Ocean Engineering 342 (2025) 122830

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Research paper

The impact of risk control options in reducing/preventing risk in case of a flooding event

Francesco Mauro [a,*], Donald Paterson [b], Dracos Vassalos [c]

[a] University of Trieste, Trieste, Italy
[b] Sharjah Maritime Academy, Khorfakkan Sharjah, 180018, UAE
[c] University of Strathclyde, Glasgow, Scotland, UK

ARTICLE INFO

Keywords:
Risk-assessment
Passenger ships
Risk control options
Crashworthiness
Risk prevention

ABSTRACT

Safety in case of a flooding event is a primary concern in the design process of passenger ships and should be thoroughly assessed from the initial design phases. To evaluate the risk of flooding events, an effective metric is needed to compare various design solutions. The Potential Loss of Lives (PLL) is a valuable tool for quantifying this risk from the early stages of design, enabled by a multi-level framework developed during the FLARE project, which enhances the reliability of predictions as the design progresses. This approach facilitates the examination and assessment of countermeasures, known as Risk Control Options, aimed at reducing or preventing risk in the event of flooding. This study analyses the implementation of different Risk Control Options across a sample of nine passenger ships, including cruise and Ro-Pax vessels. The analysis is conducted at various levels of fidelity in accordance with the established framework, highlighting the effectiveness of mitigation and prevention measures in reducing PLL.

1. Introduction

Flooding is a major threat to the safety and operability of ships, and it remains one of the leading causes of maritime casualties worldwide (Mujeeb-Ahmed et al., 2021). The consequences of internal flooding, from hull breaches, structural damage, or failures in watertight integrity, can rapidly compromise a vessel's stability and buoyancy, leading to capsizing or sinking (Vassalos, 2016). As modern ship design trends push toward greater size, complexity, and automation, rigorous flooding risk assessment has become a fundamental component of maritime safety engineering and regulatory compliance (Vassalos and Paterson, 2021).

Flooding risk assessment for ships involves evaluating the likelihood and consequences (Aven, 2012, 2022) of water ingress under various damage scenarios, such as collisions, groundings, and side contacts (Bulian et al., 2019a). This includes both deterministic and probabilistic methods, which analyze parameters such as damage location, extent, ship geometry, and the time-dependent progression of flooding (Vassalos, 2020).

The recent developments of project FLARE (FLARE, 2022) focuses on the possibility to asses the risk with multiple levels of fidelity (Vassalos et al., 2022c), allowing designers to use both simplified or advanced methods for the flooding risk determination (Mauro et al., 2023b). In this sense, besides the concept of flooding risk, the concept of risk mitigation has been introduced, providing solutions to reduce the risk levels onboard vessels (Cardinale et al., 2022). These solutions are called risk control options (RCOs) and could be active or passive devices. The most valuable solutions are the implementation of foam installations (Vassalos et al., 2022b), the adoption of crashworthy reinforcements (Naar et al., 2002; Paik, 2020) or changes to the internal layout and protection of openings of the ship.

During project FLARE, a set of 9 passenger ships has been selected for testing the developments achieved in the running project (Luhmann et al., 2022), resulting in the possibility of testing the impact of the RCOs directly by the implementation of designers in their sample projects. Such a possibility allows for comparing the effect of RCOs at different levels of accuracy, thanks to the multiple level flooding risk assessment framework developed during the project. All the selected RCOs have been assessed with the lower level of fidelity tools (Level 1), which means employing static solvers for damage stability. Some of the devices have been also tested with more advanced tools for damage stability (Level 2.1), allowing for a comparison of the risk level obtained by employing different fidelity methods. Unfortunately, none of the design teams implemented all the possible RCOs not allowing for determining a ranking among the risk mitigation measures; however, the indication provided by the study suggests the suitability of RCOs in reducing risk,

* Corresponding author.
E-mail addresses: fmauro@units.it (F. Mauro), Donald.Paterson@sma.ac.ae (D. Paterson), d.vassalos@strath.ac.uk (D. Vassalos).

https://doi.org/10.1016/j.oceaneng.2025.122830
Received 2 July 2025; Received in revised form 25 August 2025; Accepted 10 September 2025
Available online 21 September 2025

especially after a detailed and correct analysis of preliminary calculations.

The present work gives a detailed analysis of the positive effects in reducing the risk of flooding provided by the application of risk control options. The study highlights the differences achieved by various design teams in applying RCOs according to their design strategies and interpretations of flooding risk reduction strategies. To present the main achievements and findings, the paper has the following structure:

- Section 2 presents the multi-level risk assessment framework developed during project FLARE.
- Section 3 describes the different kinds of RCOs employed in the present study.
- Section 4 presents the database of ships considered for the analysis.
- Section 5 describes the implementation of RCOs according to designers expertise and constraints.
- Section 6 presents the results of the multy-level risk assessment.
- Section 7 summarises the main findings of the study and gives some hints for future developments.

Following the above-mentioned structure, the paper demonstrates the effectiveness of different RCOs in mitigating and preventing the risk of flooding onboard passenger ships. With the RCOs selection and implementation driven by different design teams with different design strategies and philosophies, the obtained results indicate that the trend for future passenger ship designs should include an extensive range of RCOs to reduce and prevent the risk of flooding. The present work gives the first example in the literature of the application of RCOs to the flooding risk reduction of passenger ships, providing a framework to be followed for RCOs implementation and evaluation. Furthermore, the paper stresses the differences achievable by different interpretations of the working principles of RCOs.

2. Risk assessment multi-level framework for the vessel life-cycle

Safety assessment in the case of flooding is a recursive process in the life-cycle of passenger ships. Therefore a framework for flooding risk assessment needs the iterative execution of the following steps:

- Definition of ship loading conditions and calculation scenarios.
- Flooding risk evaluation on the selected scenarios.
- Identification of flooding risk mitigation or prevention measures.
- Implementation of the countermeasures (i.e. Risk Control Options).
- Reassessment of flooding risk.

These steps could be performed either in designing a new unit, retrofitting an existing one or changing a vessel operational profile.

The risk can be measured through the Potential Loss of Lives (PLL), a metric which follows the conventional general definition of risk:

$$PLL = p_f c_f \tag{1}$$

where p_f is the probability of a flooding event and c_f is its consequence. To assess the risk of flooding through the vessel life-cycle it is necessary to determine an attained index PLL_A and compare it with a tolerable level of risk. It could be convenient to evaluate the PLL_A per years of service PLL_A^*, providing a more flexible tool for the assessment of multiple operational profiles. Then, the PLL_A^* for each operational scenario can be assessed with a formulation structured as Eq. (1) but having a more detailed description of p_f and c_f:

$$PLL_A^* = \sum_{i=1}^{N_{hz}} \sum_{j=1}^{N_{op}} \sum_{k=1}^{N_{ld}} \sum_{h=1}^{N_c} p_{f_{i,j,k,h}} c_{f_{i,j,k,h}} \tag{2}$$

where N_{hz} is the number of hazards, N_{op} is the number of operational areas, N_{ld} is the number of loading conditions and N_c is the number of flooding cases. The probabilities and consequences of Eq. (2) are defined as:

$$p_{f_{i,j,k,h}} = p_{hz_i} p_{op_j} p_{ld_k} p_{c_h} = p_{hz_i} p_{op_j} p_{ld_k} p^*_{c_h} \left(1 - s_{c_h}\right) \tag{3}$$

$$c_{f_{i,j,k,h}} = FR_{i,j,k,h} POB_{i,j,k,h} \tag{4}$$

According to the flooding risk assessment framework developed during project FLARE (2022), the number of hazards N_{hz} is equal to three, comprehending to three different damage types: collisions, bottom and side groundings. The number of operational areas N_{op} is also three, considering to operation in open seas, in restricted or in port areas. Two loading conditions are considered ($N_{ld} = 2$), corresponding to $T_1 = T_l + 0.75\left(T_s - T_l\right)$ and $T_2 = T_l + 0.45\left(T_s - T_l\right)$, with T_s and T_l the deepest and light subdivision draughts as defined by SOLAS (IMO, 2020). The adoption of two draughts has been promoted by designers after the execution of preliminary studies in the early developments of Project FLARE (Paterson et al., 2019). The number of cases N_c is set to 10,000 for each hazard and loading condition, which means a total of 180,000 flooding cases. The selection of 10,000 cases as significant for a hazard at one loading condition is a compromise between effective convergence study (Bulian et al., 2016; Mauro and Vassalos, 2022; Mauro et al., 2022a) and designers necessities (Mauro et al., 2023b). For the generation of damage cases, use is made of a non-zonal approach (Bulian et al., 2016; Mauro and Vassalos, 2022). The first three probabilities defined by Eq. (3) result from damage database analysis, specific for passenger ships (Mujeeb-Ahmed et al., 2021; Mujeeb-Ahmed and Vassalos, 2022). The damage case probability p_{c_h} can be found by employing the common definition of p and s-factors (Pawlowski, 2004; IMO, 2009; Vassalos et al., 2022a). Eq. (4) describes the consequences of a flooding accident. In this case, the consequence is modeled as the product between the fatality rate FR and the number of people onboard POB. As all the quantities appearing in Eqs. (3) and (4) change scenario by scenario, the risk assessment process requires a global number of cases equal to $N = N_{hz} N_{op} N_{ld} N_c$, each one to be assessed with survivability and evacuation analyses.

As a result, the total number of calculations is considerably high, requiring a great deal of computational effort, specially once the assessment is to be performed by means of first-principles tools (Mauro and Vassalos, 2024a). However, the adoption of a multi-level framework can consistently reduce the computational load, employing different computational tools according to the level of fidelity and accuracy needed by different phases of the vessel life-cycle. This is of utmost importance for the framework applicability, especially during the design phase (Mauro et al., 2023b).

2.1. Multi-level framework

During the EU funded project FLARE, several frameworks have been studied, developed and applied. Initially considering survivability only, and, afterwards, extending the developed concepts to risk. These frameworks connected for the first time the practical needs of designers with the research-oriented approach of the academy, providing a suitable compromise between calculation time and robustness (Mauro et al., 2023b). In fact, the global characterisation of flooding risk through a complete set of first-principles direct calculation is not practicable due to the excessive amount of computational time, which is not in line with the timing of the design process. Therefore, a multi-level approach has been hypothesised with consequent multi-fidelity results, but still significantly improving the in-force regulatory frameworks for damage stability of passenger ships.

The multi-fidelity framework acts on the determination of the parameters associated to the flooding and evacuation processes, meaning on the parameters composing the following formulation of PLL_A^* for a single scenario:

$$PLL^*_{A_{i,j,k,h}} = p^*_{i,j,k,h}\left(1 - s_{i,j,k,h}\right) c_{f_{i,j,k,h}} \tag{5}$$

According to Eq. (5), p^* indicates the weight and the probability of occurrence of a flooding scenario, while s determines the survivability to the flooding event. c_f is the consequence described as in Eq. (4). The probability p^* is determined during the input preparation phase of the survivability assessment, which, according to the multi-level framework starts at a Level 1. Level 1 or Level 2 survivability assessments determines s through different simplification for damage stability calculations. The same applies for the evacuation analyses needed to asses consequences c_f (i.e the fatality rate FR). Going deeper into details, the multi-level framework considers the following levels:

- *PLL Level 1*: this first level is totally based on static damage stability calculations, evaluating p-factors according to the non-zonal approach and s-factors according to SOLAS indications. As the number of fatalities is strictly related to the time it takes the vessel to capsize, the determination of FR needs an approximation because static calculations does not give any information on the time to capsize (TTC). More specifically, the following extremely simplified formulation is given:

$$FR = \begin{cases} 0.8 & \text{if } s < 1 \\ 0.0 & \text{if } s = 1 \end{cases} \tag{6}$$

  This simplified and conservative approach is derived from the method used in the EMSA III Project (EMSA, 2020), the results of which were used to support political decisions at IMO, leading eventually to SOLAS 2020 regulations for damage stability.
- *PLL Level 2*: compared to Level 1, a Level 2 prediction is based on direct dynamic simulations for damage survivability. Thus, it is possible to evaluate TTC and directly compare it with the time to evacuate (TTE) the ship. TTC is an output of a dynamic analysis, that according to the framework should be carried out with validated rigid-body time domain simulations (Ruponen et al., 2022b,a), giving the best compromise between calculation time and reliability of given results. TTE results from time-domain evacuation analyses. However, the multi-level framework allows for considering two sub-levels of accuracy for the TTE, leading to:
  - *PLL Level 2.1*: this sub-level of approximation considers only time-domain simulations for the TTC evaluation. More specifically, the time to capsize is evaluated from the roll angle time-series, considering a threshold of 50 degrees. TTE is estimated without the need of performing direct evacuation analyses, making reference to the following empirical formulation for the fatality rate FR:

$$FR = \begin{cases} 0.0 & \text{if } TTC > n \\ 0.8\left(1 - \frac{TTC-n}{30-n}\right) & \text{if } 30 \le TTC \le n \\ 0.8 & \text{if } TTC < 30 \end{cases} \tag{7}$$

    where n is the maximum allowable evacuation time in minutes according to MSC.1/Circ. 1533. Eq. (7) requires that TTC is expressed in minutes. The simplified formulation given for the FR intrinsically considers the nature of the capsize detected with dynamic simulations, assuming that is impossible to evacuate the ship in case of a rapid transient capsize.
  - *PLL Level 2.2*: this level represents the highest level of accuracy for the FLARE framework. Here, also the direct calculation of TTE is considered by employing direct time-domain evacuation simulations. In the analysis, the flooding simulation results of the selected case can be imposed to the evacuation solver, allowing to consider the ship motions and the flooding path in the evacuation analysis. To reduce computational effort, such simulations are not performed on all the scenarios but only for the critical cases identified by the dynamic survivability calculations. The reliability of evacuation analysis is increased by the opportunity to consider motions and flooding path imported from the dynamic flooding simulations. In this case, FR (or 1-FR) can be determined by the direct comparison between the TTC and the evacuation path (see Fig. 1).

