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The importance of first-principles tools in estimating passenger ship safety

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ABSTRACT

A passenger ship's design is a multifaceted process that involves numerous aspects of marine engineering and naval architecture with the main goals being, performance, functionality, safety and cost. Between these, safety is a crucial component with passengers' safety a top priority. Ship safety requires accurate assessment using a suitable measure from the beginning of the design process. For this purpose, the Potential Loss of Life can be used to assess safety from a risk perspective. However, multiple levels of reliability can be achieved in the final assessment of flooding risk, de-pending on the approximations and assumptions made in evaluating the consequences of a given hazard. This relates principally to assessing the dynamic stability of a damaged ship in waves and to the different tools employed for such assessment. The conventional approach of designers relies on the execution of simplified static analyses whilst the indications shown by years of research suggest the application of first-principle tools. The present work highlights the importance of performing damage stability calculations based on rigorous hydrodynamic modelling of the motion of a damaged ship to achieve a more reliable estimation of the safety level. The conclusions are endorsed by reporting the results of conventional and first-principles risk analysis on a set of reference passenger ships.

1. Introduction

The design of passenger ships is a complicated process in which the evaluation of multiple aspects of naval architecture and marine engineering goes hand in hand. At the same time, damage stability represents a key element in the design process providing lifecycle flooding risk management for the vessel (Vassalos, 2022). In particular, the estimation of flooding risk is an important factor to be taken into account when designing new passenger ships (Atzampos, 2019; Papanikolaou et al., 2013; Vanem et al., 2007). However, designers prefer a compliant approach to damage stability with limited cases where an in-depth risk approach has been followed. This trend changed over the last few years, making more of an effort to use First Principles tools for designing passenger ships (Vassalos, 2016) and giving designers suitable guidelines on how to apply such tools (Mauro et al., 2023b).

The direct consequence has been the establishment of a multi-level approach to flooding risk assessment applicable not only during the design phase but also in the entire vessel lifecycle (Vassalos et al., 2022b). Such an approach consists of applying different levels of approximation to the components influencing the flooding risk, thus also on the execution of flooding simulations in irregular waves. There are multiple options for the execution of damage stability calculations, starting from simplified static analyses (Ruponen, 2014; Braidotti and Mauro, 2020; Dankowski, 2013) up to complex and time-demanding CFD calculations (Ruth and Rognebakke, 2019; Sadat-Hosseini et al., 2016). A good compromise between the computational effort and the accuracy of the results is provided by rigid-body time domain simulations (Spanos and Papanikolaou, 2012), traditionally applied more in research by academia but recently also by designers (Mauro et al., 2023b). The reason for the moderate application of advanced tools by designers derives from the number of calculations needed to fulfil the damage stability framework requirements, which requires the simulation of about 10,000 breaches per damage type and draught (Bulian et al., 2019; Ruponen et al., 2019). The number of simulations becomes even more considerable while assessing survivability in adverse weather conditions because of the stochastic nature of irregular waves (Spanos and Papanikolaou, 2012). However, recent benchmark studies on damage stability (Ruponen et al., 2022b,a) highlight the suitability of rigid-body-based simulation for reproducing damage cases in adverse weather conditions, underlying the importance of the hydrodynamic modelling of the flooding process. Furthermore, several studies stressed how it is possible to save calculation time for time-domain simulations by proper filtering of critical damage cases (Mauro et al., 2022a,b).

Therefore, it is extremely important to pursue the way of employing first-principles tools for estimating the flooding risk of a passenger

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ship. The present work addresses this issue by providing a comparison between the safety levels evaluated by employing conventional static calculations and dynamic analysis for the flooding simulations. Thanks to the adoption of the Possible Loss of Life as a metric of risk it is possible to directly compare the safety level of a ship according to the different prediction methodologies. The comparison is here shown on a set of passenger ships, including both Ro Pax and cruise vessels. The results confirm the importance of adopting the more advanced simulation techniques based on rigid-body calculations, thus consistent hydrodynamic modelling, to effectively estimate the flooding risk level of the ship.

2. Damage stability and flooding risk simulation methodologies for ship design

The assessment of damage stability after a flooding occurrence is one of the most relevant attributes of the design of a passenger ship, as it is directly connected to the safety level of the design thus to the risk of possible loss of lives during an accident. With the design process of a passenger ship being one of the most complex issues, the assessment of damage stability should be flexible enough to be adaptable to the different stages of the design that may take into consideration changes in the internal layout or the loading conditions of the vessel.

As such, it is important to target the right methodology allowing for the best balance between calculation effort and output accuracy, not only for a single calculation, but taking into account its flexibility to assess different phases of the design process with the progressive increase in the complexity of the design. Conventional approaches to damage stability have different approximation levels, significant outputs and computational efforts (Ruponen et al., 2022b; Bačkalov et al., 2016; Manderbacka et al., 2019; Papanikolaou, 2007). Among these, designers still prefer to adopt extremely simplified regulation-compliant approaches based on existing regulation frameworks (IMO, 2009, 2020). With all the developments achieved in modelling damage stability in the last years (Vassalos, 2016) it is no longer advisable for designers to pursue simplistic regulation-based analyses. It is, therefore, necessary to have a deeper look at the possible options available to address damage stability. The following list provides an overview of all available methods in literature to assess damage stability on passenger ships, distinguishing between motion equations resolution and body forces calculations:

- *Static calculations*: this is the most simplified method to assess the damaged condition of a ship and is based on hydrostatic calculations only. The results provide the residual GZ curve for the damaged ship in the final or intermediate stages of flooding. Such methodology is employed by current regulation framework on damage stability (IMO, 2009, 2020).
- *Quasi-static simulations*: this methodology gives an indicative evaluation of the flooding progression with time, modelling the flooding rates by employing Bernoulli's equation. In any case, the motions of the ship derive from static assumptions, calculating the static balance of forces in 3 Degrees of Freedom (DOF): heave, roll and pitch (Braidotti and Mauro, 2020; Dankowski, 2013). The results are normally corrected by empirical coefficients for roll motion (Ruponen, 2014). The simulations assume that the water surface inside the ship compartments is parallel to the undisturbed sea water level.
- *Rigid-body dynamic simulations*: the method couples the rigid-body dynamics of the vessel in 4 to 6 DOF with the simulation of water progression (Jasionowski, 2001). Such a technique allows for evaluating the performance of a damaged ship also in adverse weather conditions (Spanos and Papanikolaou, 2012). The approach to coupling the water progression with vessel motions is not unique and several methodologies can be used for modelling the water motions inside compartments. Modelling assumptions start from simple quasi-static flat horizontal surface models (Kat, 2000; Letizia, 1997); complexity arises with lumped mass modelling (Papanikolaou et al., 2000a) (which may consider also an inclined flat free surface (Acanfora and Cirillo, 2017; Manderbacka and Ruponen, 2016)) or dynamic resonance models (Lee, 2015) up to the adoption of the shallow water equation (Janssen et al., 2013; Santos and Guedes-Soares, 2008).
- *CFD simulations*: such techniques evaluate the internal water motions from the numerical integration of RANS equations (Ruth and Rognebakke, 2019; Sadat-Hosseini et al., 2016). The methodology allows for evaluating the ship motions in 4 to 6 DOF, considering the fluid forces (both internal and external) as an input to the rigid body motion equations. However, this calculation methodology has a substantially higher computational effort compared to all the above-described methodologies, which considering that a damaged vessel, because of excessive damping and added inertia effects, is not undergoing significant motions.

