# AN AREA-SPECIFIC SURVIVABILITY ASSESSMENT FOR PASSENGER SHIPS

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## *ABSTRACT*

*The survivability of a passenger ship after an accident is assessed by a probabilistic framework covering hazards like collisions and groundings. Such assessments are a key determinant for the internal ship arrangement and layout, affecting ship design and operation. The framework pertains to static assessment, but it is common to use the same damage definitions for dynamic calculations. In the latter case, besides the breach characteristics, the environmental condition selection is of paramount importance. In the specific, irregular waves modelling, it is necessary to simulate the damage scenarios. In the common dynamic approaches to survivability, attention is paid to the significant wave height of the calculation, considering the wave period constant. The wave height is not always reflecting real scenarios but is derived from statistics of collisions (GOALDS project). However, wave height and period influence ship dynamic in waves (in intact or damaged conditions), impacting survivability after damage. Aiming at a direct assessment of ship survivability and the probability of loss of lives determination in realistic operational scenarios, it is essential to properly study the influence of combined variations of wave height and periods and their occurrence. In the present study, dynamic simulations are carried out in site-specific conditions derived from the Global Wave Statistics. Critical cases are derived from conventional survivability analyses on a sample passenger ship. The same cases are then analysed using wave height and period combinations typical of the main sea areas of interest for passenger ships. This enhanced analysis allows to clearly identify the limiting environmental conditions for the critical damage cases, evaluating the effective survivability of the ship to a specific damage in an operational area.*



## KEY WORDS

Damage stability; Design for safety; Design for operations; Irregular waves; Scatter Diagrams; Survivability.


## INTRODUCTION

Damage stability for passenger ships has largely developed as a subject over the last 60 years, reaching the most relevant scientific advances in the last two decades. Therefore, damage stability and in particular the study of survivability after an accident are nowadays a key part of the design process of a passenger ship, providing a life/cycle flooding risk management for the vessel (Vassalos 2020). As a consequence, survivability of a passenger ship 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 compliant-based approach. Nowadays, one of the goals of FLARE project is to overtake 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. In that respect, the probabilistic framework considers the irregular wave environment by giving importance to the significant wave height $H_s$ only, deriving formulations from statistics of accidents (Vassalos et al, 2021). The modelling of the wave period is not directly considered, as it may directly derive from application of one parameter wave spectra, or it is assumed that waves should be modelled with a constant slope. However, wave period is also influencing the ship dynamics in waves, both in intact and damaged conditions.

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The final goal of FLARE project is to promote the application of direct methods for ship survivability analyses. Therefore, the introduction of the variability of wave period in time-domain dynamic simulation is a substantial improvement to reach a more reliable survivability prediction, especially for the operational design of a new vessel. To this end, a novel method is here presented to evaluate survivability to specific damage cases in a selected sea area. The method uses statistics deriving from wave measurements available in the literature, but can also be applied to more site-specific data, where available.
In the present work, the procedure is explained and applied to a small sample cruise ship, considering a small subset of collisions and side groundings filtered from static calculations that may lead to capsize in irregular waves. The analysis is performed considering three different sea areas of potential interest for cruise ships, namely: the Caribbean Sea, the Western Mediterranean and the Baltic Sea. The obtained results show the different survivability level of the same damages in different sea areas, stressing the importance of modelling also the wave period to obtain more reliable site specific survivability prediction for a passenger ship.

## SHIP SURVIVABILITY

Survivability is associated to the probability that a ship may capsize or sink when subjected to a potential feasible flooding scenario. As such, survivability evaluation provides useful information about the design parameters that affect the ship stability in flooding conditions.
In general, the survivability to flooding, or its complementary term vulnerability, of passenger ship is widely well represented mostly for cases related to water on deck damage conditions, involving large undivided compartments leading often to very rapid capsize. This is almost evident for Ro-Pax vessels. However, same capsize modes have been highlighted also for cruise ships, where smaller compartments are present, but corridors, lift and staircases are complicating the progress of the flooding process. For such a reason, the direct simulation of accidents due to flooding is extremely important to identify weakness and provide appropriate countermeasures in the design phase of passenger ships.
The assessment of survivability during the design phase of a passenger ship is determined by a probabilistic framework. The process consists in carrying out numerical time-domain dynamic simulations of a ship subjected to a specific damage scenario. Each damage scenario corresponds to a breach, whose dimension and location are defined by probabilistic distributions, and an environmental condition. The probabilistic distributions for the damage characteristics are defined from statistical analyses of accident databases (Bulian, et al. 2020) and can model several damage types, namely collisions, bottom and side groundings, adopting a non-zonal approach. The environmental condition considers only the significant wave height $H_s$, sampling this parameter according to the following cumulative distribution (Luhmann, 2019a):

$$F(H_s) = \exp(-\exp(1.717 - 0.9042\ H_s)) \qquad [1]$$

This cumulative distribution is considering statistics from worldwide operations and considers a maximum wave height of 7 meters. The definition of this distribution is not taking into account the variations on wave periods, leading the actual ship survivability assessment of damage ships to be a function of $H_s$ only for the environmental conditions. Such an approach is still an improvement compared to distributions based on accident statistics only; however, it is still incomplete for an accurate description of the operational environment of the ship. Being the survivability assessment performed by means of time-domain simulations, the results of the analysis are strongly influenced by the modelling of the environmental loads to be used during the simulations.
In the optic to improve the effective analysis of operational conditions in the ship survivability assessment, the identification of effective environmental conditions is essential. It is, therefore, useful to study an alternative method to assess survivability after an accident in a real operational environment.

