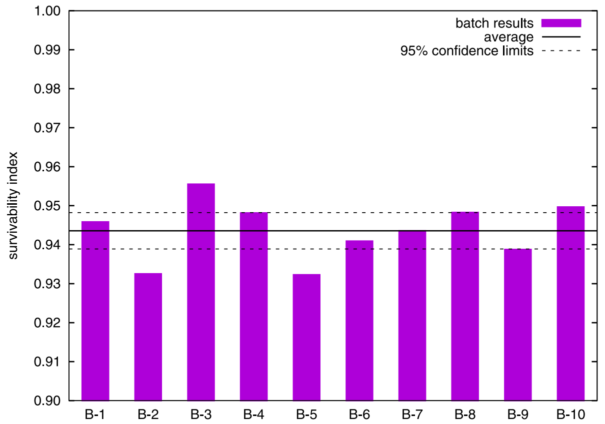

Figure 7. Survivability index for 10 batches, with 1000 random damages in each, for the original design.

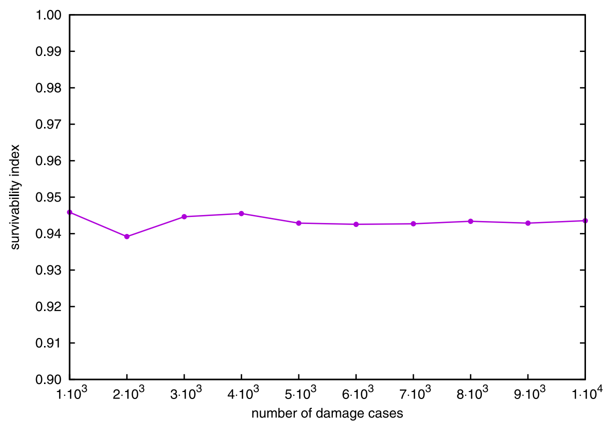

Figure 8. Average survivability index as a function of the number of random damage cases.

amidships with length between 20 and 25 m that result in $s = 0$. Especially, in cases with a lesser vertical damage extent, fast down-flooding is needed to both equalise the flooding and to lower the centre of gravity.

Based on the analysis of the progressive flooding for several critical cases ($s < 1$) with damage length of less than 35 m, some possible design improvements were

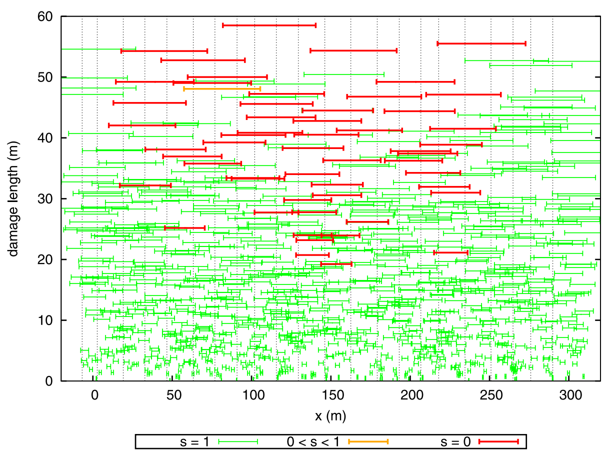

Figure 9. Visualisation of the results for the original design; each line represents a single damage in the Batch 1; the length of the line equals to the damage length and the colour illustrates survivability.

Table 2: Studied design modifications to improve survivability.

Modification	Description
Improved cross/down-flooding	Down-flooding hatches from Deck 2 to Deck 1 added to zones 9, 11, 12 and 13
	Cross-flooding area increased in zones 9–13 & 15 on Deck 1 and in zone 15 on Deck 2
	Blowout panels added to zones 14 & 15 in the laundry and linen store areas on Deck 1
	Blowout panel added to allow faster equalisation of asymmetric flooding in the store area on Deck 3
	Double bottom, cross-flooding opening between the grey water tanks in zone 5
Watertight bulkhead deck in bow	Improved cross/down-flooding as presented above
	Watertight bulkhead deck in bow, forward from zone 17; modified vertical connections
	WT door added on the service corridor on bulkhead deck between zones 18 and 19
GM + 0.3m	Original design but GM for initial condition is increased by 0.3 m

identified. Most notably, insufficient cross-flooding was found out in several cases. Furthermore, the 'forward shoulder' area has several damage cases with $s = 0$, where the problem is up-flooding to the bulkhead deck due to increased bow trim.