Each method has its advantages and disadvantages concerning calculation times, accuracy of the results and applicability to the design process of a passenger ship. The easiest and fastest methods to apply are those of static and quasi-static nature. However, aiming for more physic-based damage stability results, there is the need to adopt the more advanced flooding simulation techniques. Having said this, the use of CFD computation is not applicable, as, despite the potentially high accuracy level and fidelity of the physical modelling, the computational time is too high even for a single simulation (Ruponen et al., 2022a). The necessity of performing multiple simulations on several damage cases suggests the use of time-domain simulations. Quasi-static codes fulfil computational time requirements; however, they are not suitable for performing accurate simulations in adverse weather conditions. Therefore, rigid-body dynamic simulations nowadays present the right compromise between calculation accuracy and computational effort, as highlighted by recent benchmark studies on damage stability (Ruponen et al., 2022b,a).

The next section describes more in detail the modelling of a damaged ship in adverse weather conditions according to rigid-body motion equations.

2.1. Rigid-body dynamics modelling of a damaged ship

As mentioned above, a good compromise between simplicity and meaningful representation of physics is based on rigid body dynamics, modelling water ingress-egress according to a Bernoulli-based model. To follow this approach, it is necessary to develop a time-domain numerical prediction tool capable of simulating the vessel's dynamics and accounting for the flooding process progression. To this end, the governing equations of the damaged ship are derived from the law of conservation of linear and angular momentum. Then, considering the body-fixed reference system described in Fig. 1, the following set of equations describes the rigid body motions of a ship:

$$m\left(\dot{\boldsymbol{v}}+\boldsymbol{\omega}\times\boldsymbol{v}\right)=\boldsymbol{f}_{\boldsymbol{E}} \tag{1}$$

$$\boldsymbol{I}\dot{\boldsymbol{\omega}}+\boldsymbol{\omega}\times\boldsymbol{I}\boldsymbol{\omega}=\boldsymbol{M}_{\boldsymbol{E}} \tag{2}$$

Where, m is the mass of the intact ship, $\boldsymbol{I}$ is the matrix of inertia and $\boldsymbol{v}=(\dot{x},\dot{y},\dot{z})$ and $\boldsymbol{\omega}=\left(\dot{\phi},\dot{\theta},\dot{\psi}\right)$ are the velocity vector and the angular velocity vector of the rigid body, respectively, subject to external forces $\boldsymbol{f}_{\boldsymbol{E}}$ and external moments $\boldsymbol{M}_{\boldsymbol{E}}$. Eq. (1) describes the conservation of the linear momentum and Eq. (2) of the angular momentum. Starting from the above-described formulation, it is possible to derive the equations for a damaged ship (Spanos et al., 1997; Santos et al., 2002).

Considering the floodwater within different compartments as a free mass, it is possible to model these as additional rigid bodies, leading to the following set of equations for a damaged ship:

$$\begin{aligned}&m_w\left(\dot{\boldsymbol{v}}_w+2\boldsymbol{\omega}\times\boldsymbol{v}_{\boldsymbol{w}}+\dot{\boldsymbol{\omega}}\times\boldsymbol{r}_{\boldsymbol{w}}+\boldsymbol{\omega}\times\left(\boldsymbol{\omega}\times\boldsymbol{r}_{\boldsymbol{w}}\right)\right)\\&\quad+\dot{m}_w\left(\boldsymbol{v}_{\boldsymbol{w}}+\boldsymbol{\omega}\times\boldsymbol{r}_{\boldsymbol{w}}\right)\\&\quad+\left(m+m_w\right)\dot{\boldsymbol{v}}+\dot{m}_w\boldsymbol{v}+\boldsymbol{w}\times\left(m+m_w\right)\boldsymbol{v}=\boldsymbol{f}_{\boldsymbol{E}}\end{aligned} \tag{3}$$

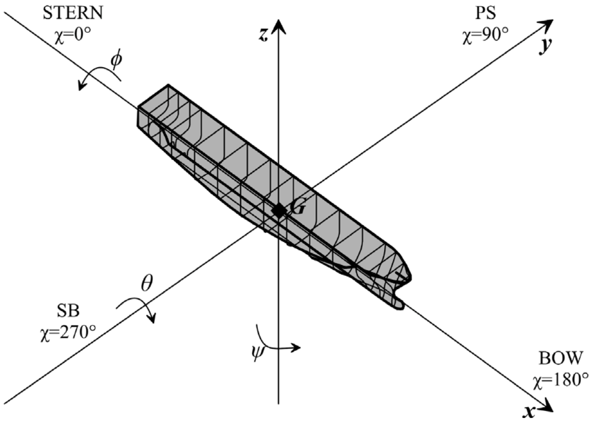

Fig. 1. Reference system for damaged ship motion calculations.

$$\begin{aligned} & m_w\left(\left(\boldsymbol{\omega}\times\boldsymbol{r_w}\right)\times\boldsymbol{v_w}+\boldsymbol{r_w}\times\left(\dot{\boldsymbol{v}}+\dot{\boldsymbol{v}}_w+\boldsymbol{\omega}\times\left(\boldsymbol{v}+\boldsymbol{v_w}\right)\right)\right) \\ & \quad +\dot{m}_w\left(\boldsymbol{r_w}\times\left(\boldsymbol{v}+\boldsymbol{v_w}\right)\right) \\ & \quad +\left(\boldsymbol{I}+\boldsymbol{I_w}\right)\dot{\boldsymbol{\omega}}+\dot{\boldsymbol{I}}_w\boldsymbol{\omega}+\boldsymbol{\omega}\times\left(\boldsymbol{I}+\boldsymbol{I_w}\right)\boldsymbol{\omega}=\boldsymbol{M_E} \end{aligned} \tag{4}$$

Where m_w is the total mass of floodwater and $\boldsymbol{I_w}$ is the associated matrix of inertia. $\boldsymbol{v_w}$ and $\boldsymbol{r_w}$ are the relative velocity and position of the floodwater mass with respect to the body-fixed reference system. This kind of modelling for floodwater differentiates most of the codes employed for the evaluation of damage stability; here, we are referring to the modelling implemented in code PROTEUS 3 (Jasionowski, 2001), employed during this research, which recently demonstrated good performance in benchmark activities for damaged ships (Ruponen et al., 2022b,a).

