Proceedings of 15th International Marine Design Conference (IMDC-2024)
June 2-6, 2024
Amsterdam, the Netherlands

The importance of first-principles tools for safety enhancement in the design of passenger ships in the case of flooding events.

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ABSTRACT

The design of a passenger ship is a complex process covering multiple aspects of naval architecture and marine engineering to address performance, functionality safety, and cost as primary objectives. Between them, safety is a key element focusing on the people on board. In this sense, ship safety in the case of flooding events needs proper estimation from the first stages of the design process employing an appropriate metric. To this end, safety can be evaluated as a risk by calculating the Potential Loss of Life. Thanks to a multi-level framework developed during project FLARE, it is possible to calculate the risk associated with an accident, increasing the level of reliability as the design process advances. The framework aims at employing first-principles tools from the early stages of the design process, abandoning static calculations and empirical formulae as soon as data is available to set up advanced calculation techniques. Then, the framework adopts rigid-body time-domain calculations for the flooding simulations, advanced evacuation analysis tools, and direct crash simulation to evaluate collision damages. The process allows for testing alternative design solutions for the ship to enhance safety. Investigating risk control options is also possible, considering active or passive systems such as fixed foam installations, deployable barriers, or crashworthiness. Such an approach allows for evaluating safer solutions, respecting other design constraints and cost-related aspects. The present work describes the risk assessment framework for the case of flooding events, together with the different levels of accuracy that can be achieved, showing the improvements that could be reached by employing alternative risk control options.

KEYWORDS

Risk-based design; flooding risk assessment; passenger ships; risk control options.

INTRODUCTION

The design of passenger ships is a complex process involving the concurrent evaluation of multiple aspects of Naval Architecture and Marine Engineering. Between them, damage stability is a key part of the design process, providing a lifecycle flooding risk management for the vessel (Vassalos, 2020). Consequently, the estimation of flooding risk is a relevant attribute for the design of new passenger vessels (Atzampos, 2019, Papanikolaou et al., 2013, Vanem et al., 2007). However, the approach to risk has never been deeply applied by designers, who prefer to adopt a compliant-based approach to damage stability. In recent years the trend has changed, giving more importance to the application of first principles tools in the design process of passenger ships (Vassalos, 2016), and providing designers with suitable guidelines for their application (Mauro et al., 2023a).
The application of this different kind of approach led to the formulation of a multi-level flooding risk assessment framework during the EU-founded project FLARE (Vassalos et al., 2022a), suitable for the flooding risk estimation through the whole

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Submitted: 23 Febraruy 2024, Revised: 2 April 2024, Accepted: 1 May 2024, Published: 26 May 2024

Conference paper, DOI: https://doi.org/10.59490/imdc.2024.909 e-ISSN: 3050-4864

ship lifecycle. The advantages of this framework are given by the implementation of a multi-level approach to risk, allowing a designer to choose the most appropriate tools to use during the design process, starting from simple assumptions and simulations up to perceiving fully first-principles-based predictions. The application of first-principles tools concerns principally three aspects of the flooding risk assessment, namely the damage generation, the survivability analysis and the evacuation analysis. For each topic, suitable options are available to achieve different levels in the reliability of predictions as indicated by the multi-level framework for risk assessment. Furthermore, the flexibility of the provided framework allows for the use of the first-principles tools as a design instrument for the identification and evaluation of the benefits of suitable risk control options (RCOs).
This paper presents the main concept of the multi-level framework for risk assessment for the specific case of the design phase of a passenger ship. A description of the main first-principles tools is provided for the generation of breaches, flooding simulations and evacuation analysis. To demonstrate the applicability and flexibility of the multi-level framework, a worked example is presented on two reference ships, a cruise and a Ro-pax, highlighting how first-principles-based tools can be used also for the design of RCOs, like the implementation of fixed foam installations, deployable barriers, and crashworthy structures. Simulations are performed with different levels of reliability, highlighting how the application of first principles tools influences not only the general estimation of the risk level but also the impact of each selected RCO on the reduction of risk. Finally, the obtained results raise questions on the actual praxis in passenger ships'design, highlighting how the application of active or passive RCOs may change the attained flooding risk level of a vessel without the need for searching for more capillary compartmentation of the internal layouts.

FLOODING RISK ASSESSMENT FRAMEWORK

The assessment of flooding risk during the design phase of a passenger ship (or ship in general) passes through the recursive execution of the following main points:

1. Definition of calculation scenarios and ship main particulars.
2. Flooding risk evaluation.
3. Identification of suitable vulnerability mitigation measures.
4. Reassessment of the flooding risk.

These steps relate to the design of a new unit as well as to the retrofitting of an existing vessel or a change in the operational profile of the ship.
The risk can be measured through the Potential Loss of life (*PLL*), which follows the general formulation of risk as given by the following equation:

$$PLL = p_f \cdot c_f \quad [1]$$

p_f represents the probability of flooding and c_f is the consequence of the flooding event. For the evaluation of risk during the project of a passenger ship it is necessary to identify an attained index PLL_A to be compared with a tolerable level of risk. In case all the vessel life-cycle has to be taken into account, a more general model for PLL_A can be considered, evaluating the attained PLL_A per year of service (PLL_A^*), which provides more flexibility to assess multiple operational scenarios. Then, the definition of PLL_A^* for every single scenario has the same form of equation [1] but with a more in-depth definition of p_f and c_f.

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

In equation [2], N_{hz} is the number of possible hazards (which corresponds to collision, bottom and side groundings, i.e. N_{hz}=3), N_{op} is the number of operational areas (open seas, restricted or port areas), N_{ld} is the number of loading conditions and N_c is the number of flooding cases (depending on the ship subdivision). Consequently, the associated probabilities and consequences of an event have the following formulations:

$$p_{f_{i,j,k,h}} = p_{hz_i} \cdot p_{op_j} \cdot p_{ld_k} \cdot p_{c_h} = p_{hz_i} \cdot p_{op_j} \cdot p_{ld_k} \cdot p_{c_h}^* \left(1 - s_{c_h}\right) \quad [3]$$

$$c_{f_{i,j,k,h}} = FR_{i,j,k,h} \cdot POB_{i,j,k,h} \quad [4]$$

The probabilities described by equation [3] result from the statistical analysis of damage databases, specifically for passenger ships. The probabilities of the damage case can be described by employing the common definition of the p and s-factors (Pawlowski, 2004, IMO,2009, Vassalos et al., 2022b). On the other hand, equation [4] describes the consequences of a hazard, which are given by the fatality rate *FR* and the number of people onboard *POB*. All the quantities change scenario by scenario, thus, the final risk assessment requires the execution of $N=N_{hz}N_{op}N_{ld}N_c$ scenarios to be assessed with flooding survivability and passenger evacuation tools.

The resulting number of scenarios is considerably high as is the computational load, but they can be reduced by applying the concept of a multi-level framework, employing different types of tools according to the level of accuracy required by different stages in the vessel life cycle. This is of utmost importance, especially for the design phase.

Multi level-framework

The studies performed during Project FLARE led to the definition of calculation frameworks, initially oriented to survivability only and subsequently extended to risk. Such frameworks provide a connection between the research-oriented vision of the flooding problem and the designer and operators' practical point of view (Mauro et al. 2023a). A global first-principle characterization of flooding risk is difficult to achieve because of the calculation time and availability of suitable codes. Therefore, a multi-level approach, with consequent multi-fidelity results, significantly improves in-force damage stability frameworks for passenger ships.

The main assumptions of the multimodal framework refer to three characteristics of the flooding process determination: the occurrence, the survivability and the fatality in a given scenario. Therefore, the definition of *PLLA** of equation [2] assumes the following form for the case of a single scenario:

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

According to equation [5], the probabilities and weights associated with the scenario occurrence are identified by p^*, while s describes the scenario's survivability and c_f the consequences as per equation [4]. Concerning the probabilities, the occurrence is identified during the input preparation phase of a Level 1 survivability assessment. Level 1 or Level 2 damage stability calculations determine survivability, while evacuation analyses determine fatality.

