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Exploring smart methodologies for critical flooding scenarios detection in the damage stability assessment of passenger ships

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ABSTRACT

A more contemporary damaged stability assessment of a passenger ship can be addressed with a non-zonal approach, assessing multiple damage types and environmental conditions and employing dynamic analysis for ship survivability. This direct method necessitates the generation and simulation of many damage scenarios. However, the probabilistic models for damage characteristics describe many damages that are not critical for ship survivability. To restrict the number of damage scenarios, hence calculation time, designers currently apply empirical rules, such as critical damages are only above two compartments, considering that damage stability regulations currently in force to ensure survivability levels beyond this damage extent. However, a rigorous approach is lacking. The present work explores the use of more scientific methods as damage filters. The first method uses preliminary static calculations. The second uses the energy absorbed by the ship during an impact, and the third is suitable for a purely dynamic approach. The paper critically compares the three methodologies on two sample passenger ships for collision damages, showing their respective advantages and disadvantages.

1. Introduction

The survivability of passenger ships after a flooding event is a relevant attribute for the design of new vessels (Atzampos, 2019; Papanikolaou et al., 2013; Vanem et al., 2007). However, the nature of damage stability study has been mainly applied by designers with a regulations-based approach, which is not advisable for a key issue in marine safety (Vassalos, 2022). Nowadays, one of the goals of the FLARE project (Luhmann et al., 2022; FLARE, 2018-2022) is to change this culture, giving more importance to first principle-based tools for vessel survivability during the design process of a passenger ship (Vassalos, 2016).

The assessment of damage stability with direct calculations requires the modelling of complicated phenomena, related to the coupling between ship motions and the dynamic process of floodwater and its interaction with the ship and the wave environment. The modelling can be performed with different simplification levels, leading to different confidence for the obtained results. Use can be made of extremely simplified static approaches, up to high fidelity and computationally expensive fluid dynamics calculations. However, a good compromise between accuracy and calculation effort is reached by the adoption of time-domain simulations based on rigid body dynamics. Even applying this simulation-based approach, the computational effort to perform an exhaustive assessment of damage stability remains high (Ruponen et al., 2022). The probabilistic framework used to quantify the final survivability using a non-zonal approach requires a large number of damage cases to be analysed. In literature, several indications are given for calculations in calm water, ranging from 10,000 breaches per loading condition and damage type (Ruponen et al., 2019) for quasi-static flooding simulations and up to 200,000 breaches per loading condition and damage type for static analyses (Bulian et al., 2020). This becomes even more considerable when survivability in waves should be estimated, as the stochastic nature of irregular waves has to be taken into account (Spanos and Papanikolaou, 2012). The work presented here aims to provide a rational and a methodology for sampling damages in the most effective and rigorous manner for such applications.

Considering damages resulting from ship-to-ship collisions and analysing the marginal distributions for the damage breach extent

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available in probabilistic frameworks (IMO, 2009; Bulian et al., 2019a), it is evident that a large number of generated cases is not critical for vessel survivability. Therefore, it is reasonable to reduce the number of cases to be analysed with dynamic simulations. A common but purely empirical approach to reducing this number is to consider only critical damage cases involving, for example, more than two adjacent zones. Even though this approach could be considered valid from a design point of view, it is not founded on scientific considerations.

In the present work, three alternative approaches are explored, aiming at critical damages identification, leading to reducing the number of dynamic calculations to be performed in the survivability assessment of a passenger ship. The first method is based on the analysis of static survivability calculations, the second evaluates the critical scenarios based on the energy absorbed in the collision and the last is considering dynamic simulations only. All the presented methods are based on randomised quasi-Monte Carlo breach sampling processes (Mauro and Vassalos, 2022) that already reduce sample size compared to state of the art direct non-zonal methods. The three methods are applied to two sample reference passenger ships, showing potentials and criticality of the procedures for critical damage identification.

2. Scenarios definition for damage stability assessment

The damage stability assessment for a passenger ship requires the creation of appropriate damage scenarios, that, following a modern and comprehensive probabilistic framework (Paterson et al., 2020), are divided into collisions, side and bottom groundings. These damages are often referred to as C00, B00 and S00 damages representing collisions, bottom and side groundings. The probabilistic framework used by SOLAS and its extensions proposing the application of a non-zonal approach is considering specific geometrical characteristics for these damages (Zaraphonitis et al., 2015a; Bulian and Zaraphonitis, 2017).

2.1. Non-zonal collision damages

In this study, only collisions (C00 damages) will be considered in critical scenarios detection and filtering, employing a direct non-zonal approach. To define such damage cases during static or dynamic analysis, five geometric characteristics have to be considered, feeding into probabilistic marginal distributions, which involve five random variables:

- Potential damage location X_D (m);
- Potential damage length L_D (m);
- Potential damage penetration B_D (m);
- Lower vertical limit z_{DW} (m);
- upper vertical limit z_{UP} (m).

In addition, the side of the damage (port or starboard) needs to be added as an additional random variable, otherwise, two individual samplings have to be performed: one for the port side and one for the starboard side. This damage definition for collision extends the conventional SOLAS distribution with the description of lower limit damage extent (Bulian et al., 2019b), thus increasing consistency of the probabilistic model of the damage.

Damage dimensions are considered independent, except for damage length L_D and damage penetration B_D. For such variables, an empirical rule has been introduced to avoid the generation of damages having too high penetration concerning length according to the following criteria:

$$B_{D_{max}} = \begin{cases} 15b\dfrac{L_D}{L_s} & \text{if } \dfrac{L_s}{L_D} < 30 \\ \dfrac{b}{2} & \text{if } \dfrac{L_s}{L_D} \geq 30 \end{cases} \tag{1}$$

where b is the local breadth of the ship at the considered waterline and L_s is the subdivision length. The application of such a constraint implies a preferential order in the sampling of damage dimensions but it is not influencing the sampling process itself. Additional attention should be paid for breaches located at ship extremities (Pawlowski, 2004), as the X_D coordinate should be modified in case the potential damage exceeds ship extents (Bulian and Francescutto, 2010).

While generating C00 damages, attention should be paid to the L_D generation, where the distribution depends on the vessel subdivision length L_s. Fig. 1 presents an example of the different L_D distributions that can be obtained by incrementally changing L_s. The maximum L_D limit of 60 m for vessels above L_s = 198 m, leads to having a different density function for the higher L_D, which results in a fatter tail compared to shorter ships. However, the higher damage length for long ships has a significant lower L_{Dmax}/L_s ratio compared to the shorter ones.

2.2. Sampling damages for static and dynamic calculations

The probability density functions of the damage characteristics are used to generate individual breaches for both static and dynamic analyses considering a non-zonal approach. For static analysis, the geometric characteristics are sufficient to determine a damage case. For a dynamic calculation, also an additional variable has to be taken into account for the weather condition. In fact, besides the damage itself, it is necessary to define also the significant wave height H_{sD} representing the sea state at which the simulation should be carried out. The analysis of accident statistics in project (HARDER, 2000-2003) led to the definition of a marginal cumulative distribution of significant wave heights having the following formulation:

$$F\left(H_{sD}\right) = \exp\left(-\exp\left(\alpha - \beta H_{sD}\right)\right) \tag{2}$$

with the regression parameters $\alpha = 0.16$ and $\beta = 1.12$. Such modelling leads to considering 99% of the sea states below a significant wave height of 4 m in which pertinent accidents have taken place. The formulation (2) has been revised taking into account an updated set of accidents (reported in detail by Ventikos et al. (2018)), proposing $\alpha = 0.6887$ and $\beta = 1.1958$ as new parameters (Paterson et al., 2017). However, the use of the accident database may not consider future developments in the operation of cruise ships, which are more and more moving to a worldwide operation profile, hence being exposed to higher sea states in which the risk needs to be evaluated. For such a reason, differently from the HARDER approach, Luhmann et al. (2017) assume that sea states are independent of previous occurrences of a collision, suggesting the adoption of worldwide wave statistics for H_{sD} determination. This means keeping formulation (2) by employing $\alpha = 1.1717$ and $\beta = 0.9042$ as regression parameters (Luhmann et al., 2017; Paterson et al., 2017). In any case, the distribution has an upper truncation at 7 metres to avoid sampling unrealistically high H_{sD} values. Such value is in line with the outliers limitations reported by Ventikos et al. (2018) in their accident statistical analysis.

