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Evolution of ship damage stability assessment—Transitioning designers to direct numerical simulations

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ABSTRACT

Theory and application of damage stability followed over the years two dissociated paths: static assessments and dynamic simulations. The first approach, being easy to apply and understand, has been preferred by ship designers and regulators; the second, more advanced and first-principle oriented, has been mainly reserved for research or high-level consultancy, especially for passenger ships. Nowadays, the availability of numerical flooding simulation tools across the scientific community and calculation power in the industry allows for a possible definitive transition of damage stability assessment towards direct numerical analyses. However, research should softly drive designers towards more advanced processes via a suitable didascalic calculation framework. The multi-level approach pursued in project FLARE is an example of such a transition from static to dynamic damage stability assessment. The present work initially carefully reviews the probabilistic concept of damage stability, critically comparing the prescriptive statistical methods with direct ones and providing insights and guidance on how researchers and designers can reconcile with the original implicit assumption of the probabilistic approach. Secondly, the development of the multi-level framework highlights incongruences concerning modelling of damages between static and dynamic assessments, disfavouring the comprehension of dynamic results to designers. Two detailed examples highlight the differences in dynamic simulation results between different damage breach modelling, leading to completely different flooding paths for the same damage case. Finally, the paper indicates how a compromise between academic approach and application could help designers to start their transition towards direct numerical damage stability analyses.

1. Introduction

The focus on damage stability in the last decades has developed through a series of collaborative research projects moved by the need for understanding the flooding process, its risk and consequences (potential loss of lives) after serious accidents at sea (Vassalos, 2016).

As a result of years of research on damage stability and flooding risk, besides the possibility to perform model experiments (Manderbacka et al., 2015; Siddiqui et al., 2020; Valanto, 2022), there is the availability of numerous codes addressing the damage stability problems, employing different levels of approximation, equation resolutions and body forces calculations. Therefore the survivability can be assessed with different fidelity levels and damage stability codes can be distinguished according to this fidelity metric:

– *Low fidelity*: this category covers the static methods, based on hydrostatic calculations for the damaged condition. Such codes supply the necessary information to provide statutory damage stability assessment.
– *Low/Medium fidelity*: this category includes codes evaluating the flooding progression with time, modelling flooding rates with Bernoulli's equations but using a static balance for ship motions (usually considering only heave, roll and pitch (Dankowski, 2013; Braidotti and Mauro, 2020), with empirical correction for roll motion (Ruponen, 2014)). The water surface in the flooded compartments is considered parallel to the undisturbed sea level.
– *Medium/High fidelity*: this is the category grouping all the simulation methods based on rigid-body dynamics (4 or 6 DOF),

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Nomenclature

α	Wave slope
γ	Elongation parameter for JONSWAP wave spectrum
ϕ	Intact and damaged ship roll angle
θ	Intact and damaged ship pitch angle
χ	Ship-wave encounter angle
A	Attained subdivision index
C_d	Discharge coefficient
H_s	Significant wave height
H_s^*	Critical wave height
L_{PP}	Length between perpendiculars
L_s	Subdivision length
L_x	Damage longitudinal length
L_y	Damage lateral length/penetration
L_z	Damage vertical length/height
N_{DC}	Number of damage cases
N_{DCf}	Number of filtered damage cases
N_s	Number of sampled breaches
N_{sf}	Number of filtered breaches
m_W	Floodwater mass
p	Probability of damage, p-factor
s	Probability to survive a flooding event, s-factor
w	Weighting factors for survivability
X_F	Longitudinal position of damage forward end
X_M	Longitudinal position of damage centre
Y_F, Y_{F_P}	Reference lateral positions for bottom grounding damage
z^*	Reference vertical coordinate for damage generation
z_{LL}	Damage lower vertical limit
CFD	Computational Fluid Dynamics
DOF	Degrees of Freedom
EMSA	European Maritime Safety Agency
eSAFE	enhanced Stability After a Flooding Event
FLARE	Flooding Accident Response
GA	General Arrangement
GOALDS	GOAL based Damage Stability
HARDER	Harmonization of Rules and Design Rational
ITTC	International Towing Tank Conference
IMO	International Maritime Organisation
JONSWAP	Joint North Sea Wave Project
MC	Monte Carlo
PLL	Potential loss of lives
RANS	Reynolds Averaged Navier–Stokes
RQMC	Randomised Quasi-Monte Carlo
SEM	Static Equivalent Method
SOLAS	Safety of Life at Sea

modelling water ingress/egress with Bernoulli's equation (Jasionowski, 2001), and coupling floodwater motions with ship dynamics. The modelling of internal water motions could vary between codes, ranging from quasi-static flat free surface (de Kat, 2000; Letizia, 1997), lumped mass models (Papanikolaou et al., 2000; Acanfora and Cirillo, 2017; Manderbacka and Ruponen, 2016), dynamic resonance models (Lee, 2015) or shallow-water equation (Janßen et al., 2013; Santos and Guedes Soares, 2008).

– *High fidelity*: here the CFD simulations are included, meaning techniques modelling the internal motion of fluids from the numerical integration of RANS equations (Ruth and Rognebakke, 2019; Sadat-Hosseini et al., 2016). The method allows a direct coupling between the fluid forces (internal and external) and the 4–6 DOF resolution of rigid body equations. However, such resolution requires much higher computational time than other described fidelity models.

A full compliance with regulations implies the adoption of low fidelity models. However, aiming for the utilisation of direct approaches to survivability, higher fidelity models are advisable. Actually, a good and applicable compromise between accuracy and calculation time is given by medium/high fidelity models (Vassalos, 2022). On the other hand, the sole application of a dynamic approach with medium/ high fidelity models may result to difficult immediate interpretation and understanding by designers, that should in any case deal with owners, operators and statutory requirements. Therefore, the low fidelity static methods cannot be discarded but can be used as a starting point for more advanced analyses. To this end, a multi-level hybrid framework has been set up to guide the designers into the field of direct dynamic flooding analyses, starting from consolidated practice with low fidelity models and procedures. The framework is limiting the use of dynamic simulations to a more detailed analysis of a set of critical static cases, aiming at a possible increase of the Attained survivability index (IMO, 2009). Such a framework is the first attempt to let the designers involved in calculation processes that have been mainly reserved to academic research or high-level consultancy. Moreover, the interconnection between researchers and designers vision of the damage stability assessments allows for detecting unexpected incompatibilities between geometrical modelling practices in dynamics and statics.

In the present work, after an initial critical review of the survivability concept developed across years of research (Section 2), the multi-level hybrid framework is presented (Section 3), highlighting the gaps in breaches definition between the static and dynamic approaches to damage stability and how these have been solved to match the framework necessities (Section 4). In Section 5, such differences are shown for two reference cruise ships, considering simulations in calm water. The differences between the two breach geometrical modelling highlight how it is fundamental for the future developments in damage stability assessment going towards a fully direct approach, starting from the damage definition with crash analyses, that could provide the effective geometry of the breach. Furthermore, critical analysis of the results highlights the gaps (Section 6) between the presented didascalic design-oriented framework and an effective rigorous approach based on direct methods, especially once irregular waves are considered.

2. The survivability concept

Survivability is a concept strictly related to the damage stability assessment of a ship. The in-force regulations measure the safety level of a vessel through the Attained Survivability Index (A-index), a weighted sum of partial indices evaluated at three different draughts:

$$A = \sum_i w_i A_i = 0.4A_s + 0.4A_p + 0.2A_l \quad (1)$$

$$A_i = \sum_{j=1}^{N_{DC}} p_j s_j \quad (2)$$

where the indices s, p and l in Eq. (1) denote the deeper the partial and the light subdivision draughts, respectively. The partial indices described by Eq. (2) is composed of two terms p_j and s_j that should be evaluated for a set of N_{DC} damage cases. The p_j is the probability of occurrence of the jth damage case and is usually referred as p-factor. The s_j is the probability to survive after flooding during the jth damage case and is usually referred to as s-factor.

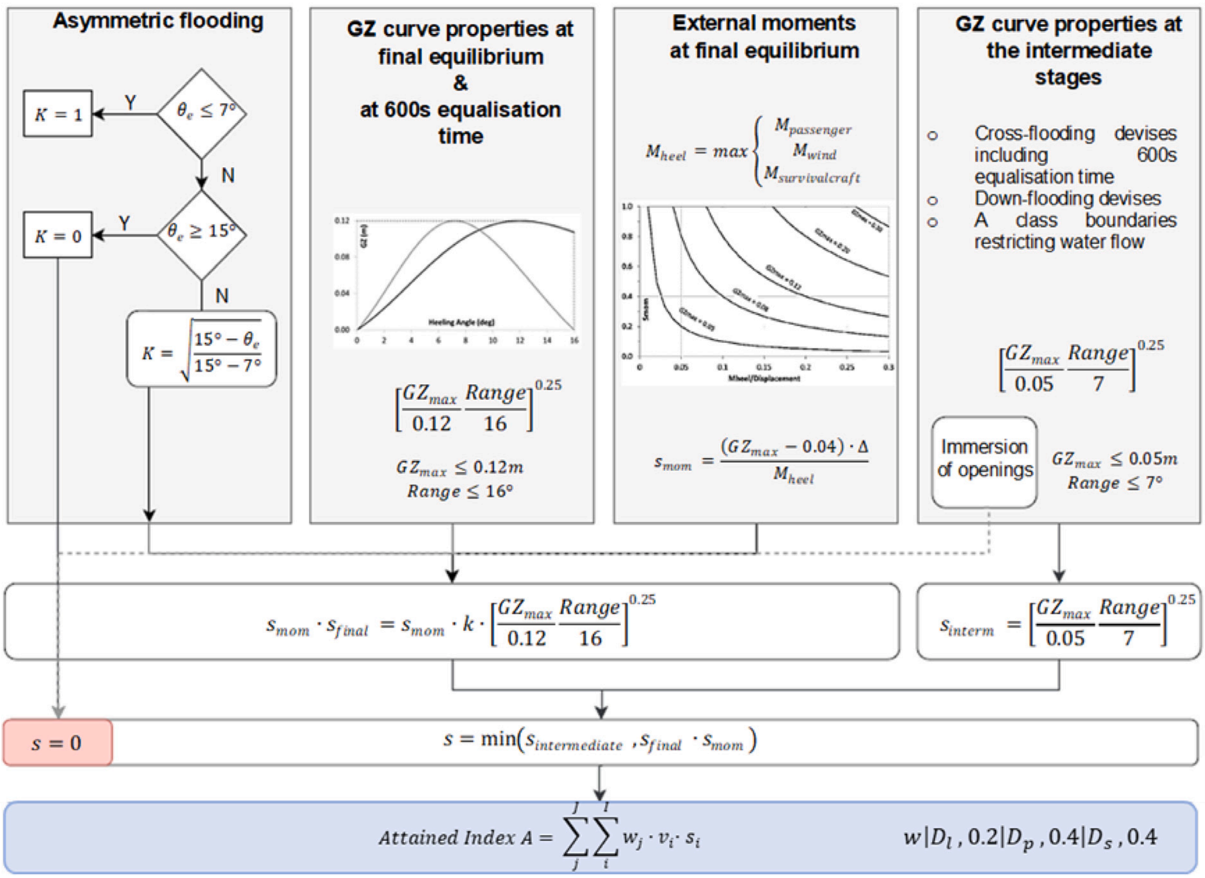


Fig. 1. s-factor definition and calculation process according to SOLAS (Vassalos and Mujeeb-Ahmed, 2021).