Based on these observations, three design improvements were developed, as listed in Table 2. The improved cross/down-flooding arrangement is illustrated in Figure 10. The improvements for watertight integrity of the bulkhead deck in the forward part are presented in Figure 11. Note that an additional WT-door in the service corridor is needed to prevent progressive flooding to the undamaged compartments in the bow area. While the original design was optimised for SOLAS2009, the increased damage stability requirements in the SOLAS2020 amendments mean that the required subdivision index is increased from 0.849–0.898. Therefore, an increase of 0.30 m in the initial metacentric height was also studied, without any modifications to the compartments and openings.

The critical cases ($s < 1$) for all design variations are presented in Figure 12. The improved down/cross-flooding arrangement provides a notable increase of the survivability index, Figure 13. The main reason for this is that the maximum allowed heel angle is not exceeded in the beginning of flooding for the relatively short damages amidships. The WT bulkhead deck in the bow further improves the situation. However, the biggest impact is achieved simply by increasing the GM.

Four damage cases with different flooding characteristics, Figure 14, were selected for a detailed comparison in order to study the effects of the design modifications. In each case $s = 0$ for the original design. In case 132, this is caused by excessive heeling in the beginning of flooding, and in the other three cases the ship capsizes. The time histories of heel angle with different design changes are shown in Figure 15.

In case 256, the enhanced cross/down-flooding arrangement significantly improves the situation, and

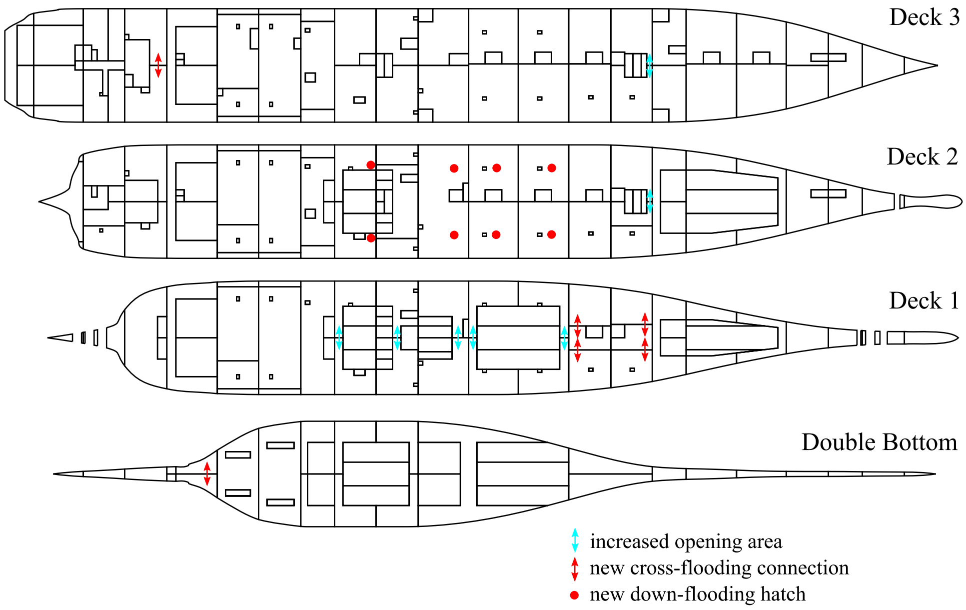

Figure 10. Modelled improvements for cross/down-flooding.

the ship does not capsize during the 3 h period. However, a stable equilibrium is not reached, as in the case of increased GM. Long damages in the forward shoulder area, such as the case 892, lead to increased bow trim and eventually up-flooding to the bulkhead deck. Survivability in this kind of damage case can only be improved by adding a watertight deck to the forward part. For the other parts of the ship, increasing the GM is the most effective way to achieve better survivability.