The paper provided by Vassalos et al. (2022c) gives the full details, justifications and applied examples for the FLARE multi-level risk assessment framework; therefore, these are omitted here for the sake of brevity. The definition of the individual probabilities and values associated with occurrences, survivability and fatality changes not only according to the scenario or with the selected level of approximation according to the multi-level framework but also with the phase of the vessel operational life. The following section describes the specific case of the design phase, which is the focus of the present work.

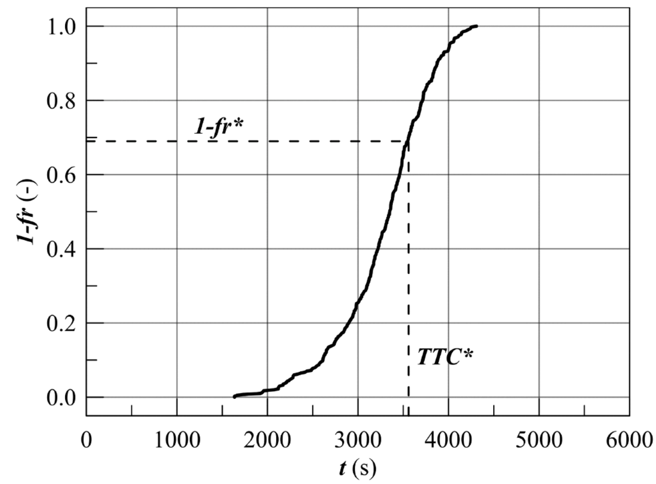


Fig. 1. Fatality rate determination for a critical flooding case according to a Level 2.2 prediction.

2.2. Design phase framework

A risk framework for flooding risk assessment in the design phase should be capable of defining all the inputs and parameters needed for the estimation of PLL^*_A according to Eq. (2), employing the information available in this specific stage of the vessel life-cycle. Furthermore, at the design stage, the framework should be compliant with the in force regulations on damage stability, providing outputs relevant to the statutory damage stability framework. Then, all the definitions and selections on frequencies and probability associated with occurrence, survivability and fatality rate of a scenario should be properly revised, having an impact on the generation of cases to be analysed. The main focal points can be summarised as follows:

- *Hazards definition*: the framework handles three types of casualities ($N_{hz} = 3$): collisions, bottom and side groundings. The framework adopts specific frequencies of occurrence p_{hz} that are interchangeable with the relative weights w necessary to define the attained subdivision index A in the statutory damage stability framework. Such p_{hz} values, global or specific for vessel type, derive from database of accidents analysis and are reported in Vassalos et al. (2022a), together with the corresponding w values.
- *Operational areas*: during the design phase only the open sea condition is considered ($N_{op} = 1$), restricting the survivability calculations to a significant wave height H_s of 4 metres. This assumption is essential to take into account while assessing Level 1 or Level 2 risks.
- *Loading conditions*: as already mentioned above, the framework considers two draughts T_1 and T_2 with equivalent weight on the final assessment. Such an assumption is maintained across the different levels, not following the SOLAS indications based on three draughts. The selection of two draughts has been promoted by designers during the studies performed in project FLARE (Vassalos et al., 2022c).
- *Calculation scenarios*: according to the FLARE risk assessment framework, the number of calculation conditions changes with the chosen level. In case of a Level 1 prediction, a starting number of 10,000 breaches is generated for each one of the possible hazards. The generation implies the determination of damage location and dimensions through the sampling from relevant cumulative distributions

(Bulian et al., 2019a). In case a Level 2 is selected, the initial number of conditions is lowered to 1000 to reduce the computational effort as the dynamic flooding simulations require more computational time. In any case, the damage distributions employed for Level 1 and Level 2 assessments remains the same and are an updated version of the ones described in SOLAS for collisions (Bulian et al., 2019b) and in EMSA III project for bottom and side groundings (Bulian et al., 2020).

To take into consideration the above assumptions in the estimation of risk, the formulation of PLL_A^* of Eq. (2) should be rewritten in the following forms for Level 1 and Level 2 assessment, respectively:

$$PLL^*_{A_{Level1}} = \sum_{i=1}^{3}\sum_{k=1}^{2}\sum_{h=1}^{N_c^*} p_{hz_i} p_{ld_k} p^*_{c_h} \left(1 - s_h^*\right) FR_{i,k,h} POB_{i,k,h} \tag{8}$$

$$PLL^*_{A_{Level2}} = \sum_{i=1}^{3}\sum_{k=1}^{2}\sum_{h=1}^{1{,}000} p_{hz_i} p_{ld_k} \frac{1}{1000} \left(1 - s_h^*\right) FR_{i,k,h} POB_{i,k,h} \tag{9}$$

Eqs. (8) and (9) differ mainly for the definition of case probability p_c^* and for the total amount of cases N_c^* to be analysed. The breaches generation follows a non-zonal approach (Bulian et al., 2016; Mauro and Vassalos, 2022) either in the case of Level 1 or Level 2 assessment. More specifically, the framework suggests the employment of an enhanced sampling method based on a Randomised Quasi-Monte Carlo technique (Mauro and Vassalos, 2022). However, while selecting a Level 1 assessment based on static calculations it is not necessary to consider multiple times damages that penetrate the same internal compartment. In such a case, it is convenient to group them, leading to a final amount of cases $N_c^* < 10{,}000$, strictly depending on the internal layout of the considered ship. This grouping process led to the definition of probabilities associated with the group of damages, which defines the scenario probability p_c^*. Conversely, while using a dynamic approach for survivability assessment (Level 2), the grouping becomes impossible because the breach dimensions influence the amount of water that could ingress/regress the ship at each time step. Then, for Level 2 calculations, all the damages are equiprobable; thus, considering 1000 damages, the p_c^* is equal to $\frac{1}{1000}$ (Mauro et al., 2023b).

A Level 2 assessment allows also to adopt an hybrid approach (Mauro et al., 2022a), filtering breach cases to be assessed with dynamic analyses (Mauro et al., 2022b). However, the hybrid process accepted by designers involved in project FLARE, accounts for an empirical filtering of data, choosing the breach with the wider opening area as the representative of all the damages harming the same compartments (Mauro et al., 2023b). Regardless, FLARE's recommendations and advancements are meant to standardise the use of dynamic analyses in the damage stability evaluation of passenger ships, opting for a Level 2 flooding risk assessment or an hybrid approach as shown in Fig. 2. For the determination of survivability s_h^*, the Level 2 approach considers the result of the time-domain simulation, in case the vessel survives it is equal to 1, 0 otherwise. This is valid in the simplified approach of the framework, where only one time-domain simulation is considered for each damage case. (Mauro et al., 2023b) A more detailed and thorough estimation of s_h^* requires more calculations, as exhaustively described in Mauro and Vassalos (2024b).

For the consequences evaluation, and FR in particular, preliminary calculations performed during the FLARE project detect small differences between a Level 2.1 and a Level 2.2 assessment (Vassalos et al., 2022c). During project FLARE, the application of Level 2.2 design phase framework on one cruise ship and one Ro-Pax vessel highlights a substantial equivalency of the final PLL_A^* assessed with the case of a Level 2.1 prediction; thus, assessing FR with a not sophisticated method according to Eq. (7).

However, it is of utmost importance to encourage the application of first principle tools for increasing the reliability of the results since the

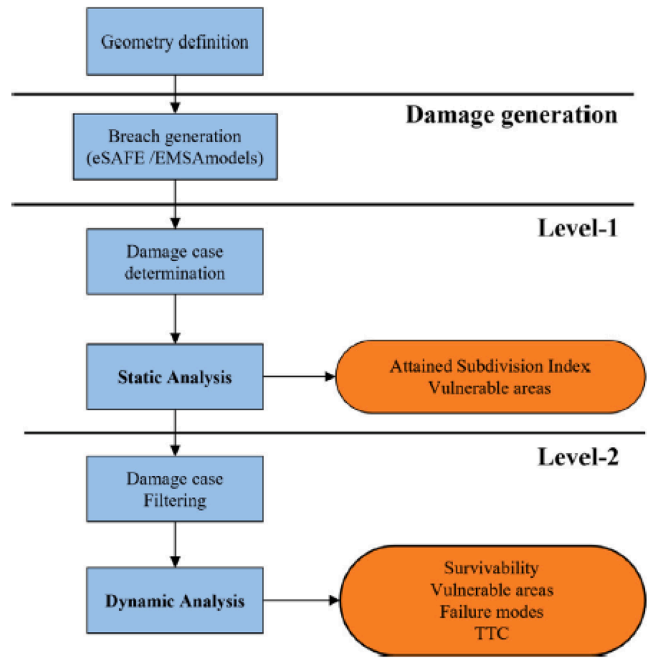


Fig. 2. Flowchart of a multi-level hybrid damage stability framework.

first stages of a design, promoting their application for the generation of breaches, the flooding simulations and the evacuation analyses.

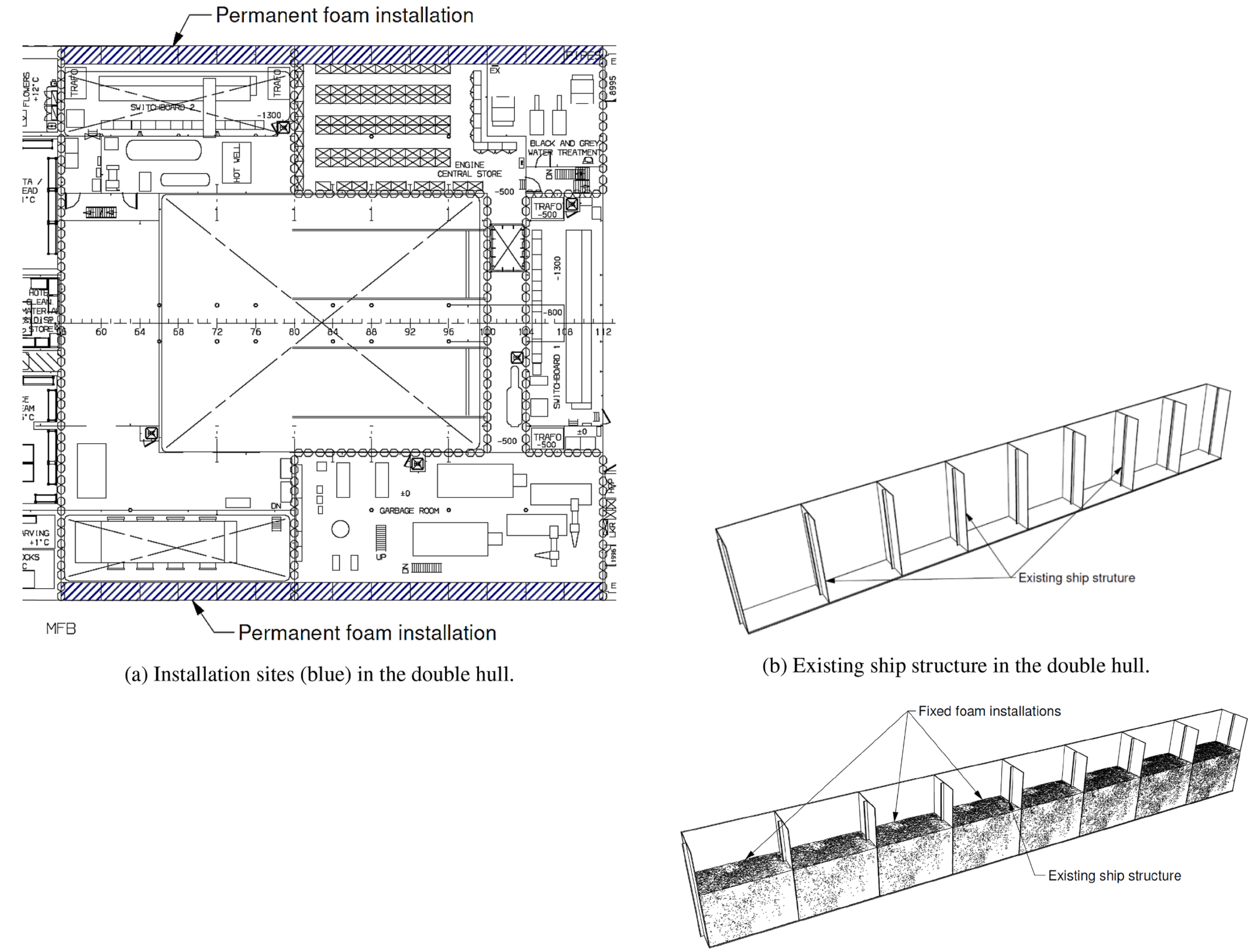
Notwithstanding the above, the FLARE framework for flooding risk assessment during the design phase is still a powerful design tool to assess the risk level of a passenger ship. Moreover, the capillary definition of inputs and calculation conditions make the framework a robust base to assess also the differences in term of attained risk PLL_A^* between different design alternatives. This is extremely relevant specially in the case of studying the effect of some active or passive devices or design solutions (i.e. the Risk Control Options) in reducing/preventing the risk of flooding.