The given assumption for floodwater modelling implies the mass point is moving due to the acceleration field restrained by predetermined surfaces describing the centre of buoyancy position at different flooding levels. This FMPS (Free Mass Potential Surface) model can be summarised by the following system of equations (Papanikolaou et al., 2000b):

$$\begin{cases} \dot{\boldsymbol{r}}_w=\boldsymbol{v_w}-\left(\boldsymbol{v_w}\boldsymbol{n}\right)\boldsymbol{n} \\ \dot{\boldsymbol{v}}_w=\dot{\boldsymbol{v}}_f-\left(\dot{\boldsymbol{v}}_f\boldsymbol{n}\right)\boldsymbol{n} \end{cases} \tag{5}$$

Where $\boldsymbol{n}$ is the time-varying normal vector to the potential surface of floodwater motions and $\dot{\boldsymbol{v}}_f$ is the total forcing acceleration acting on the floodwater mass expressed as:

$$\dot{\boldsymbol{v}}_f=\boldsymbol{g}-\left(\dot{\boldsymbol{v}}+\dot{\boldsymbol{\omega}}\times\boldsymbol{r_w}+\boldsymbol{\omega}\times\left(\boldsymbol{v}+\boldsymbol{\omega}\times\boldsymbol{r_w}\right)\right)-2\boldsymbol{\omega}\times\boldsymbol{v_w}-\mu^*\boldsymbol{v_w} \tag{6}$$

where $\boldsymbol{g}$ is the acceleration of gravity and μ^* is an artificial damping coefficient derived from the experimental data on box-shaped volumes (van der Bosch and Vugts, 1966). As mentioned above, by modelling the coupling between the internal water motions and the vessel motions according to this technique, a good representation of experimental results can be achieved, especially for complex configurations of the internal layout of the damaged vessel. This was particularly evident in the case of recent benchmarking activity, especially for cruise ships (Ruponen et al., 2022a), where flooding simulations in waves was fairly well approximated by software PROTEUS 3, which includes the above modelling of internal water motions.

Proper modelling of the ship and flooding dynamics is certainly a step forward from conventional static or quasi-static calculations; however, the interpretation of the results from time-domain analysis is quite different from static ones, as the survivability of the ship is only described by a 0 or a 1 variable (i.e. the ship capsizes or not) which is somewhat different from the s-factor employed for the static analyses and implemented in statutory calculations. Therefore, it is necessary to define which are the relevant quantities coming out from a time-domain simulation that can be used for safety assessment in a modern damage stability framework.

2.2. *Relevant calculation outputs for contemporary survivability analysis*

The calculations performed employing time-domain software allow for obtaining several outputs for each single scenario. The simulations consider as relevant inputs to the PROTEUS 3 software the damage type, the breach dimensions, the vessel loading conditions (intact state) and the environmental conditions. Each one of the mentioned inputs derives from dedicated distributions provided by modern damage stability frameworks (Bulian et al., 2019; Ruponen et al., 2019; IMO, 2020). As such, each one of the simulations to be carried out by time-domain analysis has different characteristics and it is not directly traceable with the damage case concept of static calculations (Mauro et al., 2023b), which means all time-domain cases have the same probability of occurrence and each one is contributing to the final result according to the concept of a Monte-Carlo integration. Consequently, the results of the simulations provide an unique set of data per each simulation, offering the user with a detailed set of information for each of the simulated damages.

In this respect, the main outputs that are provided by the simulations are:

- *Vessel motions and accelerations*: the 6 DOF (or 4DOF if surge and yaw variations are not simulated) time series of the motions of the ship during the flooding event.
- *Wave records*: a recording of the wave profile hitting the ship during the analysis.
- *Flooding path records*: a record of the flooding progression, including all the flow rates through each opening onboard, including the level of water in all the flooded compartments.
- *Total mass of floodwater*: the variations and the final amount of floodwater entering the ship during the process.
- *Time to Capsize*: the time taken from the opening of the breach until the vessel reaches an inclined position at 40 degrees.

All these outputs are very helpful for the forensic analysis of a flooding event, allowing a designer to understand the effectiveness of certain watertight doors/barriers in order to identify weaknesses in the internal layout of the ship (Paterson et al., 2023). However, the need to link the calculations to the concept of survivability necessitates identifying which is the most relevant output to be considered for the inclusion in a damage stability framework. For this purpose, the attribute that identifies most with the concept of survivability is the Time to Capsize (TTC), which intrinsically describes whether the ship capsizes or not during a simulation and the time at which it takes place.

The TTC provides also the possibility to classify different kinds of simulations. In fact, considering the value of TTC it is possible to distinguish between different capsize modes that may occur while running a flooding scenario.

When a flooded scenario is studied, the following capsize modes can be identified according to different values of the associated TTC:

- *Transient capsize*: the capsize occurs in the beginning of the flooding process. The water rapidly inrushes through the breach, causing a rapid and large inclination into or away from the breach side. The oscillation occurs in a time interval generally shorter than the vessel's natural roll period.
- *Progressive capsize*: in this case, the water propagates through unprotected flooding paths within the ship, slowly diminishing stability until the vessel sinks, capsizes or reaches a stationary condition. This capsize may take from minutes to hours.
- *Stationary capsize*: there is no more significant water ingress/egress and the average ship motions are almost constant or with an amplitude of oscillation dependent on the external loads only (wind, waves). During this phase the vessel can capsize after hours due to external loads action.

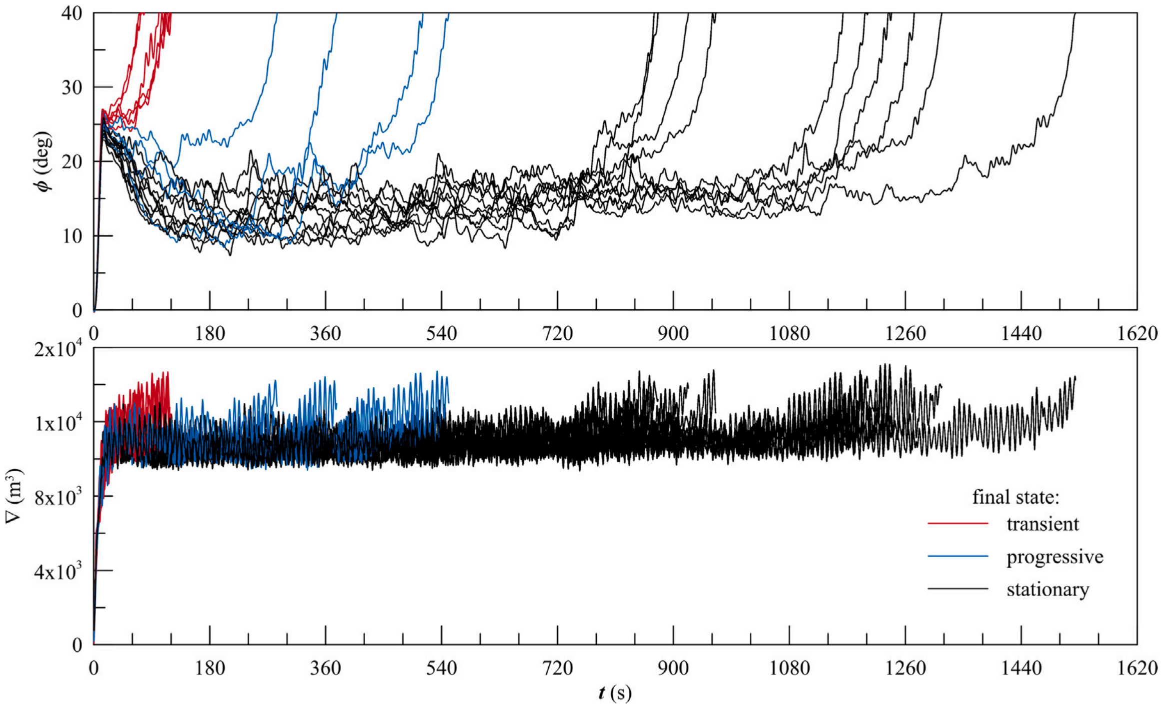

Fig. 2. Roll angle (*top*) and floodwater volume (*bottom*) time traces for 20 repetitions of the same sea state and damage for the FLARE benchmark cruise ship employing the PROTEUS 3 solver (Mauro and Vassalos, 2024).