5.4. Effect of waves

The previously presented simulations were performed in calm water. However, also waves can have an effect on the flooding process. The current study focuses on passenger ships that always try to avoid harsh sea conditions. Consequently, the wave effects on the motions of a damaged ship are often small, van't Veer (2004). In this study, a simplified approach has been applied. Ship motions and the righting lever curve are calculated in calm water, but the instantaneous wave elevation is used for the evaluation of the in-flooding rate through the breach openings. This method simulates the pumping effect of waves on the flooding process.

The external sea level is varied by using an instantaneous wave elevation:

$$\zeta(t) = \sum_{j=1}^{N} a_j \cos(-\omega_j t + \varepsilon_j) \tag{2}$$

In order to ensure that the generated time-series do not comprise repeating sequences, a random number generator is used to distribute discrete amplitudes a_j, frequencies ω_j and phase angles ε_j of the wave components. In this study, the number of components is $N = 100$.

The amplitude components are calculated from the wave spectrum $S(\omega)$:

$$a_j = \sqrt{2 \cdot S(\omega_j) \cdot \Delta\omega_j} \tag{3}$$

The original design and the batch B-1 damage cases were used. For seaway, the JONSWAP spectrum with significant wave heights (H_s) of 1.0, 2.0 and 4.0 m were applied, assuming a beam seas condition. A shorter constant time step of 1.0 s was used in order to capture the changes in the wave elevation.

The effect of the sea state on the survivability index is presented in Figure 16, and the critical damage cases are illustrated in Figure 17. With a wave height of 1.0

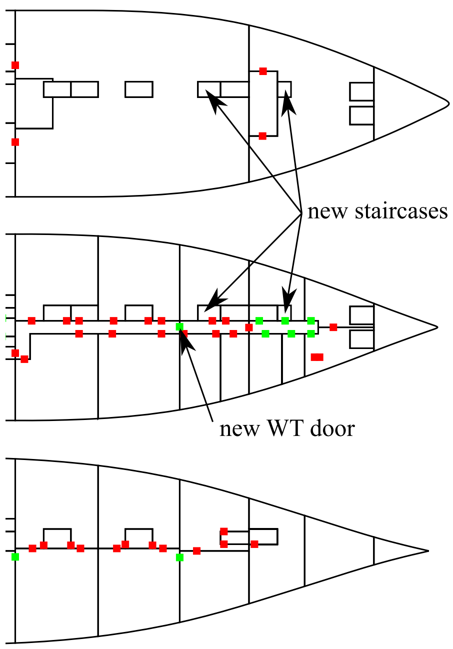

Figure 11. Design modifications for watertight bulkhead deck in the bow.