The nature of p-factors is widely described by Vassalos et al. (2022b) and industry and research are nowadays jointly abandoning the traditional statutory "zonal" method for collisions only (Pawlowski, 2004), following a modern direct methodology, the "non zonal" approach (Bulian et al., 2016; Mauro and Vassalos, 2022b), for their determination, especially for complex internal layouts as passenger ships and different damage types (Bulian et al., 2020). Relevant is also the applicability of the "non zonal" approach to both static and dynamic analyses, using the same damage dimension distributions and sampling methodologies to generate breaches. The only difference remains the grouping of cases leading to the same group of compartments open to sea embedded in the static approach, not sensible to the differences of breach area as a direct rigid-body dynamic analysis.

Different is the case for the s-factor. Even though Vassalos and Mujeeb-Ahmed (2021) provide a clear overview of the evolution and insight of the probability of surviving an accident, the static-oriented statutory definitions of s-factor remains far to be aligned with a rigorous probabilistic definition. As a probabilistic framework describes the damage stability assessment of a ship, the following definition is appropriate:

$$s = p\left(H_s \leq H_s^*\right) = \int_0^{\infty} f_c\left(H_s\right) p_s\left(H_s\right) \mathrm{d}H_s \tag{3}$$

where, H_s is the significant wave height at which the collision occurs, H_s^* is a critical wave height identifying the limiting survival condition for the damaged ship, $f_c(H_s)$ is the probability density function of the H_s encountered in a potential collision event (IMO, 2009; Jasionowski, 2009), and $p_s(H_s)$ is the probability of surviving flooding in the given sea state. Such a definition intrinsically includes the exposure time concept or, using different wording, it considers evaluating the A-index as the marginal probability for time to capsize, assuming time sufficiently long to have a capsize occurrence in most cases. However, the conventional and well known definition of s-factor from static analyses embedded in SOLAS regulations (IMO, 2020), considers only ship stability residual parameters (see Fig. 1).

Customarily, H_s^* derivation is implicitly considered with the s-factor calculations, but not always directly reported in the assessment results. In this sense, the s-factor eclipses the presence of the critical sea state and instead, survivability is more likely expressed directly as a function of ship stability residual parameters.

2.1. s-factor and critical sea state H_s^*

The effective inclusion of the sea state for survivability has been introduced during project (HARDER, 2000-2003) through the Static Equivalent Method (SEM). The original SEM method (Vassalos and Papanikolaou, 2002a,b) linked the critical sea state H_s^* to ship performance in waves (dynamic elevation of floodwater resulting from action of waves on the vehicle deck, h), applicable only to RoPax with large undivided spaces like vehicle decks, leading to the following formulation:

$$H_s^* = \left(\frac{h}{0.085}\right)^{\frac{1}{1.3}} \tag{4}$$

During project HARDER, formulation (4) was updated following a statistical relationship between dynamic water head h, the freeboard, the critical heel angle and the mean significant survival wave height, and afterwards harmonised with SOLAS s-factor as follows (Tuzcu, 2003):

$$H_s^* = 4\frac{GZ_{max}}{TGZ_{max}}\frac{Range}{T\,Range} = 4s^4 \tag{5}$$

It is noteworthy to mention that the above survival factor, produce a survival probability relating to the dynamic effects of encountering waves only when the vessel had reached final equilibrium after damage.

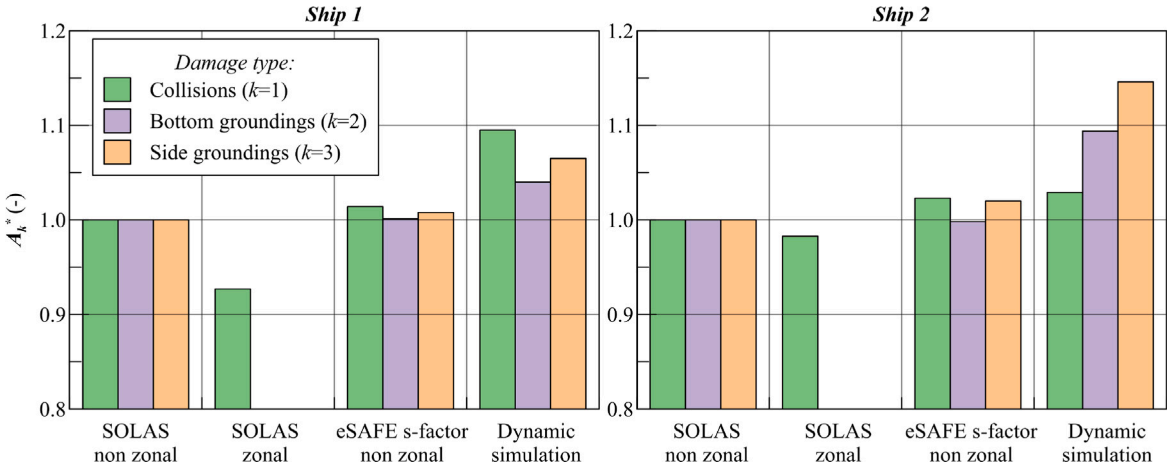


Fig. 2. Comparison between static, regressions and dynamic simulation results on two sample cruise ships.

After some tentative of inclusion of additional parameters related to the damage ship geometry (like the residual buoyancy volume of the damaged ship) during project (GOALDS, 2009-2012), the main advances for survivability definitions have been reached in project (eSAFE, 2016-2018). This is the first project where the focus on cruise ships has been maintained throughout the research effort, and where all results are based on numerical time-domain simulations for the assessment of the critical wave height in relation to residual stability parameters.

Based on dynamic simulations results, a new cruise ship-specific formula for predicting the H_s^* has been derived on the basis of GZ properties through regression of the simulation results. Following this, a new s-factor formulation that accounts more accurately for cruise vessels has been proposed using a regression formulation of the significant wave height distribution at the time of accident. The results of two ships of different size indicated that a scaling methodology should also be applied. The most suitable scaling parameter was found to be the *Effective Volume Ratio* λ; a parameter which accounts for both the scale of the damage and of the vessel. Employing this strategy, a wider database ranging the whole cruise ship size has been covered, leading to the following regression:

$$H_s^* = 7\left[\frac{\min\left(\lambda Range, TRange\right)}{TRange}\frac{\min\left(\lambda GZ_{max}, TGZ_{max}\right)}{TGZ_{max}}\right]^{1.05} \tag{6}$$

where the parameters have been set up with the following values: $TGZ_{max} = 0.30$ metres and $TRange = 30$ degrees. Two different formulations for the s-factor were derived, considering wave statistics from collision events (HARDER, 2000-2003) or global wave statistic distribution. The last one with the following form:

$$s\left(H_s^*\right) = \exp\left(-\exp\left(1.717 - 0.9042 H_s^*\right)\right) \tag{7}$$

Such a formulation is considering the trend foreseen for new cruise ship designs towards wider open sea worldwide operations, where a limitation of H_s to 4 m, as for collision statistics, may result in a serious underestimation of dynamic loads.

2.2. Static against dynamic survivability

Project eSAFE gave also the opportunity to compare on cruise ships the impact on the survivability of different statutory and statistical approaches in relation to direct time-domain analyses. Such comparisons have been performed on a small set of cruise vessels, considering not only the collision damages but also breaches derived by newly developed bottom and side groundings damage models (Bulian et al., 2020). Setting as a reference the non zonal A-indices for different damage types obtained with SOLAS s-factor, results with different approaches for p-factors, s-factors and calculation method can be compared by evaluating:

$$A_k^* = \frac{A_{h,k}}{A_{0,k}} \tag{8}$$

where $A_{0,k}$ are the partial A-indices obtained with the non zonal approach and SOLAS s-factors for different damage types ($k = 1$ collisions, $k = 2$ bottom groundings an $k = 3$ side groundings), and indices h relates to the method used ($h = 1$ zonal with SOLAS s-factor, $h = 2$ non zonal with eSAFE s-factor and $h = 3$ non zonal with dynamic simulations).

The numerical results and the regression analyses show to be consistent in ranking different ships. However, the static results are always more conservative compared to the dynamic approach. As an example, Fig. 2 shows the behaviour of indices expressed as per Eq. (8) on two sample cruise ships, confirming what has been stated above.

Therefore, the statistical analyses provided in eSAFE has not enough granularity to assess the survivability of a passenger ship. Such a consideration formed the bases for project (FLARE, 2018-2022), expanding the adoption of numerical time-domain simulations for ship survivability (Vassalos et al., 2022d).

3. The multi-level hybrid framework

The experience gained from the last three decades of joint research between academy and industry on damage stability issues (summarised in Section 2) point out the need to incentivate the adoption of direct numerical flooding simulations for the assessment of survivability after accidents.

However, the interpretation of the results provided by the past research projects gives two distinct interpretations about the adoption of direct methods:

- *The researcher vision*: direct methods are the right solution for damage stability assessment and can be pursued in all the phases of the analyses. Starting from damage generation up to the execution of time-domain rigid-body flooding simulation to assess survivability.
- *The designer vision*: the adoption of direct methods is subordinated to static calculations. Advanced methods should be used only to check detected critical conditions, finalised to a fictitious increase of the attained subdivision index (as for the trends shown in project eSAFE or EMSA studies).

Project FLARE had to deal with both the above mentioned interpretations but has initially started with a more research focused vision. Therefore, the developments started with rigorous benchmark studies

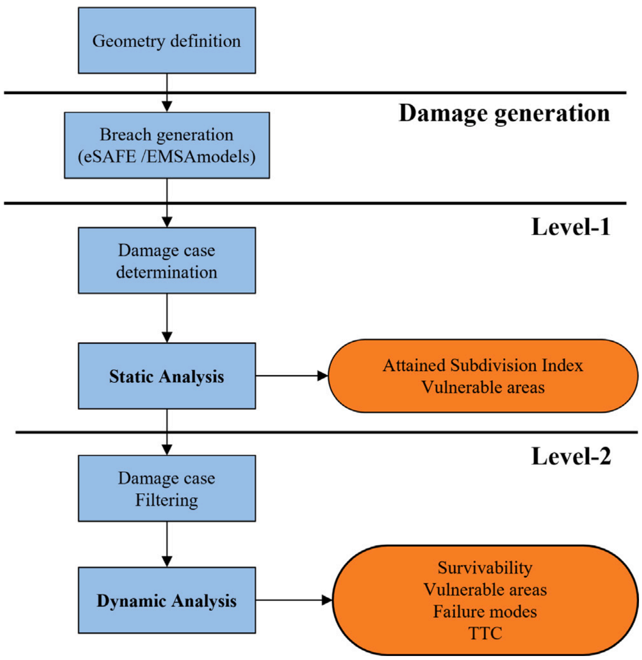


Fig. 3. The multi-level hybrid damage stability framework.

for crash analyses (Kim et al., 2022) and flooding (Ruponen et al., 2021, 2022b,a), the development of rigorous calculation methodology for crashworthiness (Conti et al., 2021; Zang et al., 2021), and the definition of first principle-based multi-level frameworks for damage stability assessment (Mauro et al., 2022b,a).