Fig. 2 provides an example of the simulations performed by the software PROTEUS 3 during the mentioned benchmarking activities for the case of a collision on a cruise ship. The figure shows the time trace for 20 consecutive repetitions of the same case in irregular waves for the roll motion and the amount of floodwater, identifying the different types of capsize according to the TTC value. Here, the simulations refer to the same damage breach and difference in TTC is mainly due to the stochastic nature of the irregular waves used in the simulations (Mauro and Vassalos, 2024).

When an accident occurs in calm water, then the detection of a capsize is only governed by the floodwater progression. In an irregular wave environment, the phenomenon is subject to the randomness of the sea state. In the latter case, it is then not possible to identify a-priori whether the capsize will occur or not in one of the three above-mentioned modes. When a time domain simulation is performed, a capsize event can be easily recognised from the time history of the roll angle. Thus, when the roll signal exceeds a given threshold (generally above 40 degrees) the vessel capsizes, determining in such a way the associated TTC. Dedicated studies can be performed also on the quality of the TTC, interpreting it as the failure of a system (Mauro et al., 2023a; Mauro and Vassalos, 2024), providing more insight into the stochastic nature of the time-domain simulations in irregular waves.

In essence, TTC could be used as an effective metric for the identification of the survivability level of the ship from the perspective of a modern damage stability framework as it will be described in the following section.

3. Flooding risk as a metric for safety

In the in-force regulations for damage stability, there is no recognised methodology to consider the output of a time-domain simulation in the evaluation of the survivability of the vessel. In fact, the SOLAS regulations (Bačkalov et al., 2016; Manderbacka et al., 2019) consider the Attained survivability index (A-index) as a final metric for ship safety, providing all the methodology to calculate it as a function of the righting levers of the damaged ship. Some authors (Ruponen et al., 2019) tried to apply the same concept to the output of quasi-static calculations; however, its application to time-domain analysis is still arguable due to the non-stationary nature of all the simulations. It is therefore necessary to introduce a different metric that allows considering both static and time-domain calculations for the estimation of ship safety.

For this purpose, use can be made of the concept of risk due to a flooding event. Risk is identified as a combination of the probability that an issue occurred and its consequence. As such, it can be described with the following equation:

$$risk = p_f \cdot c_f \tag{7}$$

where p_f is the probability and c_f the associated consequences. In the specific case of a risk due to a flooding event, the risk can be associated with a variable that gives a measure for the risk usually identified with the Probability of Loss of Lives (PLL). Recent studies on flooding risk in project FLARE (Vassalos et al., 2022b) promote the adoption of PLL as a metric to assess the risk, proposing to use an attained PLL to assess the risk for a given scenario, according to the following formulation:

$$PLL_A^* = \sum_{i=1}^{N_{hz}} \sum_{j=1}^{N_{op}} \sum_{k=1}^{N_{ld}} \sum_{h=1}^{N_c} p_{f_{i,j,k,h}} \cdot c_{f_{i,j,k,h}} \tag{8}$$

N_{hz} is the number of possible hazards, which in a probabilistic framework for damage stability, as described by project FLARE, consists of collisions, side and bottom groundings ($N_{hz} = 3$). N_{op} is the number of operational areas, which could be in open seas, in restricted or port areas. N_{ld} is the number of loading conditions, which according to the FLARE framework is limited to two loading conditions. Finally, N_c is the number of flooding cases, which depends on the internal subdivision of the ship. The associated probabilities and consequences have the following form:

$$p_{f_{i,j,k,h}} = p_{hz_i} \cdot p_{op_j} \cdot p_{ld_k} \cdot p_{c_h} = p_{hz_i} \cdot p_{op_j} \cdot p_{ld_k} \cdot p_{c_h}^* \left(1 - s_{c_h}\right) \tag{9}$$

$$c_{f_{i,j,k,h}} = FR_{i,j,k,h} \cdot POB_{i,j,k,h} \tag{10}$$

The probabilities defined in Eq. (9) result from database analyses performed on the collection of accident statistics specific to passenger ships. Concerning the probability of the damage case, it is possible to express it as a function of the so called p and s-factors (p^*_{ch} and s_{ch} in Eq. (9)), commonly used for damage stability analyses as per SOLAS regulations (IMO, 2020; Pawloski, 2004; Vassalos et al., 2022a). Eq. (10) defines the consequences, which are given by the fatality rate FR of each damage case and the people at risk on board (POB) for the associated case. Therefore, risk assessment necessitates the investigation of $N = N_{hz} \cdot N_{op} \cdot N_{ld} \cdot N_c$ possible scenarios, considering not only the flooding survivability (as it is usual in damage stability assessment) but also the consequences of the flooding process in terms of loss of lives.

Then, the determination of risk requires the application of advanced simulation techniques that require the employment of dedicated software not only for flooding simulations but also for evacuation analyses. As such, the applicability of the risk calculation could be seriously compromised as it would require the execution of too many complex and time-consuming calculations. Designers, especially during the first stages of design, necessitate the availability of faster instruments to assess the risk, without using tools that require a too-capillary modelling of the inputs. This is the case, for instance, of evacuation analyses. Then, the approach pursued during project FLARE promotes the application of a multi-level framework, allowing for considering different steps of approximation in the global process.

3.1. Multi-level approach to flooding risk

The multi-level approach to flooding risk consists of taking into account different simplification levels across the different steps of the risk evaluation. Such approximations relate to the evaluation of survivability and to the determination of the fatality rate (FR). This relates directly to the kind of approach and software used for the evaluation of risk.

To this end, two different levels can be defined according to the kind of software used for the survivability evaluation. A Level 1 approach implies the employment of static analyses for survivability and a Level 2 employs dynamic time-domain simulations. However, different levels of approximation may be applied also to the evacuation analysis, considering whether a software is employed for the calculations. A more detailed overview of the different levels is given by the following description:

- *Level 1*: the process is fully based on static analyses. As such, no evacuation analysis is utilised and the estimation of FR is performed according to empirical formulations.
- *Level 2*: the estimation of survivability is performed through dynamic time-domain simulations. However, the execution of evacuation analyses can be still not applicable for time reasons; therefore, two different sub-levels of approximation are given:
    1. *Level 2.1*: the estimation of FR is performed through empirical formulations derived from inputs available from dynamic survivability analysis.
    2. *Level 2.2*: the fatality rate is derived by directly comparing the estimated time to evacuate and the time to capsize of a given scenario. This level implies the execution of an evacuation analysis for each scenario.

The given description of the available levels of this flooding risk framework clearly distinguishes between approaches based on first-principle tools and simplified approaches. However, design necessitates that some assumptions have to be taken into consideration when the software capability does not match the timing schedule of a project. This is the specific case of Level 2.2 predictions where the necessity of performing a large amount of time-domain flooding simulations and evacuation analysis makes its applicability impossible for the actual computational capabilities of ship designers. Then, the comparison should focus only on the Level 1 and Level 2.1 methods which will be further described in the next subsection.

3.2. Level 1 and Level 2.1 estimation of flooding risk

Level 1 and Level 2.1 approaches are two simplified methodologies that allow for saving time during the design process compared to the execution of a full first-principles-based approach. However, saving computational time goes in the opposite direction to the accuracy and reliability of the final results. In fact, not performing an evacuation analysis requires the estimation of the fatality rate FR through simplified methods, mostly empiric considerations. In any case, the estimation of FR is different between the Level 1 and Level 2.1 approximations, as the inputs deriving from different methods to assess survivability allow for the application of different low fidelity assumptions to derive the final PLL.