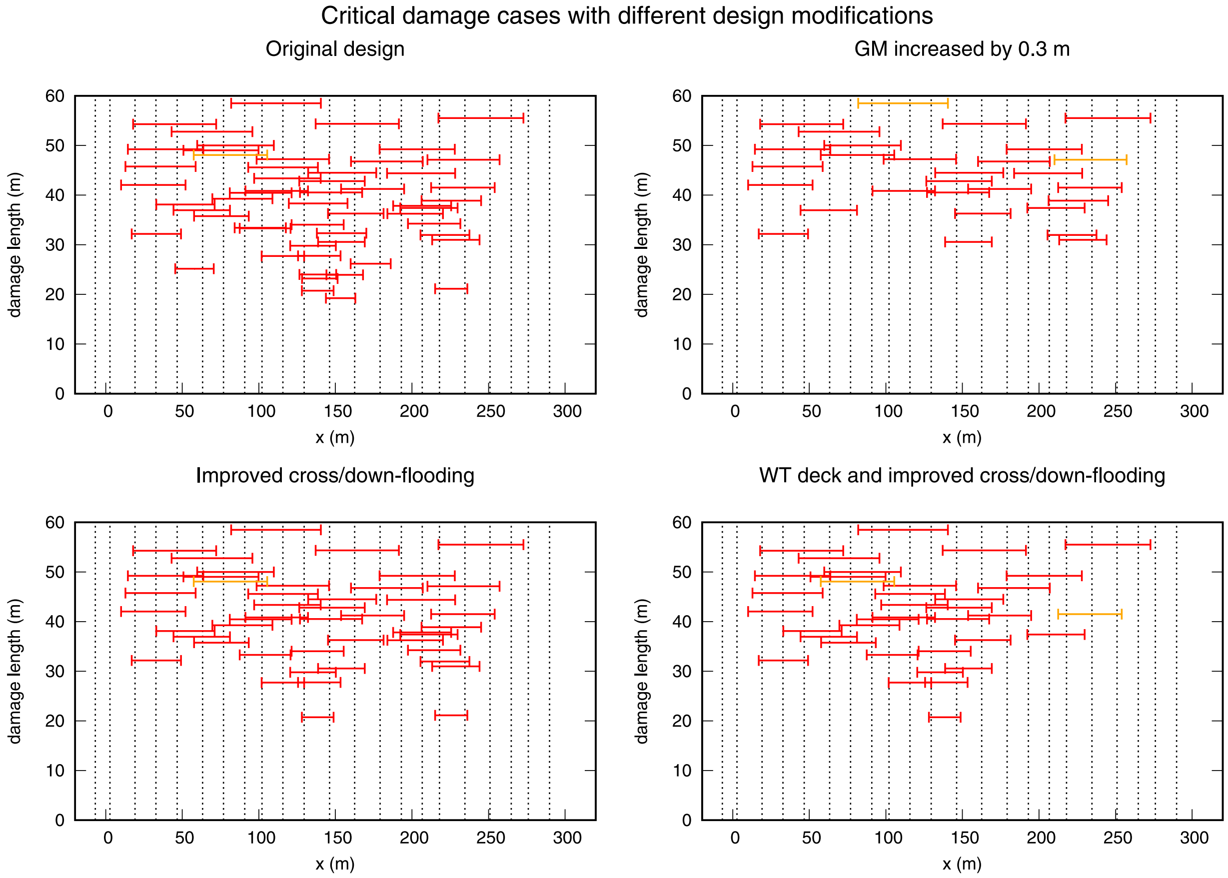

Figure 12. Comparison of critical damage cases (s < 1) in Batch 1 with different design modifications.

m, the effects are marginal. With wave height of 2.0 m, the survivability index is decreased by 2.5% and with $H_s = 4.0$ m by 8.0%.

A more detailed analysis of the wave effects on a single damage case is presented in Figure 18. With $H_s = 1.0$ m, the development of heel angle is almost identical to the calm water condition. Larger significant wave heights result in accumulation of water on the bulkhead deck, and thus slowly increasing the heeling, and when $H_s = 4.0$ m, the capsize limit is reached in 30 min.

In general, the wave pumping model is likely somewhat conservative in high waves since it does not account for the dynamic heave motion of the ship. Yet this assumption should be validated with dedicated model tests.

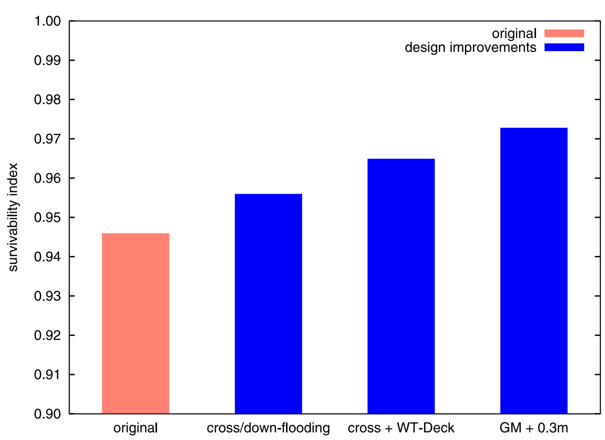

Figure 13. Effect of studied design modifications on the survivability index.

6. Discussion

In this study, the applied survivability criteria during progressive flooding were based on the s-factor for intermediate stages in the current SOLAS Ch. II-1. The pumping effect of waves increases the progressive flooding to the bulkhead deck, and thus the survivability is decreased in several cases with a higher significant wave height. Based on the results of this study, it seems that the s-factor for the final stage of flooding could be a more suitable survivability criterion after the transient stage instead of the intermediate s-factor.