Therefore, the definition of the levels in the multi-level framework is as follows:

- *PLL Level 1*: the approach is fully based on static damage stability calculations. The expected number of fatalities depends on the time it takes the vessel to capsize, and the static analysis does not account for time. Then, the estimation of fatality rate in this stage needs some approximation. To keep the methodology as simple as possible and to account for the dependencies between survivability and fatality rate, the following extremely simplifying assumption is made:

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

  This simple and conservative approach follows the method used in the EMSA III Project, the results of which were used to support political decisions at IMO, leading eventually to SOLAS 2020 regulations for damage stability.
- *PLL Level 2*: The main additional parameters distinguishing Level 2 from Level 1 flooding risk estimation are the Time to Capsize *TTC* and the Time to Evacuate *TTE*. The *TTC* describes the time it takes the vessel to capsize/sink after a flooding event occurs. Therefore, the use of *TTC* requires the execution of time-domain flooding simulations, thus neglecting the static approach. The *TTE* defines the time necessary for an orderly evacuation of passengers and crew onboard a passenger ship after a flooding hazard occurred. Hence, the *TTE* determination implies the execution of time-domain evacuation analyses. However, according to the multi-level framework, also simplified methods oriented to a fast TTE evaluation are available, providing two sub-levels for the Level 2 analysis. Such options are:
  - *PLL Level 2.1*: for this level of approximation, only time domain flooding simulations are required to determine TTC. Evacuation analyses for TTE evaluation are omitted; therefore, an empirical formulation is needed to derive *FR* as follows:

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

    where n is the maximum allowable evacuation time in minutes according to MSC.1/Circ. 1533. The assumption on *FR* intrinsically considers the nature of the capsize event as a function of the *TTC*, assuming the impossibility of evacuating the ship during fast transient capsizes cases.
  - *PLL Level 2.2*: In this level the direct evaluation of *TTE* is considered. Starting from significant cases described by time-domain flooding simulations, where it is realistic to proceed with an evacuation analysis, ship motions and floodwater can be imported in the evacuation software. Such a coupling allows comparing the evacuation process and the associated *TTC*.

The full details, justifications and also applied examples for the FLARE multi-level risk framework are provided by Vassalos et al. (2022b) and are not rediscussed here for the sake of brevity. The individual definition of probabilities and values associated with occurrences, survivability and fatality changes not only with the selected level between the above-presented options but is also depend upon the phase of interest during the vessel life-cycle. Here the focus is on the design phase.

Design Phase framework

The application of a risk framework for the design phase of a passenger ship implies the definition of the main inputs and all parameters in equation [2] to allow the evaluation of PLL_A*, with input and information available in this specific stage of the vessel life cycle. Moreover, the application of the framework during the design phase requires to refer to regulations, assumptions, and outputs relevant to the statutory damage stability framework. This reflects in the selection of the frequencies and probabilities associated with the occurrence, survivability and fatality of a scenario and, consequently, in the generation of the cases to be analysed. The focal points can be summarised as follows:

- *Possible hazards*: the framework handles three kinds of casualties (N_{hz}=3); collisions, side, and bottom groundings. These hazards imply the adoption of specific frequencies of occurrence p_{hz}, corresponding to the relative weights w used to define the A-index in the damage stability frameworks. Suitable values for p_{hz} derive from database analyses and are reported in Vassalos et al. (2022b) with the associated w.
- *Operational areas*: Only the open sea (N_{op}=1) is taken into account for design purposes, restricting the wave conditions to a representative sea state that corresponds to a significant wave height H_s of 4 metres. When assessing risks at Level 1 or Level 2, such an assumption is taken into account.
- *Loading conditions*: the framework adopts two drafts T_1 and T_2 with the same weight on the final assessment and corresponding to 0.45 and 0.75 times the design draught of the ship, respectively. Such an assumption is maintained across the levels and does not follow the SOLAS standards, which are based on three draughts. The assumption has been promoted by designers during the activities of Project FLARE (Vassalos et al, 2022c).
- *Calculation scenarios*: Depending on the level chosen for the risk assessment, there are a different number of scenarios. 10,000 breaches are created for every type of danger in order to produce a Level 1 prediction, sampling the location and dimensions from relevant cumulative distributions. The number of scenarios is lowered to 1,000 breaches for each danger since time-domain simulations take longer to complete than a static approach. The damage distributions mentioned in Levels 1 and 2 are the same as those in SOLAS for collisions and EMSA III for bottom and side groundings.

According to the given assumptions, equation [2] can be modified by rewriting the occurrence terms provided by equation [3], resulting in the following final formulations valid for Level 1 and Level 2 predictions, respectively:

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

$$PLL^{*}_{A\,Level2} = \sum_{i=1}^{3}\sum_{k=1}^{2}\sum_{h=1}^{1,000} p_{hz_i}\, p_{ld_k}\, p^{*}_{c_h}\left(1-s_{c_h}\right)FR_{i,,k,h}POB_{i,k,h} \qquad [9]$$

the two equations differentiate themselves mainly in the determination of the scenario's occurrence p_c* and the final number of scenarios N_c. Such differences are strictly connected with the level of damage stability calculations. The generation of breaches is equivalent between Level 1 and Level 2, following a non-zonal approach requiring the sampling damage characteristics with an enhanced Randomised Quasi-Monte Carlo technique. But by using a static assumption (Level 1), it makes no sense to make a distinction between instances that harm the same set of internal compartments. Therefore, the final amount of scenarios to evaluate is N_c*<10,000 and strictly depends on the ship's internal layout. All cases referring to the same damaged compartments are grouped to determine the scenario occurrence p_c*. Conversely, when using dynamic simulations (Level 2), the grouping becomes impossible because the breach's diameter affects how much water enters and exits the system. Then, for Level 2 calculations, all cases are equiprobable and all the 1,000 scenarios are considered with the same p_c*. The Level 2 framework permits a hybrid approach, taking into account only the case with the higher breach longitudinal area resulting from static calculations (Mauro et al. 2023a). Regardless, FLARE's recommendations and advancements are meant to standardise the use of dynamic analyses in the damage stability evaluation of passenger ships, leading to the selection of Level 2 flooding risk assessment.

Concerning evaluating the consequences and *FR* in particular, preliminary calculations performed during the FLARE project highlight small differences between Level 2.1 and Level 2.2 assessments (Vassalos et al., 2022c). The application of Level 2.2 design phase evaluation on one cruise ship and one Ro-pax highlights the significant equivalency of the final risk level that is reached, whether or not sophisticated evacuation analyses are used.

However, it is of utmost importance to encourage the application of first principle tools for increasing the reliability of the results since the first stages of a design, promoting their application for the generation of breaches, the flooding simulations and the evacuation analyses. This will be discussed in the following sections, together with the applications of measures to mitigate the risk and how to use first-principles tools to reduce the global risk onboard a passenger ship.

FIRST PRINCIPLES TOOLS FOR FLOODING RISK

The determination of flooding risk during the design process of a passenger ship implies the evaluation of different components of risk, both for the frequencies and consequences estimation. In dealing with the flooding of ships, the first step is determining the source of the flooding, which means establishing how the flooding breach has been generated. Secondly, the flooding process needs to be analysed for the associated environmental conditions, determining the flooded compartments and the time to a possible sinkage/capsize event. Finally, in case there is sufficient time before a capsize event, it is necessary to simulate the evacuation process for the ship.
For all the issues mentioned above, there are different available solutions for identifying the associated relevant quantities, with different levels of approximation. Here, the focus is on employing first principle tools for the prediction of risk; therefore, the principal direct method for modelling breach dimension, flooding dynamics and evacuation will be shortly described.

Breach generation

The generation of breaches derived from collisions with other ships or grounding has a serious implication on the evaluation of flooding risk in the design process of a passenger ship. The common practice is to use simplified breach models, referring to box-shaped damages or unrealistic prismatic damages which follow the shape of the waterline of the ship (Mauro et al. 2023a). The breach dimensions and location are derived from statistical distributions based on database analyses of real accidents (Bulian et al. 2019).
However, to generate the breaches necessary to perform risk analysis, a first-principles approach can be pursued by performing a set of crash analyses. Such kind of approach implies the execution of a large number of Finite Elements Methods (FEM) analyses, considering a proper population of potential striking ships (Conti et al., 2022). Using conventional FEM simulations to assess the internal mechanics of the collision problem would be prohibitive in terms of total computation time. Therefore, the simulations can be carried out based on the Super Element Method. This method, which was introduced by Lützen (2001), consists of splitting the ship into very large-sized independent structural units (the so-called Super-Elements), for which closed-form analytical formulations are available. These formulas, which describe the resistance and energy dissipation of the Super-Element based on its type and deformation mechanism, are derived from experimental and numerical data.
Regarding the ship's external dynamics (rigid body movements of the ship due to the action of the hydrodynamic loads and the collision forces) during the collision event, they are addressed using a semi-coupled approach via the use of the MCOL solver (Le Sourne et al., 2001), the ships hydrodynamic properties being obtained using Bureau Veritas seakeeping analysis code Hydrostar (BV, 2019).