For the Level 1 approximation, the following approximation is suggested for the evaluation of FR:

$$FR = \begin{cases} 0.8 & \text{if } s < 1 \\ 0.0 & \text{if } s = 1 \end{cases} \tag{11}$$

This simple and conservative approach aligns with the method used in the EMSA III project. EMSA III is a project founded by the European Maritime Safety Agency, focussing specifically on the damage stability of passenger ships (post Concordia Accident), the results of which were used to support political decisions at IMO, leading eventually to SOLAS 2020 regulations for damage stability. Moreover, research in FLARE, as reported in Paterson et al. (2021), indicates that collated information from time-domain simulations on cruises an RoPax vessels provide some evidence in support of this assumption that 80% of damage scenarios in a survivability assessment are transients, in which case no time for evacuation is available.

Different is the case of a Level 2.1 prediction. The availability of time-domain simulations for each damage case leads to increasing the complexity of the formulation used for the approximation of the FR. In fact, from a dynamic analysis, it is possible to evaluate the Time to Capsize TTC of a simulation. The TTC relates to identifying the time it takes the vessel to capsize/sink after a flooding event. However, as the simulation process is influenced by the stochastic nature of the irregular waves environment, a suitable number of repetition of the same case is needed, considering the averaged value as reference TTC. In the framework developed during the FLARE project, the repetition of 5 cases is considered. This is not enough to fully capture the stochastic nature of the irregular waves (Mauro and Vassalos, 2024) but grants a good compromise between accuracy and calculation time to allow the process application by designers (Mauro et al., 2023b). In the concept of a Level 2 analysis, this should be compared with the Time to Evacuate (TTE) of the ship in the given scenario (Spanos and Papanikolaou, 2014). However, TTE can be evaluated only through evacuation analysis and, therefore, the fatality rate FR should be evaluated with another empirical formulation:

$$\begin{cases} 0.0 & \text{if } TTC > n \\ 0.8\left(1 - \frac{TTC-n}{30-n}\right) & \text{if } 30 \le TTC \le n \\ 0.8 & \text{if } TTC < 30 \end{cases} \tag{12}$$

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 as a function of the TTC, assuming the impossibility of evacuating the ship during fast transient capsizes. The full application of Eq. (12) requires the execution of simulations longer than 30 min. In the case of short 30 min simulations, as it is the case of the FLARE framework, only critical cases with $TTC < 30$ can be identified and in case the vessel survives the 30 min it is considered safe. This simplification is always oriented to increase the applicability of the process by designers (Mauro et al., 2023b).

The possibility to define the FR with Eqs. (11) and (12) allows for determining the PLL according to Level 1 or Level 2.1 methods, relying only upon the difference between static and time-domain analysis to assess the survivability of the ship. Therefore, the metric of the PLL

Table 1
General particulars of the 9 reference ships employed in the investigation.

Ship ID	Type	Regulation	L_s (m)	B (m)	T (m)	GT	Dwt (t)	POB
Ship#1	Cruise	SOLAS 2020	366.00	48.0	9.10	230,000	13,000	10,000
Ship#2	Cruise	SOLAS 2020	307.70	39.8	8.50	130,000	10,200	4,940
Ship#3	Cruise	SOLAS 2020	296.74	35.0	8.20	95,900	8,500	3,750
Ship#4	Cruise	SOLAS 2020	125.80	20.0	5.30	11,800	1,250	478
Ship#5	Ro Pax	SOLAS 2020	160.96	28.0	6.30	28,500	3,800	2,000
Ship#6	Ro Pax	SOLAS 2020	227.97	33.2	6.70	70,000	6,900	3,500
Ship#7	Ro Pax	SOLAS 2020	213.00	31.5	7.10	50,000	5,300	2,800
Ship#8	Cruise	SOLAS 90	251.40	32.0	7.80	69,490	6,324	2,800
Ship#9	Ro Pax	SOLAS 90	212.25	25.8	6.70	36,822	4,500	2,400

can be used to compare the effect of using a first-principles tool to assess survivability, as it will be presented in the next section.

4. Applied example on a set of passenger ships

The importance of modelling properly the hydrodynamic phenomena occurring during the flooding process of a ship can be demonstrated by showing the differences in suitable indicators assessing the survivability of the ship. In the previous sections, the methodology that allows for making this comparison has been shown, highlighting that the PLL can be used with both simplified static survivability analyses and more advanced time-domain analyses. As such, the present section of the paper shows these differences by applying the two different risk analyses to a set of 9 passenger ships (including Cruise vessels and Ro Pax). Such an assessment is the first complete analysis performed to compare different kinds of survivability on modern passenger ships, highlighting the differences in the PLL that will be achieved by applying a hydrodynamic-consistent methodology to assess survivability.

As mentioned earlier, the reference ships include both Cruise vessels and Ro Pax which are representative of existing designs by the world's most relevant shipyards for this market segment. As such, the projects are compliant with SOLAS 2020 or SOLAS 90 requirements according to the project delivery date. Table 1 gives an overview of the ships employed during the study, which corresponds to the sample ships dataset used through project FLARE for the application of the multi-level risk framework (Luhmann, 2019). As it can be noticed in the table, all ships except for 2 are compliant with SOLAS 2020 regulations, being representative of modern designs. Concerning the dimensions of the vessels, there are both small cruises like Ship#4 and small Ro Pax (Ship#5) as well as very large cruise vessels (Ship#1) and Ro Pax. This provides a heterogeneous database that could be used for a comprehensive analysis of the effect of hydrodynamic modelling on flooding risk.

4.1. PLL calculation assumptions

The evaluation of PLL according to the simplified methodology is regulated by the multi-level framework discussed in the previous sections. The approach is not the same as it is for the evaluation of survivability in SOLAS but relies instead on the determination of an attained level of risk, the attained PLL^*, described in Eq. (8). As such, the PLL^* is assumed to be a weighted sum of the PLL values that occur in each of the calculation scenarios. This should be compared with a maximum allowable PLL to be assessed through a Formal Safety Assessment (FSA) or a related process, including a relevant number of ships and risk control options, following an ALARP principle according to IMO-approved FSA procedures.

As highlighted in Eq. (8), the determination of PLL requires the definition of multiple frequencies for the different hazard types. Such kind of hazards are derived from statistical analysis of previous accidents and include the following aspects:

- Type of accident: collision, bottom/side grounding, contact.
- Area of operation: open sea, restricted or port area.
- Striking or struck ship.
- Aground/breaching, soft or hard terrain.
- Breach with flooding.

According to this taxonomy, relevant frequencies are derived in two possible notations: a general relative fraction or a frequency of 1/ship-year. Table 2 reports the final hazard frequencies for the specific case of a Cruise ship and Ro Pax, showing also the combination of the two (Vassalos and Mujeeb-Ahmed, 2021). As the number of accidents for individual cruise ships and Ro Pax is low, the general index has been here applied to the PLL calculations.

Concerning the frequency of the draughts, the framework suggests the employment of two draughts (instead of the three requested by SOLAS), namely the 0.45 and 0.75 of the subdivision draught, both with the same weight (i.e. 0.5). Accordingly, the permeabilities of the spaces are also defined by the framework per each draught according to the values shown in Table 3, which are different from the SOLAS standard.