## SURVIVABILITY IN AN OPERATIONAL AREA

The evaluation of survivability in a specific operational area requires the adoption of some assumptions for the modelling of the sea environment. Sea state is generally associated with an irregular wave environment, characterised by a significant wave height $H_s$, a wave period (typically zero crossing $T_z$ or peak $T_p$), and an encounter angle $\chi$. Besides, it is possible to make reference to long crested or short crested scenarios, modelling the sea states with specific spectra that take into account the above-mentioned quantities and characteristics. However, a wave spectrum reflects only one combination of $H_s$ and $T_p$ for a specific encounter angle. For the evaluation of survivability, it is then mandatory to identify the joint probability distributions of $H_s$ and $T_p$ (or $T_z$) for the operational area of interest. Several methods can be adopted, making reference to direct observations, hindcast and forecast methods for specific locations and time windows or refer to more general statistics valid for macro areas, like the one provided by the Global Wave Statistics (Hogben, et al. 1986). The latter is probably a choice that could be used in a design stage where no more specific data are at disposal, and have been used in this study, assuming as reference the omnidirectional statistics for an annual period. The details of the proposed calculation process for the survivability in a specific sea area are hereafter described.

## Scatter Diagram Approach

The adoption of a wave scatter diagram for the survivability assessment changes the conventional modelling of the sea environment usually adopted in the damage stability assessments. Also, the direct approach to damage survivability considers only the incremental change of $H_s$ as described in the previous sections. The associated wave period used to setup the spectra for the numerical simulations is determined considering a constant $H/\lambda$ ratio of 0.02 where $\lambda$ is the wave length. Such an assumption leads to investigate only specific combinations of $H_s$ and $T_z$ that are not covering nor representing a real sea area, but are just representing a few cells of a wave scatter diagram. Figure 1 shows combinations of wave parameters covered by the constant $H/\lambda$ assumption, both in case of using a Pierson-Moskowitz (PM) spectrum (Pierson, et al. 1963) or a JONSWAP spectrum (Hasselmann, et al. 1973) with peak shape/enhancement parameter $\gamma$ of 3.3, compared to the possible sea states for a reference sea area (the North Sea, Area 11 according to the Global Wave Statistics). The same figure shows also the resulting family of wave spectra covered by the constant $H/\lambda$ assumption.
A second concern is associated with the encounter angle $\chi$. Wave scatter diagrams allows to have statistics for waves coming from specific directions, usually associated with the main cardinal points (N, NE, E, SE, S, SW, W, NW), reporting also the respective relative frequencies. This is available for specific seasons or on an annual base. In this study, having no specific information of preferential directions for the environmental condition and seasonality of the operation, the general approach is described by means of the annual statistics for all the incoming directions. Then, the encounter angle between vessel and incoming waves always refers to the actual vessel heading, without the need to include the absolute direction of the incoming wave train.
Regardless the $\chi$ selection, using a wave scatter diagram as a reference for the environmental conditions implies the execution of specific simulations across the cells of the scatter diagram, using the specific $H_s$ and $T_z$ values associated to the sea area of interest. Therefore, the assumption of constant $H/\lambda$ value is no more valid, and a different approach is necessary to model the irregular waves environment.