Then, for dynamic analysis, every single damage with the associated H_{sD} is a separate damage scenario, as damage breaches with different sizes could lead to different floodwater progression inside/outside the ship. Thus, sampling 10,000 damages imply at least 10,000 separate calculations, as to obtain a reliable result more repetition of irregular wave cases is needed. For static calculations, it is not possible to observe different results from damages having different sizes but involving the same compartments. Therefore, it is useful to group all the damages assigning relative weights to damages with different occurrences: the so-called p-factors (Zaraphonitis et al., 2015b; Bulian et al., 2016; Vassalos et al., 2022). Then, static calculations are performed for a limited number of cases, usually referred to as damage scenarios, representative of the unique combinations of damage compartments detected with the sampling procedure. Therefore, the total number of damage scenarios depends on the internal geometry complexity, sampling size and sampling process. In any case, the total amount of cases to assess is lower than the total number of generated breaches.

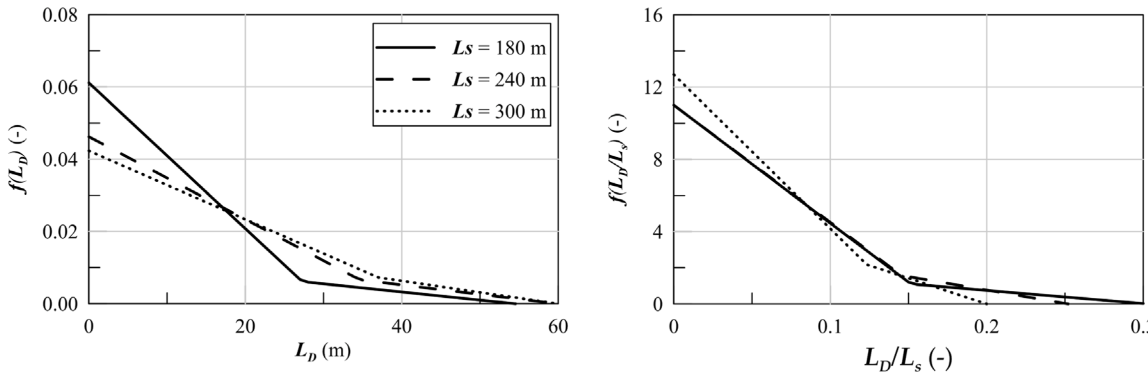

Fig. 1. Probability density functions of the dimensional (*left*) and non-dimensional (*right*) length of potential damage for a C00 collision.

Table 1
Ship#1 and *Ship#2* main particulars.

Parameter	*Ship#1*	*Ship#2*	Unit
Length overall	300.00	162.00	m
Length between perpendiculars	270.00	146.72	m
Breadth	35.20	28.00	m
Subdivision drought	8.20	6.30	m
Height at main deck	11.00	9.20	m
Metacentric height	3.50	3.40	m
Deadweight	8500	3800	t
Gross tonnage	95,900	28,500	t
Number of passengers	2750	1900	–
Crew members	1000	100	–

The random nature of the sampling process suggests performing more than one sampling repetition (Bulian et al., 2016), resulting in multiple samples that could potentially detect different damage scenarios and leading to different p-factors.

3. Reference ships

In the present explorative study on critical damage detection and filtering, use is made of two reference passenger ships. For convenience, the two vessels are here described before using them as worked examples for the developed filtering procedures. As mentioned in the introduction, use is made of a large cruise ship and a Ro-Pax vessel, being the selected test ships for most of the developments within the FLARE project (Luhmann et al., 2019). In this work, the cruise ship will be named *Ship#1* and, the Ro-Pax, *Ship#2*. The main parameters of the two ships are given in Table 1, and an overview of the general arrangement is shown in Figs. 2 and 3, indicating the subdivision used for standard static analyses. *Ship#1* is representative of a large cruise vessel, whilst *Ship#2* is a medium size passenger ferry. The ship sizes are covering the two extremes in the range of breach length definition typical of C00 damages described in Section 2, with *Ship#1* above 260 m and, *Ship#2*, 198 m.

3.1. Damage breach generation for the reference ships with a non-zonal approach

As the identification procedure for critical damages for two of the three proposed methods is based on C00 damages sampling, a brief overview of the breaches sampling and damage cases obtained is given in this Section.

The sampling process used to determine the damage cases is based on a randomised quasi-Monte Carlo method, ensuring a more uniform coverage of the potential damage space compared to conventional pseudo-random methods (Mauro and Vassalos, 2022). For this study, 3 sample repetitions of 10,000 breaches each have been used as suggested by other studies on damage sampling (Mauro et al., 2021; Mauro and Vassalos, 2022).

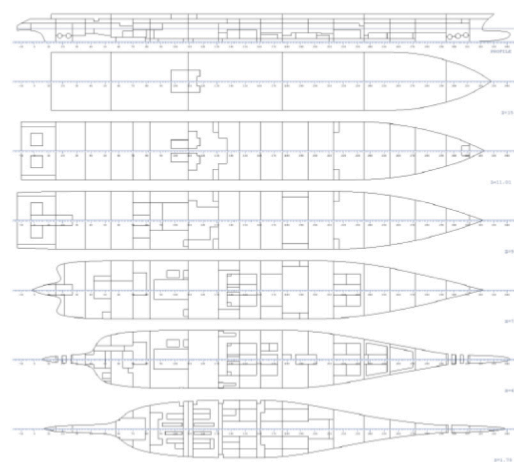

Fig. 2. *Ship#1* General arrangement.

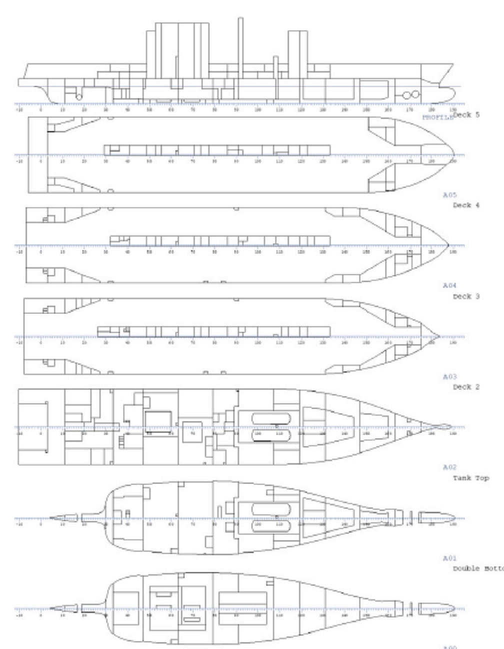

Fig. 3. *Ship#2* General arrangement.