4.2. Level 1 PLL calculations

As mentioned in the previous sections, Level 1 analyses imply the use of static stability tools only, reflecting what is the case of statutory regulations. For the specific case of static analysis, the multi-level framework promotes the use of a non-zonal approach for the damage definition (Mauro et al., 2023b). To this end, 10,000 breaches have been generated per damage type and draught according to a Monte Carlo process employing pertinent distributions for damage dimensions (Bulian et al., 2019). The results have been grouped into damage cases defining the probability of each damage case. The survivability has been evaluated for each damage case with static analysis allowing for the determination of the fatality rate FR according to Eq. (11). All these preliminary considerations are mandatory for the final calculation of the Level 1 PLL.

Table 4 shows the results of the Level 1 PLL calculation, comparing the data with the standard indices required by SOLAS for the 9 reference ships. The results highlight that there is no direct correlation between the statutory indices and the attained PLL Level 1, resulting in ships with a comparable SOLAS index do not have similar levels of risk. Such kind of result is important but it has to be taken in mind that all the results rely on purely static analyses and therefore the reliability of the assessment is low. To this end, calculations have been carried out also with the Level 2.1 model as it will be reported in the next section.

4.3. Level 2.1 PLL calculations

To highlight the importance of hydrodynamic modelling on risk, dynamic survivability simulations have been performed for the reference ships employing the software PROTEUS 3. The software capabilities have been already described in Section 2 of the paper, giving an overview of the features provided for the consideration of the coupling between internal water motion and ship ones. The application of a first principle approach to survivability implies the execution of all the sampled breaches for the damage definition. Such an approach is reflected in executing almost 30,000 dynamic simulations per ship, which is a number too high to be sustainable for designers. Therefore, a process well described in Mauro et al. (2023b) has been applied, performing dynamic analyses only on the damage cases resulting from static assumptions, inheriting the probability of each static damage case. This assumption allows for applying the calculation of PLL also for Level 2.1, without the need for additional damages to be analysed. Of course, the resulting process is less accurate than a rigorous approach to the framework but represents a reasonable compromise between the feasibility of the results and the time necessities of the design process.

According to this simplification, the amount of calculations oscillates from 1500 and 2000 damage cases to be assessed with dynamic

Table 2
Hazard frequencies for Ro Pax, Cruise ships and combined Ro Pax + Cruise ships.

Hazard type	Ro Pax		Cruise		Ro Pax + Cruise	
	f(1/ship-year)	Relative fraction	f(1/ship-year)	Relative fraction	f(1/ship-year)	Relative fraction
Collision	$2.42 \cdot 10^{-3}$	0.450	$3.02 \cdot 10^{-4}$	0.127	$1.68 \cdot 10^{-3}$	0.388
Side grounding	$1.52 \cdot 10^{-3}$	0.285	$1.21 \cdot 10^{-3}$	0.509	$1.42 \cdot 10^{-3}$	0.328
Bottom grounding	$1.42 \cdot 10^{-3}$	0.265	$8.64 \cdot 10^{-4}$	0.364	$1.23 \cdot 10^{-3}$	0.284
Total	$5.38 \cdot 10^{-3}$	1.000	$2.37 \cdot 10^{-3}$	1.000	$4.33 \cdot 10^{-3}$	1.000

Table 3
Permeabilities of passenger ships according to multi-level framework and SOLAS.

Room	Permeabilities					
	SOLAS		$T = 0.45$		$T = 0.75$	
	Cruise	Ro Pax	Cruise	Ro Pax	Cruise	Ro Pax
Engine	0.850	0.850	0.900	0.900	0.900	0.900
Auxiliaries	0.950	0.950	0.900	0.900	0.900	0.900
Stores	0.600	0.600	0.900	0.900	0.900	0.900
Accommodations	0.950	0.950	0.900	0.900	0.900	0.900
Public spaces	0.850	0.950	0.950	0.950	0.950	0.950
Tanks (Water, Fuel)	0.950	0.950	0.541	0.950	0.508	0.950
Heeling tanks	0.600	0.950	0.510	0.510	0.510	0.510
Void spaces	0.950	0.950	0.950	0.950	0.950	0.950
Ro ro spaces	–	0.950/0.900	–	0.9125	–	0.900

Table 4
PLL^* Level 1 calculations and comparison with SOLAS indices.

Ship ID	Type	Regulation	POB	SOLAS-R	SOLAS A-index	PLL^* Level 1 1/ship year
Ship#1	Cruise	SOLAS 2020	10,000	0.9173	0.9185	2.3400
Ship#2	Cruise	SOLAS 2020	4,940	0.8935	0.9067	1.0091
Ship#3	Cruise	SOLAS 2020	3,750	0.8835	0.8938	1.0888
Ship#4	Cruise	SOLAS 2020	478	0.7323	0.7436	0.2454
Ship#5	Ro Pax	SOLAS 2020	2,000	0.8611	0.8892	0.5348
Ship#6	Ro Pax	SOLAS 2020	3,500	0.8811	0.8948	0.6132
Ship#7	Ro Pax	SOLAS 2020	2,800	0.8730	0.8825	1.0698
Ship#8	Cruise	SOLAS 90	2,800	0.8730	0.7691	1.4204
Ship#9	Ro Pax	SOLAS 90	2,400	0.8675	0.8142	0.5372

simulations, depending on the size and complexity of the internal layout. The simulations to be performed in the time domain take into consideration also the presence of an irregular sea environment, that, according to the framework, is associated with a significant wave height of 4.00 metres, modelled according to a JONSWAP spectrum. All the calculations have a maximum simulation time of 30 min and assume that the vessel is at 0 speed.

The calculations are performed in 4 DOF (surge and yaw are neglected in the simulations) and all the major outputs already described in Section 2 have been monitored, in particular the time to capsize TTC. Having at one disposal such outputs allows for evaluating the fatality rate FR according to Eq. (12), and, consequently, the attained PLL^*. For compliance between Level 1 and Level 2.1 predictions, the permeabilities and the hazard occurrence remain the same as they are reported in Tables 2 and 3.

Table 5 reports the results for the attained PLL^* according to the Level 2.1 prediction, together with the standard SOLAS indices. Again, as was the case for Level 1 prediction, no direct correlation can be found between risk and statutory regulations. The fact that first-principle calculations also report the same indication provided by the simpler approach to risk confirms that the framework is providing more insight into the survivability issue than the in-force regulations. However, the main issue for this research is to provide a comparison between Level 2.1 and Level 1 approaches, thus providing the added value of using proper hydrodynamic modelling of the flooding scenario instead of static calculation. The adoption of PLL allows for that as it will be described in the following section.

Table 5
PLL^* Level 2.1 calculations and comparison with SOLAS indices.