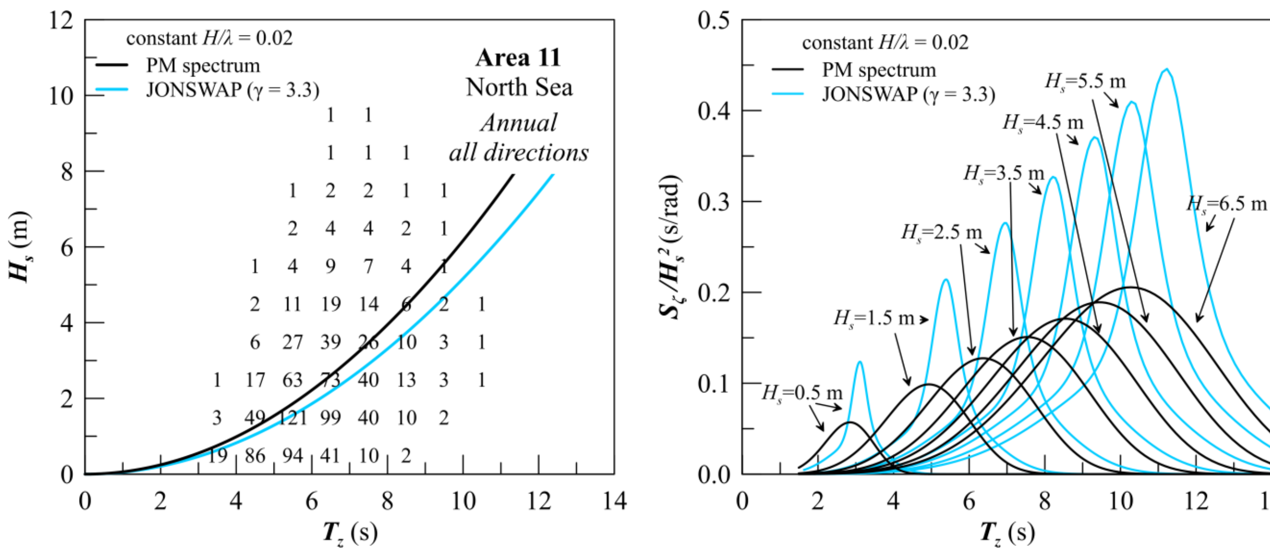


**Figure 1 : $H_s$ and $T_z$ combinations and associated wave spectra in conventional damage stability assessment**

***Irregular waves modelling***

The modelling of an irregular sea state starts from the selection of a spectral model for the wave system. The conventional approach adopted in damage survivability assessment clearly distinguish between fully developed wind-generated sea with unlimited depth and fetch, and non-fully developed sea with limited depth and fetch. This division reflects the classical approach for the ship motion analysis of intact vessels. Between the different kinds of spectra that can be adopted for irregular waves modelling, it is usual to use a PM spectrum for the fully developed sea and a JONSWAP spectrum with standard $\gamma = 3.3$ for non-fully developed seas (or for limited fetch/depth cases). However, with the two spectral formulations derived from specific locations (namely the North Atlantic area for PM and the North Sea for JONSWAP), it could be appropriate to use a more general description of the spectral parameters, allowing the description of a wider set of sea states.
For this purpose, use can be done of extended formulations of the JONSWAP spectrum, frequently used in offshore industry, that varies the elongation parameter according to the specific combinations of $H_s$ and $T_p$, ensuring more flexibility for the sea

state modelling. General formulation $S_J(\omega)$ for the JONSWAP spectrum suggests using standard parameters for the spectral equation:

$$S_J(\omega) = A(\gamma)\, S_{PM}(\omega)\, \gamma^{\exp\left[-\frac{1}{2}\left(\frac{\omega-\omega_p}{\sigma\,\omega_p}\right)^2\right]} \quad \text{where:} \begin{cases} S_{PM}(\omega) = \frac{5}{16} H_s^2 \omega_p^4\, \omega^{-5} \exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right] \\ \gamma = 3.3 \\ \sigma = \begin{cases} 0.07 \text{ for } \omega \le \omega_p \\ 0.09 \text{ for } \omega > \omega_p \end{cases} \\ A(\gamma) = 1 - 0.287\ln(\gamma) \end{cases} \qquad [2]$$

Where $\omega_p$ is the peak frequency and $S_{PM}(\omega)$ is the PM spectral formulation. However, the JONSWAP spectrum can be a reasonable model for sea states satisfying the relation $3.6 < T_p / H_s^{0.5} < 5$, that can be used in the absence of more specific observation for the sea area of interest (DNV, 2014). Such a generalisation implies changing the value of $\gamma$ for the different combinations of $H_s$ and $T_p$, that for $1 < \gamma < 7$ can be done as follows:

$$\gamma = \begin{cases} 1 & \text{for } T_p / H_s^{0.5} \ge 5 \\ \exp\left(5.75 - 1.15\, T_p / H_s^{0.5}\right) & \text{for } 3.6 < T_p / H_s^{0.5} < 5 \\ 5 & \text{for } T_p / H_s^{0.5} \le 3.6 \end{cases} \qquad [3]$$

With the scatter diagrams making reference to $T_z$ instead of $T_p$, requires the conversion between the two periods as a function of $\gamma$, adopting the following polynomial model (DNV, 2014):

$$\frac{T_z}{T_p} = 0.6673 + 0.05037\gamma - 0.00623\gamma^2 + 0.0003341\gamma^3 \qquad [4]$$

Equation [4] has the same limitation for $\gamma$ values as equation [3]; however, having the resulting model [3] bounds that are intrinsically inside the validity of $\gamma$, the validity of [4] is intrinsically satisfied through the possible domains of $H_s$ and $T_z$ present in a scatter diagram. Figure 2 shows the variations of $\gamma$, $T_p$ and $H/\lambda$ ratios as a function of $H_s$ and $T_z$. This kind of modelling grants a sufficiently general model for the sea states that could be faced in the sea areas available in the Global Wave Statistics, allowing to automatically investigate a wider range of wave parameter combinations compared to the standard constant $H/\lambda$ approach with standard spectral definitions. In case more specific measurements or spectral models are available, these can be used instead of the proposed general approach.

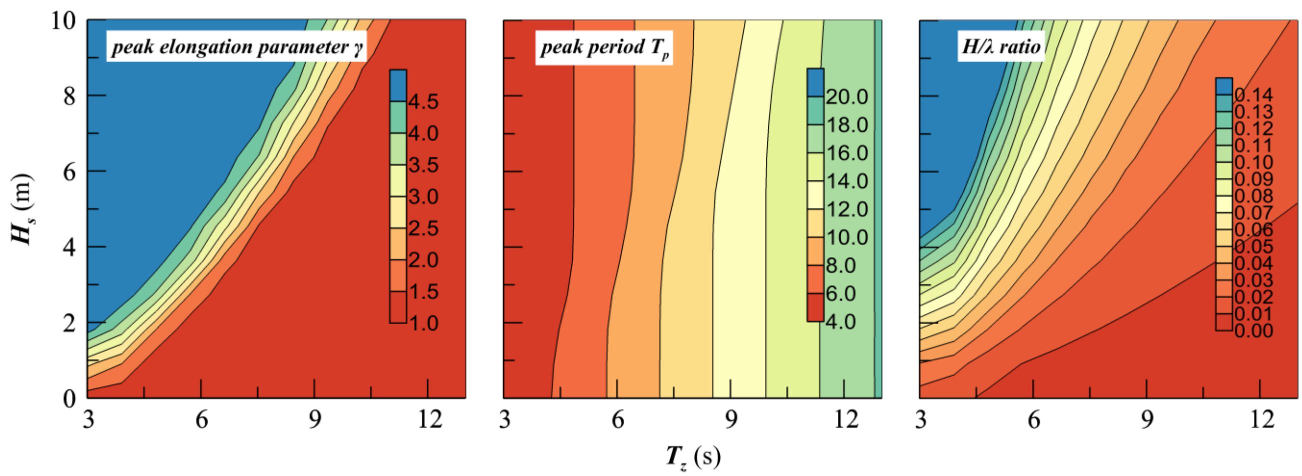


**Figure 2 : Variation of $\gamma$, $T_p$ and $H/\lambda$ with $H_s$ and $T_z$ values**

It should be noted that the above considerations are valid for a long-crested sea without the presence of a swell. However, the same modelling can be applied superposing a swell and considering an additional directional spreading parameter for short crested sea modelling.