However, such an amount of new information and methodologies is hard to be directly applied by designers, used to perform classical calculation processes and having confidence with outputs of more simple analyses. It was then necessary to start a parallel development of simplified approaches aimed at gradually introducing designers to calculation methods and analyses not conformal with their standards. To this end, for the specific case of damage stability assessment, a multi-level hybrid framework has been jointly developed within the FLARE project. Such a framework has been conceived in a way to be initially familiar with designer practice for damage stability, starting from statutory static calculations with some additions from project eSAFE (non zonal approach and groundings), adding softly dynamic calculation as a second step. The resulting hybrid two-level framework is slightly different from what initially described by Mauro et al. (2022a), and can be summarised in the following steps:

1. *Damage generation*: direct generation of collision, side and bottom groundings damages using a non zonal approach.
2. *Level-1 assessment*: static damage stability assessment following the next two main steps:
   - *Damage grouping*: identification of unique damage cases to be used for static calculations.
   - *Static calculation*: determination of the s-factor for each damage case as well as of the partial and global attained survivability indices.
3. *Critical damages selection*: identification of relevant cases to be analysed with dynamic analyses.
4. *Level-2 assessment*: dynamic flooding simulations

The main steps of the framework are shown in Fig. 3. For a better understanding of the process, the steps of the procedure are hereafter described in more detail.

3.1. Damage generation

The first step to assess survivability of a passenger ship or a ship in general is defining the dimensions and locations of the different damage types that may occur in the ship life-cycle. As highlighted by Mauro et al. (2022b), there are principally two ways for determining distribution pertinent to different damage characteristics: a probabilistic and a direct one. The two approaches differ for the final level of accuracy and, of course, the calculation time. It is undoubtful that direct methods based on crash analyses (Conti et al., 2021; Kim et al., 2022) are actually giving the most accurate way to determine the breach dimension and shape, however they require the execution of dedicated sets of crash analyses to determine suitable databases for collisions (Conti et al., 2021) or groundings (Taimuri et al., 2023), also in combination with traffic analysis and hindcast of specific route scenarios (Zang et al., 2021).

Therefore, the hybrid multi-level framework adopts probabilistic distributions for damage dimension and locations according to models developed across the aforementioned research studies on ship damage stability. The following models are familiar and can be adopted by designers of passenger ships for collision and groundings:

Collisions : the model follows the general information of SOLAS (IMO, 2009), thus using distributions derived from studies performed by Lützen (2001). In addition, the lower vertical extent limit (Bulian et al., 2019b) is added as proposed during project eSAFE.

Bottom groundings : the modelling of bottom groundings started from studies provided in project GOALDS (Bulian and Francescutto, 2010) and continues up to the final definition of a probabilistic model during project EMSA3 (Bulian et al., 2016) and eSAFE (Bulian et al., 2019a). The final eSAFE model is adopted in the hybrid framework.

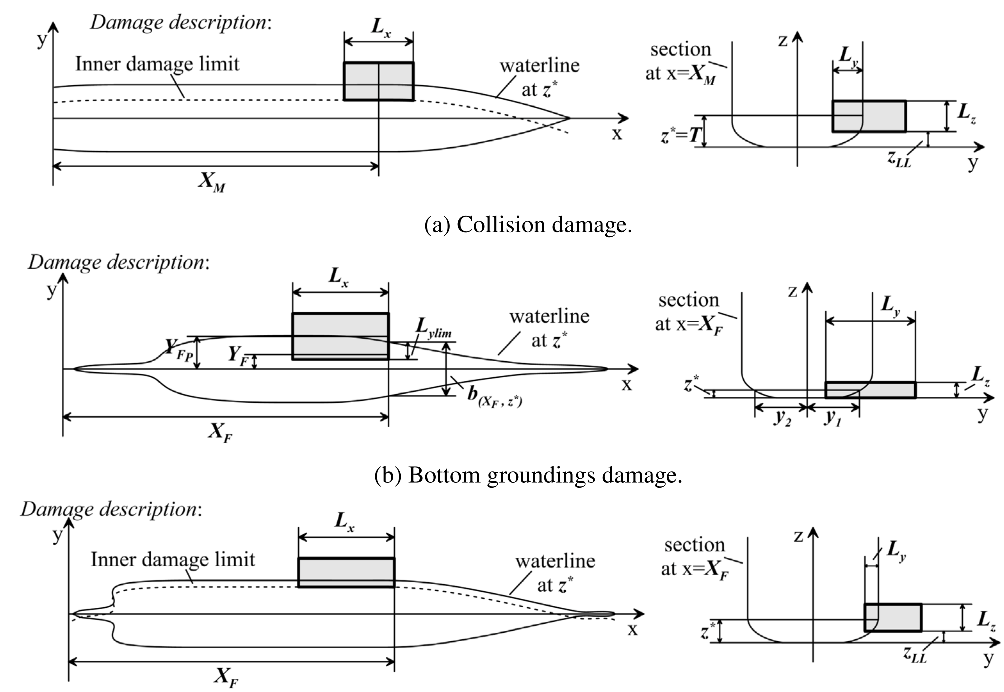
Side groundings : side groundings/contacts are the last damage type that has been studied in damage stability-related projects. The modelling implemented in the framework is the one resulting from studies provided in EMSA3 and eSAFE projects (Bulian et al., 2020).

Fig. 4 shows locations, dimensions and shape of the above-described damage models. A detailed overview of these models is available in Bulian et al. (2019a), Bulian et al. (2020) and Mauro et al. (2022a), giving the distributions and algorithm descriptions for the breach generation process employing the non-zonal approach. All the mentioned breaches models are dependent on the vessel draught. Therefore, each loading condition requires a specific breach generation. The standard SOLAS framework requires the analysis of three draughts (see Eq. (1)); however, preliminary studies in project eSAFE (Paterson et al., 2019) and FLARE (Luhmann, 2021a) suggests to use an assessment based on two draughts only. Hence the hybrid framework is based on two draughts (T_1 and T_2) defined as follows:

$$\begin{cases} T_1 & = 0.75\left(T_s - T_l\right) \\ T_2 & = 0.45\left(T_s - T_l\right) \end{cases} \tag{9}$$

where T_s is the deepest subdivision draught and T_l the light subdivision loads defined in SOLAS.

To further reduce the calculation effort, the designers specifically request to use an initial number of samples N_s of 10,000 per each draught and damage type, using a conventional crude Monte Carlo sampling implemented in commercial software developed during project eSAFE (Lindroth et al., 2017a). This is an approximation as multiple research studies suggest the adoption of a higher number of samples (Bulian et al., 2016, 2020) or the use of advanced sampling techniques (Mauro et al., 2021; Mauro and Vassalos, 2022b) to ensure A-index convergence.



(a) Collision damage.

(b) Bottom groundings damage.

(c) Side groundings damage.

Fig. 4. Breach modelling for different damage types.

3.2. Level-1 assessment

Level-1 assessment relates to static calculations. The process reflects the calculation techniques amended by SOLAS regulations (IMO, 2009) but applies the non-zonal approach. Furthermore, the assessment follows the guidelines given by FLARE for the selection of loading conditions and associated permeability of the internal spaces (Luhmann, 2021b). The main target of the Level-1 assessment is the determination of ship survivability and the identification of possible critically vulnerable areas along the vessel. The survivability assessment of the hybrid framework adopt equation (1) reduced for the two FLARE draught T_1 and T_2, using different weights depending on the damage type and the ship type, thus distinguishing between cruise ships and Ro-pax. Adopted weights derive from an enhanced accident database analysis (Mujeeb-Ahmed et al., 2021) and Table 1 shows the resulting w values. Partial indices evaluation is congruent with Eq. (2). This assessment in the non-zonal framework is comprehensive of collisions, side and bottom groundings. The non-zonal approach generates N_s breaches through the sampling process; however, several damages hit the same compartments in the ship. As static analysis is not sensitive to the variation of the breach dimensions within a group of damaged rooms, such breaches identify a single damage case with a given occurrence, determining the already mentioned p-factors. The proper formulation for the occurrence of a damage case is as follows:

$$p_j = \frac{n_j}{N_s} \tag{10}$$

where n_j is the number of breaches leading to the same damage case, i.e. to the same group of compartments open to the sea. This process identifies the N_{DC} unique damage cases to be used in Eq. (2). Of course N_{DC} changes for all the loading conditions and damage types, as it is specific for a given damage distribution.

An important change for Level-1 assessment is the granularity of the internal layout of the ship. Traditionally, static assessment is performed with a reduced number of compartment compared to the dynamic calculations. However, with the objective of using a harmonised model applicable also in dynamics, the same granularity of a dynamic calculation is adopted, increasing the number of compartments and connections. Such modelling is intrinsically increasing the number of unique cases N_{DC}, thus, possibly causing convergence issues to the Monte Carlo process with an initial sample size N_s to the magnitude of 10,000. On the other hand, it should be noted that the value of the integral (the A-indices) is quite close to 1 (the upper limit of the integrating function) and other studies on Monte Carlo like integration on discrete functions in $(0,1)$ shows that convergence of the integral is faster when the integration function is close to the upper or lower limit (Mauro and Nabergoj, 2022; Nabergoj and Mauro, 2022).

Table 1
Weighting factors w for A index evaluation in the hybrid framework.

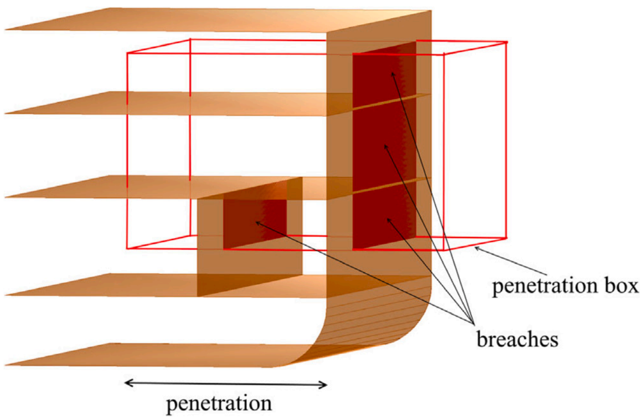
	Cruise		Ro-Pax	
	$T_{1_{FL}}$	$T_{2_{FL}}$	$T_{1_{FL}}$	$T_{2_{FL}}$
Collisions	0.025	0.025	0.125	0.125
Bottom groundings	0.190	0.190	0.170	0.170
Side groundings	0.285	0.285	0.205	0.205

In the present study and FLARE project, static calculations performed by the designers adopt the commercial software NAPA (Lindroth et al., 2017b). The software incorporates all the features necessary to perform non-zonal calculations due to continuous developments throughout the previously mentioned industry-oriented projects on damage stability (eSAFE, 2016-2018; Zaraphonitis et al., 2015). In any case, the procedure and methods suitable for a Level-1 prediction apply to any tool capable of calculating the static equilibrium of a damaged ship.

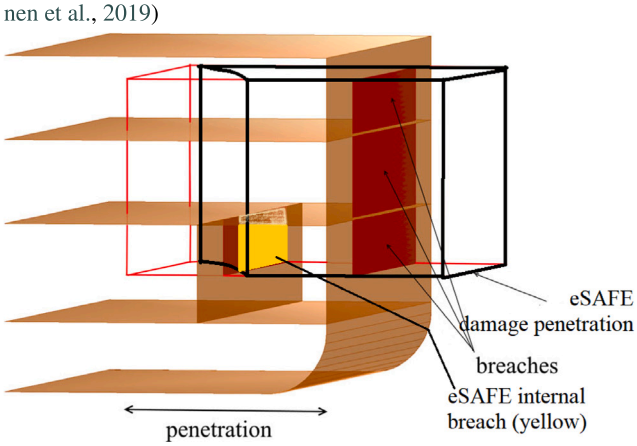
The execution of a large amount of calculations in Level-1 analyses is not a main issue, as running a single static calculation is a matter of few seconds on regular laptops.