3. Risk control options for flooding

In the last decades, several design and operational measures have been considered to increase the survivability of a damaged passenger ship. These devices or solutions are usually called Risk Control Options (RCOs) and could have different level of complexity and working principles (Tompuri et al., 2020). As such, some of them are directly applicable to an existing layout of a ship, others require a local or global reconfiguration of the internal spaces (Vassalos et al., 2016).

RCOs may be effective for risk reduction or prevention in different phases of the vessel lifecycle. As such, they are usually divided into two main categories: design measures and operational measures (pre and post-accident). Typically, design measures includes passive countermeasures, meaning systems/solutions that are permanently installed on the vessels like the implementation of a crashworthy structure (Naar et al., 2002), a change in the layout or subdivision (van't Veer et al., 2004; Ruponen et al., 2019), equalisation systems for asymmetric flooding (Vassalos et al., 2004) or other design measures to limit progressive flooding (Kang et al., 2018). Operational measures before an accident occurrence considers the prevention of collisions/groundings during navigation (Montewka et al., 2022) and the appropriate training of the crew (human factors). Post-accident countermeasures typically includes the use of active flooding mitigation systems (Vassalos et al., 2016).

In the progress of project FLARE, the different kinds of RCOs have been considered, analysed and hypothesised for on-board application in direct contact with designers, classification societies and academy. As



(a) Installation sites (blue) in the double hull.

(b) Existing ship structure in the double hull.

(c) Void spaces partially filled with foam.

Fig. 3. Permanent foam installation example.

a result, the most effective solutions in terms of applicability and cost effectiveness (Hamann et al., 2022) are the following:

- Fixed foam installation (passive device).
- Deployable watertight foam barriers (active device).
- Implementation of a crashworthy structure (passive device).
- Changes of internal layout and openings (passive device).

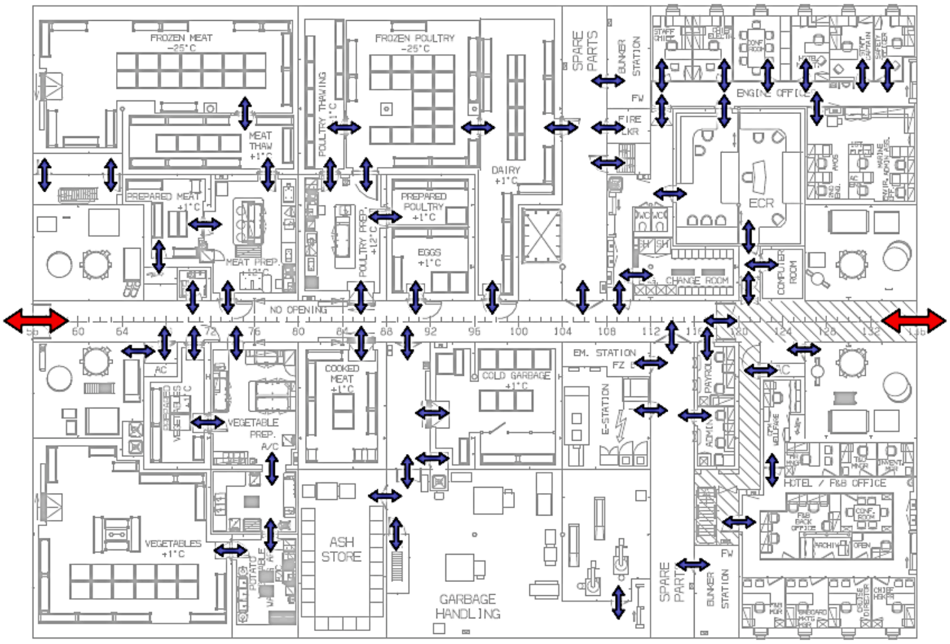
In the following, the above-mentioned options are discussed and described in order to understand their working principles prior to analyse the effect of their implementation on the flooding risk reduction of passenger ships.

3.1. *Permanent foam installations*

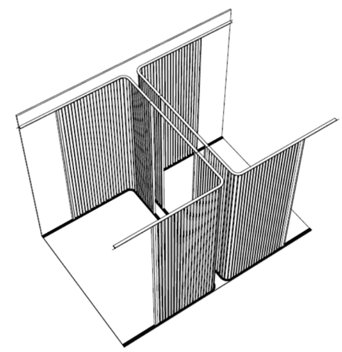
The first RCO selected to investigate flooding risk reduction onboard passenger ships is the installation of permanent foam. The system aims to increase the ship's initial stability and restoration forces in the event of flooding after an accident. The stability increase is independent from the fact that the areas interested by foam installation are flooded or not after the damage occurs, as the foam cannot be replaced by floodwater. The permanent foam is installed in void spaces along the ship, trying to cover the most vulnerable areas, respecting the original layout of the vessel as a part of a passive flooding protection system (Vassalos et al., 2022b).

These installations have the advantage of being impenetrable and works similarly to buoyancy tanks, as the permeability of the associated space changes. Therefore, foam could provide buoyancy in the damaged areas instantaneously after the hazard occurs. Thanks to this effect, the device is particularly efficient in reducing the risk of transient capsize cases, meaning capsizes that occurs extremely rapidly after the damage occurrence. In fact, transient capsizes are closely linked to the insufficient reserve of stability during the early stages of flooding. Therefore, the passive foam installations act as an additional reserve of stability aiming at improving initial stability. Fig. 3 shows a possible site of installation for permanent foam in available void spaces on a lower deck of a passenger ship.

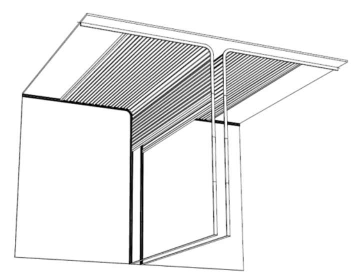
The identification of the most vulnerable area of the ship where it is preferable to install the permanent foam could be derived directly from a Level 1 flooding risk assessment. Analysing the damage cases having a high value of the product $p_c^*(1-s_c)$ it is possible to identify a *static risk profile* of the vessel (Vassalos et al., 2021). The area at high risk are those where it is advisable to install the passive RCO. Of course, the final selection of the area where to install the foam should take into account the available void spaces at disposal, in order not to drastically change



(a) Main (red) and secondary (blue) flooding paths on a cruise ship zone.



(b) Horizontally deployable shuffles.



(c) Vertically deployable shuffles.

Fig. 4. Flooding paths on a cruise ship and deployable barriers examples.

the internal layout of the vessel. This kind of RCO is suitable both in case of a retrofitting of an existing unit or in the case of a complete new design. The latter option could give more freedom in the foam installation, predisposing void spaces in dedicated areas along the ship.

3.2. Deployable watertight foam barriers

The second type of RCO considered during project FLARE is also related to a foam installation; however, instead of a fixed installation as in the previous case, here the application concerns a deployable active device to activate only in case a flooding event occurs. The installation of such devices should take into account the flooding path development after an accident.

Once the flooding process progresses in a complex environment (as it is the case of the internal layout of a passenger ship), the progressive flooding paths can be divided into major and minor floodwater paths. Major paths are referring to large passageways that link two adjacent zones of the ship, acting as principal arteries that quickly disperse floodwater through the vessels. On the contrary, the minor paths are small narrow passages that connect local areas, allowing a local collection of water. Fig. 4a gives an overview of the difference between main and secondary flooding path in a specific zone of a cruise ship. An effective strategy to prevent progressive flooding progression onboard a passenger ship is to limit the transition of floodwater between contiguous zones, which means to interrupt the main flooding paths (Vassalos et al., 2022b). To this end, deployable foam barriers are a good solution to prevent this specific flooding situation, without the need of design changes to the interior layout of the vessel.

Deployable barriers are composed of two lightweight shutters spaced 30 cm apart, usually composed of steel laths or GRP with an A-class fire rating. Therefore, the deployable devices can be used also in case of fire incidents. For the specific case of flooding, the interstice between the shutters is filled with expanding foam, delivered from a compressed foam canister. In order to comply with the local arrangements and structures in different locations of the ship, the shutters can be mechanically adjusted to be deployed either horizontally (see Fig. 4b) or vertically (Fig. 4c). In addition, the barrier may be extended up to 30 metres over intermediate supports in a matter of minutes, limiting and managing floodwater channels that were previously determined to be crucial.

The flexibility of the device allows for installing the selected RCO in areas that were identified as critical for the flooding progression while analysing the flooding progression time traces of critical damage scenarios simulations (means employing a Level 2 assessment). Furthermore, the presence of a deployable barrier can be considered also while simulating the evacuation paths after an hazard, obtaining a more realistic estimation of the Time to Evacuate. This provides an effective benefit over the passive countermeasure systems which provide less flexibility and effectiveness in likely critical loss circumstances.

3.3. Crashworthy structures

The last RCO studied for reducing the risk of flooding is crashworthiness. This is an effective risk mitigation measure against flooding studies since the early 90s (Egge and Bockenhauer, 1991; Pedersen, 1994; Naar et al., 2002; Paik, 2020; Bai and Paik, 2024). However, the lack of suitable tools for its extensive application in the early design stages of passenger ship and the complexity introduced by the Alternative Design and Arrangements process outlined in MSC.1/Circ.1212 have limited its application.

In general, crashworthiness refers to the structural capacity to withstand impact and minimise the extent of damage resulting from collisions or groundings. Consequently, the design of crashworthy structures in passenger ships requires a comprehensive reevaluation of the layout of main longitudinal and transverse structural elements, with an emphasis on optimising energy absorption and damage localisation. Project FLARE provided dedicated effort in studying potential design solutions in the attempt of considering crashworthiness as a suitable RCO for preventing flooding risk. The strategy was to derive a suitable scaling method from the conventional distributions employed to generate damage dimensions (Mauro and Vassalos, 2022) to enhanced new distributions considering the implementation of specific crashworthy reinforcement along the hull (Cardinale et al., 2022). By employing super-element codes (meaning codes modelling only the main relevant resistance structures of the ship) for crash analyses (Sourne, 2020; Buldgen et al., 2012; Conti et al., 2022), corrections have been derived for the following damage dimensions of specific damage types involved in flooding risk assessment:

- *Collisions*: damage length, damage penetration, damage height.
- *Bottom groundings*: damage length.
- *Side groundings*: damage length.

The correction has the form of a scaling function, obtaining the new damage dimension d^* by multiplying the one derived from statistical distributions for a scaling factor λ ($d^* = \lambda d$). As the resulting damage is always smaller than the original one, λ is always less than 1. The reference study considers the following types of reinforcements, pertinent to different damage types:

1. *Doubling of inner bottom plating thickness*: only for bottom groundings.
2. *Doubling the number of girders within the inner bottom*: only for bottom groundings.
3. *Increase of bottom structures material grade to AH36*: only for bottom groundings.
4. *Installation of a double hull at B/20 with transversal web frames and an inner plate of 12 mm*: for collisions and side groundings.
5. *Installation of a double hull at B/10 with transversal web frames and an inner plate of 12 mm*: for collisions and side groundings.
6. *Installation of a double hull at B/30 with transversal web frames and an inner plate of 12 mm*: for collisions and side groundings.
7. *Installation of a double hull at B/20 with transversal web frames and an inner plate of 7 mm*: for collisions and side groundings.
8. *Installation of a double hull at B/20 with transversal web frames and an inner plate of 17 mm*: for collisions and side groundings.
9. *Increase of side shell plating thickness by 10 mm*: for side groundings only.
10. *Doubling of hull thickness*: for collision only.

During the preliminary study in FLARE, the ten possibilities mentioned above have been implemented on a reference ship, considering collisions with a set of 11 possible striking ships (Conti et al., 2022; Mauro et al., 2023a). The developed approach allows for considering the implementation of a crashworthy structure through all the levels of the flooding risk assessment framework. In fact, the strategy of scaling the damage dimensions influences only the definition of the inputs; more specifically, it influences the compartments affected by the damage. Therefore, crashworthiness is directly considered in the preparation phase of the survivability calculation, thus allowing the estimation of risk with either a Level 1 or Level 2 approach.

3.4. Internal layout and openings

An option to reduce the risk of flooding onboard is finding design solutions that limit the floodwater propagation after an accident. In this sense, instead of studying an active system, like the foam barriers, it is possible to analyse which are the most critical areas subject to flooding and mitigate the risk by changing the local internal layout or by reinforcing the local openings.

Such options imply the execution of progressive flooding simulations on the original layout of the ship, to identify the flooding progression paths and the most critical openings. Most vulnerable openings are determined from the analysis of the critical damage cases identified with a Level 1 assessment. Those cases should be than assessed with a Level 2 analysis, determining which are the openings that are mostly involved in the different flooding processes. Afterwards, it is possible to increase reinforcements of these doors in such a way to make them more resistant to the water hydrostatic pressure.

Another solution is the identification of an alternative layout for a specific section of the ship. Having identified the flooding paths may allow to study alternative solutions for rooms and corridors in such a way to limit the flooding progression in that area. This kind of solution should be studied carefully as it involves also the layout change for all auxiliaries located in the area. As such, the last option could generate extra costs (especially in case of a retrofitting) that may limit the applicability of this RCO.