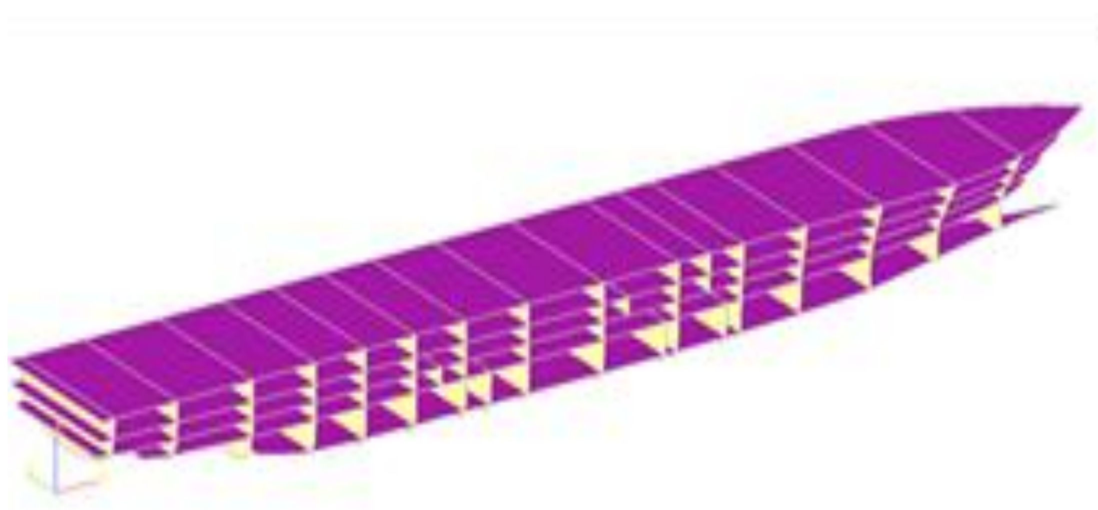

Figure 1: Example of super-element model for crash analyses.

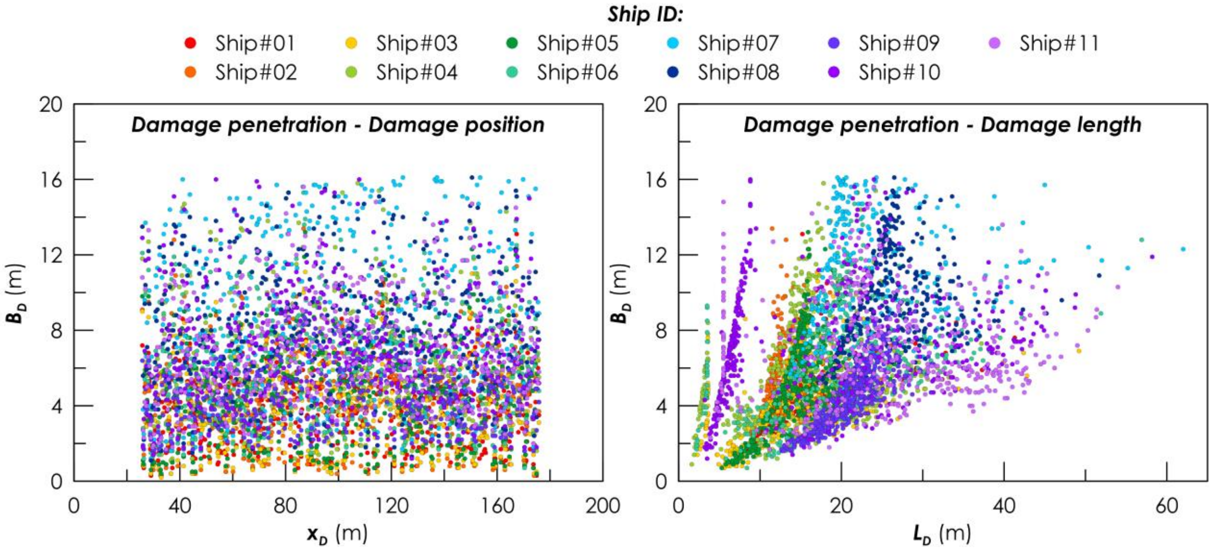

Figure 2: Example of damage dimensions derived from super-element calculations.

These two principal features are considered in the software SHARP, which allows for performing fast collision simulations. The accuracy of this method was recently reconfirmed during Project FLARE, by benchmarking against Finite Element codes (Kim et al., 2022). Furthermore, the methodology allows for building damage databases suitable not only for the generation of damages in the design stage (Conti et al., 2022) but also for the estimation of risk in real-time applications (Mauro et al., 2023b). Figure 1 gives an example of the super-element modelling of a passenger ship, while Figure 2 shows an example of the damage penetration derived from crash analyses as a function of the damage position and length.

The adoption of this direct technique to estimate the damage dimensions permits the generation of a reliable input for the damage simulations, but still following the approximation of box-shaped damages.

Flooding simulations

The assessment of the flooding process after a casualty with direct calculations implies the modelling of a complex phenomenon, coupling the motion of the ship with the behaviour of the flooding process and their relative interaction with the ship and the wave environment (Vassalos, 2020). Different levels of simplification apply to the problem modelling with associated different levels of confidence for the obtained results.

Among the possible solutions, the adoption of time-domain simulations on rigid bodies offers a good compromise between calculation time and the accuracy of the provided results. The damaged ship motions derive from fundamental motion equations as the law of conservation of linear and angular momentum. These laws normally apply to rigid bodies, thus systems where the mass is constant during the simulations; here, the floodwater changes at each time interval. The problem is approximated by extending the rigid body motion equation to the internal fluid mass, resolved in a body-fixed reference system. Then, six scalar equations are defined for linear and angular motions having the following vector form in the case of angular motions:

$$\begin{aligned}
&\left(I_s^{'}+I_w^{'}\right)\cdot\frac{\mathrm{d}}{\mathrm{d}t}\vec{\omega}^{'}+M_w\cdot\left[\vec{r}_w^{'}\times\frac{\mathrm{d}}{\mathrm{d}t}\vec{v}_{Gs}^{'}\right]+M_w\cdot\left[\left(\vec{\omega}^{'}\times\vec{r}_w^{'}\right)\times\vec{v}_w^{'}\right]+\\
&+M_w\cdot\left[\vec{r}_w^{'}\times\left[\frac{\mathrm{d}}{\mathrm{d}t}\vec{v}_w^{'}+\vec{\omega}^{'}\times\left(\vec{v}_{Gs}^{'}+\vec{v}_w^{'}\right)\right]\right]+\\
&+\frac{\mathrm{d}}{\mathrm{d}t}M_w\cdot\left[\vec{r}_w^{'}\times\left(\vec{v}_{Gs}^{'}+\vec{v}_w^{'}\right)\right]+\left(\frac{\mathrm{d}}{\mathrm{d}t}I_w^{'}\right)\cdot\vec{\omega}^{'}+\vec{\omega}^{'}\times\left[\left(I_s^{'}+I_w^{'}\right)\cdot\vec{\omega}^{'}\right]=\vec{M}_{Gs}^{'}
\end{aligned}\tag{10}$$

where I_s and I_w are the ship and internal fluid mass moment of inertia, ω is the rotational velocity vector, M_w is the internal fluid mass and r_w and v_w are the position and velocity vectors of the internal fluid mass centre. v_{Gs} is the ship velocity vector and M_{Gs} is the external moment acting on the ship. A more detailed explanation of all relevant terms together with the complete model in six degrees of freedom is available in Jasionowsky (2001). The right-hand side of equation [10] represents the external forces and moments acting on the ship with respect to its centre of mass. The sloshing motions of the floodwater can be modelled as a lumped mass (Papanikolaou et al, 2000), while water ingress/egress, the water accumulation and progression follow a simplified model based on the Bernoulli equation. These methods are implemented in the software PROTEUS3, used in this study, which has been recently tested and compared with other software during project FLARE (Ruponen et al., 2022a, 2022b), highlighting its suitability for the modelling of critical scenarios in waves for passenger ships