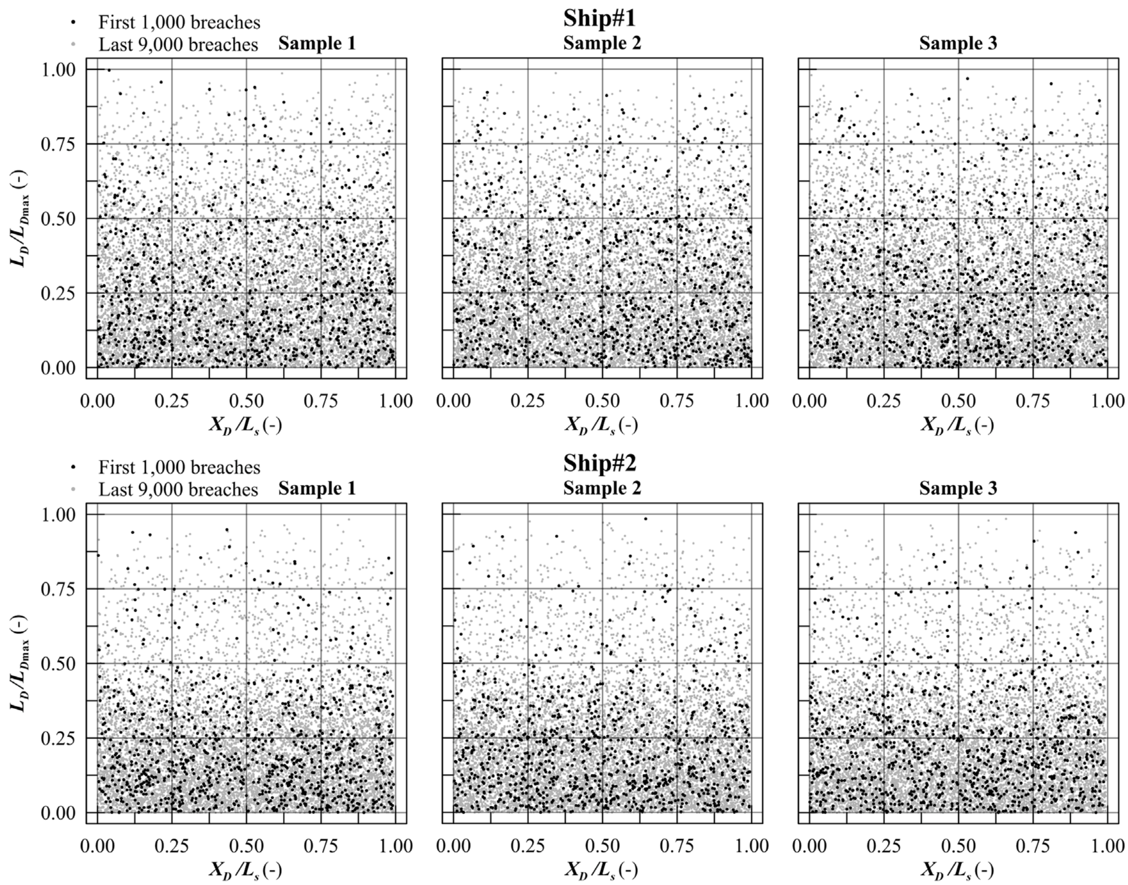

Fig. 4. Non-dimensional damage length and position for *Ship#1* (*top*) and *Ship#2* (*bottom*).

In Fig. 4, the outcome of the damage sampling process is shown for *Ship#1* and *Ship#2*. The representation is limited to the distribution of damage length L_D at the respective X_D position in non-dimensional form. In the two figures, the three samples are represented, highlighting the distribution of the first 1000 breaches compared to the total of 10,000 breaches. It can be observed that the different nature of the marginal distributions for damage length between the two ships (see Fig. 1), implies that for *Ship#1* there is a smoother transition between relatively short and long damages, whilst for *Ship#2* the density of relatively short damages is higher than for long ones. This aspect will affect the survivability of the two ships as it depends on the detection and definition of the critical cases.

4. Static analysis filtering

A straightforward way to identify critical scenarios to be further analysed through dynamic simulations could be derived from the analysis of static calculations.

The static stability assessment is performed on the damage cases derived from the sampling of marginal distributions, grouped in unique damage scenarios with associated p-factors. Calculations performed on these unique cases allow determining the survivability of the ship for the associated damage scenario, thus evaluating the s-factor. From this analysis, three categories can be figured out, according to the s-factor value:

- $s = 0$: cases where the vessel can be considered statically capsized or with insufficient residual stability margin;
- $0 < s < 1$: cases with reduced stability reserve that may lead to capsizing in case a wave environment is faced;
- $s = 1$ cases where the vessel can be considered safe and potentially has a sufficient reserve of stability to face waves.

Even though, as a first approximation, it can be considered that cases with $s = 0$ lead to a dynamic capsize (Karolius et al., 2018), it is wiser to consider the first two categories as those potentially leading to a capsize for dynamic simulations. The geometrical model used for static calculations differs from that used in dynamics, where more openings and internal rooms are modelled, therefore a direct comparison cannot be performed between the two approaches. It has been observed that the results from static predictions are usually more conservative than a full dynamic-based vulnerability assessment in calm water (Paterson et al., 2017; Atzampos, 2019); however, especially when irregular waves should be considered it is advisable not to discard a-priori all uncertain cases.

As mentioned in the previous sections, the execution of static calculations is not performed on all the damage cases generated from the sampling procedures. Single damages are regrouped in damage cases involving the same adjoining compartments. This process reduces the number of cases where the s factor needs to be evaluated, taking into account the weight of each single damage case through the p-factor. These two factors can be representative of risk.

The factor $p(1 - s)$ can be used to give a rough estimate of the risk associated with a particular damage case. In Fig. 5, an example is given for the two ships, highlighting the most vulnerable areas of the two ships, considering all three damage samples generated. The static calculations refer to the loading conditions shown in Table 1. Comparing the results in Fig. 5 for the two ships, it is noteworthy that *Ship#2* has an overall risk level higher than *Ship#1*. This can be further visualised in Fig. 6, where the s-factor of every single damage for the three samples is highlighted concerning non-dimensional damage position and length, thus neglecting the grouping present in the risk profile. Thus, each point in the diagrams is representative of a potential case to be further analysed with more advanced dynamic simulations.

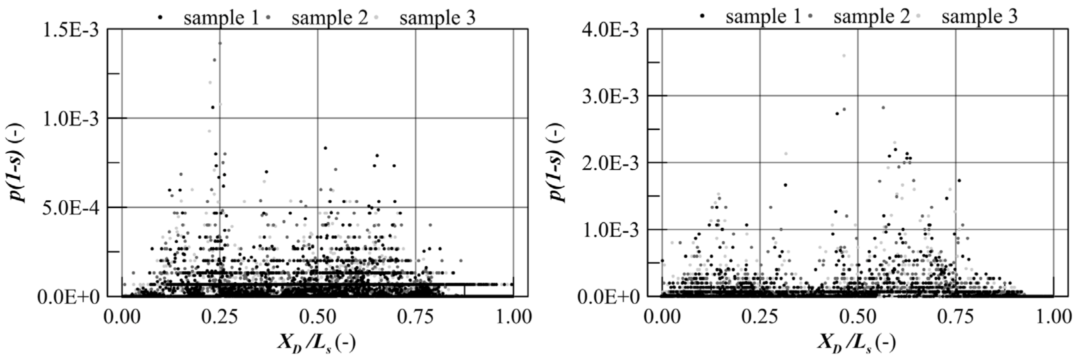

Fig. 5. Risk profile for *Ship#1* (*left*) and *Ship#2* (*right*).