3.3. Critical damages selection

The selection of critical cases is performed with a screening of the static results obtained in the Level-1 assessment. The process follows

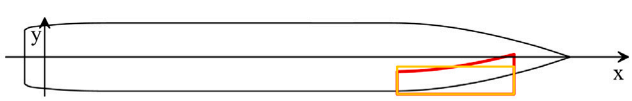


(a) Modelling of breach openings with a box-shaped model (Ruponen et al., 2019)

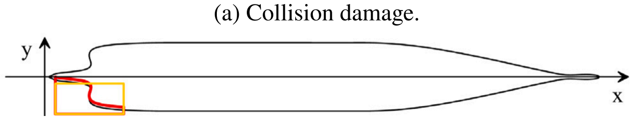


(b) Modelling of breach openings with a eSAFE-shaped model

Fig. 5. Notional example for box-shaped and eSAFE-shaped modelling for breach openings.



(a) Collision damage.

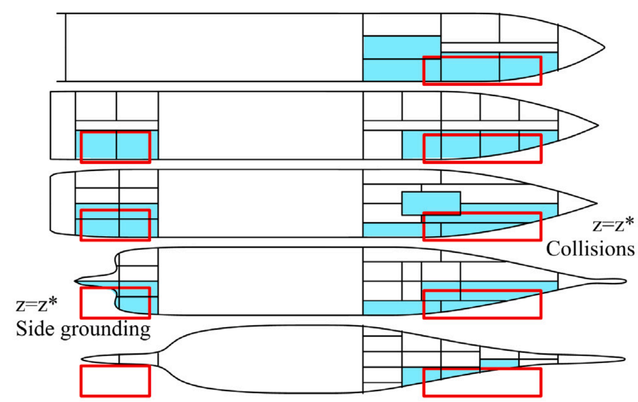


(b) Side grounding damage.

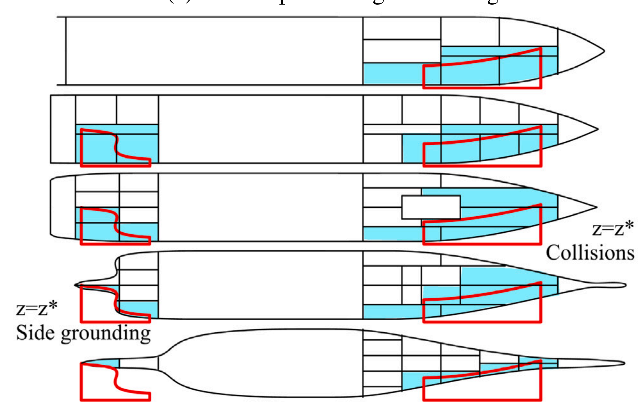
Fig. 6. Difference between eSAFE-shaped (*red*) and box-shaped (*yellow*) damages on a ship GA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the basic process described by Mauro et al. (2022b) for static analyses results, using as risk metric the factor $p(1-s)$.

The method considers only the cases with $s < 1$, thus unsafe cases according to the static assessment and weighting them with the associated p-factor. Therefore the most risky cases are those with $s \neq 0$ and an high p-value, which means that those are damages most probable to occur according to the adopted probabilistic framework. As highlighted by the explorative study on the filtering techniques (Mauro and Vassalos, 2022b), one of the issues associated with the adoption of this static filtering based on $p(1-s)$ is the selection of the filtering threshold. The initial studies suggested the adoption of a value of $1/N_s$. However, designers, after preliminary tests, propose the adoption of a threshold value of 2E-4, independently of the sampling size N_s, but



(a) Box-shaped damage modelling.



(b) eSAFE-shaped damage modelling.

Fig. 7. Differences between damaged compartments considering a box-shaped or eSAFE shaped compartment for collisions (*fore*) or side groundings (*aft*).

based on potential changes on the associated A-index. Such a selection is oriented to limit the number of damage cases to be analysed with the dynamic simulation, observing that for a set of 10 different passenger ships, such a threshold value was always passing to the next step less than 500 damage cases per condition (meaning combination of draught and damage type). Such an assumption is not based on scientific criteria and the threshold value can be changed independently for each analysis by the framework user.

The final output of the filtering process is a set of N_{DCf} unique damage cases, which is a subset of the N_{DC} analysed in the Level-1 assessment.

3.4. Level-2 assessment

Level-2 assessment is finally involving the dynamic rigid-body flooding simulations. The hybrid framework allows for potentially using all kinds of *medium/high* fidelity tools (according to the nomenclature given in Section 1). However, the practical implementation and initial usage by the designers during project FLARE is restricted to PROTEUS3 software, which is based on the resolution of 4DOF rigid-body ship motion equations (surge and yaw are not considered), coupled with the floodwater dynamics. The flooding process is governed by Bernoulli's equation, while the water inside compartments is modelled as a lumped mass. Froude–Krylov and restoring forces are integrated up to the instantaneous wave elevation both for regular and irregular waves. Radiation and diffraction are derived from 2D strip theory. Hydrodynamic coefficients vary with the attitude of the ship during the flooding process (heave, heel and trim). The vessel is assumed free to drift, with drift forces evaluated by empirical formulations. Further detailed

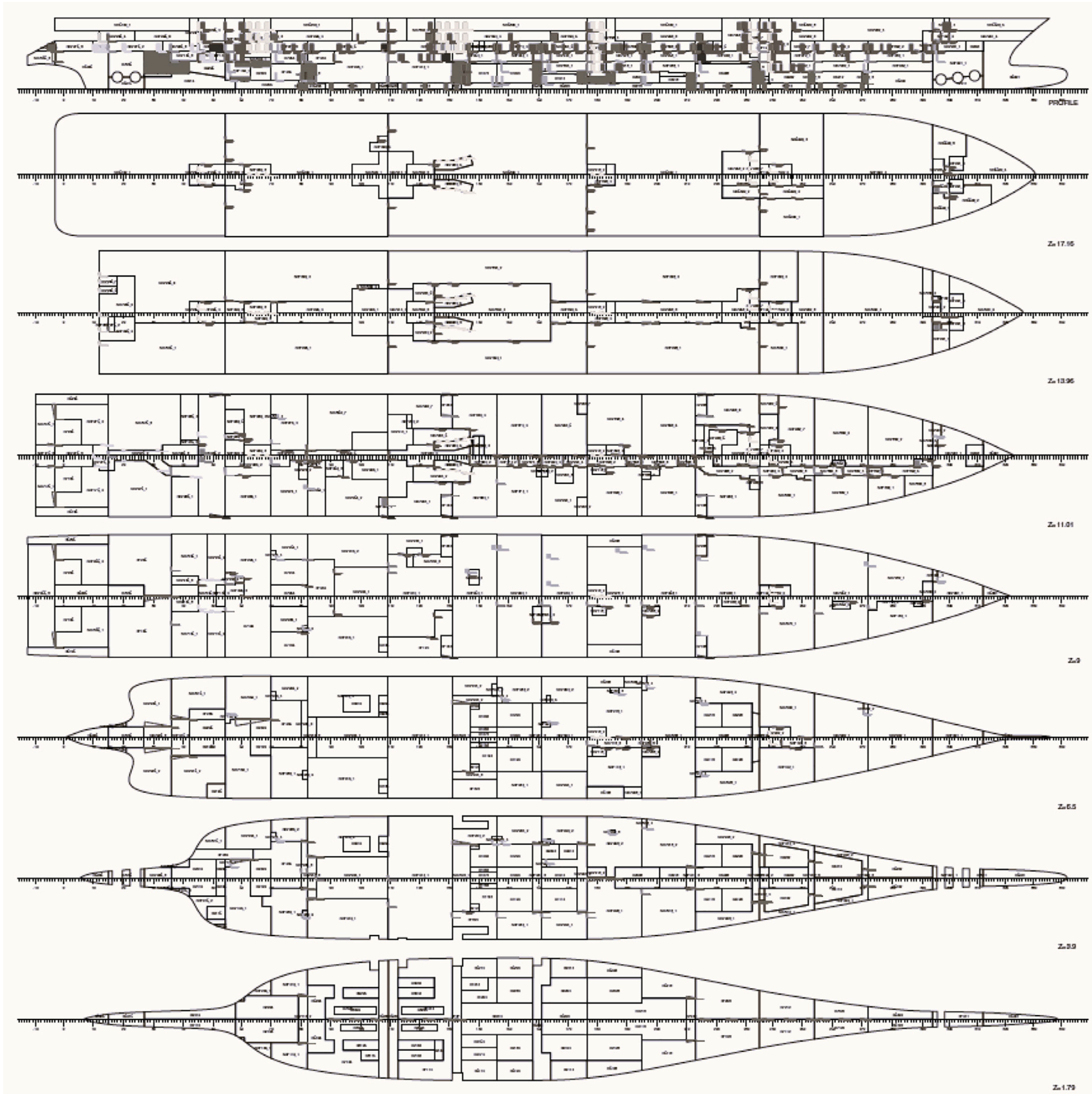


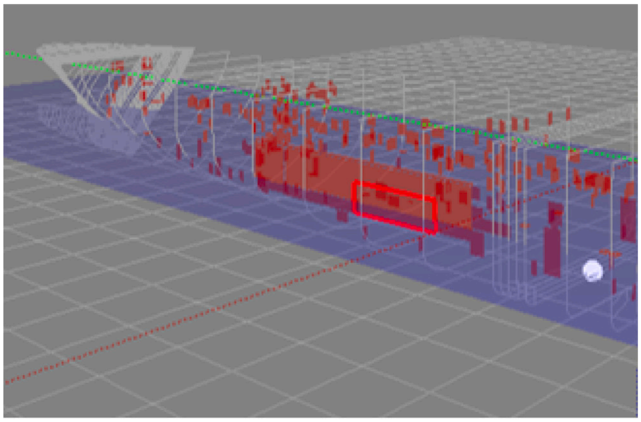
Fig. 8. Internal layout and openings for Ship A dynamic model.

information is given in Jasionowski (2001). Therefore, all calculations and solutions presented refer to the usage of this *medium/high* fidelity tool, employing specific calculation settings as discussed subsequently.

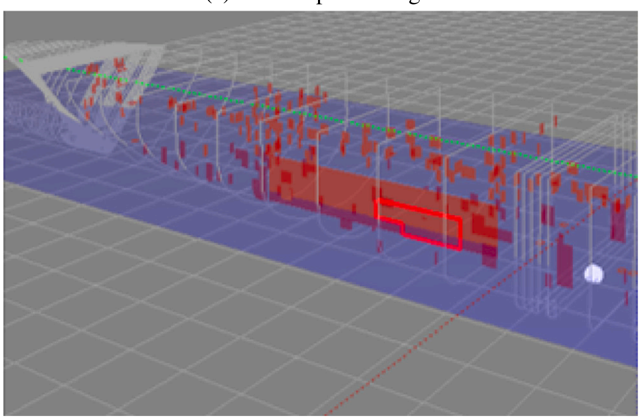
The calculations are performed on the reduced set of filtered damage cases, considering prescribed initial and environmental conditions. The main assumptions and settings for the dynamic calculations are as follows:

- *Rigid body motions*: 4 DOF simulation considering sway, heave, roll and pitch motions of the damaged ship.
- *Floodwater motions*: floodwater motions are modelled according to a lumped mass model and the equations are coupled with the rigid body ship motions. The surface of the water inside the compartment is parallel to the undisturbed sea water level.
- *Water ingress/egress*: flow across internal (doors, stairs, etc...) and external openings (breaches) is modelled by Bernoulli equation with a fixed discharge coefficient C_d of 0.6.
- *Hydrodynamic coefficients and loads*: hydrodynamic loads are derived from 2D strip theory calculations at different draughts, pitch and heeling angles on the intact geometry. Body forces are then calculated interpolating the coefficients according to the actual attitude of the ship. Drift forces effects are neglected.
- *Initial conditions*: the encounter angle χ between ship and waves is fixed at 90 or 270 degrees (beam seas) depending on the damaged side. The vessel speed is always 0 knots. The simulation starts with the intact vessel at given initial conditions, then the breach is opened after 20 s. The maximum simulation time is 30 min from the breach opening.
- *Environmental conditions*: irregular waves with a significant wave height H_s=4.0 metres, modelled according to a JONSWAP spectrum (Hasselmann and Olbers, 1973) with peak parameter γ = 3.3, considering a constant wave slope α of 0.02. Wind loads are not considered in the calculations.