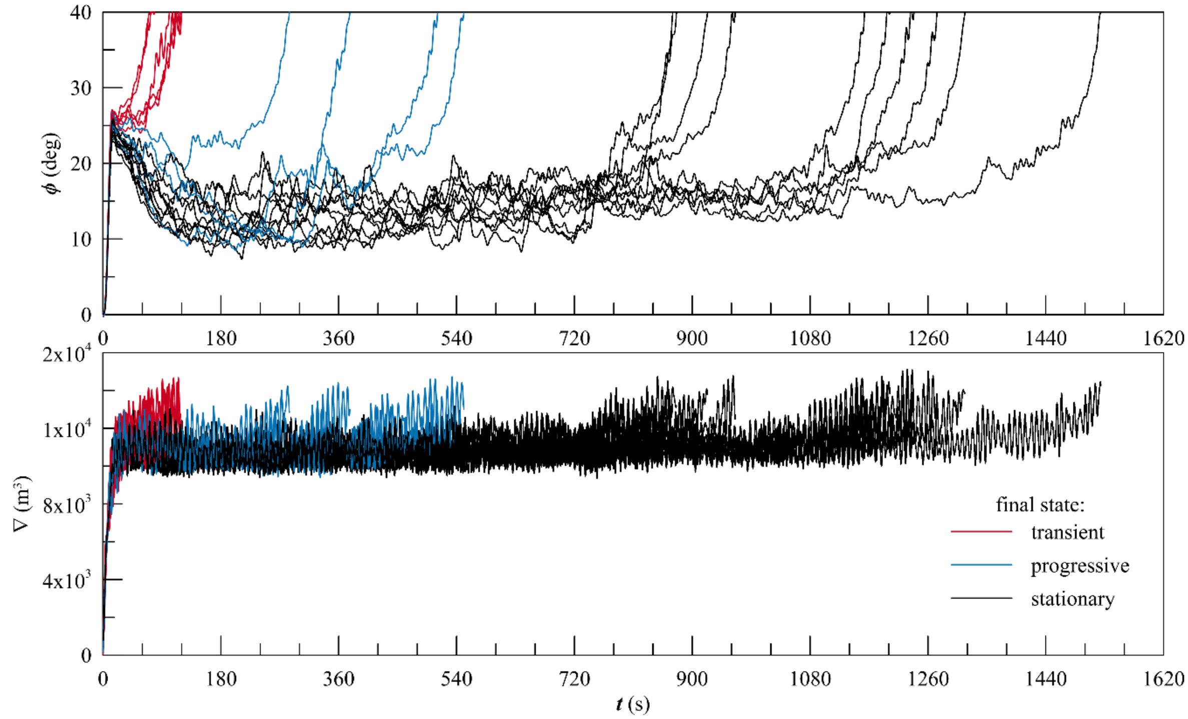

Figure 3: Example of roll (up) and floodwater (down) time histories derived from flooding simulations.

(Mauro et al., 2023a). Figure 3 shows the outputs of a set of dynamic simulations, representing the roll time history from the occurrence of the hazard until the ship capsizes and the amount of mass water entering/leaving the ship.
The time-domain simulations imply the modelling of water ingress/egress from/to the ship; therefore, the breach dimensions strongly influence the dynamics of the flooding process and the evaluation of the time to a possible capsize/sinkage event (The time to capsize).

Evacuation analysis

Another aspect of a risk assessment is related to the evacuation of the ship. Once there is sufficient time before an upcoming sinkage/capsize event, it is worth assessing the time needed to evacuate the ship. This, in turn, allows for evaluating how many fatalities may occur by comparing the Time to capsize obtained by flooding analyses and the time to evacuate derived from the evacuation analysis.
There are different approaches to the evacuation analysis, employing different kinds of simplifications and modelling of the evacuation path. In fact, it is possible to perform the evacuation with simplified methods by employing the hydraulic analogy (Nasso et al., 2019), assuming that corridors are like pipes and the passengers are the mass flow flowing through them. This method is admitted by the MSC.1/Circ. 1533 for evacuation analyses of passenger ships; however, the methodology is too simplified to capture well the evacuation process and the possible occurrence of some congestion points during the evacuation path. For such a reason, it is convenient to employ more advanced methodologies based on the direct evaluation of the pedestrian path of each evacuee, considering the interaction with the rest of the environment (Vassalos et al., 2003, Azzi et al, 2011, Kwee-Meier et al, 2016).
Among the different software that provides the possibility to perform the advanced evacuation analysis of a passenger ship, there is software EVI. EVI, developed by the University of Strathclyde and distributed by Safety at Sea, is based on the concept of “evacuability”, meaning the ability of an individual to evacuate the ship. The resulting evacuation index takes into account a wide range of parameters, which can be collected in two separate groups, namely the Initial Conditions and the Evacuation Dynamics. The first group considers the layout of the ship, the demography of the population its initial distribution and the response time to danger, while the second group takes into account the walking speed of each agent, the interaction between passengers and crew and between agent and layout of the ship. Figure 4 shows the modelling layout of a Main Vertical Zone in EVI for a passenger ship.

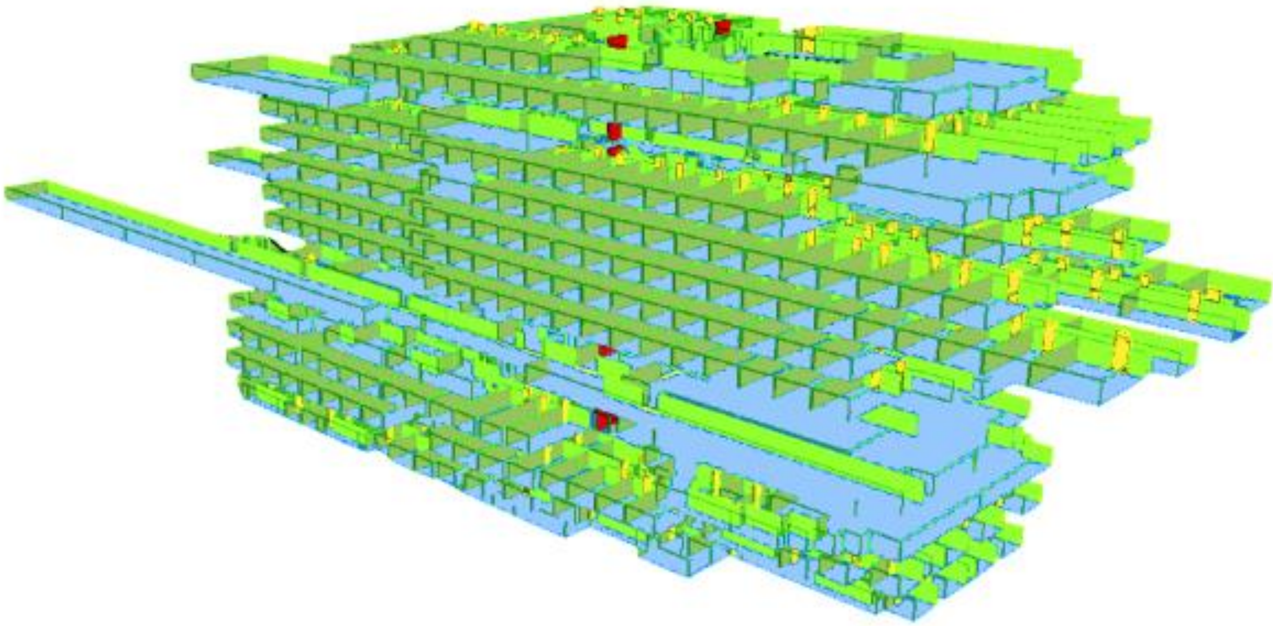

Figure 4: Example of modelling a Main Vertical Zone with software EVI.

Furthermore, the evacuation analysis could be performed by imposing the dynamic motions and the flooding progression determined by dynamic flooding analysis. Such a coupling allows for extending the reliability of evacuation results as the dynamics of the ship and its interaction with the evacuees are implicitly considered.

RISK CONTROL OPTIONS

The safety of a passenger ship is strictly related to its internal layout, as highlighted by dynamic flooding analyses and evacuation simulations. Nonetheless, a passenger ship's interior design must take into account unique considerations for passenger comfort as well as safety regulations pertaining to additional potential death threats, such as fire. Increasing internal layout restrictions in an attempt to reduce flooding may compromise the ship's ability to make money. Therefore, it is necessary to look at possible solutions aimed at increasing safety in a possible accident during the ship operation, thus increasing ship resilience to a failure event. Such solutions are usually referred to as Risk Control options (RCOs), as they aim to the reduction of the risk, i.e., in our case, of the Potential Loss of Life.