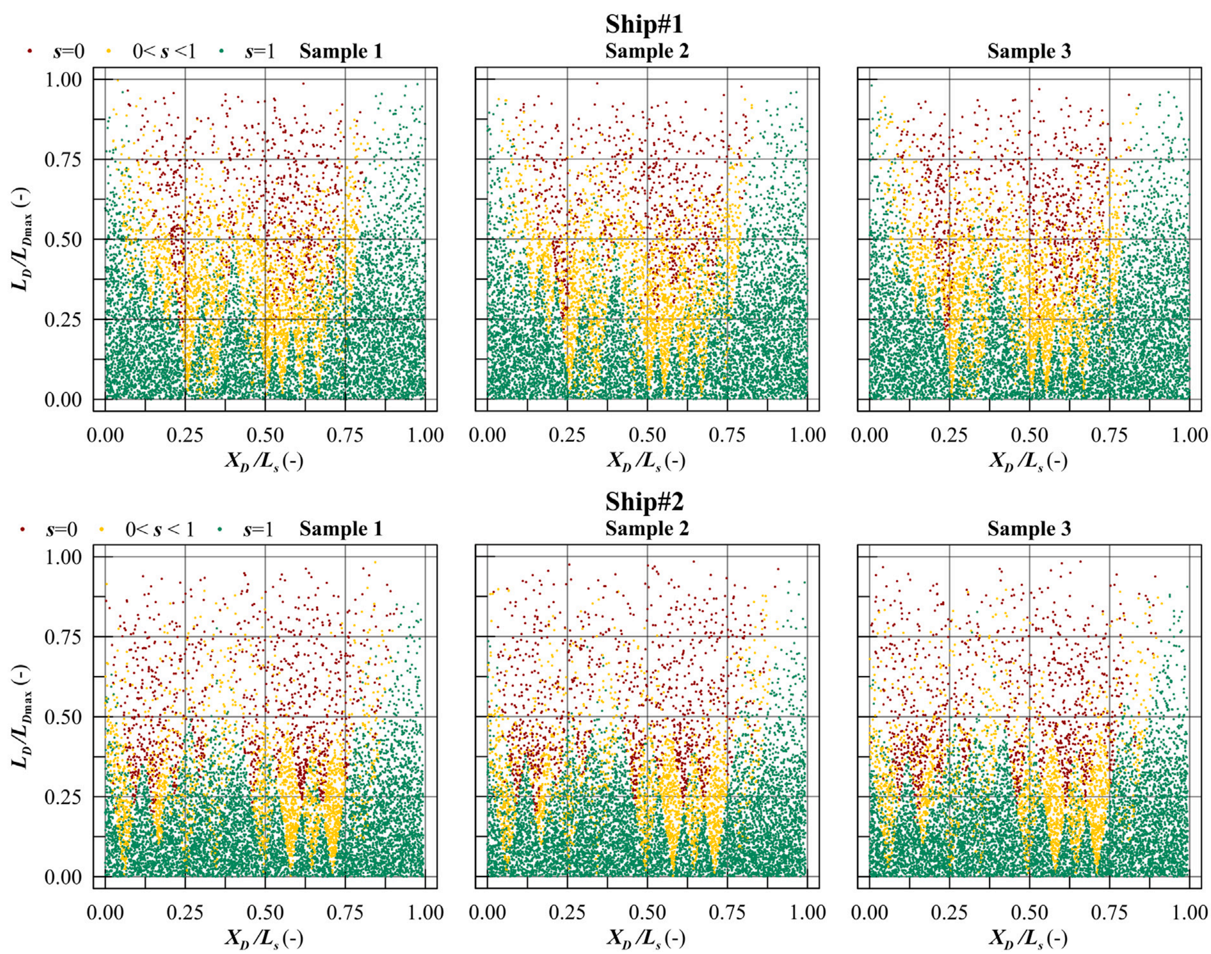

Fig. 6. Survivability factor for *Ship#1* (*top*) and *Ship#2* (*bottom*).

It is then straightforward to filter out all the cases with $s = 1$ and keep only the other cases for further analysis. By following this approach, for *Ship#1* 65.0% of cases can be filtered out, whilst 66.5% of cases can be discarded for *Ship#2*. Instead, considering only the cases with $s = 0$, 91.7% and 88.9% of the damages can be filtered out for *Ship#1* and *Ship#2*, respectively.

It is also possible to mitigate the pure filtering based on the s-factor, using the risk profile reported in Fig. 5. The damage cases reported in that figure are representative of the unique damage cases for static calculation, thus the cases with higher risk are those having $s \neq 0$ and a high p-value, thus cases which are more probable to face according to the reference probabilistic framework. Therefore, it can also be possible to consider as a filtering option the combined effect of both p and s, thus the risk. In this case, all the damages under a certain risk threshold can be filtered out.

In Fig. 7, an example is given for the two ships, considering as risk threshold the value of 1E-4, which means considering only cases with $s = 0$ and intermediate cases having a global risk comparable to or higher than an immediate capsize. Therefore, this filtering reduces the cases where $0 < s < 1$, resulting in an intermediate number of cases compared to the previous two simpler options.

The adoption of such filtering allows for evaluating vessel survivability also with dynamic simulations, evaluating an index A_{dyn} directly from the set of filtered data, assuming that the vessel survives for the other cases. Therefore, supposing that N_D is the total number of samples and N_F is the number of cases remaining after the filter