Ship ID	Type	Regulation	POB	SOLAS-R	SOLAS A-index	PLL^* Level 1 1/ship year
Ship#1	Cruise	SOLAS 2020	10,000	0.9173	0.9185	1.7730
Ship#2	Cruise	SOLAS 2020	4,940	0.8935	0.9067	0.7840
Ship#3	Cruise	SOLAS 2020	3,750	0.8835	0.8938	0.8334
Ship#4	Cruise	SOLAS 2020	478	0.7323	0.7436	0.1955
Ship#5	Ro Pax	SOLAS 2020	2,000	0.8611	0.8892	0.3649
Ship#6	Ro Pax	SOLAS 2020	3,500	0.8811	0.8948	0.6154
Ship#7	Ro Pax	SOLAS 2020	2,800	0.8730	0.8825	0.9313
Ship#8	Cruise	SOLAS 90	2,800	0.8730	0.7691	1.2542
Ship#9	Ro Pax	SOLAS 90	2,400	0.8675	0.8142	0.4677

4.4. PLL comparison and general remarks

The previous sections presented the calculations executed on a set of 9 passenger vessels, estimating the attained PLL^* according to Level 1 and Level 2.1 of a modern risk-based survivability framework. The study demonstrated that the risk metric is not correlated with the statutory indices used by in-force regulations. However, the fact of utmost importance is that the metric of PLL allows for directly comparing results obtained with static and dynamic simulations for survivability, resulting in assessing the importance of using first principle tools for risk assessment due to flooding. Table 6 reports the comparison between the indices obtained with Level 1 and Level 2.1 prediction, reporting the relative difference and the percentage difference between the two. The general trends shown in the results indicate that the adoption of Level 2.1, thus of advanced hydrodynamic analysis, reduces the final amount of risk also above 12%–30%, depending on the vessels.

Going in deeper detail, it may be observed that the dynamic analysis for Ship#6 did not produce any benefit for the PLL as the large majority of the simulations resulted in a sink/capsize of the ship. For the other sample ships designed according the SOLAS2020 requirements the reduction of the PLL obtained by the flooding simulations is about 20% or higher, while for the two existing ships (ship#8 and ship#9), built according to SOLAS 90 the reduction of the PLL is approximately 12%.

Such results and changes in PLL are due to the different fate of the ship detected by static or dynamic analyses. The results of dynamic simulations showed that most of the cases (approximately 66%) selected from the static cases, showed survival while the static results showed non-survival. Such a matter is of utmost importance for the analysis of risk, as a too-conservative and simple approach overestimates risk compared to a situation where the hydrodynamic of the vessel and the coupling with the motion of the internal water after flooding are taken into account. Therefore, a proper modelling of the hydrodynamic behaviour of a flooded vessel is beneficial to the understanding of the survivability of a vessel, allowing the designer to assess the risk associated with the flooding event taking into account also the presence of irregular waves. However, it has to be recognised that Level 2.1 is still an approximation, not concerning the modelling of survivability but concerning the modelling of the fatality rate FR.

It should be noticed that the provided results are related to the employment of software PROTEUS 3 for the dynamic survivability analysis. The adoption of a different software may lead to somewhat

Table 6
Comparison between Level 1 and Level 2.1 risk analyses.

Ship ID	Type	Regulation	POB	PLL^* Level 1 1/ship year	PLL^* Level 2.1 1/ship year	Difference	Percentage
Ship#1	Cruise	SOLAS 2020	10,000	2.3400	1.7730	−0.5670	−24.2%
Ship#2	Cruise	SOLAS 2020	4,940	1.0091	0.7840	−0.2251	−22.3%
Ship#3	Cruise	SOLAS 2020	3,750	1.0888	0.8334	−0.2554	−23.5%
Ship#4	Cruise	SOLAS 2020	478	0.2454	0.1955	−0.0499	−20.3%
Ship#5	Ro Pax	SOLAS 2020	2,000	0.5348	0.3649	−0.1699	−31.8%
Ship#6	Ro Pax	SOLAS 2020	3,500	0.6132	0.6154	0.0022	+0.4%
Ship#7	Ro Pax	SOLAS 2020	2,800	1.0698	0.9313	−0.1385	−12.9%
Ship#8	Cruise	SOLAS 90	2,800	1.4204	1.2542	−0.1662	−11.7%
Ship#9	Ro Pax	SOLAS 90	2,400	0.5372	0.4677	−0.0695	−12.9%

different results in terms of the percentages of reduction of risk as differences where highlighted in the TTC prediction during benchmark testing in project FLARE (Ruponen et al., 2022a).However, the general remarks provided can be valid as a general trend between the employment of static and dynamic analyses.

5. Conclusions

The present work presents a comparison between the application of advanced hydrodynamic modelling of a flooding event and the application of statutory static survivability analyses. Thanks to the application of a multi-level framework developed during project FLARE it has been possible to directly compare static and dynamic analyses using the attained PLL^* as a metric for the risk due to flooding. Both methods present a simplified empirical methodology to assess the consequences in terms of loss of life, as the fatality rate FR is estimated according to simplified formulations. However, the application of a full first-principle approach is not applicable, due to the large amount of calculations needed for advanced evacuation analyses.

The investigation on a set of 9 passenger ships allows for direct evaluation of the differences between simplified results obtained by static analysis and dynamic simulations obtained by employing PROTEUS 3 software. The reliability of the simulations is granted by the recent results of benchmarking activities, showing that PROTEUS 3 is capable of reproducing the behaviour of a flooding event in irregular waves, especially in the presence of complex internal layouts as is the case for Cruise vessels. The simulations performed on the reference ship show, except for one single ship, reductions in the risk profile of the vessel of about 12 to 30% of PLL^*. Such a result is achieved because static calculations are overestimating the number of real capsize cases for all the vessels. In fact, most of the simulations performed with dynamic analysis survive the 30-minute simulations, resulting in higher mean TTC values that reflect in a lower final value of the FR. It has to be observed that despite the hydrodynamic modelling in PROTEUS 3 being more advanced than a static or quasi-static simulation, it is still an approximation of the physics of a flooding event and that the application of a different simulation code for dynamic analyses can produce somewhat different results. Only the numerical modelling with viscous CFD codes could achieve a realistic evaluation of the coupling between the internal and external motion of the ship. However, due to the complexity of the simulation and the high computational effort needed to run a simulation, the applicability of such methods is not achievable with the necessity of designers. In fact, a rigid-body dynamic simulation presents nowadays for the simulation of flooding scenarios the best compromise solution between reliability and computational effort.

Notwithstanding the above, proper modelling of ship and floodwater hydrodynamics is a step forward in obtaining reliable predictions of the final fate of a vessel after a flooding accident occurs. The insight and forensic capability of a time-domain simulation are far above the number of outputs achievable with the employment of static analyses. Furthermore, the modern risk framework now available reduces the amount of dynamic calculations needed to assess the risk on a passenger vessel, favouring the applicability of advanced tools by designers.

CRediT authorship contribution statement

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

Declaration of competing interest

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

Data availability

Data will be made available on request.

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References

Acanfora, M., Cirillo, A., 2017. A simulation model for ship response in flooding scenario. Proc. Inst. Mech. Eng. M 120, 231.

Atzampos, G., 2019. A Holistic Approach to Damage Survivability Assessment for Large Passenger Ships (Ph.D. thesis). University of Strathclyde, Glasgow, Scotland, UK.

Bačkalov, I., Bulian, G., Chichowicz, J., Eliopoulou, E., Konovessis, D., Leguen, J., Rosen, A., Themelis, N., 2016. Ship stability, dynamics and safety: Status and perspectives from a review of recent STAB conferences and ISSW events. Ocean Eng. 116, 312–342.

van der Bosch, J., Vugts, J., 1966. On roll damping by free surface tanks. Trans. SNAME 108 (4), 1–11.

Braidotti, L., Mauro, F., 2020. A fast algorithm for onboard progressive flooding simulation. J. Mar. Sci. Eng. 8 (5), 369.