4. Ship database

During project FLARE, a number of sample ships, representative of large cruise vessels and Ro-Pax ferries, has been provided to reflect the typical designs of the existing world-wide fleet. For the identification of the most suitable vessels, the following general constraints were applied to the world-wide fleet database (SHIPPAX, 2019), setting the focus on large ships:

- Gross tonnage > 10,000 GT.
- Length > 120 metres.
- Number of Main Vertical Zones (MVZ) > 2.

The database resulting from these constraints is shown in Fig. 5 for the cruise ships and in Fig. 6 for the Ro-Pax vessels. The graphs represent the Gross Tonnage versus the number of passengers N_p for each ship in the database, being the two variables present in the database that could link the vessel size with the POB. Observing the cruise ships distribution

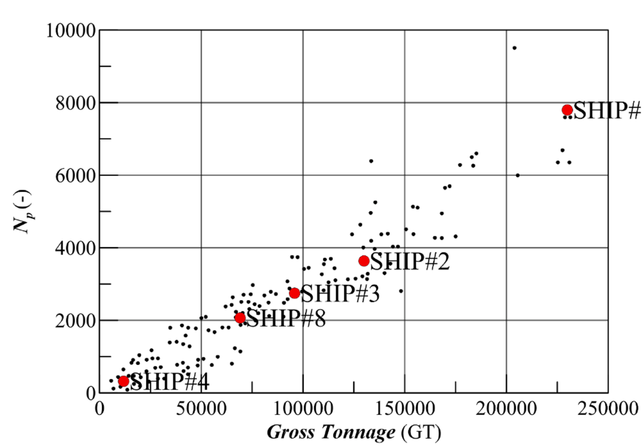


Fig. 5. Cruise ships database and sample ships selected for the study.

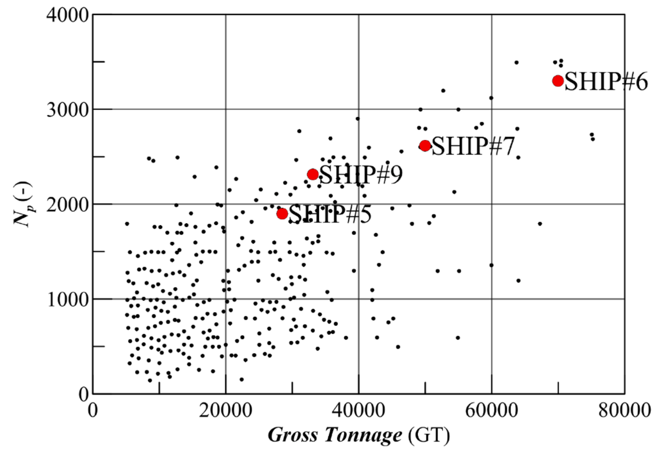


Fig. 6. Ro-pax ships database and sample ships selected for the study.

(Fig. 5), a linearity between the two parameters can be observed. To have a suitable sample of this fleet in the project it has been concluded to select 5 ships from approximately 10,000 GT to more than 230,000 GT.

The distribution of Ro-Pax ferries shows a much greater variety (Fig. 6). The reason for this may be different objectives in the design and operation of Ro-Pax ships. Some ships have the focus on cargo transport with a smaller passenger capacity; others are rather designed for a large number of passengers. Another reason may be the specific design of some RoPax ships for one special trade, which may induce design constraints and unusual design concepts. As the focus in the FLARE project is on the development on measures to enhance safety after flooding these measures may be proven even with a smaller selection of ships. Therefore only four Ro-Pax ships have been selected between 28,000 GT and 70,000 GT, where the focus is laid on passenger transport.

The figures also show the nine ships selected for the risk analysis studies in FLARE (Luhmann et al., 2022). These sample ships are not existing ships but are realistic complete designs provided by the industry that have never been materialised. This solution has been adopted to share the results of the research, avoiding possible issues with the intellectual property rights of shipping companies. In any case, the adopted projects have been developed up to the advanced stage of design (ready to built conditions) and reflect the actual state of the art of passenger ship design. 7 of the 9 ships are compliant with modern SOLAS 2020 regulations, while 2 ships (older projects) have been designed according to SOLAS 90 regulations. Hereafter, a short description of the vessels is provided:

- *SHIP#1*: this is the project of a modern large cruise ship propelled with 3 pod units. The 6 main engines are dual fuel, so the vessel has space under the bulkheads to fit the LNG tanks. The ship accommodates 10,000 POB. The vessel has 8 MVZ and is compliant with SOLAS2020, Intact Stability Code, Load Line Convention, MARPOL, IGF Code and Marine Labour Convention 2006.
- *SHIP#2*: the project conceived a modern large cruise ship with two pod units as main propulsors. Also in this case the vessel is equipped with LNG tanks to supply the 5 main dual fuel engines installed onboard. The ship accommodates 4940 POB The vessel has 6 MVZ and is compliant with SOLAS2020, Intact Stability Code, Load Line Convention, MARPOL, IGF Code and Marine Labour Convention 2006.
- *SHIP#3*: the vessel is a large cruise ship (with 3750 POB) equipped with two conventional propellers. Main engines are conventional diesel generators. The ship is designed with 6 MVZ and is compliant with SOLAS2020, Intact Stability Code, Load Line Convention, MARPOL and Marine Labour Convention 2006.
- *SHIP#4*: this is an example of a small cruise vessel designed for exploration cruises, that accommodates 478 POB. The ship is equipped with two conventional propulsors and standard diesel generators. The design presents 3 MVZ and is compliant with SOLAS2020, Intact Stability Code, Load Line Convention, MARPOL and ICE rules.
- *SHIP#5*: this is a project of a modern small Ro-Pax, accommodating 3000 POB. The vessel is equipped with dual fuel diesel engines and the space for LNG tanks is fitted below the bulkheads deck. The design presents 4 MVZ and is compliant with SOLAS2020, Intact Stability Code, Load Line Convention, MARPOL and Marine Labour Convention 2006.
- *SHIP#6*: this is a project of modern large Ro-Pax, accommodating 3500 POB. The vessel has 5 main fire zones and is compliant with SOLAS2020, Intact Stability Code, Load Line Convention, MARPOL and Marine Labour Convention 2006.
- *SHIP#7*: this design refers to a LNG fueled Ro-Pax ship where the LNG tanks are located under the bulkhead deck in an area traditionally dedicated to car holds. The vessel accommodates 2800 POB and has 5 MVZ. The design is compliant with SOLAS2020, IS code 2008, Load Line Convention and MARPOL.
- *SHIP#8*: this is a relatively old design of a Cruise ship accommodating 2790 POB. The ship is designed with 6 MVZ and is compliant with SOLAS 90, Load Line Convention, IMO resolution A749 and MARPOL.
- *SHIP#9*: this is a relatively old design of a Ro-Pax vessel capable of accommodate 2400 POB. The ship has 5 MVZ and the design is compliant with SOLAS90, Stockholm agreement, Load Line Convention, IMO resolution A749 and MARPOL.

Table 1 summarises the main particulars of the nine reference ships. No one of the reference designs is equipped with RCOs, but dedicated calculations have been carried out to derive the PLL_A^* according to the FLARE flooding risk assessment framework described in Section 2. Results are available for Level 1 and Level 2.1 predictions (Mauro and Vassalos, 2024a), and are briefly reported in Table 2. The implications

Table 1
Reference ships main particulars.

			SHIP#1	SHIP#2	SHIP#3	SHIP#4	SHIP#5	SHIP#6	SHIP#7	SHIP#8	SHIP#9
Vessel type	–	–	Cruise	Cruise	Cruise	Cruise	Ro-Pax	Ro-Pax	Ro-Pax	Cruise	Ro-Pax
Length over all	L_{OA}	m	373.00	308.00	300.00	128.00	162.00	229.00	213.00	264.00	211.30
Length between perpendiculars	L_{PP}	m	346.50	299.40	270.00	113.70	146.72	214.32	195.40	222.00	195.30
Subdivision length	L_s	m	366.00	307.71	296.74	125.80	152.22	227.97	213.00	220.00	212.25
Breadth	B	m	48.00	39.80	35.20	20.00	28.00	33.20	31.50	32.00	25.80
Design draught	T	m	8.80	8.20	7.95	5.10	6.10	6.50	6.95	8.55	6.50
Subdivision draught	T_s	m	9.10	8.50	8.20	5.30	6.30	6.70	7.10	8.82	6.70
Construction height	D	m	12.40	11.80	11.00	7.23	9.20	9.70	10.30	10.45	9.40
Number of passengers	N_p	–	7,800	3,640	2,750	323	1,900	3,300	2,617	2,070	2,315
Number of crew members	N_{cm}	–	2,200	1,300	1,000	155	100	200	183	720	85
Persons on Board	POB	–	10,000	4,940	3,750	478	2,000	3,500	2,800	2.790	2,400
Gross tonnage	GT	–	230,000	130,000	95,900	11,800	28,500	70,000	50,000	69,100	36,822
Deadweight	DWT	t	13,000	10,200	8,500	1,250	3,800	6,900	5,300	6,270	5,575

Table 2
Level 1 and Level 2.1 risk assessment results for the nine reference ships.

Ship ID	Type	Regulation	SOLAS 2020 R-Index –	SOLAS A-Index –	PLL_A^* Level 1 1/ship year	PLL_A^* Level 2.1 1/ship year
SHIP#1	Cruise	SOLAS2020	0.9173	0.9185	2.3400	1.7730
SHIP#2	Cruise	SOLAS2020	0.8935	0.9067	1.0091	0.7840
SHIP#3	Cruise	SOLAS2020	0.8835	0.8938	1.0888	0.8334
SHIP#4	Cruise	SOLAS2020	0.7323	0.7436	0.2454	0.1955
SHIP#5	Ro-Pax	SOLAS2020	0.8611	0.8892	0.5348	0.3649
SHIP#6	Ro-Pax	SOLAS2020	0.8811	0.8948	0.6132	0.6154
SHIP#7	Ro-Pax	SOLAS2020	0.8730	0.8825	1.0698	0.9313
SHIP#8	Cruise	SOLAS90	0.8730	0.7691	1.4204	1.2542
SHIP#9	Ro-Pax	SOLAS90	0.8675	0.8142	0.5372	0.4677

of using a Level 1 or a Level 2.1 assessment for flooding risk have been widely discussed by the authors in previous publications (Mauro et al., 2023b; Mauro and Vassalos, 2024a) and are not repeated here for the sake of brevity. However, the results reported in Table 2 are the reference points for each project, means the base for a comparison with alternative designs aimed at increasing the safety of the ship.

All the design teams performed Level 1 and Level 2.1 calculations with the same softwares. More specifically, NAPA Stability (NAPA, 2025) has been used for static calculations and PROTEUS3 (Jasionowski, 2001) for time-domain damage stability analyses. The selection of static software has been decided by designers, as is the standard used in the industry. For the time-domain analysis, PROTEUS3 provided a good agreement with benchmark studies, especially in simulating flooding in waves. Software limitations concerns the application of Bernoulli model for the flooding progression and 2D strip theory for the hydrodynamic coefficients. However, dealing with geometries with more then 500 internal spaces, the flooding model gives the right compromise between accuracy and calculation time. Concerning hydrodynamic loads, the limitation are for high sea states, where nonlinearities are present. However calculations have been performed for moderately high sea states, where the software highlighted good reproduction of results.

The vessels selected for the study comes from 5 different design teams, four representing the industry and one the academy. The following section illustrates the different strategies employed by each team for their vessels to try reducing risk in the most efficient way.

5. RCOs implementation

Starting from the initial design configuration and assessed risk level, the nine reference ship designs have been upgraded by the respective design teams by implementing different kinds of RCOs. More specifically, the options presented in Section 3 have been considered, analysing which ones were suitable with internal layout of the vessels, without requiring an extensive re-elaboration of the internal layout. As such, not all the solutions have been implemented on all the ships, as designers judged that some solutions were not applicable to some of the ships under analysis. In addition to the RCOs presented in Section 3, in some cases also the combination between the proposed solution has been hypothesised. In the following sections, a brief overview of the design choices to implement RCOs for flooding risk reduction is presented ship by ship. Table 3 summarises the single design solutions tested for each ship, together with the nomenclature used to identify the different types of RCOs. As mentioned, the study considers not only the implementation of single RCOs but also the combined deployment of different risk mitigation solutions. Table 4 gives an overview of the RCOs combinations studied for each vessel. All the new design solutions were implemented to the reference ships and reassessed according to the flooding risk

Table 3
RCOs implemented and analysed for each reference ship design.