## Survivability of a Critical Case

The scatter diagram approach requires that calculations are performed for all the combination of $H_s$ and $T_z$ present in the analysed sea area. Having determined the environmental condition settings, it is then possible to perform dynamic survivability calculations for each cell of the scatter diagram. For each wave condition, it is possible to evaluate if the vessel survived or not within the total simulation time. Then, considering the wave occurrences, the survivability for a critical damage case in the selected sea area can be calculated according to the following formulation:

$$s_A = \sum_{i=1}^{N_H} \sum_{j=1}^{N_T} p_{w_{ij}} s_{ij} \qquad [5]$$

where $N_H$ and $N_T$ are the number of wave heights and zero crossing periods observed in a sea area, $p_w$ is the occurrence associated to each couple of $H_s$,$T_z$ in the scatter diagram and the survivability $s$ is evaluated as follows for each observed combination between $H_s$ and $T_z$:

$$s_{ij} = \sum_{k=1}^{Nr} \frac{I_{s_k}}{N_r} \quad \text{with } I_{s_k} = \begin{cases} 1 & \text{if the vessel survives} \\ 0 & \text{if the vessel capsize} \end{cases} \qquad [6]$$

Such framework is similar to operability calculations used for ship motions and already successfully extended to other fields of hydrodynamics as dynamic positioning (Mauro, et. al. 2020); therefore, it could be applied also to survivability of ships. However, the scatter diagram approach for motions is generally referred to frequency domain calculations. Here, dealing with time domain simulation, it is necessary to take into account the stochastic nature of an irregular sea environment. It is then necessary to perform multiple repetitions $N_r$ of the same sea state. In the present study, a $N_r$ =10 has been considered, being a reasonable initial value to consider the variability on the obtained results from dynamic damage simulations (Spanos, et al. 2014, Cichowicz, et al. 2016). The function $I_s$ in equation [6] is not only influenced by the number of repetitions of each dynamic simulation, but also by the exposure time in the wave environment; thus, by the maximum simulation time $t_{max}$ used for the simulations. Here, simulations have been carried out setting $t_{max}$ to 30 minutes as it is usual for probabilistic assessment of passenger ship survivability (Vassalos, et al. 2021) and intrinsic in the SOLAS survivability definition (IMO,2019). An example of the scatter diagram approach application is given in Figure 3, where the process of determining the $s_{ij}$ is clearly visible from the roll motion $\phi$ time traces of multiple simulations at different environmental conditions.

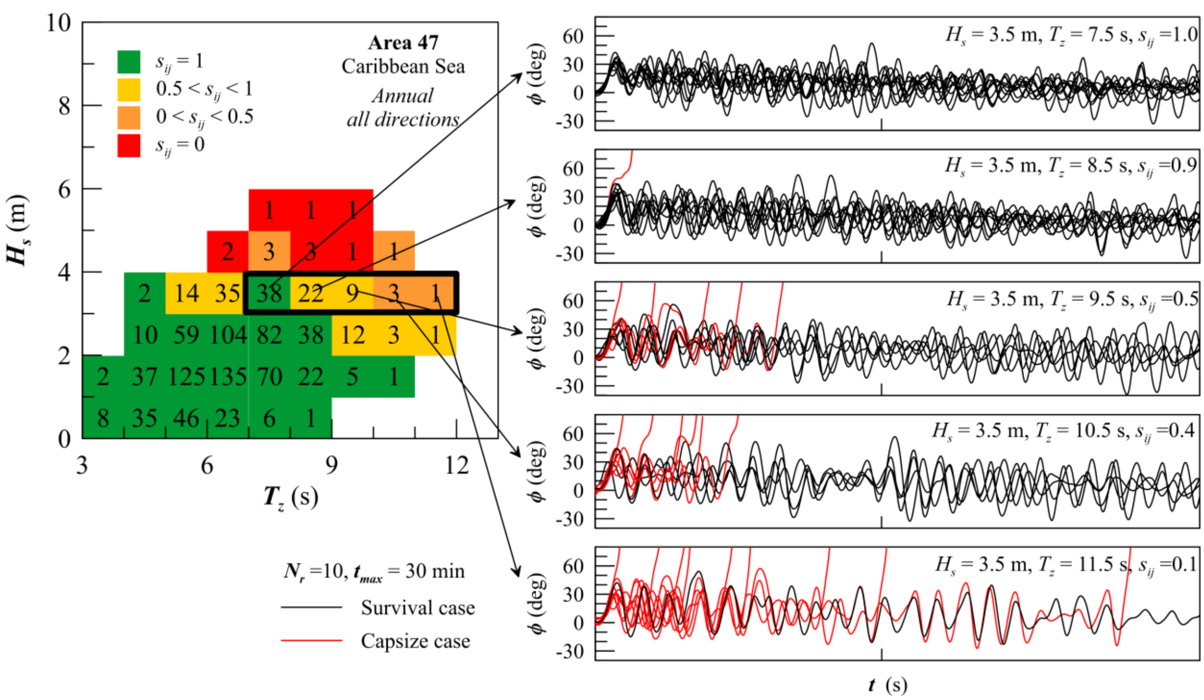


**Figure 3 : Example of scatter diagram approach with $s_{ij}$ determination on $N_r$ repeated simulations**

## APPLICATION ON A SMALL CRUISE SHIP

In the present study, use has been made of one of the sample ships available within the FLARE project (Luhmann, 2019b). This specific vessel is a small cruise ship with a total capacity of 478 persons on-board. The main characteristics of the vessel are listed in Table 1 and an overview of the profile is given in Figure 4. The vessel is compliant with SOLAS 2020 probabilistic damage and has been modelled for dynamic simulations, considering 271 compartments and 227 internal connections.