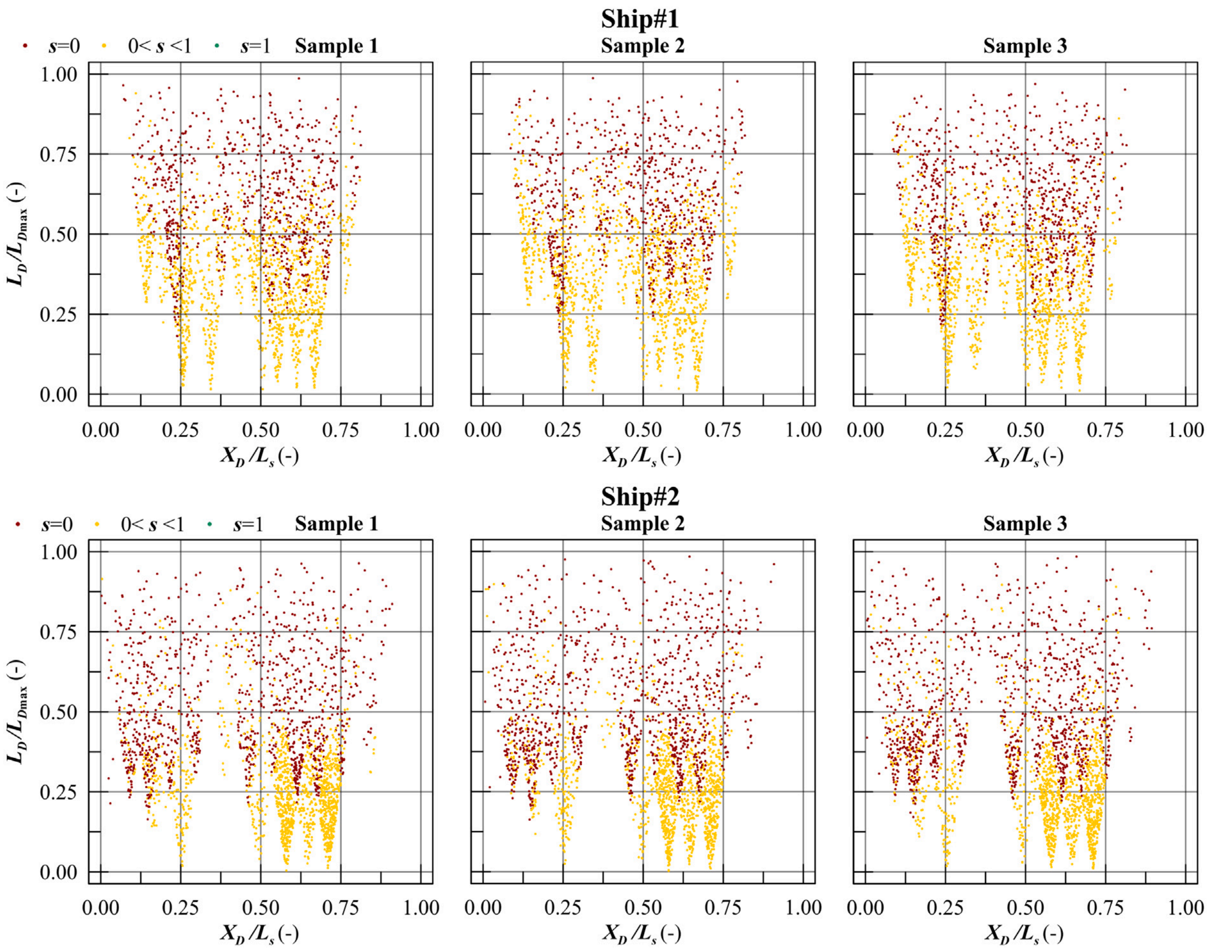

Fig. 7. Damages with risk level above 1E-4 for *Ship#1* (*top*) and *Ship#2* (*bottom*).

application, the survivability index becomes:

$$A_{dyn} = 1 - \frac{1}{N_D}\left(N_F - \sum_{i=1}^{N_F} s_i^*\right) \tag{3}$$

where s^* is the survivability factor of the dynamic simulation that is equal to 1 if the vessel survives after the maximum simulation time or equal to 0 if the vessel capsizes before the end of the simulation. The process described here is valid for calm water cases; however, it can be extended to irregular waves adopting an alternative definition of the s-factor in the preliminary calculations (Cichowicz et al., 2016).

5. Damage energy-based filtering

Another approach could be pursued to filter out minor damages resulting from the non-zonal sampling process of the probabilistic damage stability framework; this time, without the need to perform preliminary static analysis. This approach is based on the energy absorbed by the vessel during an accident. Therefore, it is necessary to adopt a method to evaluate the energy absorbed by the ship after a damage with specific geometric characteristics occurring. To this end, several methods could be applied to have different levels of approximations and, consequently, different calculation and pre-processing times. These methods include simple empirical formulae, analytical methods based on the so-called super-element solutions and finite element modelling techniques.

Simple empirical formulations require the knowledge of the damage extents and an estimate of the structural volume of the ship related to the damaged area. Super-element method and finite element modelling require knowledge of the vessel's structural components and configurations. Finite element methods are certainly more accurate than all the other methods, however, this requires a higher calculation time which is not reasonable to apply when thousands of damage scenarios have to be created.

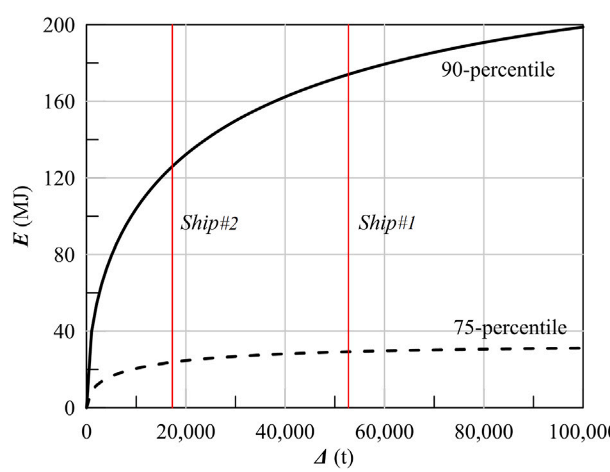

Fig. 8. 75 and 90-percentile energy limits for *Ship#1* and *Ship#2*.

Regardless of the method used to evaluate impact energy, the application of this energy-based approach requires the definition of a threshold level, identifying the limit of what can be considered critical damage to the ship. To this end, use can be made of statistical analyses of collisions available in the literature (Lützen, 2001). Here, damages

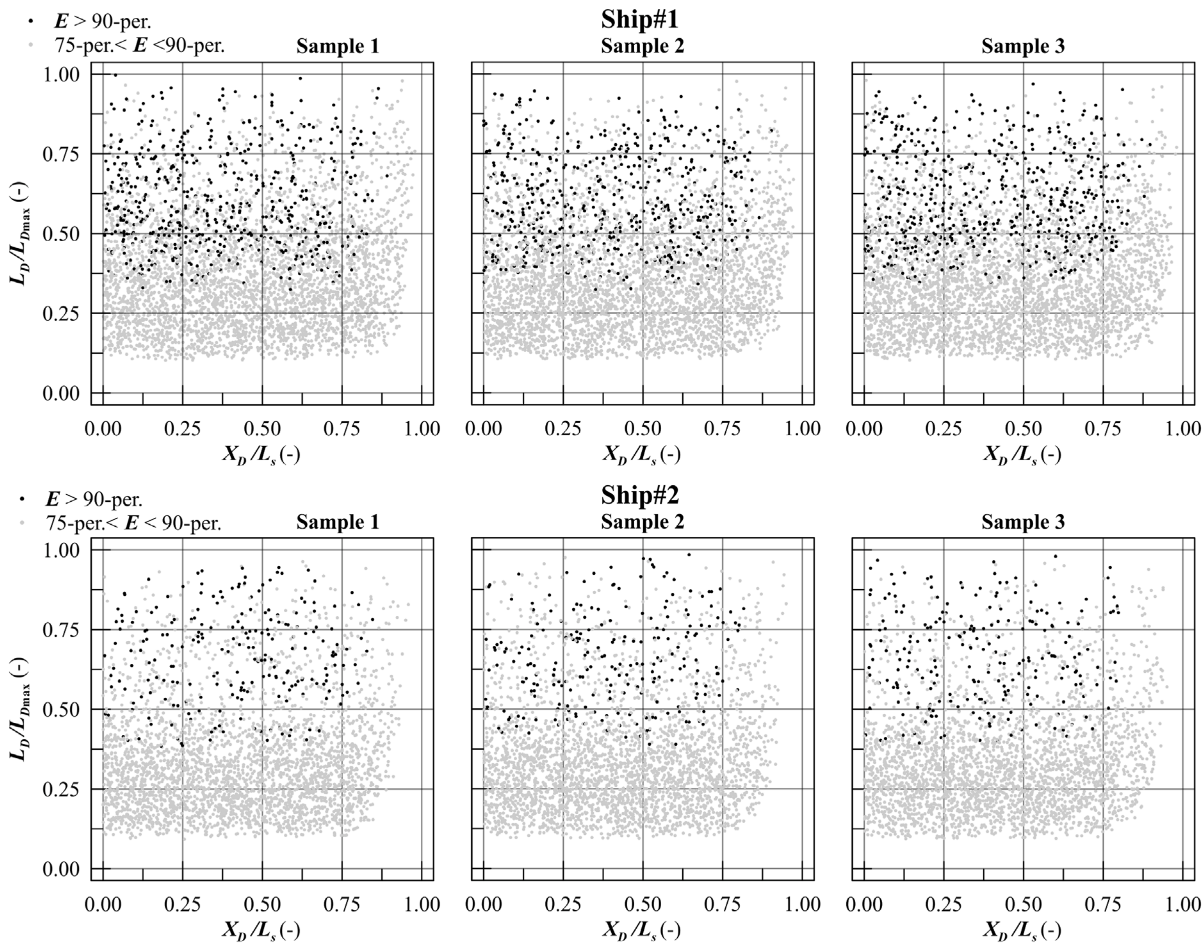

Fig. 9. Application of energy based damage filter for *Ship#1* (*top*) and *Ship#2* (*bottom*).

deriving from ship-to-ship collisions have been considered and an analysis of the associated energy for each impact has been performed, deriving representative curves that show an exponential behaviour of the energy absorbed by the struck ship as a function of displacement. Regression curves are given to identify the 25, 50, 75 and 90-percentile of the energy absorbed by vessel collisions worldwide. These values refer to damages located in the middle of the struck vessel, but they are used here for the whole ship purely as a demonstrative example. In Fig. 8, the 75 and 90-percentile curves are shown, identifying the respective limits for *Ship#1* and *Ship#2*.