Compared to the full dynamic framework or to the hybrid one proposed by Mauro et al. (2022a), here the dynamic calculations are not performed on all the breaches corresponding to the damage cases, but only on one significant breach per damage case. As already mentioned for the Level-1 assessment, the damage generation process produces N_s breaches, that are grouped in N_{DC} damage cases having probability of occurrence evaluated with Eq. (10). These unique cases are then filtered according to the procedure described in Section 3.3, resulting in N_{DCf} unique filtered damage cases. However, this subset of cases is



(a) Box-shaped damage.



(b) eSAFE-shaped damage.

Fig. 9. Breach openings for Damage A1 according to the different damage modelling.

representative of a specific number of breaches N_{sf} corresponding to:

$$N_{sf} = N_s \sum_{h=1}^{N_{DCf}} p_h \tag{11}$$

where the p_h are the p-factors inherited by the filtered cases. In principle, to be coherent with the physics of dynamic simulations, all the breaches have to be considered, as at different opening dimensions corresponds a different inflow/outflow rate and, consequently, the flooding progress will be different. However, searching for a reduction of cases to be analysed, only a significant breach per damage case is considered in the hybrid framework. As a starting point, the breach having the largest longitudinal projected area is selected for dynamic analyses, assuming that this will be the case leading to the higher flow rate and potentially the most critical of the cases. Such an approximation is simplistic and need to be carefully checked but follow the concept of the worst-case approach usually pursued in damage stability in case of uncertainties in the process.

Concerning the calculation time, dynamic simulation requires much higher computational effort than static calculations. Considering the assumptions and settings of the proposed framework, a simulation in irregular waves runs on average 4 to 5 times faster than real-time (using a regular laptop without parallelisation), which means 100 times longer than a static calculation. Such a computational issue stresses the necessity to reduce the number of dynamic analyses performed in Level-2 assessment throughout proper critical cases.

4. The gap on breaches definition

During the conception of the multi-level-hybrid framework, the focus was more on the initial inputs and the data exchange between the two assessment levels, neglecting a peculiar difference between static and dynamic analyses: the damage geometry. Such a difference exists since the "non zonal" approach has been introduced but has never been tackled during the first static-dynamic comparisons in project eSAFE and remains hidden until first detailed comparisons on the same damage cases have been carried out in FLARE.

As reported in Section 3.1, the modelling of breaches follows specific probabilistic models to determine the breaches dimensions and locations with the shape presented in Fig. 4. Observing the different damage shapes, it is evident that in the case of bottom groundings the damage form is box-shaped. For collision and groundings that is no true any longer, as the inner damage limit follows a surface extruded from the actual draught waterline, shifted by the damage lateral penetration L_y. Such kind of damage geometry is intrinsically considered by the non-zonal breach generation tools employed for static calculations (Mauro and Vassalos, 2022b) and actually used by designers of large passenger ships for damage stability assessment. On the other hand, damage modelling for dynamic simulations has always employed a different shape form, selecting for simplicity box-shaped damages. Fig. 5(a) shows the typical box-shaped damage modelling for dynamic simulation, with the associated definition of the additional openings to simulate water ingress/egress. Fig. 5(b) compares the same case of the previous figure with an eSAFE-shaped damage model (in black), highlighting the potential influence of the curved internal limit of the damage (here magnified for better representation purposes) on the resulting internal openings.

The conventional dynamic modelling has been used throughout project eSAFE, without updating properly the damage characteristics, as the predefined collision model in PROTEUS3 does not include the modelling of the lower vertical limit z_{LL} and the model extent from baseline as in the standard SOLAS modelling. Concerning PROTEUS3, only few calculations given by Atzampos et al. (2019) and the preliminary simulations provided in FLARE (Guarin et al., 2021; Mauro et al., 2022b) consider the lower limit in the damage, but still employing a box-shaped approximation.

As the eSAFE-shaped damages follow the waterline at calculation draught as internal limit for both collisions and side groundings, the box-shaped model can approximate the eSAFE-shaped model only for collision and groundings developing in zones where the waterline is at full breadth, as it could be only around midship. In case a damage develops through the fore or the aft part of the ship, the waterline deviates from the previous "ideal" condition, and, consequently, eSAFE-shaped and box-shaped damages may differ a lot. An example is given in Fig. 6, where it is possible to observe a collision case (Fig. 6(a)) and a side grounding one (Fig. 6(b)). The collision case shown in Fig. 6(a) developed in the for part of the ship and the yellow and red lines represent the damage volume projection of the calculation waterplane for the box-shaped and eSAFE-shaped damage, respectively. In both cases the penetration L_y is measured from the breach midpoint X_M starting from the waterline at the corresponding calculation draught. The box-shaped model is then developing across the damage length assuming the inner limit at the same coordinate given by the penetration at the damage centre. On the contrary, eSAFE-shaped damage inner coordinate follow the waterline form. As a consequence, the box-shaped design has a lower penetration in the fore part of the damage and a higher penetration in the aft part of the damage compared to eSAFE-shaped damage. With reference to the side grounding case in Fig. 6(b), it is located in the aft part of the ship, considering a lower z^* waterline compared to the collision case. Here, it can be observed that, for differences in the construction of the breach, the box-shaped damage is not affecting the ship through the whole damage length, thus leading to undamaged compartments in the aft-ship.

The two reported cases represent the possible main macroscopic incongruences between the two damage-shape models, and are valid for both side grounding and collision models. In fact, the main difference is due to the consideration of the waterline form by eSAFE-shaped

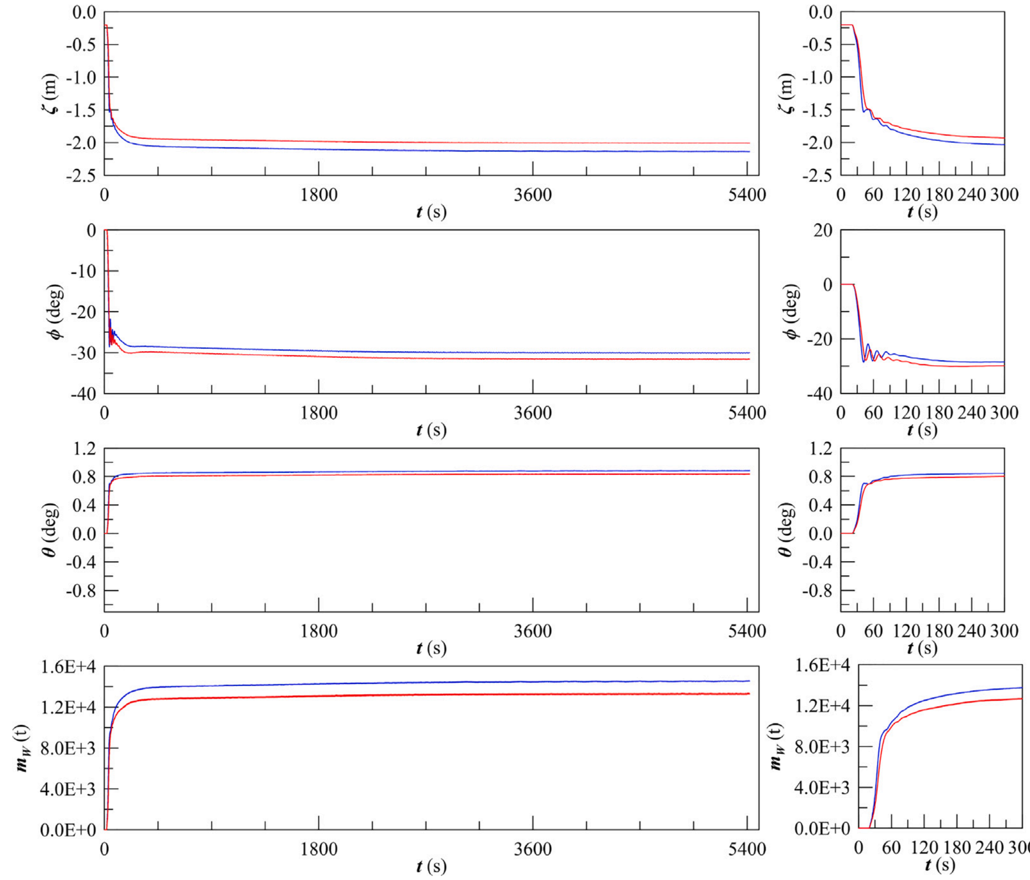
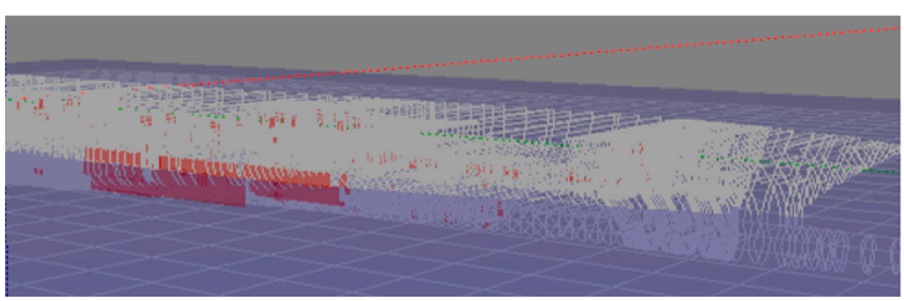
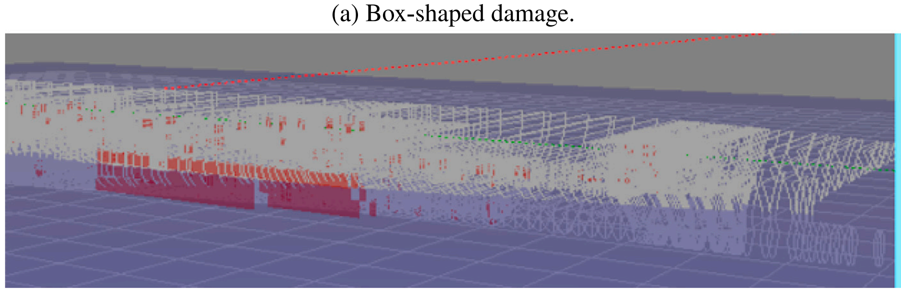


Fig. 10. Time-series of dynamic simulations in calm water between Box-shaped (*blue*) and eSAFE-shaped (*red*) breach for damage A1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(a) Box-shaped damage.



(b) eSAFE-shaped damage.

Fig. 11. Breach openings for Damage A2 according to the different damage modelling.