RCO	ID	Description	Ships #1	#2	#3	#4	#5	#6	#7	#8	#9
Foam installations	A1	Deployable barriers	–	–	–	–	–	–	–	–	✓
	A2	Permanent installations	✓	✓	✓	✓	–	✓	✓	✓	✓
Chrashworthiness	B1	Doubling inner bottom thickness	–	–	–	–	–	–	–	–	–
	B2	Doubling number of inner girders	–	–	–	–	–	–	✓	–	–
	B3	Steel upgraded to AH36	–	–	–	–	✓	–	–	–	–
	B4	Double hull offset B/20, thickness 12 mm	–	–	✓	–	–	✓	–	–	–
	B5	Double hull offset B/10, thickness 12 mm	–	–	–	–	–	✓	-	✓	–
	B6	Double hull offset B/30, thickness 12 mm	–	✓	–	–	–	✓	✓	✓	–
	B7	Double hull offset B/20, thickness 7 mm	–	–	–	–	–	✓	–	–	–
	B8	Double hull offset B/20, thickness 17 mm	–	–	–	✓	–	✓	–	–	–
	B9	Side shell thickness +10 mm	✓	–	–	–	✓	–	–	–	–
	B10	Doubling hull thickness	–	–	–	–	–	–	–	–	–
Internal layout	C1	Double hull with 1 m width	–	–	✓	✓	–	–	–	–	–
Openings	D1	Reinforced doors	✓	–	–	–	–	–	–	–	–
	D2	Additional doors to bulkhead deck	–	✓	–	–	–	–	–	✓	–

Table 4
RCOs combinations implemented on the nine reference ships.

	SHIP#1	SHIP#2	SHIP#3	SHIP#4	SHIP#5	SHIP#6	SHIP#7	SHIP#8	SHIP#9
RCOs combinations			C1 + A2 C1 + B4	A2 + B8	B3 + B9		B5 + B6 A2 + B5 + B6	A2 + B6 B5 + B6	D2 + A2

The abbreviations refer to the nomenclature of Table 3.

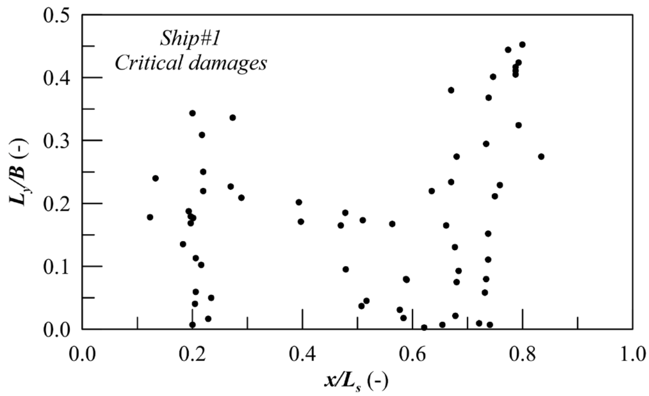


Fig. 7. Critical collision damages considered for Ship#1.

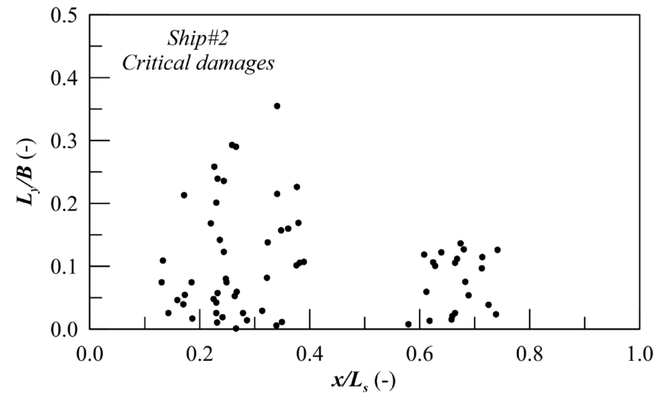


Fig. 8. Critical collision damages considered for Ship#2.

assessment framework. Finally, all the changes in loading conditions due to the implementation of the RCOs have been considered by designers in the reassessment of the flooding risk.

5.1. SHIP#1

The selection of the RCOs for this vessels derive from the analysis of Level 1 and Level 2.1 PLL_A calculations. Fig. 7 shows the critical collision damages used by designers to implement the RCOs. The Figure shows the non-dimensional penetration of the collision damage (L_y/B) as a function of the non-dimensional longitudinal position of the centre of the damage (x/L_s). At this stage, designers didn't follow a concept of optimal possible RCO but focused on the implementation of possible solutions having less impact on the original layout of the vessel. As reported in Table 3, the following RCOs have been considered:

- *Reinforced doors on bulkhead deck*: the purpose of this RCO is to improve the damage stability performance of the vessel by reinforcing critical openings on the bulkhead deck. More specifically, designers select to reinforce the fire doors leading to the staircases, in such a way to slow down water ingress from lower decks.
- *Passive foam installations*: the second selected RCO for this ship is the application of fixed passive foam installations. The foam has been applied in void locations under the bulkhead deck, filling a final volume of 5,873 m^3. To not compromise the functionality requirement of the ship, preference has been given to void spaces only, without changing the layout of the ship. As such, the locations where to apply foam are not optimal, with reference to the static risk profile of the vessel.
- *Side shell thickness increase of 10 mm*: this risk control option associated with crashworthiness aims at improving safety in case of side groundings. According to the distribution of most critical side groundings damages, designers selected to reinforce the area from $0.3L_{PP}$ to $0.8L_{PP}$. The vertical extent of the reinforcements goes from the bilge up to the bulkhead deck. Such a solutions led to a weight increase of 450 t, with a consequent effect on the draught and position of the vertical centre of gravity.

For this case, the resulting RCOs are not representative of an optimal disposition of the devices but represent a compromise solution between potential risk loss and cost of changes.

5.2. SHIP#2

The selection of the RCOs to implement on SHIP#2 reflects the choices of designers after the analysis of flooding risk at both Level 1 and Level 2.2 on the original vessel configurations. Fig. 8 shows the collision damages used by designers to study RCOs implementation. Also in this case, the design team didn't focus on optimising the impact of RCOs on flooding risk but preferred to minimise the consequences on the internal layout. From these considerations, the following RCOs have been studied:

- *Permanent foam installations*: with the vessel being equipped with an LNG fuel system, the spaces around the LNG tanks are designed to be void spaces or, in some cases, dedicated to crew cabins. The design team decided to fill all the spaces around the LNG tanks with permanent foam installations, moving part of the crew cabins in upper decks.
- *Double hull with offset B/30 and 12 mm thickness*: the implementation of this crashworthy measure has been decided because of its easy implementation in the engine room area. Also in this case, the selection of the location is not derived directly from the static risk profile of the vessel, as suggested by the risk framework, but derive from criteria of easy and effective applicability of the proposed modification.
- *Additional doors to bulkhead deck*: to limit the flooding progression along corridors, the number of watertight doors has been increased on the bulkhead deck. More specifically, the additional doors are added in correspondence with the watertight bulkheads. The designers assumed that these watertight doors are limited strength doors (called *Semi Watertight Doors*) that can be easily opened and closed as normal sliding fire doors. This allows for not compromising the escape routes in case of harms.

Also in this case, the implementation of this RCOs is not optimal for the flooding risk reduction but a compromise with the necessities of limiting changes to the internal layout of the vessel. However, starting from the above configurations, the ship equipped with RCOs has been reassessed to estimate the new risk level, bearing in mind that the potential risk reduction is mitigated by the necessity of limit the cost of changes.

5.3. SHIP#3

Also for SHIP#3, the analysis of the RCOs to be implemented is subsequent to the interpretation of results obtained from Level 1 and Level 2.1 risk analysis. The critical damages considered by designers for the RCOs implementation are shown in Fig. 9. From the initial screening, the designers decided to adopt the following countermeasures to improve safety, considering also combinations of the simple RCOs solutions:

- *Double hull with offset B/20 and 12 mm thickness*: the implementation of a non watertight crashworthy structure has been decided to reinforce the areas around the engine room. These areas were at high risk of flooding, especially for damages due to collisions and side groundings. The implementation of the crashworthy structure was compliant with the static risk profile of the vessel and does not require a rearrangement of the internal layout. Fig. 10 shows the location and extend of the double hull.

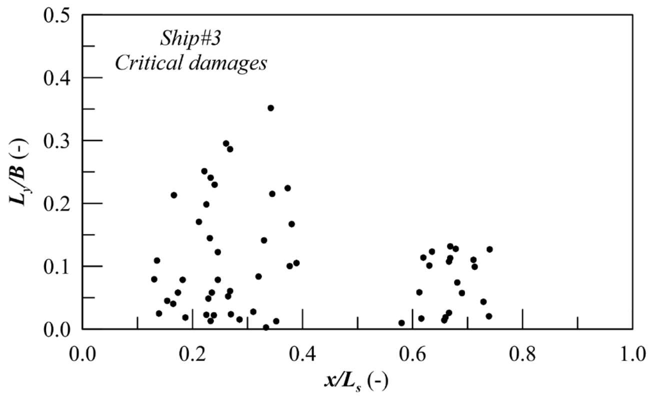


Fig. 9. Critical collision damages considered for Ship#3.

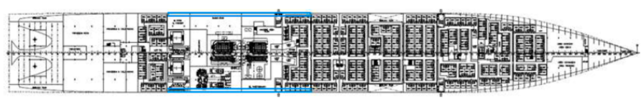


Fig. 10. Double hull location on Ship#3.

- *Double hull with 1 m width*: taking into account the same considerations of the previous RCO, the designers decided to reinforce the engine areas with a watertight double hull. The extension of this double hull is the same of the previously described RCO.
- *Permanent foam plus double hull with 1 m width*: this is a first combination between different RCOs. As the implementation of a double hull with 1 m width generates void spaces between the reinforcement and the side shell, designers decided to fill these spaces with permanent foam. Of course, the extension of the foam installations is the same as the additional double hull.
- *Double hull with offset B/20 and 12 mm thickness plus double hull with 1 m width*: this second combination of RCOs has been implemented by designers to test the joint benefits of having a reinforced and watertight double hull. The location and extension of the RCOs is the same as the individual solutions.

In this case, the RCOs are installed in ares that are effectively at risk for the initial design configuration. Therefore, it is reasonable to assume a higher risk reduction compared to the previous two ships.

5.4. SHIP#4

SHIP#4 was assessed in its original configuration with a flooding risk analysis at Level 1 and Level 2.1. The critical damages employed for the RCOs studies are shown in Fig. 11. For this ship, the design team performed an accurate analysis of the most vulnerable areas, trying to collocate the reference RCOs precisely in the regions at high risk of flooding. As shown in Tables 3 and 4, the following RCOs and combination of RCOs have been considered by designers:

- *Permanent foam installations*: the analysis of the static risk profile of the ship highlights two region at high risk, a particularly severe one in the aft and a minor one at the fore shoulder. To this end, void spaces have been identified in both the regions to fill them with foam.
- *Double hull with offset B/20 and 17 mm thickness*: From the analysis of the collision damages it has been noted that the majority of breaches resulting into a capsize of the ship are located in the aft compartments of the ship. As a first step the double hull has not been considered watertight therefore the unique impact on the PLL is generated by the reduction of the dimension of the affected breaches (according to the λ introduced in Section 3.3).
- *Double hull with 1 m width*: to further improve the benefits of a double hull not being watertight, the design team decided to implement a watertight double hull exactly in the same positions of the previous RCO.
- *Double hull at B/20 with permanent foam installations*: this combination of RCOs has been detected for installation, targeting the area located in the aft compartments of the vessel. Here a combined effect of a non-watertight double hull and passive foam has been studied.

In this case, the RCOs are installed in ares that are effectively at risk for the initial design configuration. Therefore, it is reasonable to assume an higher risk reduction compared to the previous two ships.

5.5. SHIP#5

SHIP#5 was assessed in its original configuration with a flooding risk analysis at Level 1 and Level 2.1. The designers considered the critical side grounding damages reported in Fig. 12 to study the RCOs implementation. For this ship, the designers decided not to change the internal layout of the vessel or to fill void space with foam protections. Only crashworthy enhancements have been targeted by the design team, resulting in the application of the following RCOs:

- *Steel upgrade to AH36*: This RCO reinforces the bottom of the hull by upgrading the steel grade from normal strength steel (yield strength of 236 MPa) to higher strength steel, AH36 (yield strength of 355 MPa), thus improving the bottom grounding crashworthiness of the vessel. As there was not found a particularly vulnerable area regarding bottom groundings, the whole bottom is reinforced.
- *Side shell thickness +10 mm*: This risk control option is intended for the improvement of side grounding crashworthiness characteristics of a vessel. Results indicate that regarding side groundings, the most vulnerable area is located amidships. The vertical extent of the side

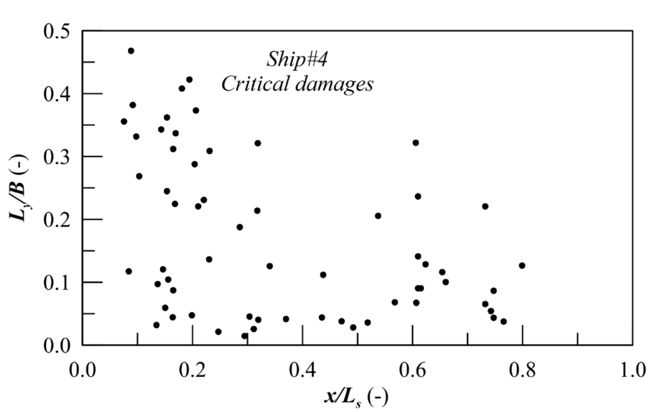


Fig. 11. Critical collision damages considered for Ship#4.