The risk control options can be passive, thus fitted permanently on the ship like fixed foam installation in ship voids or the adoption of a crashworthy structure, or active like watertight deployable barriers used only during emergencies. The following section describes a set of possible solutions to be installed onboard or to be considered during the design phase of a modern passenger ship.

Permanent foam installation

In order to increase the ship's initial stability and restoration forces in the event that these areas are directly or indirectly flooded after an incident, permanent foam is installed in the void spaces of the ship as part of a passive flooding protection system.

These installations function similarly to buoyancy tanks and have the extra advantage of being impermeable, which allows them to provide buoyancy in the damaged region instantaneously. Reducing the likelihood of transient capsize cases, which are also closely linked to insufficient reserve of stability during the early stages of flooding, is the goal of this type of improvement in initial stability and additional reserve of stability. Figure 5 shows a possible site for foam installation in available void spaces on the lower decks of a passenger ship.

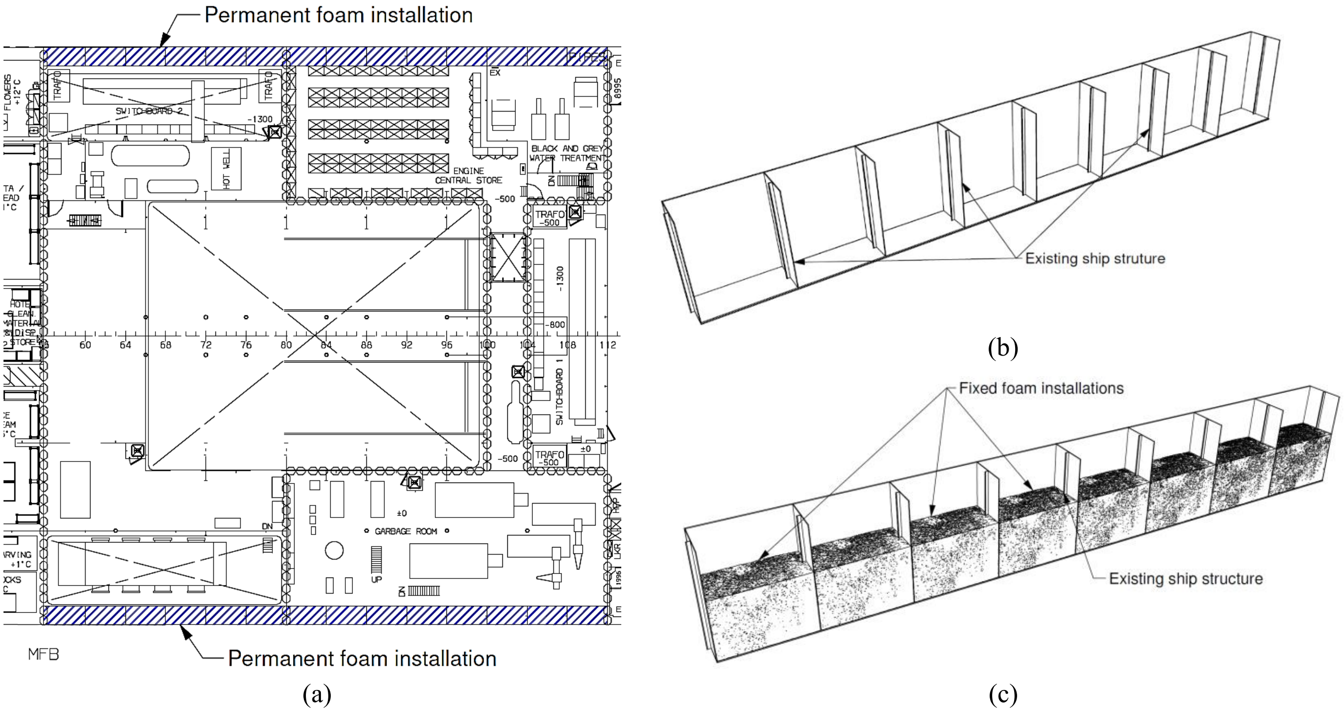

Figure 5: (a) permanent foam installation sites (blue) in a double hull. (b) Existing ship structures in the installation site. (c) Void spaces filled with foam.

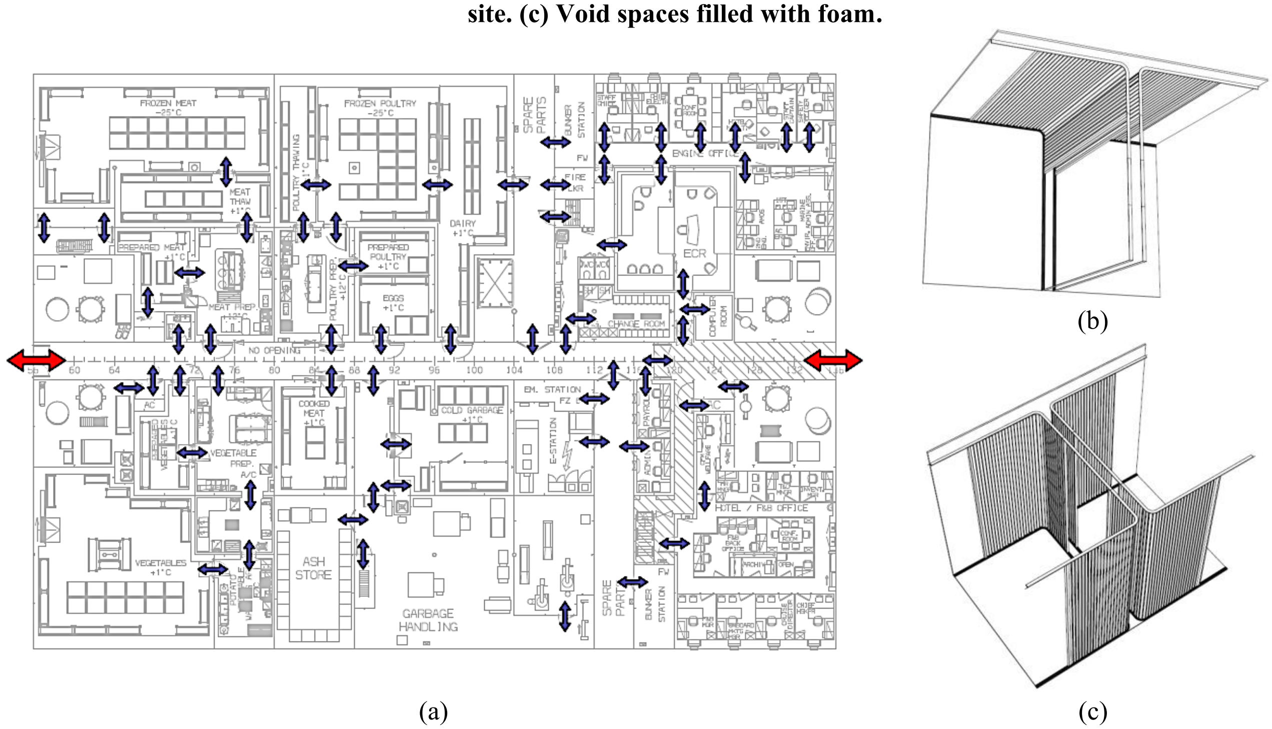

Figure 6: (a) main (red) and minor (blue) flooding path on a cruise ship deck zone. (b) Vertically deployable shutters. (c) Horizontally deployable shutters.

Deployable watertight barriers

During the flooding process of a complex environment, like the internal geometry of a ship, the progressive flooding paths can be divided into major progressive floodwater paths. Minor paths are narrow passageways and areas that are connected to one another inside a certain area; they are thus routes that permit the ship to collect water locally. The main paths are essentially wide passageways that link two adjacent areas of the ship, acting as arteries that might quickly disperse floodwater throughout the vessel (refer to Figure 6a). The best course of action for managing progressive flooding in ships is

to restrict the main arteries. Deployable barriers are a good way to prevent flooding in this situation without changing the interior design of the ship. Deployable barriers consist of two lightweight shutters spaced 30 cm apart, usually composed of steel laths or GRP with an A-class fire rating. Shutters can be deployed also in case of fire casualties or drills. In case of flooding, the cavity between shutters is filled with expanding foam delivered from a compressed foam canister. In order to comply with specific local structural characteristics and arrangements, the shutters can be mechanically adjusted to be deployed either vertically (see Figure 6b) or horizontally (see Figure 6c). 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.
In this way, an appropriate damage control plan may be established and adequately carried out based on the outcomes of time domain flooding simulations, perhaps with the help of an appropriate decision support system. This makes it possible to isolate the affected area after any critical flooding event that is predicted and for which progressive flooding is the cause of the loss. The implementation of evacuation evaluations for certain important instances is implied by this technique, which aims to determine whether deployable impediments impede the evacuation process. This provides a clear benefit over current damage control strategies, which are mostly based on fixed design measures and are therefore less flexible and effective in likely critical loss circumstances.