For this explorative application on *Ship#1* and *Ship#2*, the energy associated with every single damage has been calculated employing the approximate empirical formulation given by Minorsky (1959). The authors are fully conscious of the extremely simplified nature of the formulation, but it represents an estimated level of energy that could be calculated in an early-design stage, without knowing the effective structural layout of the ship under analysis, which will lead to more complicated and accurate methods. However, this approach may provide an effective filter for early design stage calculations of damage stability at a sufficient level of granularity.

In Fig. 9, an overview is presented of the obtained results derived from this simplified energy method for the two reference ships. According to the threshold levels of 75 and 90-percentile of energy collision distribution, 46.7% of the damages for *Ship#1* are above the 75-percentile, whilst 4.9% exceeds the 90-percentile limit. For *Ship#2*, 32.9% of the damages are above the 75-percentile and only 2.0% exceed the 90-percentile of absorbed energy. The different distribution of damages between the two ships is influencing the obtained results, as *Ship#2* has a higher damage density in the region where low energy is detected, resulting in a higher filtering ratio compared to *Ship#1*.

On the other hand, the obtained results reflect the approximated nature of the Minorsky formulation, giving intrinsically more weight to damages with higher penetration. Applying this formula, damages with high longitudinal and vertical extents, but with low penetration are filtered out as they have low absorbed energy. However, these damages are identified as capsizes in static analysis ($s = 0$) and most likely may be detected as transient capsizes with dynamic simulations.

This filtering process can be applied to samples of damages for dynamic simulations as the final determination of dynamic survivability can be applied according to Eq. (3). Moreover, the energy filter is applicable also in case wave distribution is sampled for irregular sea calculations.

6. Critical scenarios search for dynamic analysis of ship survivability

The above-described methodologies for damage filtering presuppose that damage cases are sampled from conventionally adopted probabilistic frameworks, thus aiming to determine survivability with either a zonal or non-zonal approach. These approaches are intrinsically derived from static analysis or intrinsically suppose that a preliminary static assessment has been carried out. However, another possibility could be given by substituting the preliminary static analysis using a reduced set of dynamic simulations.

As already mentioned in Section 2, the definition of a damage scenario for dynamic analysis is considering every single breach sampled from marginal distributions for location and dimension and the

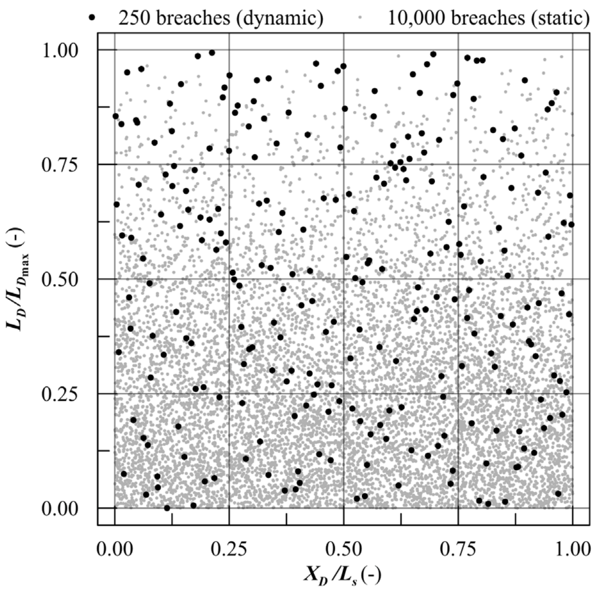

Fig. 10. Uniform damage length distribution for *Ship#1* for preliminary dynamic analysis.

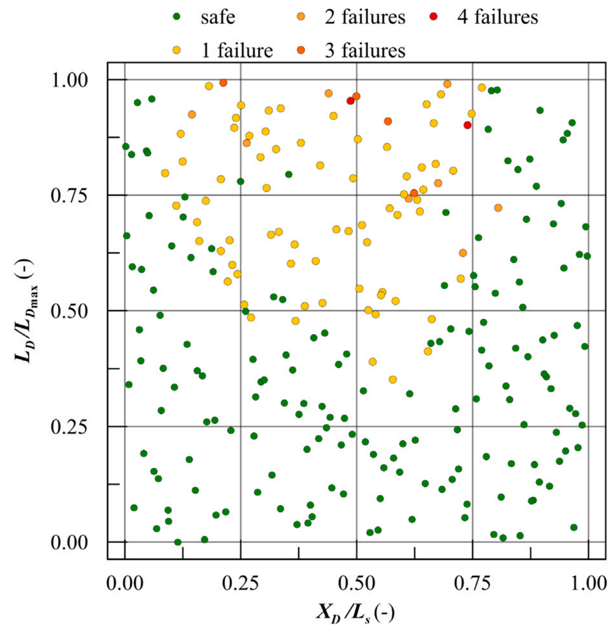

Fig. 11. Critical cases resulting from preliminary dynamic calculations for *Ship#1*.

weather condition. Therefore, the adoption of probability distributions recommended by the in-force probabilistic framework for damaged ships can be used also to perform a survivability assessment with a dynamic approach. However, sampling according to the above-mentioned marginal distribution will lead to the same samples shown in Fig. 4 for the two reference ships; thus, distributions with a high density of small damages most probably will not lead to capsizing in dynamic simulations. However, inside a Monte Carlo process for survivability determination, all these 'safe' cases must be analysed to obtain the final value. Instead of calculating directly all the damage cases derived from samples of 10,000 scenarios, it could be interesting to perform a preliminary set of simulations on a reduced set of scenarios to identify critical areas directly with a dynamic approach. To this end, the marginal distribution provided by SOLAS should be abandoned, as intrinsically leads to highly populated relatively small damages. Here it is proposed to adopt an initial sample assuming that damage location and dimensions follow uniform distributions.

The preliminary analysis can be performed according to the following steps:

- *Initial uniform sampling*: sample a reduced number of damages (e.g., 250) according to uniform distributions.
- *Preliminary dynamic calculations*: execution of preliminary dynamic calculations for the initial sample in calm water.
- *Preliminary results analysis*: analysis of the preliminary dynamic calculations to identify true capsizes or damage cases failing imposed criteria.

The above-described process applies for calm water simulations, thus performing the initial study discarding the presence of waves. Alternatively, the preliminary analysis can be performed for a given wave height, showing the influence of irregular waves on the initial sample. However, in case irregular waves are selected, the preliminary study should be performed considering the stochastic nature of the sea environment, thus repeating the simulations for at least 10 times.

The process has been here applied to *Ship#1* only, considering an initial uniform sampling of 250 damage cases for calm water. Dynamic calculations have been performed with PROTEUS 3 software (Jasionowski, 2001), for a maximum simulation time of 30 min, considering the vessel characteristics described in Table 1. Preliminary dynamic calculations consider here a maximum simulation time of 30 min to focus on the detection of particularly critical cases leading to the rapid capsize of the ship. In case the focus is also on detecting cases critical for evacuation of the vessel where progressive flooding takes place, then the maximum time can be extend up to 3 h.