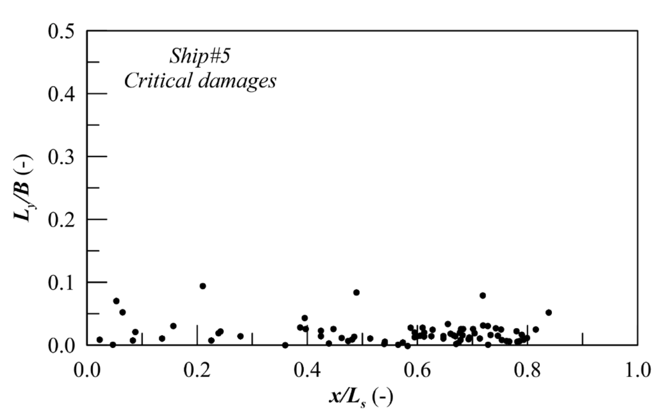


Fig. 12. Critical side grounding damages considered for Ship#5.

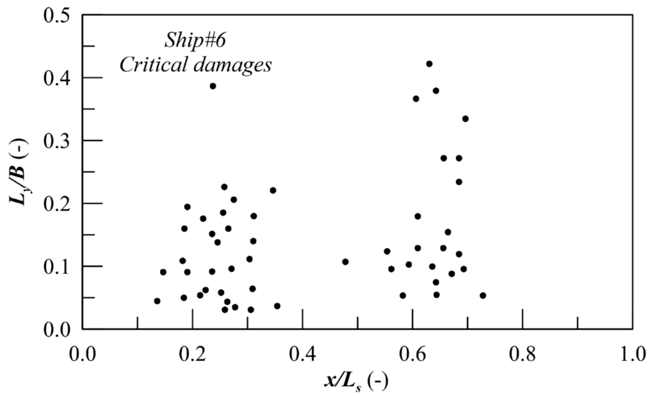


Fig. 13. Critical collision damages considered for Ship#6.

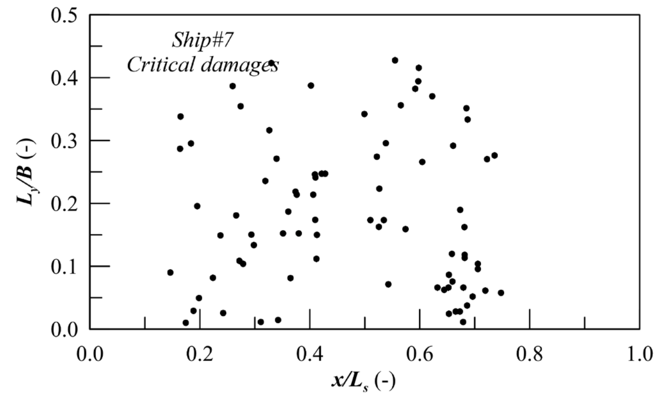


Fig. 14. Critical collision damages considered for Ship#7.

shell reinforcement is from the bilge up until the bulkhead deck. This results in a reinforced area of 1 579 m2. This equates to an added weight increase of 126.3 t. This affects the centre of gravity and draught, essentially altering the stability characteristics of the vessel.
- *Steel upgrade plus side shell thickness + 10 mm*: this combination is the pure superposition of the previous two solutions.

5.6. SHIP#6

SHIP#6 was assessed in its original configuration with a flooding risk analysis at Level 1 and Level 2.1. Fig. 13 shows the critical collision damages employed by designers to study the implementation of RCOs. For this ship, the designers focused only in the implementation of single RCOs. Therefore, no combinations have been investigated, resulting in the following solutions:

- *Permanent foam installations*: The results of the risk analysis have shown as expected that the forward and aft shoulder of the ship are the most vulnerable areas. To improve these areas void spaces have been filled with foam.
- *Double hull with offset B/20 and thickness 12 mm*: the most critical part identified during the preliminary risk analysis has been reinforced with this non-watertight structure.
- *Double hull with offset B/10 and thickness 12 mm*: the RCO covers the same area of interest of the previous option.
- *Double hull with offset B/30 and thickness 12 mm*: the RCO covers the same area of interest of the previous option.
- *Double hull with offset B/20 and thickness 7 mm*: the RCO covers the same area of interest of the previous option.
- *Double hull with offset B/20 and thickness 17 mm*:the RCO covers the same area of interest of the previous option.

In this case the designers focused in understanding the differences of the multiple options by installing all the RCOs in the same areas. This gives a fair comparison among the different crashworthy solutions as well as for the fixed foam.

5.7. SHIP#7

SHIP#7 was assessed in its original configuration with a flooding risk analysis at Level 1 and Level 2.1. The designers performed a static risk analysis prior to deciding where to put the considered RCOs, resulting in a combination between necessities and design constraints. Fig. 14 shows the critical collision damages used for risk reduction considerations. The result is the application of single and combinations of RCOs as shown in Tables 3 and 4 and briefly described hereunder:

- *Permanent foam installations*: the installation of permanent foam does not consider the most vulnerable areas along the ship. The criteria used for the installation is coming from the disposition of the void spaces in the lower part of the ship.
- *Doubling the number of inner girders*:the impact on bottom grounding assessment of this RCO was inspected. Looking at the worst selected cases for Bottom Grounding, the most fore part of the double bottom does not need to be strengthened; it is instead obvious that only very longitudinally extended breaches can generate dangerous scenarios. To this end the RCO has been installed through 3/4 of the ship length, excluding only the foremost and the aftmost areas.
- *Double hull with offset B/30 and thickness 12 mm*: This RCO has been studied to reinforce the mid part of the ship in the case of collision. In presence of void spaces, the double hull is changing to a B/10 double hull.
- *Combined Double hull with offset B/30 and B/10 and thickness 12 mm*: This combination of RCOs is similar to the previous case but is fitted in a different place of the ship, more specifically on the fore shoulder.
- *Combined double hull (B/30 and B/10 offset) and permanent foam*: This RCOs combination is the result of the previous one plus the application of fixed foam installations in the void spaces.

As mentioned, the designers try to find a compromise between design necessities and risk indication. In any case, the proposed solutions did not impact the internal layout of the vessel.

5.8. SHIP#8

SHIP#8 was assessed in its original configuration with a flooding risk analysis at Level 1 and Level 2.1. The designers employ the critical damages shown in Fig. 15 to make their considerations on the RCO to

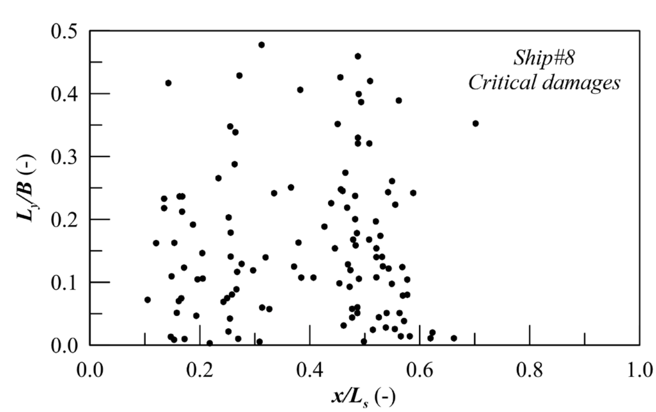


Fig. 15. Critical collision damages considered for Ship#8.

apply for risk mitigation. Looking at the static risk profile of the vessel, the designers try to implement several RCOs, without changing the internal layout of the ship. The designers decided to apply both individual and combination of RCOs (see Tables 3 and 4), resulting in the following solutions:

- *Permanent foam installations*: permanent foam installation have been installed in void spaces below the bulkhead deck, without changing the internal layout of the ship.
- *Double hull with offset B/10 and thickness 12 mm*: from the static risk profile of the ship, two main regions were identified as critical for collision damages. As a result, designer decides to implement a double hull in the aft part of the ship in the compartments adjacent to the engine room (with the engine room located between 0.25 and $0.4x/L_s$).
- *Double hull with offset B/30 and thickness 12 mm*: this RCO has been located in the same region of the previous one, just changing the lateral position of the double hull.
- *Additional doors to bulkhead deck*: the designers performed a preliminary analysis on the criticality of the doors along the ship. As a result they decided to reinforce corridor and staircase openings on the bulkhead deck to limit the flooding progression along the ship.
- *Double hull with offset B/30 and permanent foam installations*: here, in addition to the double hull, the void spaces have been filled with foam.
- *Double hull with offset B/30 and double hull with offset B/10*: This RCOs combination has been implemented fitting in void spaces in the aft and fore shoulders a double hull, considering the limiting barrier according to the available spaces.

The designers decided to fit the different types of RCOs looking partially to the risk profile of the ship, privileging the solution of not modify the internal layout of the vessel.

5.9. SHIP#9

SHIP#9 was assessed in its original configuration with a flooding risk analysis at Level 1 and Level 2.1. The designers decided to focus primarily on the flooding progression along the ship, adopting solutions not employed by the other design teams. Fig. 16 shows the critical collision damages that the designers employed for their risk reduction considerations. This results in the following list of individual and combinations of RCOs:

- *Deployable barriers*: analysing the flooding progression along the car decks, the designers decided to implement deployable barriers to limit the progression of water in case of accidents.
- *Permanent foam installations*: from the static risk profile of the vessel, the designers decide to implement foam installations in the areas of the fore and aft shoulders to be effective especially in the case of collisions.
- *Permanent foam installations and additional doors to bulkhead deck*: in addition to the permanent foam installations, the designers decided to reinforce critical openings on the bulkhead deck to limit the flooding progression.

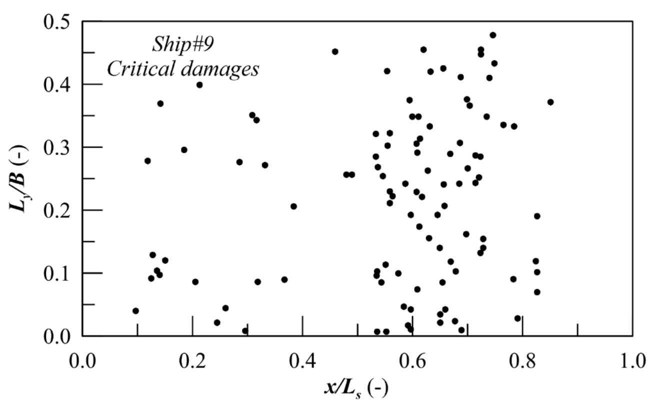


Fig. 16. Critical collision damages considered for Ship#9.

The focus of the designers on flooding progression results in the implementation of the solution of the deployable barriers, which is unicum among the different design teams. In addition, the adoption of the static risk profile for the foam installation is in line with the rest of the ships.

6. Multi-level assessment of RCOs

After the selection of the RCOs to implement on the 9 ship designs considered in the study, a second iteration of the risk evaluation had to be performed to evaluate the effectiveness of the implemented solutions. As described in Section 2, the risk assessment framework conceive multiple level to assess the risk due to flooding. According to this framework, the risk can be assessed at a Level 1 or a Level 2 (with the subcases 2.1 and 2.2). As such, designers have the opportunity to select the assumption levels, according to their experience and time-schedule.

In this study, designers follow the principles of the proposed framework, assessing the risk levels for the RCOs configurations at a Level 1 or a Level 2.1, meaning with a pure static assumption or using dynamic flooding analysis. Not all the design solutions have been tested at both levels as sometimes designers stop the analysis at a Level 1.

The following sections report the results of the different RCOs solutions at a Level 1 or a Level 2.1, bearing in mind that not all the configurations have been tested at Level 2.1.

6.1. Level 1 assessment

The design teams performed calculations of the PLL at Level 1 for all the RCOs implemented as described in Section 5. The Level 1 calculation is a straightforward application of static analyses of the damage stability of the ship, which is the method in which designers have the most confidence in assessing flooding risk.

Even though this method is less accurate for risk estimation, it could still give an indication of the risk reduction that could be achieved for a given RCO. Therefore, it is a suitable preliminary design instrument.

Table 5 shows the results of the Level 1 analysis, comparing the obtained results for each design solution with the condition without RCOs reported in Table 2. The results show a decrease in the PLL level for almost all the tested configurations; however, the magnitude of the reduction changes design by design due to the different strategies employed by the designers. To better understand the reduction levels it is better to give a description for each ship employing the nomenclature of Tables 3 and 4 to identify the RCOs:

- *SHIP#1*: For this ship, the PLL reduction ranges from 3 to 12 % compared to the initial condition. The lowest reduction is given by option A2 while the higher is the condition B9. An intermediate value of 7 % is achieved by configuration D1. The fact that condition A1 provide a small PLL reduction indicates that the placement of the foam installations are not placed in an efficient way. The good level achieved by the crashworthy solution B9 suggests that in this case the placement of the RCO is made in an acceptable way.
- *SHIP#2*: For this ship, the PLL reduction ranges form 1 to 11 % compared to the condition without RCOs. The lowest reduction is given by option B6 while the higher reduction is provided by solution A2. Solution D2 gives a 5 % of PLL reduction. In this case the crashworthy solution B6 is not really efficient as probably the region where it is applied is not optimal to reduce the impact of critical damages. Solution A2 indicates a fairly good placement of the permanent foam installations.

Table 5
PLL Level 1 (1/ship year) reduction of the selected RCOs.