Crashworthy structure

Another kind of RCO is crashworthiness, studied as a mitigation measure for damage stability since early 1990s. However, the lack of suitable tools to undertake this analysis as a routine has discouraged its application by designers since the early stages of the design process of passenger ships. In fact, crashworthiness is the ability of a structure to protect its occupant during an impact; therefore, the determination of a crashworthy structure for a passenger ship implies the dedicated study of a new layout for the main longitudinal and transversal elements of the ship.
In project FLARE, a dedicated study has been performed in an attempt to implement crashworthiness as a suitable risk control option to mitigate flooding risk. The scope was to derive a general scaling method from the conventional distributions used for damage dimension determination (Mauro & Vassalos, 2022) to new distributions considering the implementation of specific reinforcement to the hull (Cardinale et al. 2022). Thanks to the application of super-elements codes, as mentioned earlier, it was possible to derive corrections for specific damage dimensions according to the damage type:

1. Collisions: damage length, damage penetration, damage height.
2. Bottom groundings: damage length.
3. Side groundings: damage length

The correction has the form of a scaling function as reported in the following equation:

$$d^* = \lambda \cdot d \qquad [11]$$

Where λ is the scaling function, d is the original breach dimension derived from pertinent distributions and d^* is the new breach dimension.
The following possibilities have been analysed in the study, pertinent to different damage types:

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

The above 10 possibilities have been implemented on a reference ship, considering possible collisions with a database of 11 striking ships (Conti et al., 2022, Mauro et al., 2023b).
Thanks to this modelling it is possible to take into account the crashworthiness of the new structure in all the levels of approximation of the risk assessment framework, as the correction for crashworthiness is directly applied to the inputs, thus allowing assessments from Level 1 up to Level 2.2.

RISK MITIGATION EXAMPLES

The present section presents two test cases for the implementation of RCOs on passenger ships. The cases refer to a Cruise Ship (Ship A in the following) and a Ro-Pax (Ship B). The general particulars of the ships are reported in Table 1, while the general overview is given in Figures 7 and 8. The two cases present the evaluation of different RCOs according to the following scheme:

1. Ship A:
   1.1. Change of internal layout with the installation of passive permanent foam
   1.2. Insertion of a double hull at B/20 with a plate shell thickness of 12 mm.
2. Ship B:
   2.1. Change of internal layout with application of permanent foam.
   2.2. Insertion of deployable barriers with foam.

The resulting combination of the two examples covers all the mentioned RCOs possibilities, having fixed foam applications (Cases 1.2 and 2.1), deployable barriers (Case 2.2) and crashworthiness (Case 1.2). For all the conditions, the PLL has been calculated at Level 1 and Level 2.1. No calculations have been performed at Level 2.2 because studies in project FLARE highlight that the differences between Level 2.1 and Level 2.2 are negligible for the tested vessels (Cardinale et al. 2022).

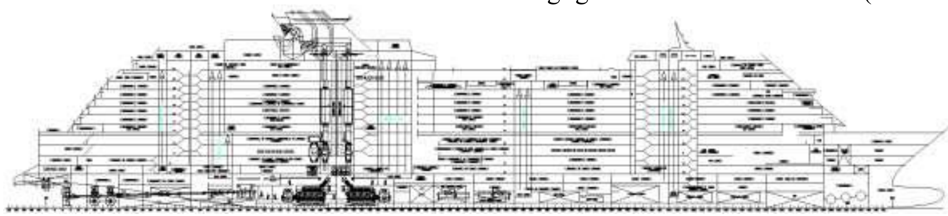

Figure 7: General Overview of Ship A

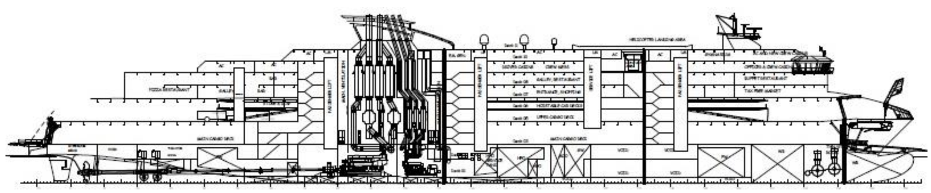

Figure 8: General Overview of Ship B

Table 1: Main particulars for Ship A and Ship B

Parameter	Symbol	Ship A	Ship B
Length overall	L_{OA}	300.00 m	211.30 m
Length between perpendiculars	L_{PP}	270.00 m	195.30 m
Subdivision length	L_S	296.74 m	212.25 m
Beam	B	35.20 m	25.80 m
Draught	T	8.20 m	6.70 m
Construction height	D	11.00 m	9.40 m
Number of passengers		2750	2315
Number of crew		1000	185
Gross tonnage	GT	95,900	36,822
Deadweight	DWT	8,500 t	5,581 t

Ship A

Ship A is an example of a large cruise ship. The ship was first assessed in its original configuration employing static and dynamic analyses for flooding risk assessment. The first round of calculations allows for identifying the attained PLL at both Level 1 and Level 2.1 according to the process described in the previous sections. However, the execution of detailed analyses offers also the possibility of identifying the most critical and vulnerable areas for flooding, thus giving the possibility to select the most suitable zones for the implementation of risk control options.

Figure 9 gives an overview of the critical damage location with the associated penetration resulting from the first analysis. The graph reports in a non-dimensional form the penetration L_y and the location x of the damage highlighting the presence of two main vulnerable areas located in the presence of the ship aft and fore shoulder. Those locations correspond to the presence of the heeling tanks in the fore shoulder and of the engine room in the aft. Due to the internal configuration of the ship, it is easier to fit risk control options in the aft shoulder instead of in the fore shoulder. For such a reason, two solutions have been applied to the re-design of the aft-shoulder space: the implementation of a crashworthy structure and the installation of permanent foam.
Figure 10 presents the first option, which means the creation of a crashworthy structure consisting of a watertight double-hull located at B/20 with local reinforcements with a thickness of 12 mm. The configuration gives a significant improvement in terms of achieved PLL, indicating a decrease of 14.6% compared to the original value for Level 1 and a decrease of 15.5% compared to the original for Level 2.1 prediction.
Figure 11 reports the second option, consisting of the installation of permanent foam inside void spaces in a double hull positioned at B/20. Such a technique allows for reducing the permeability of the void space in the double hull, thus increasing the "floatability" of the vessel. The configuration gives a lower reduction compared to the previous solution, providing a decrease of PLL of 11.9% compared to the original configuration for Level 1 and a decrease of 12.3% compared to the original configuration for Level 2.1 prediction.

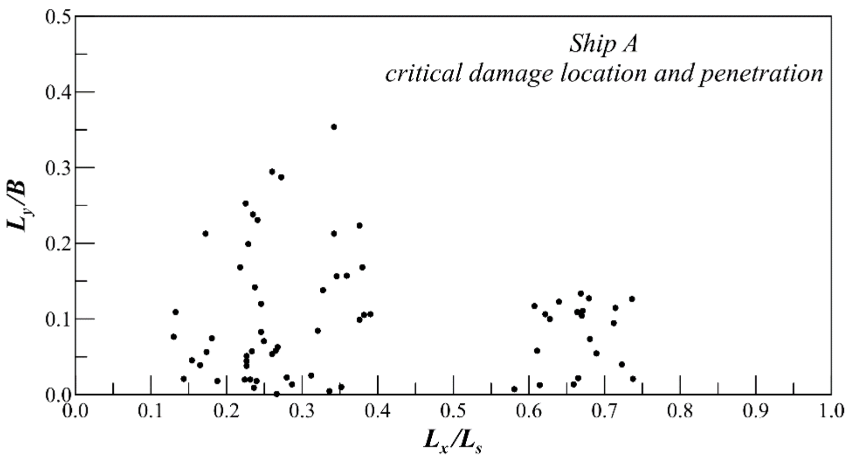

Figure 9: Critical damages location and penetration for Ship A.