The presented survivability index, equation (1), is not fully comparable to the attained subdivision index of SOLAS Ch. II-1, although similar probability distributions and criteria for the righting lever curve characteristics were applied. This is mainly because only a single initial condition is used and a more physically correct approach is employed to evaluate the intermediate stages of flooding. For comparison, basically the same ship design was studied by Lindroth et al. (2018), where the A-index for up to three zone damages was 0.7958, which is much lower than the survivability index with the proposed new method, $SI =$

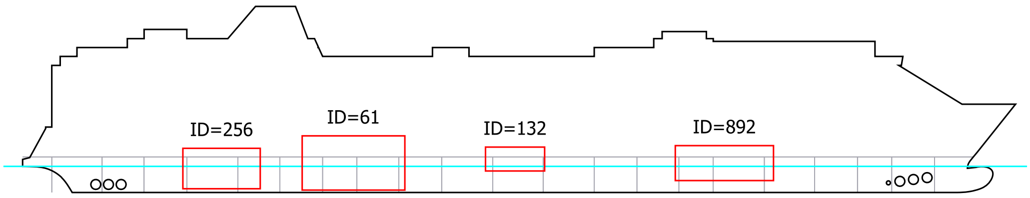

Figure 14. Selected damage cases for detailed analysis.

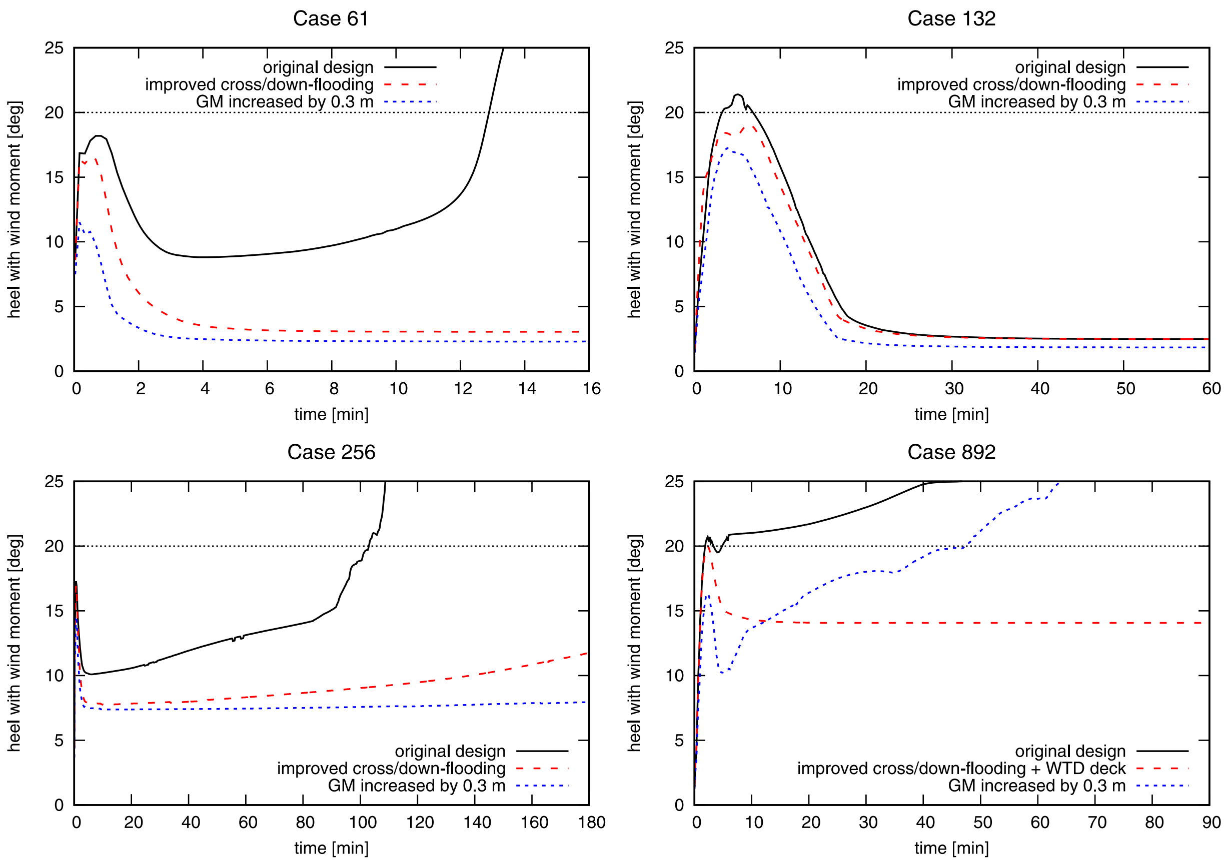

Figure 15. Time histories for selected damage cases with different modifications to the design.