The initial sample of 250 damages has been performed with the same sampling technique used for the initial samples presented in Fig. 4. In Fig. 10 an overview is given of the new sample, together with the sample adopted in previous sections. The figure is showing the distribution of non-dimensional damage length L_D against the non-dimensional damage location X_D. It is noteworthy that the uniform sampling is populating the region of longer damages with more cases than the standard sampling, thus giving a global coverage of the whole damage space. The same properties are valid also for the other dimensions not reported here for brevity.

Performing dynamic simulations on this set of damages it is then possible to identify the critical case of this reduced group of scenarios. Besides true capsizes, cases where the roll angle exceeds 40 degrees, and other criteria can be used to detect critical scenarios. In this study, the following criteria have been applied:

- *SOLAS heeling failure*: maximum heel above ±15 degrees.
- *ITTC maximum heeling*: maximum heeling above ±30 degrees.
- *ITTC average roll*: cases where 3 min average roll exceeds ±20 degrees.
- *Large average floodwater mass rate*: cases where the flooding process is still significantly progressing at the end of the simulation time, with a mass rate above 2000 t/h (Atzampos, 2019; Guarin et al., 2021).

These criteria are those normally applied to dynamic simulations in the traditional approach.

From the simulations performed for *Ship#1*, 2 true capsizes have been found; however, the following criticalities have been highlighted: 84 SOLAS heeling failures, 7 ITTC maximum heeling exceedances, 12 ITTC average roll exceedances and 2 simulations still in progressive flooding. It is notable that with such a few samples in calm water, 2 true capsizes have been detected, as, applying the same GM, no true capsize cases have been detected with the conventional sampling process on 1000 damages, even considering an H_s of 4 m. These results

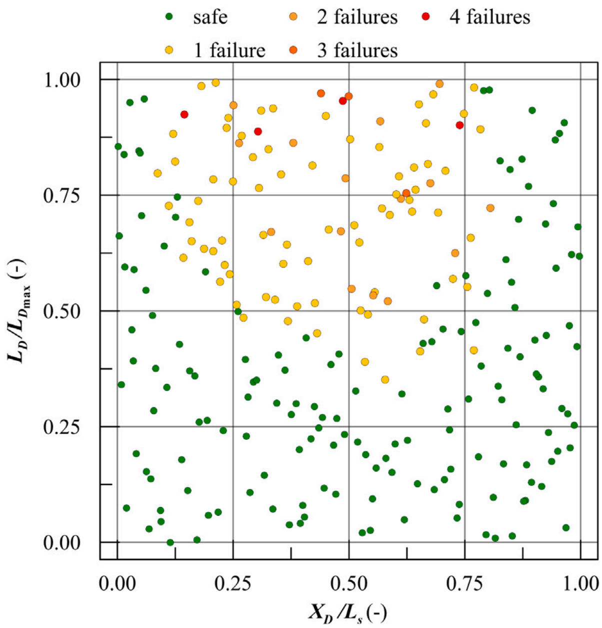

Fig. 12. Critical cases resulting from preliminary dynamic calculations for *Ship#1* considering H_s of 4 m.

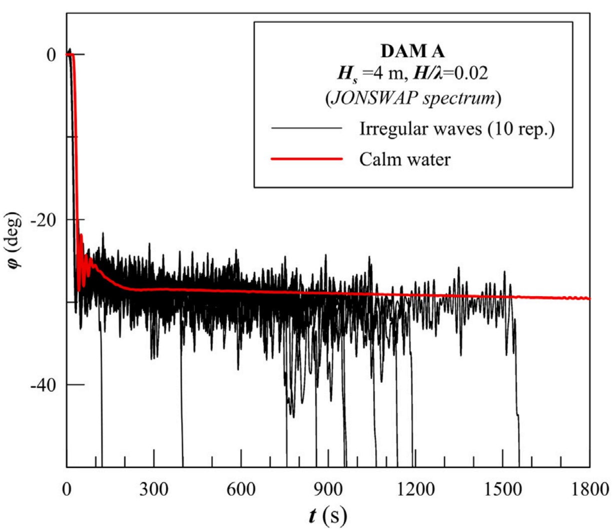

Fig. 13. Roll angle time-trace for *DAM A* in calm water and with H_s of 4 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are summarised in Fig. 11 where the critical cases are highlighted. From the graphical representation, the area where possible critical damages are located is identified. It is then evident that L_D and X_D have a strong influence on the distribution of critical cases. No direct correlation has been found with other damage dimensions, where the critical cases are almost spread through the whole domain.

From this preliminary analysis, possible filtering of damages above a certain L_D can be identified. In such a case, a full set of samples can be identified using conventional marginal distributions for damage dimensions and locations. This would allow for survivability assessment with a conventional Monte Carlo process, taking into account that the marginal distribution of L_D is sampled only above a certain threshold. This second sampling process can also consider the presence of waves, thus the total number of simulations to be performed depends on the repetitions of the single cases to take wave randomness into account.

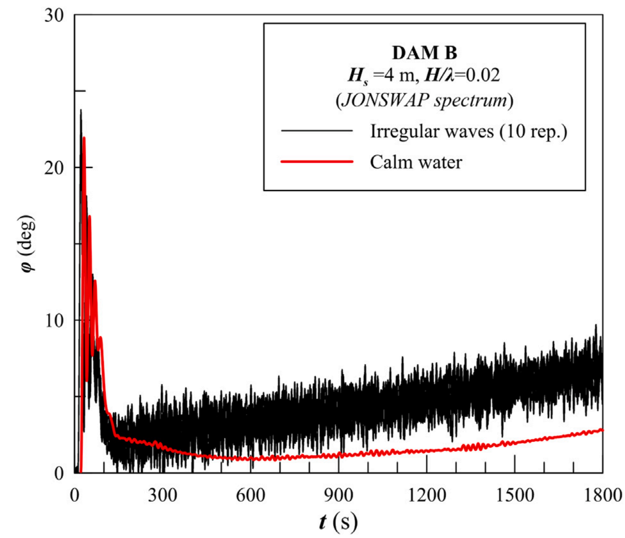

Fig. 14. Roll angle time-trace for *DAM B* in calm water and with H_s of 4 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To check the effect of irregular waves, the damage scenarios of the preliminary set have been tested considering an H_s of 4 m with a wave steepness H/λ of 0.02, employing a JONSWAP spectrum (γ = 3.3). Fig. 12 shows the results of this test, showing the highest failure level detected between 10 repetitions of the simulation in waves. The true capsizes raises from the 2 in calm water to 4 with the selected H_s. It is noteworthy that all the capsizes have been detected in the region where failure criteria occurred in calm water. Furthermore, with the considered H_s the region where critical cases may occur is not drastically changed in waves, as only 12 additional criticalities are identified in addition to the calm water case.

As an example, Figs. 13 and 14 show the 30 min time-domain simulation of two damage cases, named *DAM A* and *DAM B*. The two damages have comparable penetration and height. They are located at an X_D/L_s around 0.70, which corresponds to an high risk area according to the risk profile given in Fig. 5, on port-side and starboard, respectively. Damage *DAM A* has a $L_D/L_{D_{max}}$ of 0.80 and *DAM B* has $L_D/L_{D_{max}}$ of 0.74, thus are representative of damages of large extent. Both damages survive the preliminary dynamic calculations in calm water but failing other criteria. *DAM A* fails the SOLAS heeling and ITTC average roll criteria whilst *DAM B* the SOLAS heeling and the final floodwater mass rate criteria. Considering the simulation in waves, *DAM A* capsizes in all 10 repetitions but *DAM B* always survives. Such a behaviour was foreseeable looking at the calm water time trace (red curves), having *DAM A* an average heeling constantly around −28 degrees starting from 300 s of simulation. This matter suggests that some failure criteria are more important and restrictive than others to foresee the final fate of a flooding scenario in waves, and this should be further studied to derive more tailored failure criteria. In any case, the execution of 250 preliminary dynamic simulations does not require a lot of computational effort, as the time-domain simulations in calm-water are running almost three times faster than in real-time on a regular computer. Moreover, compared to the adoption of static calculation, this method used the same internal layout and the same openings definition for both preliminary and final calculations.