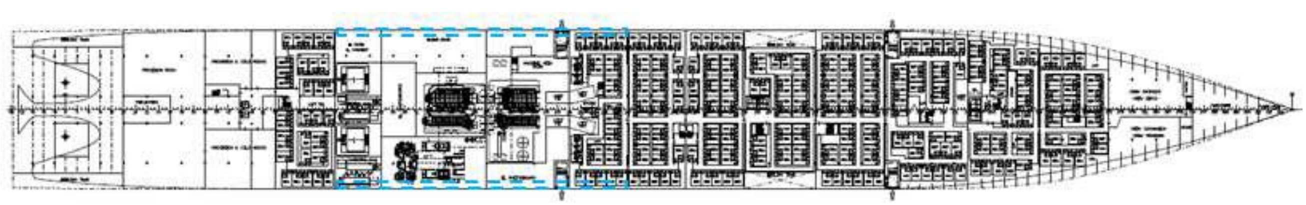

Figure 10: Crashworthy structure for Ship A.

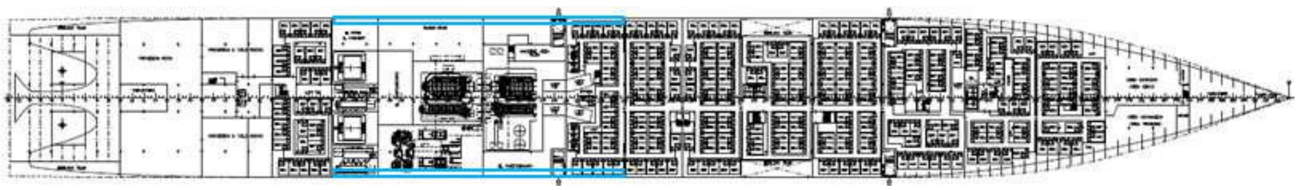

Figure 11: Double hull with foam installation for Ship A.

Ship B

Ship B is an example of a Ro-Pax vessel. As for the previous ship, the vessel was initially assessed for its original configuration through static and dynamic analyses, providing Level 1 and Level 2.1 predictions for the attained PLL. Also, in this case, the execution of detailed analyses allows for identifying the most vulnerable areas of the ship, allowing for providing the correct location of possible RCOs.

Figure 12 shows the most vulnerable areas of the ships, highlighting two main areas of risk, one in the fore shoulder and one in the aft shoulder. Compared to Ship A, most of the critical damages lie in the fore-shoulder, thus, this is the most critical area to be re-engineered by employing suitable risk control options. In this case, having the configuration of the Ro-pax 2 full car decks, it is not possible to change the volumetry in that space or change the structures of the decks, therefore it is possible to use deployable barriers as a risk control option in combination with fixed foam installation under the car decks.
Figure 13 shows the first risk control option implementation, consisting of the installation of permanent foam in void spaces under the car deck. The location of foam is concentrated in the fore shoulder, where most of the criticalities have been detected by initial analysis. It is these cases in particular that can benefit the greatest from the introduction of passive foam, as such installations work to significantly increase damage GM (restoration). Furthermore, as a passive system, the permanent foam is immediately available following the opening of the damage breach and is therefore effective during the transient phase. As void spaces have been targeted, the resultant solution is non-intrusive by nature and converts what is essentially “dead space” into an asset. The configuration gives a considerable improvement in terms of achieved PLL, registering a decrease of 47.04% compared to the original value for Level 1 and a decrease of 42.57% compared to the original for Level 2.1 prediction.

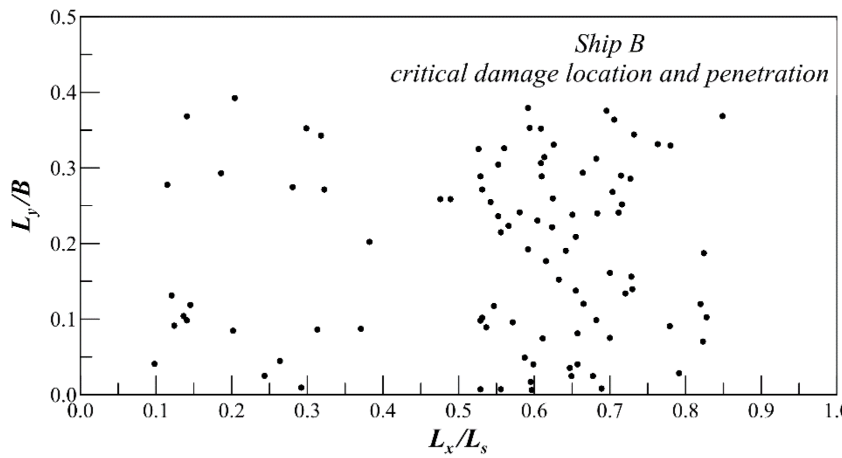

Figure 12: Critical damages location and penetration for Ship B.

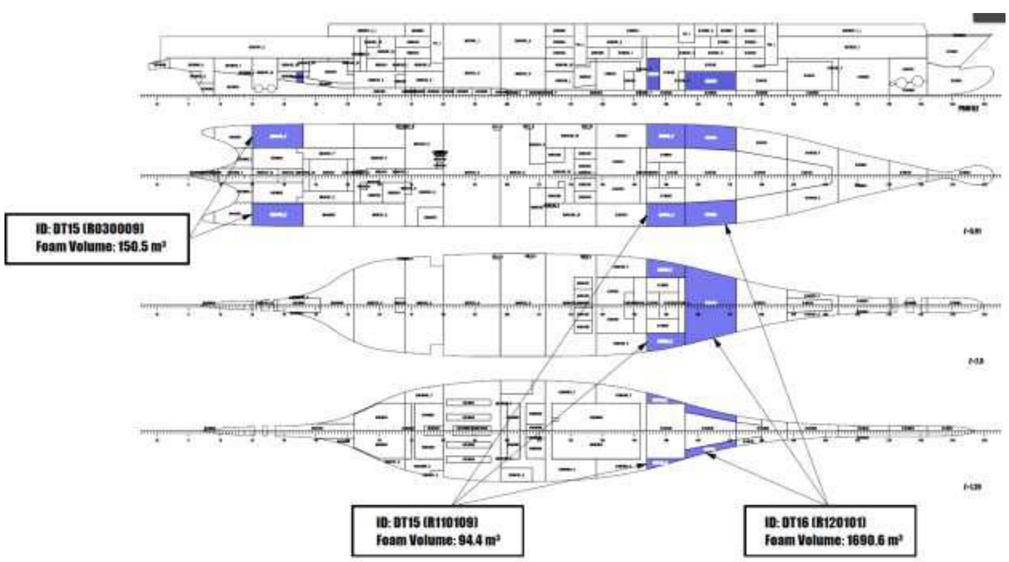

Figure 13: passive foam installations on Ship B.

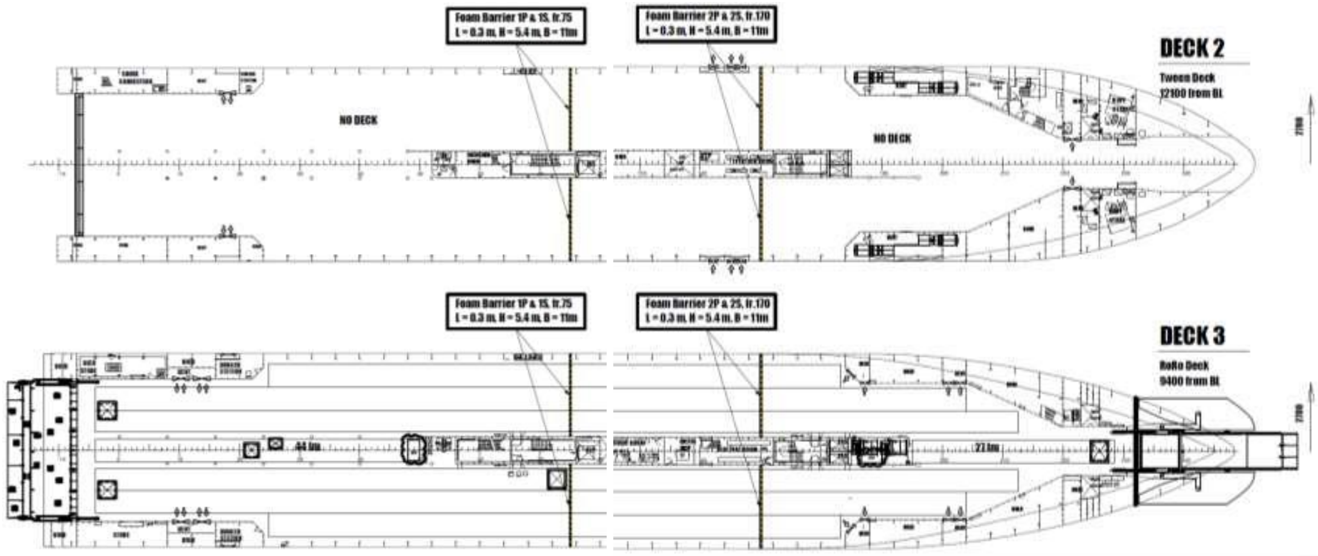

Figure 14: Deployable barriers in the car deck for ship B.