**Table 1 : Sample cruise ship main particulars**

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Length over all | 128 m | Calculation KG | 9.584 m |
| Length between perpendiculars | 113.7 m | Number of passengers | 323 |
| Subdivision length | 125.8 m | Number of crew | 155 |
| Breadth | 20.0 m | Deadweight | 1250 t |
| Calculation draught | 5.1 m | Calculation displacement | 8404 t |

**Figure 4 : Profile view of the sample cruise ship**

### Sea Areas of interest

With the selected vessel being a small cruise-ship, it is worthy to consider as reference sea areas for the analysis of critical cases areas of the world that are of typical interest for cruises. Trying to have a more general environment suitable and significant for a wide set of cruise ships, avoiding extreme and particular operational areas that could be operated by dedicated ships only (e.g. Artic or Antarctic areas), the following areas have been chosen: the Caribbean Sea (Area 47 for the Global Wave Statistics), the Western Mediterranean (Area 26) and the Baltic Sea (Area 5).

Figure 5 shows the scatter diagrams of the three mentioned areas. It is possible to observe the different nature of the three sea areas; Area 47 is characterised by waves not exceeding $H_s$ of 6 metres, but the wave periods could be up to 12 seconds, with higher density in the range between 6 and 8 seconds. Area 5 has the same limits for $H_s$, but the wave periods are quite different, with higher density between 4 and 6 seconds and not exceeding 10 s. Area 27 has $H_s$ limits up to 8 meters, but periods limitations are comparable to Area 5.

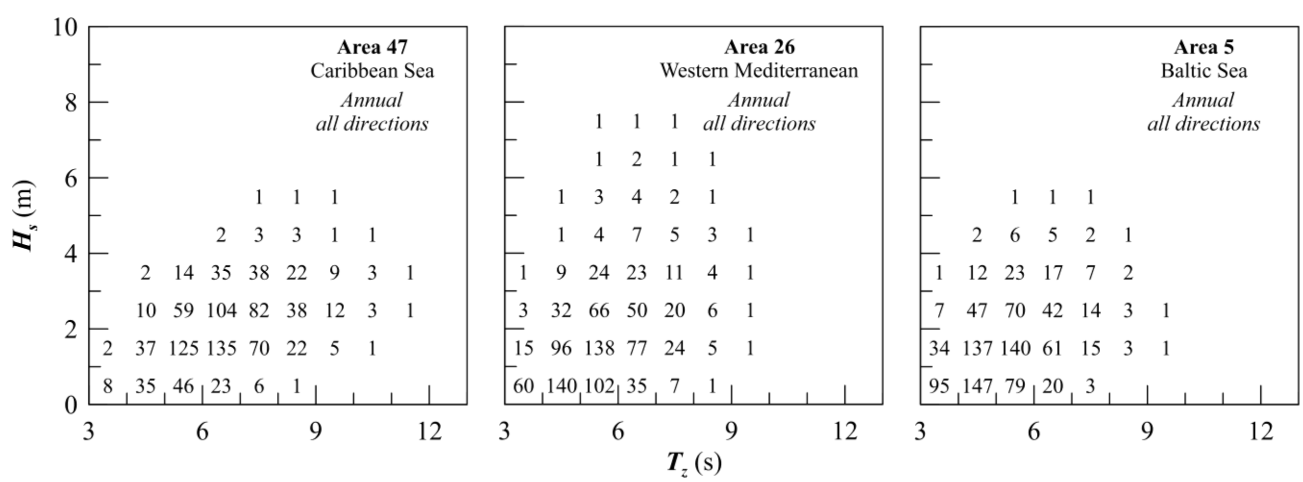


**Figure 5 : Sea areas of interest for the analysed cruise ship**

## Selected Damage Cases

To visualise the effect of evaluating survivability with a scatter diagram approach, thus considering the combination of different couples of $H_s$ and $T_z$, a set of cases derived from conventional survivability analysis has been selected. To determine the cases to be analysed with the scatter diagram approach, a hybrid method has been used, combining static and dynamic simulations in calm water, allowing the detection of potential capsize cases in irregular waves.
The reference ship was assessed through static survivability calculations for 10,000 collisions and 10,000 side-groundings, filtering critical cases according to factor *p(1-s)* (Karolius at al., 2018), where *p* is the probability associated with the occurrence of a damage and *s* is the survivability to the damage determined by SOLAS (IMO, 2019). Critical cases have been filtered considering a threshold of 4E-4. The resulting subset has been analysed through 3 hours long dynamic simulations in calm water, identifying potentially critical cases according to dynamic survivability criteria (Mauro, et al. 2021a). Therefore, besides true capsizes, the following criteria can be applied:

- *SOLAS heeling failure*: final average heel above 15 degrees.
- *ITTC maximum heeling*: maximum heeling above 30 degrees.
- *ITTC average roll*: cases where 3 minutes' average roll exceeds 20 degrees.
- *Large average floodwater mass rate*: cases where the flooding process is still significantly progressing after the end of simulation time $t_{max}$.