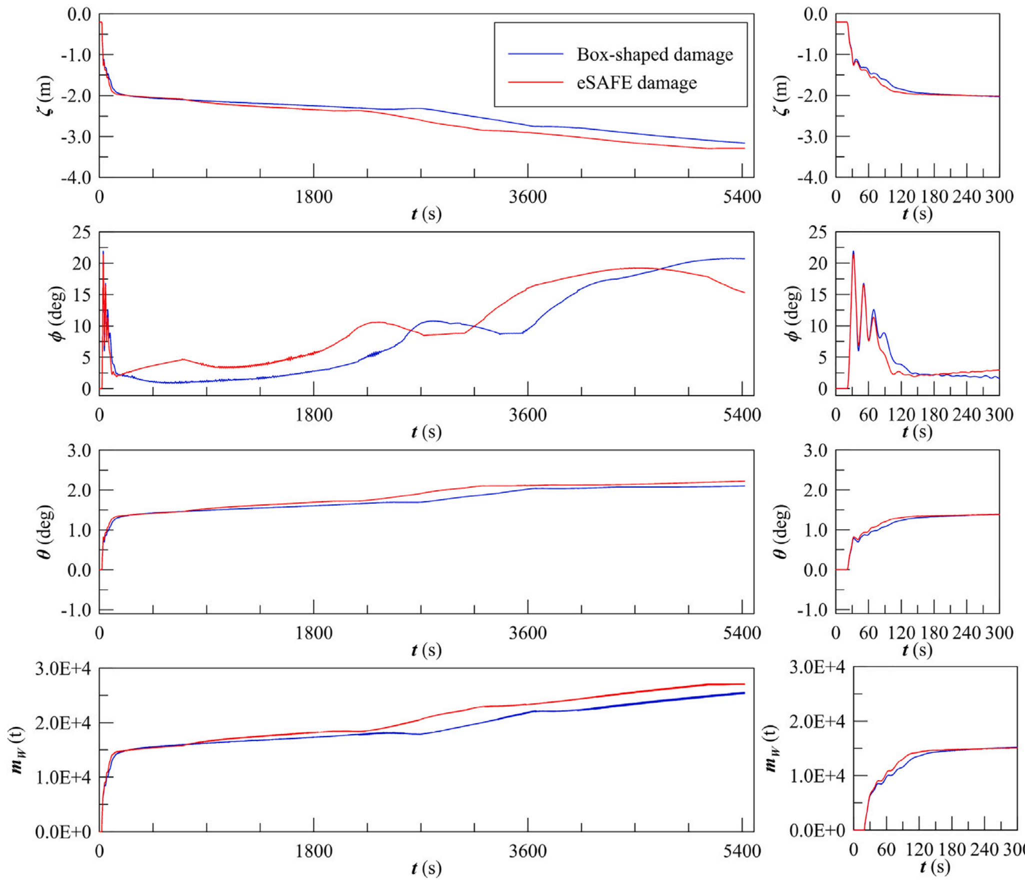


Fig. 12. Time-series of dynamic simulations in calm water between Box-shaped (*blue*) and eSAFE-shaped (*red*) breach for damage A2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

damage, which is common to both collisions and side-groundings. Therefore, regardless of the damage type, the corrective actions and incongruences remain the same. The main effect of such incongruences relates to the compartments that are open to sea at the beginning of the simulation. Fig. 7 shows the effect more in detail for a sample internal layout, demonstrating how more or few compartments can be initially flooded according to the damage location or extension.

Such a problem has a direct impact on the utilisation of dynamic simulations in cascade to static analyses, as the two initial conditions do not match, making a comparison of survivability between the two cases erroneous. Furthermore, the fact the two damage shapes are hitting different compartments is also changing the damage case of reference between static and dynamic calculation, and consequently the original p-factor distributions derived with Eq. (10). Thus, the initial intent to couple static and dynamic calculation could not be pursued by keeping the standard modelling of breaches for the two distinct analyses.

With the aim of providing a homogenisation between the static and dynamic modelling of the breach it is then necessary to select one of the two models to perform both analyses. As the designers are more used to shape models, compliant with SOLAS for collisions, the selection is to consider eSAFE-shaped models also in dynamics. This is not necessary the right choice from a physical point of view, as the shape of an eSAFE damage may be unrealistic due to the strict connection with the waterline form, but is a starting point for the homogeneisation between the two Levels analysis and it is easier to be accepted by designers. The following section describes how the problem of the new breach modelling for dynamic simulations has been solved and implemented in the hybrid framework.

4.1. Matching designers' requests

The necessity to provide the designers with a framework defining the damage conditions in a homogeneous way between Level-1 and Level-2 assessment implies a modification to the conventional way of modelling breaches inside dynamic simulation codes.

The conventional way adopted in PROTEUS3 and other *medium/high* or *low/medium* fidelity codes for damage stability consists in intersecting the hull shape and internal layout with a conventional box, assuming as new openings the lateral projection between the internal vertical surfaces and the damage box. This is already a modelling simplification, as the process is 100% correct only in case the internal layout is composed by box-shaped or at least non-convex compartments. Due to the complexity of the internal layout typical of passenger ships, it is uncommon to have only regular compartments, hence non-convex shaped may be encountered often. This means having to deal with a non box-shaped volume and with non-box shaped internal volumes. The generation of the breaches is performed according to the next steps:

1. Using non-dimensional damage dimensions and locations generated for Level-1 static assessment.
2. Calculating breach dimensional values according to the reference system and conventions used for Level-2 dynamic analyses.
3. Preliminary screening of compartments potentially hit by the damage (based on extremities x, y, z coordinates).
4. Geometrical intersection between the filtered compartments and the damage shape to identify the breach geometry.
5. Conversion of the resulting breach geometry in the dynamic-simulation code input format.

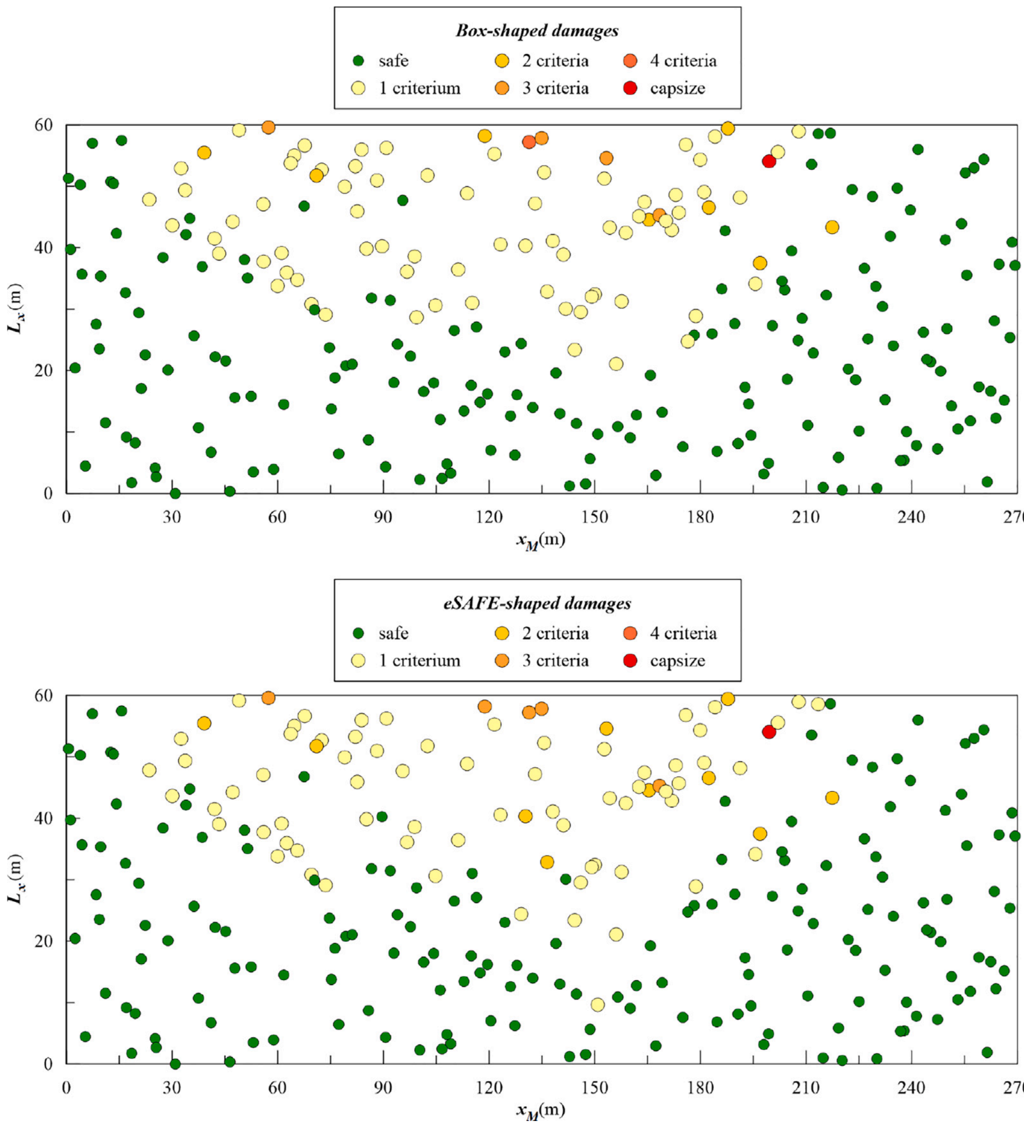


Fig. 13. Failure criteria in calm water for Ship A considering box-shaped (*top*) or eSAFE-shaped (*bottom*) damages in the preliminary dynamic analysis.

Linking the framework for dynamic simulations to PROTEUS3 software only, the studies and solutions have been provided for this calculation tool. However, the developed geometric engine can be used as base also for other medium/high fidelity tools, adapting the final additional opening to formatting, reference system and conventions of any specific software.

5. Impact of breaches definition on dynamic simulations

The implemented new tool for the breach correction between Level-1 and Level-2 assessment has been tested on two reference cruise ships that are presented in the next sections. The two analyses have been reported separately as they refer to two different studies for the evaluation of the impact of breaches definition on the dynamic simulations results. As the study has been performed together with the development of a tool for damage generation according to the procedure described in Section 4.1, the following steps have been performed:

A. Verification of breach differences between standard and new dynamic breaches, on a uniform set of damages, considering collisions as a reference.
B. Verification of the impact of breach differences on filtered damage sets according to the process described by the hybrid multi-level framework.

The first part of the verification process has been performed on Ship A and the second on Ship B. As the modelling differences concern only collision and side groundings damage types, the bottom grounding case is not analysed as the breach geometry does not change. The following two sections describe the strategies adopted for the two verification cases and the considerations and findings concerning the impact of the new-proposed breach modelling for Level-2 analyses.

5.1. Ship A

This reference vessel, one of the reference ship of project FLARE (Luhmann et al., 2019), has been used by MSRC as principal test ship across the first developments of the project (Guarin et al., 2021; Mauro and Vassalos, 2022b; Mauro et al., 2022b,a), and has been therefore used also for the preliminary implementation of the newly developed breach definition for dynamic simulations. The vessel is a large cruise vessel having the main parameters listed in Table 2. Fig. 8 shows the internal layout of the ship with the granularity and openings definition suitable for dynamic simulations. The modelling of the internal layout and openings for the dynamic model requires about one week between implementation and compliance check with the model used for static calculations.