Figure 14 shows the second risk control option implementation, consisting of the installation of deployable barriers. In determining where best to locate the foam barriers, the first consideration has been to target areas of heightened vulnerability within the vessel design. These can be identified where there are concentrations of loss scenarios. Secondly, the barriers have been located to limit, as far as possible, the number of breaches overlapping the barriers. This works to maximise the number of cases that will be positively influenced by the presence of the barriers, whereas if they were to lie within the breach extent, they would offer little to no protection. The resultant configuration has seen the implementation of 4 barriers, protecting both the fore and aft shoulders in pairs across the car deck. The configuration gives an improvement in terms of achieved PLL, registering a decrease of 15.74% compared to the original value for Level 1 and a decrease of 22.94% compared to the original for Level 2.1 prediction.

Concluding Remarks

The previous sections presented the implementation of three different kinds of RCOs to the two reference ships. The implementation results in evaluating the PLL with both simplified and advanced methodologies. More precisely, Level 1 considers only static calculations while Level 2.1 employs dynamic simulations, thus a first principle tool. Table 2 reports a resume of all the PLLs evaluated for the reported cases for Level 1 prediction, while Table 3 reports the results for Level 2.1. The implementation of RCOs led to different results comparing Ship A and Ship B, especially for the installation of the passive fixed foam system. This is essentially due to the differences in the amount of foam installed in the two designs. For Ship A, the quantity of foam is limited to the small space of the double hull in the engine room area (see Figure 11) thus ensuring few reserves of buoyancy compared to Ship B, where the total amount of foam is about 1935.5 m^3, equivalent to almost 30 % of the volume in deadweight conditions. Such a massive installation of foam was possible on Ship B because of the large number of void spaces available under the car decks, something not possible to achieve for Ship A or a cruise vessel in general. Other studies on foam application highlight that there is some margin to put more foam volume on cruise vessels, just by slightly changing the internal layout of the ship (Vassalos et al., 2021, 2022a).

Table 2: PLL Level 1 values for Ship A and Ship B.

	Damage type	No RCO	Passive foam	Crashworthy structure	Deployable barriers
Ship A	Collision	0.3549	0.3182	0.2716	-
	Side grounding	0.5349	0.4555	0.4721	-
	Bottom grounding	0.1990	0.1859	0.1859	-
	Total	**1.088**	**0.9596 (-11.90%)**	**0.9296 (-14.60%)**	**-**
Ship B	Collision	0.3412	0.1862	-	0.2622
	Side grounding	0.1603	0.0820	-	0.1546
	Bottom grounding	0.0357	0.0163	-	0.0358
	Total	**0.5372**	**0.2845 (-47.04%)**	**-**	**0.4526 (-15.74%)**

Table 3: PLL Level 2.1 values for Ship A and Ship B.

	Damage type	No RCO	Passive foam	Crashworthy structure	Deployable barriers
Ship A	Collision	0.3173	0.2674	0.2268	-
	Side grounding	0.3353	0.2956	0.3086	-
	Bottom grounding	0.1809	0.1683	0.1686	-
	Total	**0.8334**	**0.7312 (-12.30%)**	**0.7040 (-15.50%)**	**-**
Ship B	Collision	0.3284	0.1894		0.2281
	Side grounding	0.1041	0.0632		0.0988
	Bottom grounding	0.0352	0.0161		0.0334
	Total	**0.4677**	**0.2686 (-42.57%)**		**0.3604 (-22.94%)**

In any case, with the application of foam being really effective in reducing flooding risk, it could be reasonable to start thinking about different layouts for the passenger ship interior design and abandon the actual trend of extensively capillary compartmentation aimed to increase asymptotically the static A-index, which of course is not possible as saturation is reached after a small increase of the empirically determined number of bulkhead spacing of $0.03L_s$+10 m.
On the other hand, the crashworthy structure for Ship A and the deployable barriers for Ship B highlight comparable levels of flooding risk reduction while considering a Level 1 assessment. The difference between the effectiveness increases while considering the Level 2.1 characteristics where the effect of the deployable barriers in the car deck became more effective due to the reduction of water progression in the car deck, something that can be reliably evaluated with dynamic simulation only as highlighted by recent benchmarking activity on several flooding simulation codes (Ruponen et al. 2022a).
It is important to underline the differences between the PLLs evaluated with Level 1 and Level 2.1 for both ships as it underlines the relevance and impact of using first principle tools for the flooding risk assessment. All the PLLs evaluated with dynamic simulations have lower values than those obtained by Level 1. The differences arise both for Ship A and Ship B, regardless of the RCO adopted for the calculations. For the Ship A original configuration, the Level 2.1 risk is 23.40% less than the Level 1.1. For Ship B the difference in the original configuration is in the order of 12.94%. Considering the fixed foam installations, the difference for Ship A is about 23.80% and for Ship B 5.5%. For the crashworthy structure, the difference attests to 24.27% while for the deployable barriers in Ship B is 20.37%.
The difference between the values obtained with the two prediction levels is not negligible as it is always above 5%, reaching peaks around 25%. Such a matter stresses the importance of using first principle tools for flooding risk assessment in the design process of passenger ships. Furthermore, the obtained results suggest how different strategies should be pursued to design safer passenger ships, thanks to the adoption of proper cost-effective risk control options instead of relying only on the excessive compartmentation of internal spaces.

CONCLUSIONS

The present work details the application of a multi-level flooding risk assessment framework for the design phase of passenger ships, highlighting the possibility of implementing different kinds of risk control options to reduce the final risk. The paper describes the primary first-principle tools that can be used to increase the reliability of the risk analysis during the design phase of a passenger vessel, focusing on the adoption of super-element methods for breach generation and design of crashworthy structures and the application of dynamic flooding simulations to estimate the vessel survivability to a given hazard. The execution of advanced evacuation analyses has also to be taken into account to pursue a fully first-principle-based risk analysis, however, the study within project FLARE demonstrates that the gain in terms of PLL by using evacuation analyses or analytical approximation is negligible. Therefore, the implementation of a risk assessment framework for flooding is achievable by using first principle tools up to Level 2.1, thus employing dynamic simulations for vessel survivability.
The paper offers also the possibility to appreciate the flexibility of the given framework to implement different design solutions for risk mitigation. The example provided on a cruise ship (Ship A) and a Ro-pax (Ship B) allows for the testing of three different risk control options: fixed foam installation, deployable barriers and crashworthy structure. Calculations have been performed for all the configurations highlighting the efficacy of the proposed measures to the reduction of risk, always above 10% compared to the original configuration. At the same time, the calculation provided at both Level 1 and Level 2.1 for the PLL highlights differences from 5 to 25% in the final value of attained risk. Such a matter underlines the importance of using more reliable tools (thus at least a Level 2.1 prediction) in the flooding risk assessment of passenger ships.
Finally, the paper underlines how the adoption of a risk control option may increase the safety of a passenger ship and how the use of first principles tools allows for the quantification of the risk reduction provided by the RCOs themselves. The results show how active or passive solutions may significantly reduce the flooding risk on a ship, without the need for

increasing the capillarity of the internal compartmentation of the vessel. Therefore, the adoption of such tools in the design process of passenger ships may result in a new design strategy for the achievement of a generation of safer passenger vessels. It is important to stress that the first-principle tools employed for the reference study have all been validated against experiments in the last 20 years, with continuous activity of benchmarking. Such a matter gives confidence in the reliability of the final results.

CONTRIBUTION STATEMENT

D. Vassalos: Supervision; writing – review and editing. **F. Mauro:** Conceptualization; data curation, methodology; writing – original draft; writing – review and editing. **D. Paterson**: data curation, writing – review and editing. **A. Salem**: writing – review and editing

ACKNOWLEDGEMENTS

The authors want to acknowledge the partners of the EU founded Project FLARE for the constructive work leading to the findings of the present paper.

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