For the reference cruise ship, a set of 228 collisions and 262 side groundings has been filtered from static calculations and further analysed with dynamic analyses in calm water. After the execution of the 3 h dynamic analyses, the results allow to identify 113 collision scenarios and 107 side groundings that may lead to capsize in waves. From this subset, 2 collisions and 2 side groundings have been selected to show the application of the scatter diagram approach. The selected cases represent damages not satisfying 1 or 2 criteria presented in the previous list, and are the cases that have a higher *p* value in the subset. Table 2 reports the damage characteristics of the presented cases, where *x* denotes the centre of the damage for collisions and the forward end of the damage for side groundings.
All the dynamic calculations have been performed with the PROTEUS3 software (Jasionowski, 2001).

**Table 2 : Selected damages characteristics**

| DAM ID | Type | $x$ (m) | $L_x$ (m) | $L_y$ (m) | $L_z$ (m) | Criteria |
|---|---|---|---|---|---|---|
| C00-1 | Collision C00 | 35.45 | 20.51 | 1.94 | 4.19 | 1 |
| C00-2 | Collision C00 | 64.29 | 12.05 | 6.83 | 8.71 | 2 |
| S00-1 | Side-grounding S00 | 82.05 | 21.82 | 0.24 | 4.87 | 1 |
| S00-2 | Side grounding S00 | 51.13 | 25.82 | 0.57 | 2.96 | 2 |

### *Collisions (C00 type damages)*

The scatter diagram calculation for the collision cases is reported in Figure 6 for damage C00-1 and in Figure 7 for damage C00-2. The calculations have been performed for the three-selected sea areas, having an immediate impact of the resulting survivability levels. Analysing C00-1, it can be observed that the damage case can be considered safe up to a $H_s$ of 2 metres, across all the $T_z$ range. At 3 m of $H_s$, capsizes start to be observed for $T_z$ higher than 9 seconds; for $H_s$ 4 m the capsizes starts from $T_z$ higher than 6 seconds and substantially increasing $H_s$, the critical $T_z$ value decreases. As the different sea areas have different occurrence for the sea states, the final calculated $s_A$ results are different, ranging from 0.88 in Area 47 to 0.97 in Area 5.
The same considerations can be drawn for damage case C00-2, where the survivability is lower as the damage is more severe than C00-1, but the trend between $H_s$ and $T_z$ remains comparable with the previous case, shifting down the critical values. For case C00-2 the final $s_A$ values are ranging between 0.72 in Area 47 and 0.89 in Area 5, confirming that in all the sea areas the damage is more severe than C00-1, as it could have been expected with damage C00-2 not satisfying 2 criteria instead of 1.