ID	SHIP#1	SHIP#2	SHIP#3	SHIP#4	SHIP#5	SHIP#6	SHIP#7	SHIP#8	SHIP#9
none	2.3400 100.00 %	1.0091 100.00 %	1.088 100.00 %	0.2454 100.00 %	0.5348 100.00 %	0.6132 100.00 %	1.0698 100.00 %	1.4204 100.00 %	0.5372 100.00 %
A1	–	–	–	–	–	–	–	–	–23.00 %
A2	–3.00 %	-11.00 %	–8.00 %	–7.00 %	–	–5.00 %	–20.00 %	–	–43.00 %
B1	–	–	–	–	–	–	–	–	–
B2	–	–	–	–	–	–	–2.00 %	–	–
B3	–	–	–	–	–9.00 %	–	–	–	–
B4	–	–	–7.00 %	–	–	–56.00 %	–	–	–
B5	–	–	–	–	–	–58.00 %	–	–2.00 %	–
B6	–	–1.00 %	–	–	–	–55.00 %	–9.00 %	–2.00 %	–
B7	–	–	–	–	–	–50.00 %	–	–	–
B8	–	–	–	–7.00 %	–	–60.00 %	–	–	–
B9	–12.00 %	–	–	–	–5.00 %	–	–	–	–
B10	–	–	–	–	–	–	–	–	–
C1	–	–	–7.00 %	-10.00 %	–	–	–	–	–
D1	–7.00 %	–	–	–	–	–	–	–	–
D2	–	–5.00 %	–	–	–	–	–	–0.00 %	–
CMB1	–	-	-12.00 %	–26.00 %	–14.00 %	–	–13.00 %	–2.00 %	–61.00 %
CMB2	–	–	–15.00 %	–	–	–	–32.00 %	–4.00 %	–

CMB1 and CMB2 refer to the combined RCOs options described in Table 4.

- *SHIP#3*: This vessel presents not only single RCOs but also combinations of multiple RCOs. The PLL reduction is in a range between 7 to 15 %. The lowest reduction is given by configurations B4 and C1, while the highest is provided by the RCO combination C1 + B4. Solution A2 achieves a reduction of 8 % and the combination C1 + A2 of 12 %. The values obtained for the single RCOs solutions indicate that the placement of the devices is made in a fairly good way. The combinations of multiple RCOs increases the value obtained by individual solutions but is still affected by the original placement of the single devices.
- *SHIP#4*: This vessels considers both single and combinations of RCOs. The PLL reduction ranges from 7 % to 26 %. The lowest reduction is given by RCOs A2 and B8, while the highest value is reached by solution A2 + B8. Configuration C1 obtains a reduction level around 10 %. The values of the reduction obtained by the single RCOs solution indicates a fairly good placement of the devices. The combination A2 + B8 is much more effective than the single RCOs, however the reduction level is still influenced by the original placement of the single RCOs.
- *SHIP#5*: The vessel presents both single and combinations of RCOs. The PLL reduction range is between 5 % and 14 %. The lowest reduction is for configuration B9 while the highest is for the combination B3 + B9. The configuration B3 reaches an intermediate value of 9 %. The values obtained for the single RCOs indicate a fairly good placement of the RCOs. The combination B3 + B9 achieves a higher value combining the positive effect of both the RCOs employed, but is still affected by the original placement of the individual RCOs.
- *SHIP#6*: This vessel presents only solutions with single RCOs. The PLL reduction range is between 5 % and 60 %. The lowest value is provided by the configuration A2, while the highest is given by configuration B8. All the remaining configurations (B4, B5, B6 and B7) presents high PLL reduction levels, all above 50 %. The low level of reduction of configuration A2 indicates a non optimal placement of the fixed foam installations. On the contrary, the really high efficiency of all the crashworthy solutions implying the application of a double hull indicates an optimal placement of the devices.
- *SHIP#7*: This ship present individual RCOs and combinations between different RCOs. The PLL reduction ranges form 2 % to 32 %, with the higher value registered for the combination A2 + B5 + B6 and the lower value for configuration B2. Configuration B6 has a reduction of 9 % and configuration A2 of 20 %. The value of PLL reduction obtained for configuration A2 indicates a good placement of the permanent foam installation, while the low value for configuration B2 indicates that the placement is not optimal to reduce the impact of critical damages. The good reduction level obtained for the combinations of different RCOs inherits the goodness and weaknesses of the single placement of the individual RCOs.
- *SHIP#8*: This vessel present both single and combination of RCOs. The PLL reduction is in the range between 0 % and 4 %. The lowest value is for configuration D2 while the highest value is for combination B5 + B6. All the other solutions present a reduction of 2 %. The low reduction level obtained by all the RCOs solutions indicate that the placement of the devices is not good to reduce flooding risk. This is the case for both crashworthy solutions and placement of foam installations. Also the reinforcement of doors in the bulkhead deck is practically ineffective for this ship.
- *SHIP#9*: This ship presents both individual and combinations of RCOs. The PLL reduction ranges between 23 % and 61 %, with the lowest value for solution A1 and the highest for the combination D2 + A2. This is the only vessel implementing solution A1, which is effective with a 23 % of PLL reduction indicating a good placement of the deployable barriers in the car deck. The high value registered for solution A2 (about 43 %) indicates a really good placement of the foam installations along the hull. The really high value obtained by combination D2 + A2 inherits the benefits obtained by the individual RCOs.

The results obtained by the design teams on the different ships implementing different RCOs highlights the extreme subjectivity of the design choices. In fact, the results does not allow to perform a precise ranking among the RCOs as some of them are really effective on certain ships and ineffective on others. This is the case of both permanent foam installations and crashworthy structures, where the placement of the RCO is crucial to obtain a good PLL reduction.

A small ranking between RCOs can be done for crashworthy structures only for the case of Ship#6, where all the RCOs have been implemented in the same range of the ship. In this case, it is evident that the best solution is given by configuration B8, which consists of a double hull with offset B/20 and thickness 17 mm, followed by configuration B5 (double hull at B/10 with thickness 12 mm) and B4 (double hull at B/20 with thickness 12 mm).

In any case, the Level 1 PLL calculations highlights that both crashworthy solutions and foam installations can be employed by designers to reduce flooding risk, while performing an appropriate selection of

Table 6
PLL Level 2.1 (1/ship year) reduction of the selected RCOs.

ID	SHIP#1	SHIP#2	SHIP#3	SHIP#4	SHIP#5	SHIP#6	SHIP#7	SHIP#8	SHIP#9
none	1.7730 100.00 %	0.7840 100.00 %	0.8334 100.00 %	0.1955 100.00 %	0.3649 100.00 %	0.6154 100.00 %	0.9313 100.00 %	1.2542 100.00 %	0.4677 100.00 %
A1	–	–	–	–	–	–	–	–	–23.00 %
A2	–	–	–	–	–	–	–	–	–43.00 %
B1	–	–	–	–	–	–	–	–	–
B2	–	–	–	–	–	–	–	–	–
B3	–	–	–	–	–	–	–	–	–
B4	–	–	–	–	–	–	–	–	–
B5	–	–	–	–	–	–	–	–	–
B6	–	–	–	–	–	–	–	–	–
B7	–	–	–	–	–	–	–	–	–
B8	–	–	–	–	–	–	–	–	–
B9	–	–	–	–	–	–	–	–	–
B10	–	–	–	–	–	–	–	–	–
C1	–	–	–	–	–	–	–	–	–
D1	–5.00 %	-	–	–	–	–	–	–	–
D2	–	–5.00 %	–	–	–	–	–	–1.00 %	–
CMB1	–	–	–12.00 %		–	–	–	–	–61.00 %
CMB2	–	–	–16.00 %	–	–	–	–32.00 %	–4.00 %	–

CMB1 and CMB2 refer to the combined RCOs options described in Table 4.

the regions where to apply the RCOs. These considerations are purely based on static calculations; therefore, it is relevant to investigate also the RCO behaviour at a higher confidence level, meaning at a Level 2.1.

6.2. Level 2.1 assessment

To increase the reliability on the effect of RCOs in reducing flooding risk, it is advisable to use direct tools at least for the damage stability calculations, means assess the risk at a Level 2.1. As described in Section 2, the assessment at a Level 2.1 is performed through the employment of dynamic rigid body calculations in time-domain. This approach is much more time consuming than the static evaluation of a design configuration; therefore, designers decided to test at a Level 2.1 a small amount of RCOs.

Table 6 shows the results of the PLL calculations at a Level 2.1, comparing the obtained results with the one of the configuration without RCOs reported in Table 2. The results, for the few RCOs tested, are in line with the reduction levels observed for the Level 1 calculations, highlighting differences of at most 2 %. To better understand the reduction levels achievable with a Level 2.1 prediction it is worthy analyse the results ship by ship:

- *SHIP#1*: For this ship, only condition D1 has been tested. The PLL reduction in this case is 5 %, which is in line with the prediction obtained at a Level 1, with a variation of 2 %. However, the absolute value of the PLL is different as highlighted in Tables 6 and 2.
- *SHIP#2*: For Ship#2 only configuration D2 has been tested at a Level 2.1. The PLL reduction is 5 % compared to the condition without RCOs. In this case, the reduction level is exactly the same of the Level 1 prediction. Also in this case, the absolute value of the PLL is different between the two levels of prediction.
- *SHIP#3*: For Ship#3 two combined configuration have been tested, C1 + A2 and C1 + B4. Condition C1 + A2 has a PLL reduction of 12 %, which is exactly the same of the Level 1 prediction. Condition C1 + B4 has a 16 % of PLL reduction, which i 1 % more than the Level 1 prediction. Also in this case, the absolute value of PLL between the two levels of prediction is different.
- *SHIP#4*: No RCOs have been analysed for this ship at a Level 2.1.
- *SHIP#5*: No RCOs have been analysed for this ship at a Level 2.1.
- *SHIP#6*: No RCOs have been analysed for this ship at a Level 2.1.
- *SHIP#7*: For Ship#7, only the combined solution A2 + B5 + B6 has been tested. The calculated PLL reduction is 32 % which is exactly the same as the Level 1 prediction, but with a different absolute value.
- *SHIP#8*: For Ship#8 the condition D2 and the combined solution B5 + B6 have been tested at a Level 2.1. The PLL reduction registered for case D2 is of 1 %, which is 1 % higher than the reduction observed with the Level 1 prediction. For case B5 + B6, the resulting PLL value is 4 %, which is the same as Level 1 prediction. Also in this case the absolute value of the PLL is different between the two prediction levels.
- *SHIP#9*: For Ship#9, all the configurations tested at a Level 1 have been assessed also with Level 2.1 predictions. For all the three cases, the PLL reduction in percentage is exactly the same as the Level 1 predictions. Of course, the absolute value of the PLL is different between the prediction levels.

The prediction at Level 2.1 have almost the same PLL percentage reduction as the Level 1 prediction, thus they give the same design indications. However, the reliability of a Level 2.1 prediction is much higher than the Level 1, due to the application of first principle tools for the prediction. Therefore, the absolute PLL value provided by the Level 2.1 prediction is more accurate than the Level 1, thus is better applicable for flooding risk considerations.

Also in this case it is not possible to give a ranking between the different RCOs solutions because the obtained values are strongly influenced by the designers choices. Also here we have cases like for Ship#9, where the level of PLL reduction is consistent and cases like Ship#8 where the influence of RCOs is minimal.

7. General remarks

The results presented in Section 6 highlight some considerable indications on the applicability of RCOs onboard ships. As a first result, it is evident that the design team has a strong influence in the successful installation of a risk mitigation device. In fact, there are a lot of discordant results concerning the effectiveness of certain RCOs comparing different ships. For ships like Ship#6 the risk reduction level for the crashworthy structures is really high, reaching percentage of reduction around 60 % (according to a Level 1 prediction), while for vessels like Ship#8 there is only the 2 %. The same for Ship#9 with the effectiveness of foam installations (up to 61 % of PLL reduction both at Level 1 and Level 2.1), while Ship#1 or Ship#8 show a few percentage points of PLL reduction. It is evident that good results could be achieved by a good understanding of the initial flooding risk calculations, which allow for a clear identification of the most vulnerable ares where to implement RCOs.

Another important consideration is on the ranking between the different RCOs. Unfortunately none of the research team decided to implement all the risk control options available. Then a fair comparison among the RCOs cannot be done as it is influenced by the choices of the design teams. However, a small ranking can be performed for Ship#6, where the designers implemented all the kinds of double hulls available by the crashworthy modelling. In this case, the most effective solution is given by configuration B8, meaning a double hull at B/20 with thickness 17 mm. Afterwards, we have solutions B5 (double hull at B/10 with thickness 12 mm) and B4 (double hull at B/20 with thickness 12 mm). However, as the trend is not confirmed by any other test ship, it is impossible to make a real ranking between them. Noteworthy is the application of combination of RCOs, all the ships that were equipped with combinations of RCOs leads to higher level of PLL reduction, gaining the benefits of all the single RCOs. Therefore, a way towards increasing the risk reduction is going through the application of multiple RCOs onboard the same vessel.

A relevant consideration is concerning the calculation level of the framework for risk assessment. Both Level 1 and Level 2.1 predictions give the same percentage level of PLLreduction for all the considered RCOs. This is relevant because a fast prediction at a Level 1 could give a fast indication to designers concerning the efficacy of a certain RCO, without spending too much calculation time. Therefore, the Level 1 prediction could be a useful preliminary design tool for risk assessment that can guide designer in the correct path for a successful safe ship design. On the contrary, the absolute level of PLL is much different between Level 1 and Level 2.1 predictions. Then, for a correct evaluation of flooding risk, the usage of a Level 2.1 is suggested. This implies the execution of multiple time-domain simulations which are harder to implement and compute compared to static predictions. However, thanks to the multi-level risk assessment framework, the evaluation of risk at Level 2.1 can be reduced to the final configuration selected after a preliminary screening with a Level 1 assessment.