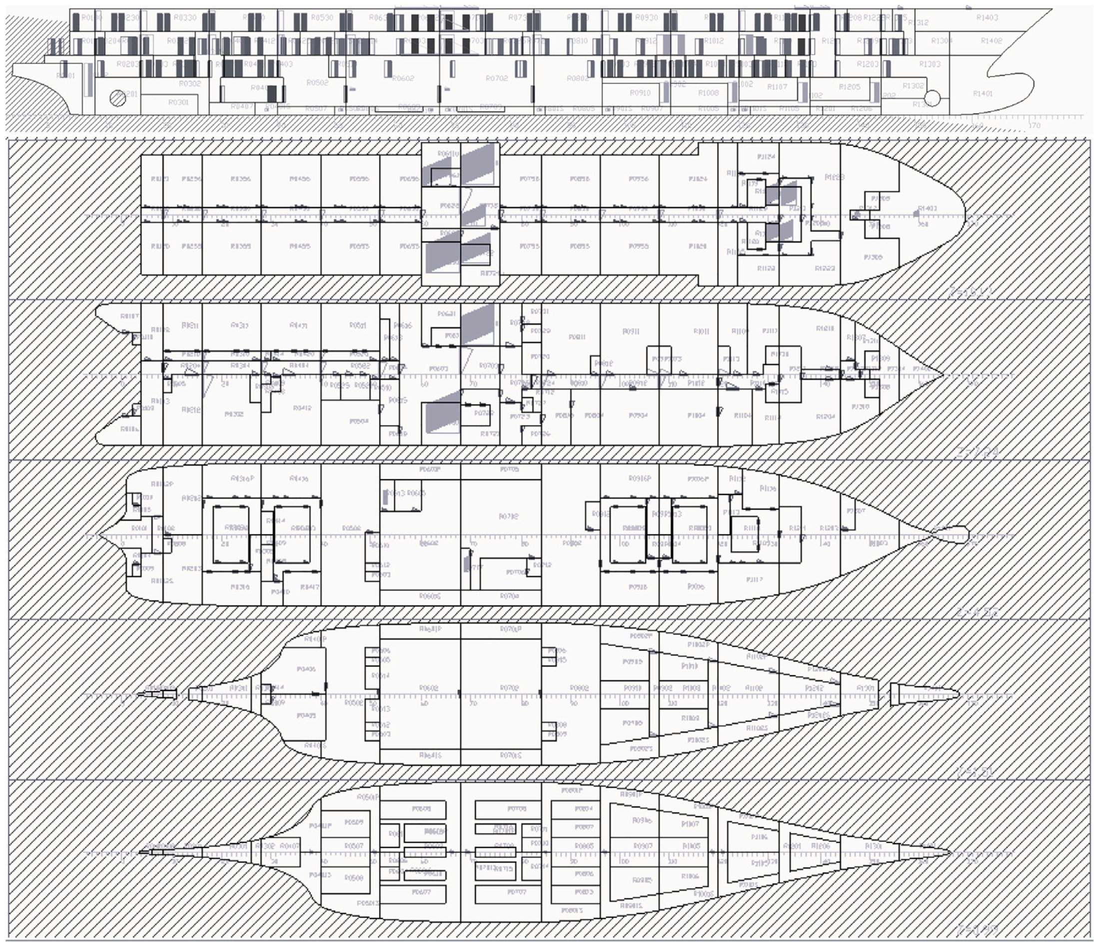


Fig. 14. Internal layout and openings for Ship B dynamic model.

Table 2
Main characteristics of Ship A.

Parameter	Symbol	Value	Unit
Length over all	L_{OA}	300.0	m
Length between perpendiculars	L_{PP}	270.0	m
Subdivision length	L_s	286.4	m
Breadth	B	35.2	m
Calculation draught	T	8.2	m
Calc. vertical centre of gravity	KG	16.796	m
Number of passenger	N_{Pass}	2,750	–
Number of crew	N_{crew}	1,000	–
Deadweight	DWT	8,500	t
Calculation displacement	Δ	50,933	t

Ship A is used for the first part of the verification study on the differences between the damages geometry. Here the focus is not primarily on the survivability of the ship, as previous analyses within FLARE (Guarin et al., 2021; Mauro et al., 2022b) show that with the calculation KG at the draught T provided in Table 2, the vessel is subject to really few capsize cases both in calm water and irregular waves, also considering extended collision breaches. In fact this vessel has been used as benchmark case test (Ruponen et al., 2022a) between different damage stability codes and to observe capsize cases with $H_s = 4$ metres in the model experiments, it has been necessary to use a higher KG values non compliant with regulations.

For such a reason, this ship has been used because of the insight in simulations already gained during FLARE project and the availability of a wide set of simulations performed with box-shaped damage cases. Therefore, this case was ideal to test the implementation correctness of the new breach modelling. To this end, a set of 250 preliminary dynamic calculations performed on the conditions reported in Table 2, which is considering box-shaped breaches derived from a uniform sampling of collision damages dimensions and location (Mauro et al., 2022b), is considered as benchmark case for the new breach modelling. As first instance, eSAFE-shaped damages have been generated for the same breach dimensions and locations and new preliminary simulations have been performed, initially, in calm water with a maximum simulation time of 1.5 h. The verification process for this first step is performed in two levels, a detailed and a global one.

5.1.1. Detailed analysis

The detailed analysis refers to the compartment hit by the damage and the shape of the breach itself. Concerning the compartment involved by the damage case, it was necessary to detect the compartments hit by the new damage model, in such a way as to verify the compliance of the dynamic breach with the one used during the Level-1 analysis. Presenting the comparison for all the 250 generated breaches for Ship A is too dispersive and not really helpful to understand the differences between the two geometrical damage models. For this purpose, the comparison is here presented on two reference damages, esplicative of the two mentioned main problems for the breach generation: the compartment being hit and the breach shape.

The reference damages are named and defined as follows:

Damage A1 : is a port collision damage located at 165.3 metres, thus between midship and the fore shoulder, with a longitudinal extension of 44.6 metres, a penetration of 3.2 metres a vertical extension of 7.9 metres and a lover vertical limit at 6.5 metres.

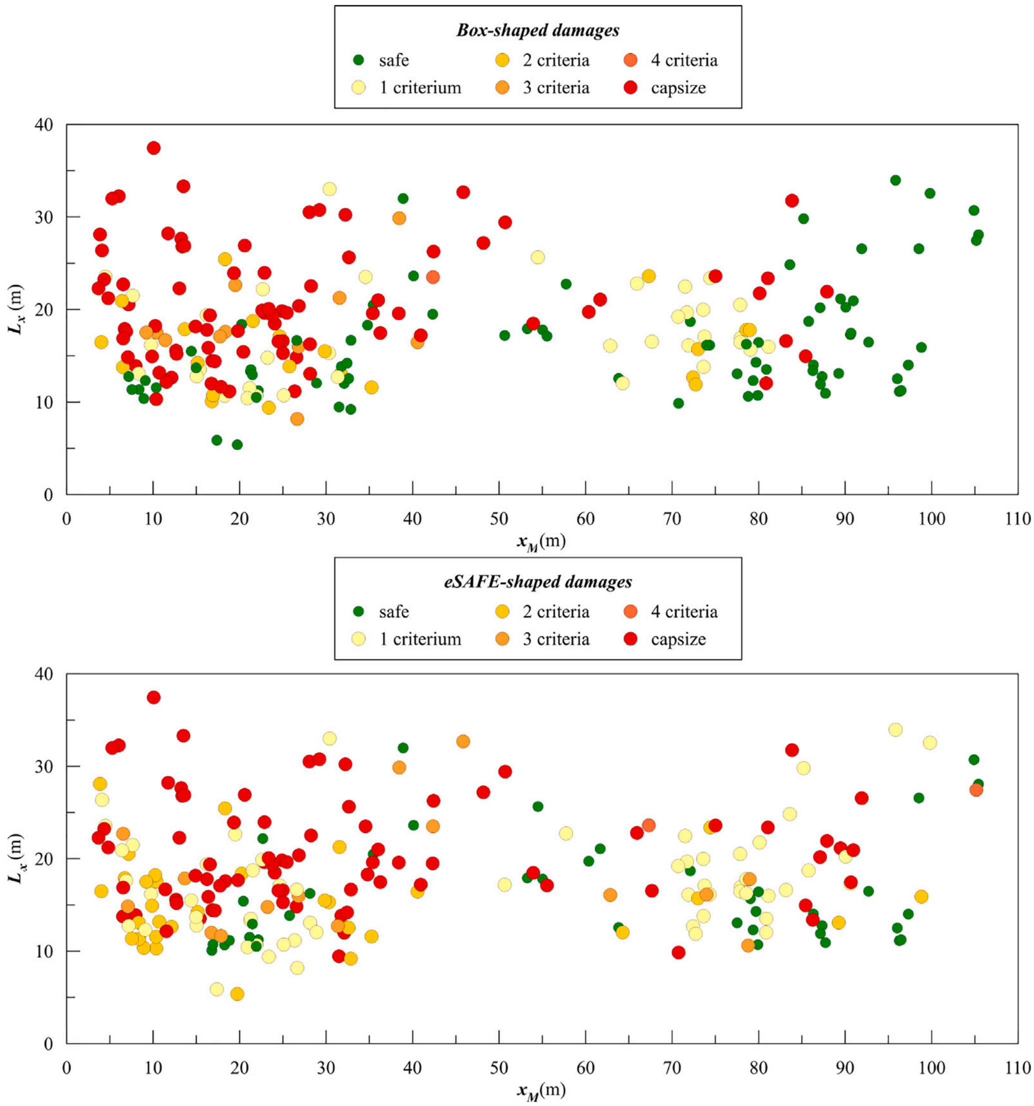


Fig. 15. Failure criteria of filtered critical collisions cases in calm water for Ship B considering box-shaped (*top*) or eSAFE-shaped (*bottom*) damages in the dynamic analysis.

Damage A2 : is a starboard collision damage located at 191.2 metres, thus across the fore shoulder, with a longitudinal extension of 48.2 metres, a penetration of 4.3 metres a vertical extension of 9.5 metres and a lover vertical limit at 1.5 metres.

Fig. 9 shows a 3D-overview of the A1 damage, splitting the box-shape damage (Fig. 9(a)) form the eSAFE-shaped one (Fig. 9(b)). As the damage lays between midship and the fore shoulder, the waterline at draught $z^* = T$ in this area is almost linear through the whole breach length. Therefore, the compartments hit by the damage should coincide between the box-shaped and the eSAFE-shaped damage. However, the shape of the compartments hit by this particular damage is not composed by boxes, but by complex geometries. This test on damage A1, is therefore oriented to check the breach shape within the compartments rather then the proper identification of hit compartments. In any case, the hit compartments with the new modelling for dynamics coincide with the static damage.

The most interesting comparison for damage A1 concerns the shape of the breach. Fig. 9 allows visualising the enhancement provided by the new tool developed for the hybrid framework. The box-shaped breach presents a set of regular rectangular breaches in each compartment (see Fig. 9(a)), not necessarily following the compartment shape. This was the standard model inside PROTEUS3, with only rectangular breaches automatically implemented for a damage case. As explained in Section 4.1, the implemented breach generation tool for the Level-2 calculations makes an intersection between the compartment and the damage volume to find the breach geometry, hence capturing the compartment shape in the breach definition. Fig. 9(b) clearly shows this enhancement, highlighting how the new tool shapes the breaches according to compartment geometry. The eSAFE breach opening for the given example follow the shape of the internal compartment, resulting in a non-rectangular opening (highlighted in red). Due to this modelling change, in the reported example, the resulting breach area of the eSAFE-shaped damage is less than the corresponding box-shaped breach area.

As the breach area is influencing the mass flow rate inflow/outflow in the hull according to the Bernoulli's equation, it is expected that a time domain simulation with the two damage modelling provides different results in terms of floodwater, hence different dynamic responses of the ship due to the coupled modelling of rigid-body and water motions. Such a behaviour should be detected also in calm water, where the result is not influenced by the stochastic nature of irregular waves, thus the difference is only due to the breach geometry. To this end, the calm water calculations for the two modelling approaches of damage A1 have been carried out in calm water starting from the same initial conditions, compliant with the ones described for the hybrid framework in Section 3.4, except for the wave and the simulation time (here set to 1.5 h).