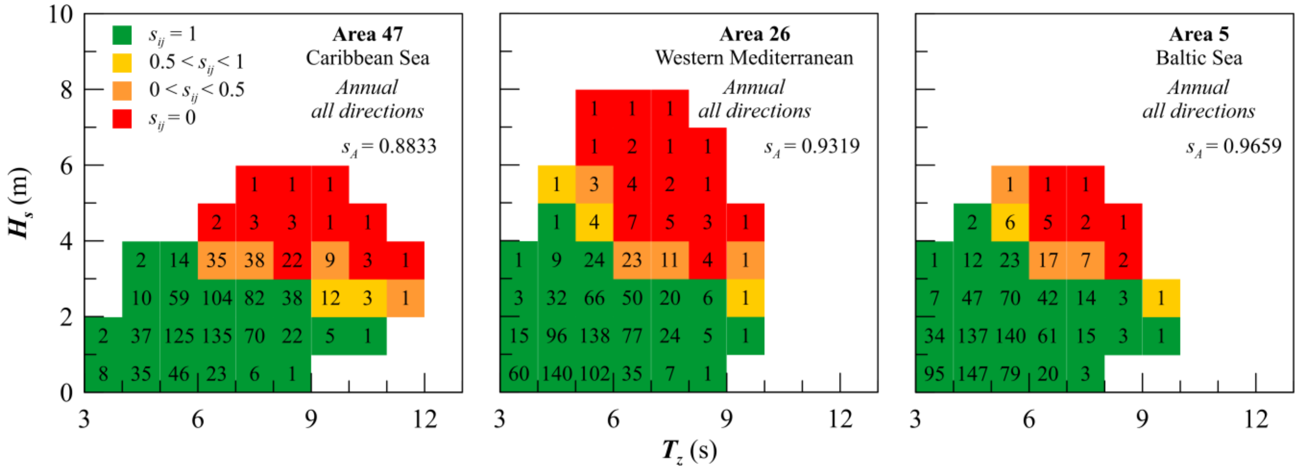


**Figure 6 : C00-1 damage case survivability in the three selected sea areas**

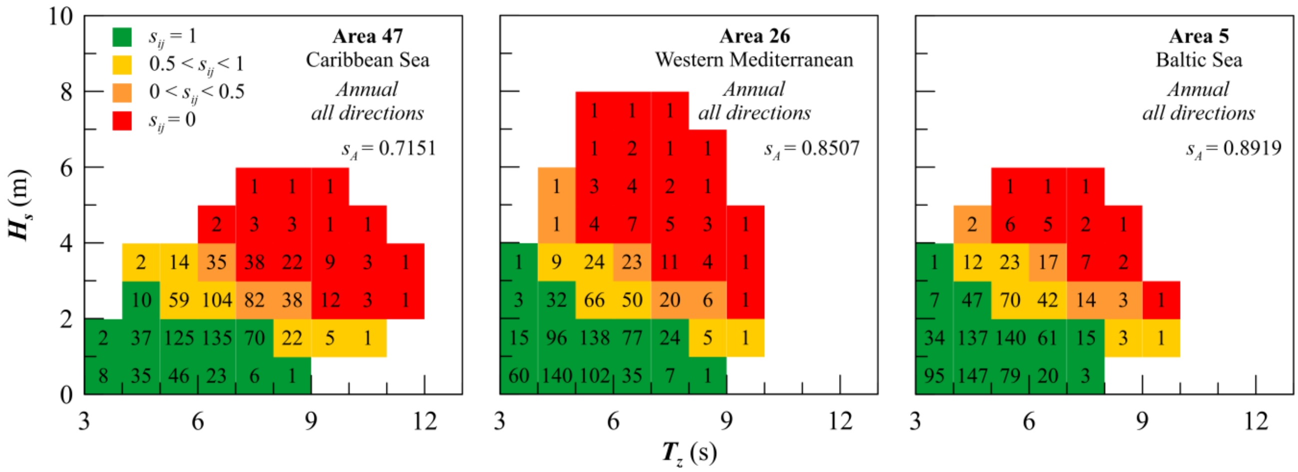


**Figure 7 : C00-2 damage case survivability in the three selected sea areas**

***Side groundings (S00 type damages)***

The same analysis for collision damages has been carried out for side grounding cases. Figure 8 shows the survivability of case S00-1 in the three-selected areas. It appears immediately that this damage case is not particularly critical as it results in full capsize cases only for waves higher than 6 meters with associated periods around 8 seconds. Such conditions are present only in Area 26 between the analysed zones. For the other wave combinations, the capsize rate is quite low, resulting in $s_A$ ranging from 0.95 in Area 47 to 0.99 in Area 5. In this particular case, there is not a clear distinction between the safe zone and the beginning of the capsize band. This is probably due to the low capsize rate of certain cases, something that is difficult to capture with only 10 repetitions.

Figure 9 reports the results for case S00-2. In this case, the transition between the full capsize area and the safe one is more evident. Also in this case, it can be observed that the capsize rate increases by increasing both $H_s$ and $T_z$. For S00-2, the final $s_A$ is ranging from 0.72 in Area 47 and 0.91 in Area 5. For this damage, there is a change of about 20% in survivability considering two different areas, mainly due to the different occurrences of the critical combinations of $H_s$ and $T_z$.