Bulian, G., Cardinale, M., Dafermos, G., Eliopoulou, E., Francescutto, A., Hamman, R., Linderoth, D., Luhmann, H., Ruponen, P., Zaraphonitis, G., 2019. Considering collision, bottom grounding and side grounding/contact in a common non-zonal framework. In: Proceedings of the 17th International Stability Workshop. Helsinki, Finland.

Dankowski, E., 2013. A Fast and Explicit Method for the Simulation of Flooding and Sinkage Scenarios on Ships (Ph.D. thesis). Hamburg University of Technology, Hamburg, Germany.

IMO, 2009. SOLAS-International Convention for the Safety of Life at Sea. Technical Report, IMO, London, UK.

IMO, 2020. International Convention for the Safety of Life at Sea (SOLAS). Technical Report, IMO, Consolidated edition as of 2020, London, UK.

Janssen, C., Bengel, S., Rung, T., Dankowski, H., 2013. A fast numerical method for internal flood water dynamics to simulate water on deck and flooding scenarios of ships. In: Proceedings of ASME 32nd International Conference on Ocean, Offshore and Arctic Engineering. Nantes, France.

Jasionowski, A., 2001. An Integrated Approach to Damage Ship Survivability Assessment (Ph.D. thesis). University of Strathclyde, Glasgow, Scotland, UK.

Kat, J.D., 2000. Dynamics of a Ship with Partially Flooded Compartments. Elsevier Science Ltd., pp. 249–263, Contemporary Ideas on Ship Stability.

Lee, G., 2015. Dynamic orifice flow model and compartment models for flooding simulations of a damaged ship. Ocean Eng. (109), 635–653.

Letizia, L., 1997. Damage Survivability of Passenger Ships in a Seaway (Ph.D. thesis). University of Strathclyde, Glasgow, Scotland, UK.

Luhmann, H., 2019. Sample Ships – Overview. Technical Report, FLARE project Deliverable D2.1.

Manderbacka, T., Ruponen, P., 2016. The impact of the inflow momentum on the transient roll response of a damaged ship. Ocean Eng. 120, 346–352.

Manderbacka, T., Themelis, N., Bačkalov, I., Boulougouris, E., Eliopoulou, E., Hashimoto, H., Konovessis, D., Miguez-Gonzalez, J.L.M., Rodriguez, C., Rosen, A., Ruponen, P., Shigunov, V., Schreuder, M., Terada, D., 2019. An overview of the current research on stability of ships and ocean vehicles: The STAB 2018 perspective. Ocean Eng. 186, 1–16.

Mauro, F., Vassalos, D., 2024. Multi-modal analysis of the time to capsize for damaged passenger ships in adverse weather conditions. 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., Bae, H., 2023a. Damage stability of passenger ships: A multi-modal analysis of the time to capsize. In: Proceedings of 19th International Ship Stability Workshop. Istanbul, Turkey.

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.

Papanikolaou, A., 2007. Review of damage stability of ships – recent developments and trends. In: Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS. Houston, Texas, USA.

Papanikolaou, A., Hamman, R., Lee, B., Lemoine, L., Mains, C., Olufsen, O., Tvedt, E., Vassalos, D., Zaraphonitis, G., 2013. GOALDS: Goal-based damage stability of passenger ships. Trans. SNAME.

Papanikolaou, A., Zaraphonitis, G., Spanos, D., Boulougouris, E., Eliopoulou, E., 2000a. Investigation into the capsizing of damaged ro-ro passenger ship in waves. In: Proceedings of the 7th International Conference on Stability of Ships and Ocean Vehicles. STAB, Launceston, Tasmania, Australia.

Papanikolaou, A., Zaraphonitis, G., Spanos, D., Boulougouris, E., Eliopoulou, E., 2000b. Investigation into the capsizing of damaged ro-ro passenger ships in waves. In: Proceedings of the 7th International Conference on Stability of Ships and Ocean Vehicles STAB. Launceston, Tasmania, Australia.

Paterson, D., Mauro, F., Vassalos, D., 2023. Ship vulnerability assessment by forensic investigation of critical damage scenarios.. In: Proceedings of 19th International Ship Stability Workshop. Istanbul, Turkey.

Paterson, D., Vassalos, D., Boulougouris, E., 2021. Results of Simulation Scenarios as Input to the Flooding Risk Model. Technical Report, FLARE, deliverable D4.4.

Pawloski, M., 2004. Subdivision and damaged stability of ships. In: Euro-MTEC Book Series, F. P. Przemyslu, Ed., Gdansk, Poland.

Ruponen, P., 2014. Adaptive time step in simulation of progressive flooding. Ocean Eng. 78, 35–44.

Ruponen, P., van Basten-Batemburg, R., van't Veer, R., Bu, D., Dankowski, H., Lee, G., 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., Aartovaara, M., 2019. Simulation-based analysis method for damage survivability of passenger ships. Ship Technol. Res. 66, 180–192.

Ruponen, P., Valanto, P., Acanfora, M., Dankowski, H., Lee, G., Mauro, F., Murphy, A., Rosano, G., van't Veer, R., 2022b. Results of an international benchmark study on numerical simulation of flooding and motions of a damaged ropax ship. Appl. Ocean Res. 123, 103153.

Ruth, E., Rognebakke, O., 2019. CFD in damage stability. In: Proceedings of the 17th International Ship Stability Workshop. Helsinki, Finland.

Sadat-Hosseini, H., Kim, D., Carrica, P., Rhee, S., Stern, F., 2016. Urans simulations for a flooded ship in calm water and regular beam waves. Ocean Eng. 120, 318–330.

Santos, T., Guedes-Soares, C., 2008. Study of damage ship motions taking into account floodwater dynamics. J. Mar. Sci. Technol. 13, 291–307.

Santos, T.A., Winkle, E.I., Guedes-Soares, C., 2002. Time domain modeling of the transient asymmetric flooding of Ro–Ro ships. Ocean Eng. 29 (6), 667–688.

Spanos, S., Papanikolaou, A., 2012. On the time dependance of survivability of ropax ships. J. Mar. Sci. Technol. 17, 40–46.

Spanos, D., Papanikolaou, A., 2014. On the time for the abandonment of flooded passenger ships due to collision damages. J. Mar. Sci. Technol. 19, 327–337.

Spanos, D., Papanikolaou, A., Zaraphonitis, G., 1997. On a 6 DOF mathematical model for the simulation of ship capsize in waves. In: Proceedings of the 8th International Congress on Marine Technology. IMAM, Istanbul, Turkey.

Vanem, E., Rusas, S., Skjong, R., Olufsen, O., 2007. Collision damage stability of passenger ships: Holistic and risk-based approach. Int. Shipbuild. Prog. 54 (4), 323–337.

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

Vassalos, D., 2022. The role of damaged ship dynamics in addressing the risk of flooding. Ship Offshore Struct. 17 (2), 273–303.

Vassalos, D., Mujeeb-Ahmed, M., 2021. Conception and evolution of the probabilistic methods for ship damage stability and flooding risk assessment. J. Mar. Sci. Eng. 9 (6), 667.

Vassalos, D., Mujeeb-Ahmed, M., 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., Mauro, F., Mujeeb-Ahmed, M., Murphy, A., Michalec, R., Boulougouris, E., 2022b. A multi-level approach to flooding risk estimation of passenger ships. In: SNAME 14th International Marine Design Conference, IMDC 2022. Vancouver, BC, Canada.