7. Discussion

The three methods described above are representative of different approaches that could be followed to assess the damage survivability of a passenger ship. This means considering the dynamic analysis

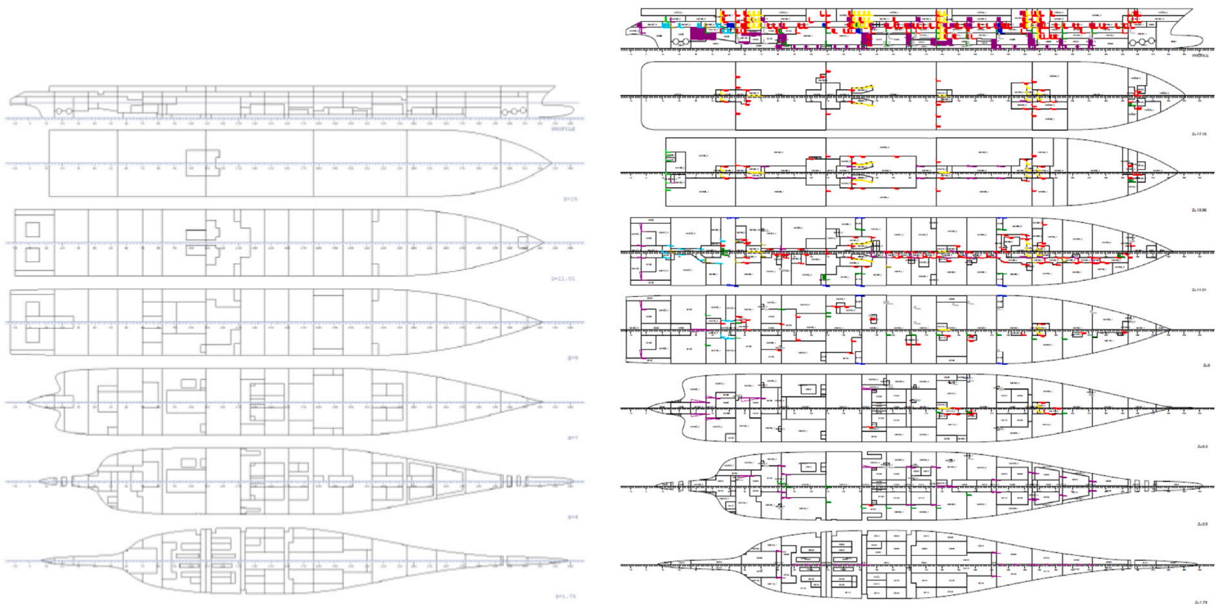

Fig. 15. Internal layout and compartment connections for static (*left*) and dynamic (*right*) calculations for *Ship#1*.

as a consequential and complementary process to static analysis or considering the dynamic analysis as totally independent from static calculations. All the methods showed the capability of reducing the number of damage scenarios compared to a traditional definition of damage cases. In any case, all methods present some positive and negative aspects, concerning the number of cases that can be reduced, the modelling simplification and the calculation time.

The filtering based on preliminary static calculation is probably the most straightforward method, directly reflecting the consequentiality of static and dynamic calculations in a damage stability framework. In the present work, different options have been presented to filter out damages cases with this approach: considering only $s = 0$ cases, considering only cases with $s \neq 0$, or mitigating the results through the risk of impact in certain areas. Considering this last option as the most suitable to identify cases to be analysed with dynamic calculations, a total amount of 2150 and 2350 potentially critical cases are identified starting from a 10,000 damages sample (as averaged values on the three samples used) for *Ship#1* and *Ship#2*, respectively. This is a good performance as about 80% of initial cases are discarded. However, the static calculations refer to a different internal layout compared to a dynamic calculations. For static analysis, the ship is modelled only up to the bulkhead deck with a simplified internal layout and fewer relevant openings. Fig. 15 shows the differences between the layouts for statics and dynamics calculations for *Ship#1*. The static model comprises 190 compartments within 6 decks, whilst the dynamic model has 364 compartments and considers 7 decks. Furthermore, the dynamic model requires defining about 430 openings between the compartments against the 30 connections present in the static model. This difference could reflect in the identification of more critical cases than what can be observed from dynamic simulations.

The energy-based filtering is a different strategy that did not require the execution of preliminary static analysis. The method has been here applied with a simplified formulation for the absorbed energy determination, and the results reflect the nature of the simplified formulations used. Nevertheless, the method identifies 4670 and 3288 critical cases for *Ship#1* and *Ship#2* respectively, considering as threshold the 75-percentile of potentially absorbed energy. Thus, the performances are lower than the previous method, but it could significantly improve if the 90-percentile of absorbed energy is used. In conclusion, regardless of the model simplifications here adopted, this method is strictly dependent on the threshold level adopted to filter the damages. This can be better identified only through dedicated studies with high fidelity simulation tools. Moreover, the adoption of a damage distribution according to the SOLAS framework can be intended already as a potential energy distribution on the ship, therefore this method could be inappropriate to use in the actual probabilistic framework but may be further studied as an alternative way to generate damages.

The approach based on dynamic simulations only is a totally different way to face the damage filtering process. No static calculations are used; thus, no uncertainties are introduced by comparing results coming from two different internal layouts and opening definitions. The adoption of a preliminary set of calculations using a uniform distribution for all the damage characteristics allows for the investigation of the whole damage space with a reduced number of sampling. In this explorative study, 250 samples have been used; however, further investigation is needed to identify an optimal number of cases to be used. The method is capable of identifying the criticality by adopting the same criteria used for traditional dynamic calculations, thus having a direct correspondence with the critical cases of the final runs for survivability assessment. This method is not directly filtering out cases but is capable of identifying a suitable threshold for the damage length to sample with conventional distribution only part of the domain, with a number of samples that can be decided in each case.

8. Conclusions

In the present explorative work, three different methods to identify critical damage conditions for passenger ships have been presented and applied on two reference ships. The methods present positive and negative aspects, proposing solutions that can be applied to a conventional damage stability framework workflow and other methods following different paths. The most conventional and simple methods based on static analysis are the direct sum between static and dynamic analysis, even though the two analyses are based on different geometries and assumptions. In any case, these methods grant a significant reduction of damage cases to analyse with dynamics. Methods from energy-based filtering are still in an embryonic form and should be further developed and analysed with the aid of more accurate models and tools. However, they could be attractive to possibly figure out possible innovative ways to generate damages, totally based on direct approaches. A fully dynamic-simulation based approach is for sure really attractive, as it represents an application of first-principles tools throughout the damage stability process. The method is capable to be applied also to investigate irregular waves in the preliminary phase. However, the calculation time can be higher than the static analysis filtering. In conclusion, there is a need to further investigate damage filtering methods to allow an even more extensive and appropriate use of dynamic simulations in a damage stability assessment process for passenger ships.

CRediT authorship contribution statement

Francesco Mauro: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing. **Dracos Vassalos:** Conceptualization, Writing – review & editing, Supervision. **Donald Paterson:** Writing – review & editing. **Evangelos Boulougouris:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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