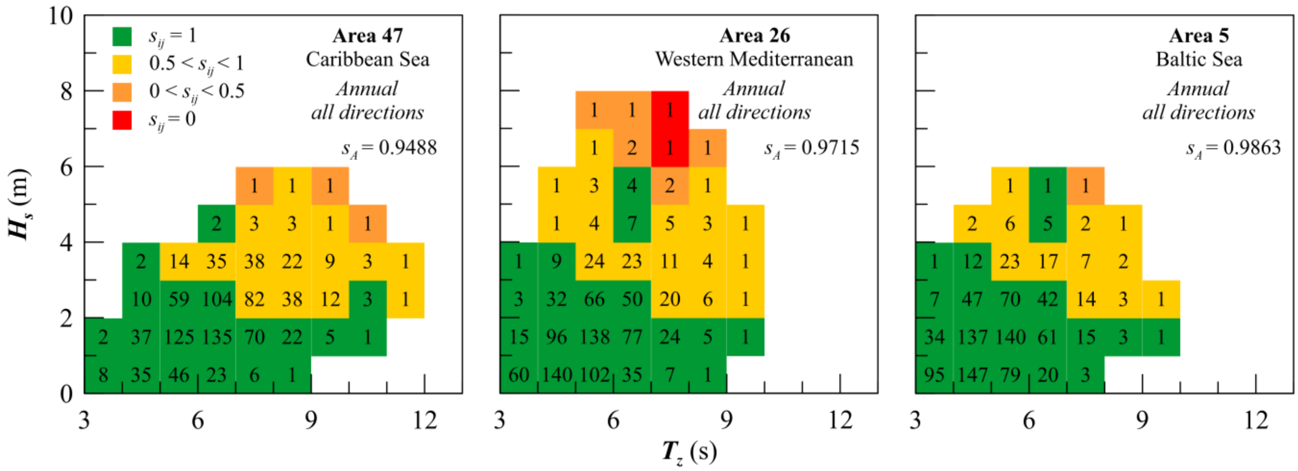


**Figure 8 : S00-1 damage case survivability in the three selected sea areas**

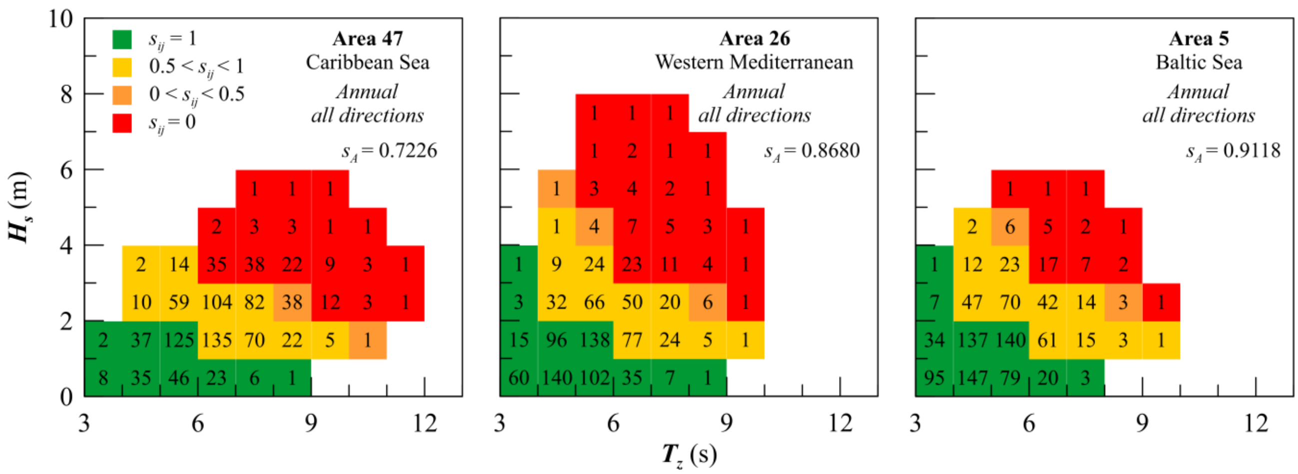


**Figure 9 : S00-2 damage case survivability in the three selected sea areas**

## Concluding remarks

The presented results for the four sample cases show a global overview of the scatter diagram approach for the four presented damage cases. A summary of the obtained values for the survivability is given in Table 3, highlighting the substantial differences that may appear by considering different operational areas for the same ship.

**Table 3 : Survivability results for the four damage cases in the three sea areas**

| DAM ID | Area 47 | Area 26 | Area 5 |
|---|---|---|---|
| C00-1 | 0.8833 | 0.9319 | 0.9659 |
| C00-2 | 0.7151 | 0.8507 | 0.8919 |
| S00-1 | 0.9488 | 0.9715 | 0.9816 |
| S00-2 | 0.7226 | 0.8680 | 0.9118 |

The presented analysis is just a first approach to the analysis of survivability in the real operational environment. In the present work, only the survivability of specific damage cases is reported, using damage cases coming from conventional non-zonal damage stability framework. The method allows to also evaluate additional parameters of interest for survivability as the time to capsize or detailed information on the flooding path inside the ship, allowing to study the variation of such parameters with the sea state. Moreover, with the process being independent from the generated damage cases, it could be also applied with damage definitions resulting from direct calculations.

The general conclusion that can be drawn from the presented results is that the variations of $T_z$ are influencing the local survivability results keeping $H_s$ constant. This is extremely important to underline, as most of the sea state of the sea areas of interest have different $T_z$ values compared to the standard periods used by standard approaches (see Figure 1). Furthermore,

besides being unrealistic, these $T_z$ values result in unfavourable conditions compared to the scatter diagram ones and are not weighted for the respective occurrences. The influence of $T_z$ affect the survivability values among the different sea areas. In fact, areas like Area 47 characterised by waves with longer periods has always the lower survivability value, also compared to Area 26 having higher waves. Therefore, for the selected test case, longer waves are more critical for survivability compared to shorter ones.
The adoption of a scatter diagram approach increases the number of calculations to be performed for a single damage case, as each damage should be simulated 10 times per each cell of the scatter diagram to obtain a global survivability for the whole ship. The complete simulation on a scatter diagram takes on average 4 hours to be executed on a workstation, parallelising the computation in 10 processes. Therefore, without having sufficient computational power at disposal, the scatter diagram approach is more appropriate for the dedicated analysis of selected critical cases, as it has been presented in the previous section. However, with the calculation framework being flexible, the process can be integrated inside a Monte Carlo assessment of damage stability, sampling also $T_z$ besides $H_s$, with an appropriate joint probability distribution reflecting the operational scenarios of interest. Another possibility could be the filtering of the most probable combination of $H_s$ and $T_z$. considering areas of operations and operational limitations of the vessel, resulting in a subset of sea state combined from different scatter diagrams. This approach has been already applied for combined comfort and station keeping analyses for a large yacht (Mauro, et al. 2021b) and could be helpful to analyse only realistic sea states for cruise vessels during operations.
As a final consideration, the present study stresses the importance of improving the prediction methods to be adopted in the survivability prediction of a passenger vessel, giving more importance to first principle models, instead of the adoption of empirical or statistical methods.

## CONCLUSIONS

A scatter diagram approach has been presented to assess area-specific survivability for passenger ships. The method allows to consider all the possible combinations between $H_s$ and $T_z$ present in a sea area, using wave occurrences from scatter diagrams as Global Wave Statistics, but potentially applicable also to local area measurements. This implies the possibility to determine area specific survivability factors for specific potentially critical damage cases, highlighting how the same damage case could lead to different probability of survival according to the preferred operational area, determining if that damage is effectively critical or not for specific vessel operation. The newly developed method has been here applied on conventional damage types derived from the non-zonal damage stability framework. However, the method itself is fully independent from the damage definition, and can be therefore applied also to site-specific damage statistics or to damage distribution derived from direct calculations. Furthermore, with $T_z$ impacting the survivability of the vessel as well as $H_s$, it could be possible as future development, to further develop the scatter diagram approach, providing a site-specific joint probability distribution for direct application in a Monte Carlo process.
The execution of a tailored analysis in different sea areas increases the computational time compared to conventional damage stability analysis; however, the possibility of executing calculations in specific operational conditions, potentially using also damage distributions specific for the operational area, is a further step forward towards the application of a full direct method for damage stability in passenger ship design.

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