0.9435. A more comprehensive comparison study between different approaches for damage generation and evaluation of survivability should be carried out in the future.

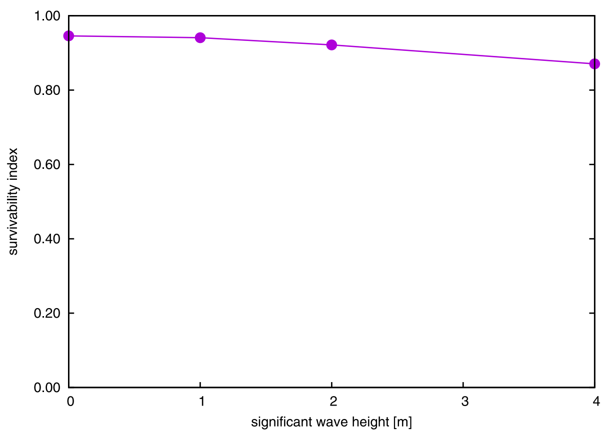

Figure 16. Effect of significant wave height on the survivability index with the original design (Batch 1).

The flooding simulations and survivability analysis for a batch of 1000 collision damages took about 30 h, when executed in four parallel processes with a business laptop (Intel® Core™ i7-7820HQ @ 2.9 GHz with 24GB of RAM). The possibility to use a cluster of computers enables a much faster total computation time. Consequently, the presented method for survivability analysis is suitable for practical design work.

7. Conclusions

Ensuring a high level of survivability after flooding is an essential part of the design process for passenger ships. For this, first principle tools that go beyond the regulatory requirements should be used. Detailed results from time-domain flooding simulation can be used to identify weak points in the design. Effects of design modifications, such as improved cross/down-flooding arrangements, can easily be quantified by performing new simulations for the same damage