In conclusion, the implementation of RCOs has a good potential in reducing the risk of flooding onboard ship, especially while implementing crashworthy solutions or foam installations (and combinations of them). However, the intensive application of RCOs onboard may change the entire design of a passenger ship, from the selection of the main dimensions up to the decision of the internal layout. It is, therefore, necessary to continue the research n this field for the design of future safer ship, looking at risk prevention rather then risk protection.

8. Conclusions

The present paper reports the application of a multi-level flooding risk assessment framework for the assessment of different RCOs to be installed onboard ships. The framework has been tested on 9 reference vessels analysed by 9 different design teams, free to apply they design philosophies to the implementation of risk control option for flooding. Among the different possibilities, the set of RCOs to be implemented are composed of active and passive foam systems, crashworthy structures and changes in internal layout or openings. As mentioned, the design teams selected the RCOs to apply to their ship according to their design strategies to reduce risk and evaluate the PLL at a Level 1 and Level 2.1. The proposed solutions consider both single RCOs and combinations of different solutions in order to maximise the PLL reduction.

All RCOs have been assessed at a Level 1, obtaining discordant results along the design teams. Some vessels highlight high reduction of risk by implementing crashworthy solutions or foam installations, others show exiguous changes in PLL. In general, the possibility of changing the internal layout or the protection of critical openings is not providing a consistent PLL reduction. In particular, the results obtained for Ship#6 in implementing crashworthy structures and for Ship#9 in foam applications shows percentage of reduction up to 60 %. This is the result of a good analysis of the preliminary flooding risk calculations on the initial ship configuration. On the contrary, Ship#8 highlights few percentage of reduction by applying any kind of RCOs. This is a case of not good evaluation of preliminary results.

Unfortunately, not all the RCOs have been tested at Level 2.1, due to the lack of time or for difficulties in preparing much more complicated calculations. However,the calculations performed show percentage of PLL reduction in line with the Level 1 prediction. Of course, the absolute value of the PLL between a Level 1 and a Level 2.1 is different.

Therefore, it can be concluded that a preliminary prediction at a Level 1 is sufficient to evaluate whether an RCO is effective or not in reducing the risk of flooding onboard the ship. However, for a detailed quantification of risk, the employment of a more advanced prediction tool is advisable, thus choosing for at least a Level 2.1 prediction.

Because none of the design team selected to implement all the available RCOs tho their ships, it is not possible to make a ranking among the different RCOs. However, the study highlights that both foam and crashworthyness can reach the same high level of risk reduction. Then, the correct implementation of RCOs is a valuable solution to reduce the risk due to flooding. This is a really important measure to prevent the risk of flooding instead of protect the ship in case of a flooding event. In fact, solutions like crashworthyness or permanent foam installations act in the direction of limit the occurence of a dangerous flooding event. The intensive application of RCOs onboard a vessel could have a consistent impact on the design of future ship, potentially changing the design of the whole vessel. Therefore, it is of utmost importance to continue in focalising the research in this direction, for designing future safer ships.

CRediT authorship contribution statement

Francesco Mauro: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Donald Paterson:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation; **Dracos Vassalos:** Writing – review & editing, Supervision, Methodology.

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.

Acknowledgments

The authors would like to thank all the partners of the EU funded project FLARE.

References

Aven, T., 2012. The risk concept - historical and recent development trends. Reliab. Eng. Syst. Saf. 99, 33–44.
Aven, T., 2022. A risk science perspective on the discussion concerning safety i, safety II and safety III. Reliab. Eng. Syst. Saf. 217, 108077.
Bai, Y., Paik, J.K., 2024. Risk Assessment and Management for Ships and Offshore Structures. Elsevier, The Netherlands.
Buldgen, L., Sourne, H.L., Besnard, N., Rigo, P., 2012. Extension of the super-elements method to the analysis of oblique collision between two ships. Mar. struct. 29, 22–57.
Bulian, G., Cardinale, M., Dafermos, G., Eliopoulou, E., Francescutto, A., Hamman, R., Linderoth, D., Luhmann, H., Ruponen, P., Zaraphonitis, G., 2019a. Considering collision, bottom grounding and side grounding/contact in a common non-zonal framework. In: Proceedings of the 17th International Ship Stability Workshop. Helsinki, Finland.
Bulian, G., Cardinale, M., Dafermos, G., Linderoth, D., Ruponen, P., Zaraphonitis, G., 2020. Probabilistic assessment of damaged survivability of passenger ships in case of grounding or contact. Ocean Eng. 218, 107396.
Bulian, G., Cardinale, M., Francescutto, A., Zaraphonitis, G., 2019b. Complementing SOLAS damage ship stability framework with a probabilistic description for the extent of collision damage below the waterline. Ocean Eng. 186, 106073.

Bulian, G., Linderoth, D., Ruponen, P., Zaraphonitis, G., 2016. Probabilistic assessment of damaged ship survivability in case of grounding: development and testing of a direct non-zonal approach. Ocean Eng. 120, 331–338.

Cardinale, M., Särkka, J., Bertin, R., Wurst, S., Murphy, A., Hamann, R., Paterson, D., Conti, F., 2022. D7.2 Analysis of Risk Control Options. Technical Report. WP 7 Project FLARE.

Conti, F., Sourne, H.L., Vassalos, D., Kujala, P., Linderoth, D., Kim, S., Hirdaris, S., 2022. A comparative method for scaling SOLAS collision damage distributions based on a ship crashworthiness application to probabilistic damage analysis of a passenger ship. Ship Offshore Struct. 17 (7), 1498–1514.

Egge, E.D., Bockenhauer, M., 1991. Calculation of the collision resistance of ships and its assessment for classification purposes. Mar. struct. 4 (1), 35–56.

EMSA, 2020. Study assessing the acceptable and practicable risk level of passenger ships related to damage stability. Technical Report. European Maritime Safety Agency.

FLARE, 2022. FLooding Accident REsponse. Technical Report. EU Horizon 2020, 2019–2022.

Hamann, R., Breuillard, A., Luhmann, H., Papanikolaou, A., Wurst, S., 2022. D8.1 Assessment of Measures Mitigating Flooding Risk of Passenger Ships. Technical Report. WP8 project FLARE.

IMO, 2009. International Convention for the Safety of Life at Sea (SOLAS). Technical Report. International Maritime Organisation, consolidated edition as of 2009.

IMO, 2020. International Convention for the Safety of Life at Sea (SOLAS). Technical Report. International Maritime Organisation, consolidated edition as of 2020.

Jasionowski, A., 2001. An integrated approach to damage ship survivability assessment. Ph.D. thesis. University of Strathclyde.

Kang, H.J., Kim, I., Choi, J., Lee, G.J., Park, B.J., 2018. A concept study for the buoyancy support system based on the fixed fire-fighting system for damaged ships. Ocean Eng. 155, 361–370.

Luhmann, H., Cardinale, M., Bertin, R., Ochs, T., Kujanpä, J., Murphy, A., 2022. D2.7 Description of Sample Ships. Technical Report. WP 2 project FLARE.

Mauro, F., Conti, F., Vassalos, D., 2023a. Damage surrogate models for real-time flooding risk assessment of passenger ships. Ocean Eng. 285, 115716.

Mauro, F., Vassalos, D., 2022. The influence of damage breach sampling process on the direct assessment of ship survivability. Ocean Eng. 250, 111008.

Mauro, F., Vassalos, D., 2024a. The importance of first-principles tools in estimating passenger ship safety. Ocean Eng. 305, 117949.

Mauro, F., Vassalos, D., 2024b. Time to capsize for damaged passenger ships in adverse weather conditions. a multi-modal analysis. Ocean Eng. 299, 117409.

Mauro, F., Vassalos, D., Paterson, D., 2022a. Critical damages identification in a multi-level damage stability assessment framework for passenger ships. Reliab. Eng. Syst. Saf. 228, 108802.

Mauro, F., Vassalos, D., Paterson, D., Boulougouris, E., 2022b. Exploring smart methodologies for critical flooding scenarios detection in the damage stability assessment of passenger ships. Ocean Eng. 262, 112289.

Mauro, F., Vassalos, D., Paterson, D., Boulougouris, E., 2023b. Evolution of ship damage stability assessment - transitioning designers to direct numerical simulations. Ocean Eng. (268), 113387.

Montewka, J., Manderbacka, T., Ruponen, P., Tompuri, M., Mateusz, G., Hirdaris, S., 2022. Accident susceptibility index for passenger ships-a framework and case study. Reliab. Eng. Syst. Saf. 218, 108145.

Mujeeb-Ahmed, P., Vassalos, D., 2022. D5.14 flooding risk model. Technical Report. WP5 Eu funded project FLARE.

Mujeeb-Ahmed, P., Vassalos, D., Boulougouris, E., 2021. Development of collision and grounding accident database for large passenger ships. In: Proceedings of the 1st International Conference on the Stability and Safety of Ships and Ocean vehicles (STAB&S 2021).

Naar, H., Kujala, P., Simonsen, B.C., Ludolphy, H., 2002. Comparison of the crashworthyness of various bottom and side structures. Mar. struct. 15, 443–460.

NAPA, 2025. Napa stability. https://www.napa.fi/software-and-services/ship-operations/napa-stability/.

Paik, J.K., 2020. Advanced Structural Safety Study with Extreme Conditions and Accidents. Springer, Singapore.

Paterson, D., Vassalos, D., Atzampos, G., Boulougouris, E., Luhmann, H., 2019. Impact of drafts on the damage survivability of cruise ships. Ocean Eng. 187, 106136.

Pawlowski, M., 2004. Subdivision and Damaged Stability of Ships. Euro-MTEC book series, Gdansk, Poland.

Pedersen, P.T., 1994. Ship grounding and hull-girder strength. Mar. struct. 7 (1), 1–29.

Ruponen, P., van Basten-Batemburg, R., Veer, R.v., Braidotti, L., Bu, S., Dankowski, H., Lee, G.J., Mauro, F., Ruth, E., Tompuri, M., 2022a. International benchmark study on numerical simulation of flooding and motions of a damaged cruise ship. Appl. Ocean Res. 129, 103403.

Ruponen, P., Linderoth, D., Routi, A.L., Aartovaara, M., 2019. Simulation-based analysis method for damage survivability of passenger ships. Ship Technol. Res. 66 (3), 180–192.

Ruponen, P., Valanto, P., Acanfora, M., Dankowski, H., Lee, G.J., Mauro, F., Murphy, A., Rosano, G., Veer, R.v., 2022b. Results of an international benchmark study on numerical simulation of flooding and motions of a damaged ropax ship. Appl. Ocean Res. 123, 103153.

SHIPPAX. Shippax database. https://www.shippax.com, Accessed on 23rd November 2019.

Sourne, H.L., 2020. The super-element method for ship collision and grounding fast analysis. In: Proceedings of the International Conference of Ship and Offshore Structures, ICSOS.

Tompuri, M., Bertin, R., Conti, F., Hirdaris, S., Kujala, P., Paterson, D., Routi, A.L., Ruponen, P., Vassalos, D., 2020. D6.5 Technical aspects for different risk control measures for flooding. Technical Report. WP6.3.1 Project FLARE.

Vassalos, D., 2016. Damage survivability of cruise ships - evidence and conjecture. Ocean Eng. 121, 89–97.

Vassalos, D., 2020. The role of damaged ship dynamics in adressing the risk of flooding. Ship Offshore Struct. , 1–25.

Vassalos, D., Boulougouris, E., Paterson, D., 2016. An alternative system for damage stability enhancement. In: Proceedings of the 15th International Ship Stability Workshop. Stockholm, Sweden.

Vassalos, D., Ikeda, Y., Jasionowski, A., Kuroda, T., 2004. Transient flooding on large passenger ships. In: Proceedings of the 7th International Ship Stability Workshop. Shanghai, China.

Vassalos, D., Mujeeb-Ahmed, P., Paterson, D., Mauro, F., Conti, F., 2022a. Probabilistic damage stability for passenger ships - the p-factor illusion and reality. J. Mar. Sci. Eng. 10 (3), 348.

Vassalos, D., Paterson, D., 2021. Towards unsinkable ships. Ocean Eng. 232, 109096.

Vassalos, D., Paterson, D., Mauro, F., Atzampos, G., Assinder, P., Janicek, A., 2022b. High-expansion foam: a risk control option to increase passenger safety during flooding. Appl. Sci. 12 (10), 4949.

Vassalos, D., Paterson, D., Mauro, F., Boulougouris, E., 2021. Life-cycle stability management for passenger ships. In: Proceedings of the 31st International Ocean and Polar Engineering Conference, ISOPE. Rhodes, Greece.

Vassalos, D., Paterson, D., Mauro, F., Mujeeb-Ahmed, M.P., Murphy, A., Michalec, R., Boulougouris, E., 2022c. A lightning intact and damage stability in a multi-level assessment framework. In: Proceedings of the 18th International Ship Stability Workshop. Gdansk, Poland.

van't Veer, R., Peters, W., Rimpelä, A.L., de Kat, J., 2004. Exploring the influence of different arrangements of semi-watertight spaces on survivability of a damaged large passenger ship. In: Proceedings of the 7th International Ship Stability Workshop. Shanghai, China.