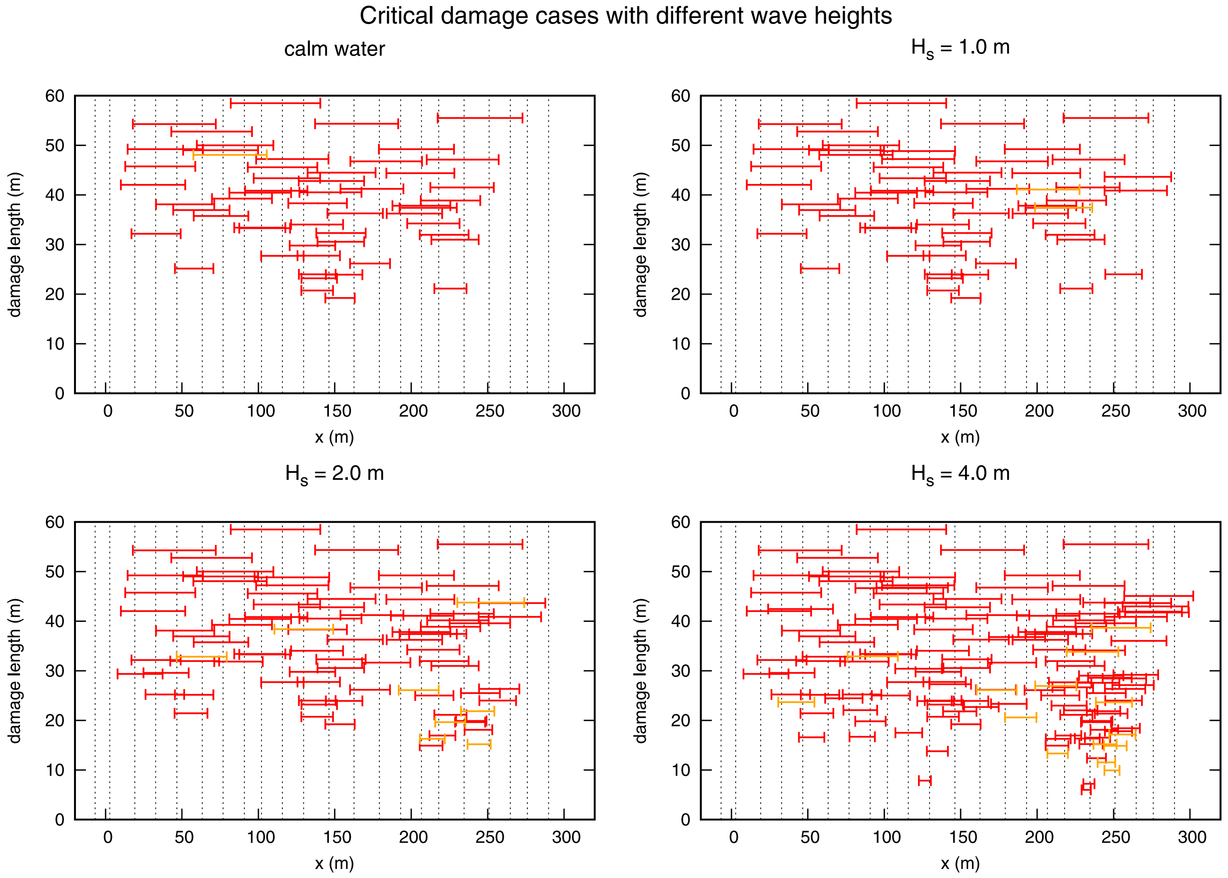

Figure 17. Comparison of critical damage cases (s < 1) in Batch 1 with different significant wave heights.

scenarios. In addition, the presented method can be used to compare ship designs, with similar main dimensions but different subdivision.

Based on the presented case study, with 1000 random collision damages, critical areas of the ship can be identified, and the effect of design improvements can be studied. However, more damage cases, e.g. 5000–10,000, are needed for a more reliable assessment of the actual survivability level. The presented study

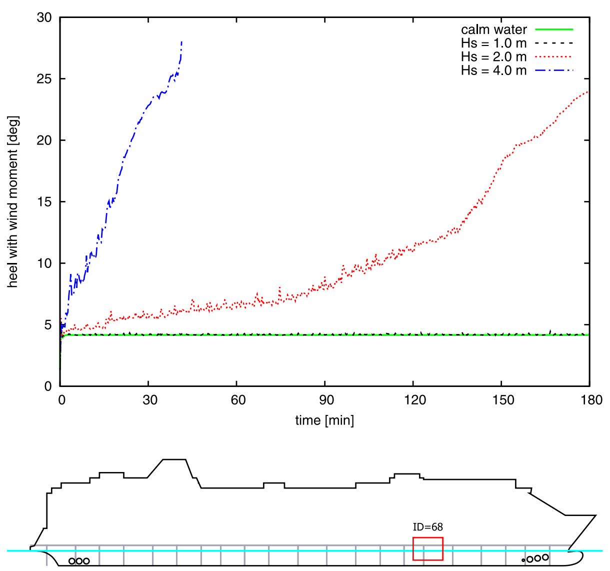

Figure 18. Effects of waves on progressive flooding in the case 68 with the original design.

was limited to collision damages, but the same approach can also be used for any suitable damage statistics. For example, grounding damages with probability distributions from the EMSA III project, Bulian et al. (2016), could be used.

The results indicate that the heel angle alone is not a sufficient measure for survivability, and appropriate criteria for reserve stability must be considered as well. In moderate sea states, the s-factor for intermediate stages in SOLAS Ch. II-1 may be used, but with high waves the pumping effect and resulting accumulation of water and progressive flooding on the bulkhead deck indicates that the s-factor for the final stage should be used already after the transient flooding stage. Alternatively, the wave pumping effect could be included, but in order to avoid overly conservative results, the probability distribution for the significant wave height is needed. Most notably, the type of damage should also be accounted for since grounding accidents occur in shallow water.

Progressive flooding is the most critical factor in the sinking and capsizing of large passenger ships with dense non-watertight internal structures inside watertight compartments. Consequently, time-domain simulation tools, specifically developed for accurate calculation of slow progressive flooding, are needed for a reliable analysis of the survivability of a damaged passenger ship. Combined with relevant distributions for damage extent, such tools can be used for assessing the actual level of survivability. Moreover, analysis of flooding progression in critical damage cases enables identification of design modifications to improve the survivability.

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No potential conflict of interest was reported by the authors.

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