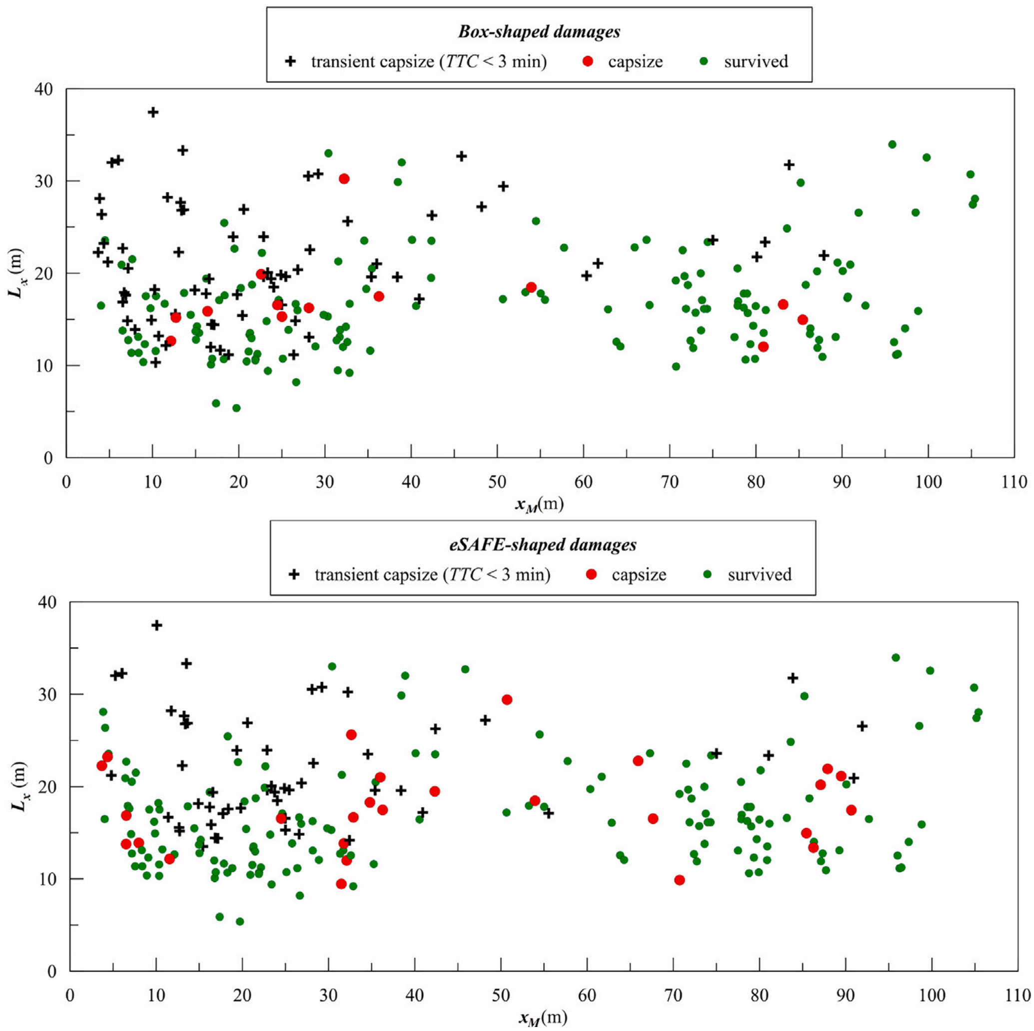


Fig. 16. Capsize analysis of filtered critical collisions cases in calm water for Ship B considering box-shaped (*top*) or eSAFE-shaped (*bottom*) damages.

Fig. 10 shows the simulations results for the two damage modelling on damage A1. Dedicated graphs illustrate the time series of the heave ζ, roll ϕ and pitch θ of the ship, together with the floodwater mass m_W. The time series are reported with the addition of a zoom for the first 300 s of simulations to highlight the transient behaviour of the ship. It should be noted that the simulations start with the ship in intact conditions at draught T and breach openings are activated after 20 s of simulations. This is not necessary for calm water simulations but is needed for a smooth start of simulations in waves and is part of the standard PROTEUS3 settings for dynamic simulations. Analysing the obtained results, it is evident that the enhanced modelling of the breach shape is changing m_W, providing a lower mass inflow compared to the original box-shaped simulation. Such a difference in m_W directly reflects in the ship motions; the heave ζ is consequently reduced because of the lower amount of water entering the ship, different is the case of roll ϕ and pitch θ. These two values are influenced by the flooding path inside the ship, which is changing as a function of m_W and motions. In this case the new eSAFE-shaped modelling shows a lower trim θ and a higher ϕ compared to the box-shaped simulation. The presence of a higher steady ϕ for the eSAFE-shaped damage is an index of potential higher susceptibility to capsize events in case of the occurrence of additional external loads (as e.g. waves).

The example of damage A1 highlights that even in the case where the two damage models should be comparable, the enhanced model is changing the global behaviour of the time-domain simulation. In such example probably the new solution is more reliable than the previous one, as the new breach exactly represents the intersection between the compartment and the damage volume instead of the old simplistic rectangular projection used in PROTEUS3.

Damage A2 is a case selected to visualise the differences in compartment detection between eSAFE and box-shaped damages. The damage is located across the fore-shoulder of Ship A, thus in a region ideal to capture the fore rastremation of the reference waterline and, consequently, increasing the shape differences between eSAFE-shaped and box-shaped damages.

Fig. 11 shows the 3D-view of damage A2, splitting the box-shape damage (Fig. 11(a)) form the eSAFE-shaped one (Fig. 11(b)). In this case the macroscopic difference between the two damages is evident, as the original box-shaped damage is not detecting the foremost compartments of the double bottom, compared to the eSAFE-shaped damage, highlighting the importance of modelling the behaviour of the waterline to match the Level-1 static damage case.

Damage A2 in the eSAFE-shaped form is presenting the additional flooding of a couple of small compartments in the double bottom. Therefore, it could be expected that initially there will be a small difference in the amount of floodwater entering the ship, but as the compartment will be immediately flooded the effect will be not amplified by time as for damage A1. However, the main difference will be caused by the presence of less residual buoyancy for the eSAFE shaped damage, affecting additional damaged compartments at the bottom of the hull.

Also for damage A2 the calculations in calm water have been provided with the same conditions described for damage A1. Fig. 12

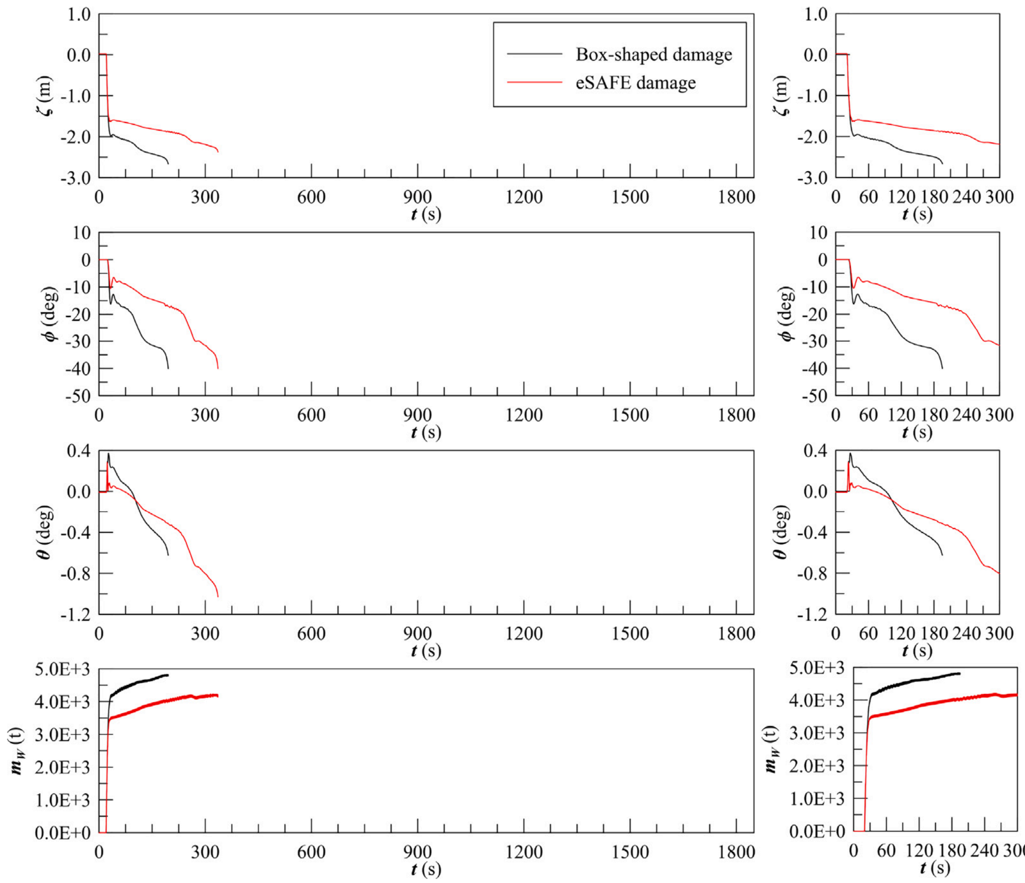


Fig. 17. Comparison between box-shaped (*black*) and eSAFE-shaped (*red*) modelling for damage B1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shows the results in the same format described for Fig. 10. Considering the zoom window on the first 300 s of the simulation, the expected trend between the two simulations is respected, with just small differences in the reported time traces. Significant differences appear when advancing the simulation time. It is possible to observe that the roll ϕ realisations are totally diverging between the two damage modelling types, having an impact also on the other motions and m_W but with a lower magnitude. The different behaviour of the ϕ motion time-trace indicates that the two simulations may react in a different way to the application of additional external loads, thus underlying the importance of a homogeneous modelling between Level-1 and Level-2 predictions.

The two presented cases highlighted that the developed tool for the modelling eSAFE-shaped breaches inside PROTEUS3, thus providing a damage affecting the same compartments of a Level-1 simulation case, is capable to improve the damage definition of the standard dynamic simulations also for cases where the two damage models are coincident. Furthermore, the preliminary dynamic analyses in calm water highlight differences for both the presented cases on Ship A, stressing again the importance of a homogeneous modelling between static and dynamic calculations. However, it is relevant checking also the macroscopic effect on survivability of the two geometric damage models, thus performing the global analysis presented in the next section.

5.1.2. Global analysis

At a macroscopic level, the differences are checked on the global results of the preliminary dynamic analyses in calm water, checking the presence of direct capsizes or evaluating the following failure criteria:

- *Final floodwater mass rate*: the water is still flooding inside the vessel with a mass rate above 2000 t/h.

Table 3
Critical cases according to eSAFE-shaped and box-shaped collision damages for Ship A.

Criteria	Box-shaped	eSAFE-shaped
True capsize	1	1
Final floodwater	2	1
ITTC average roll	12	16
ITTC maximum heeling	7	5
SOLAS maximum heeling	84	89

- *ITTC average roll*: the average roll over 3 min exceeds ±20 degrees.
- *ITTC maximum heeling*: the maximum heeling of the simulation is above ±30 degrees.
- *SOLAS maximum heeling*: the maximum heeling of the simulation is above ±15 degrees.

Those are the criteria normally applied to dynamic simulations (Guarin et al., 2021). In these simulations, the true capsize is considered when the vessel reaches an heeling above 90 degrees, instead of the 40 considered by other authors (Ruponen et al., 2019, 2022b). Such a choice has been made seemingly on large passenger ships, as it has been observed that often in case of extended openings, the ship has a large initial oscillation with an amplitude between 40 and 45 degrees but still sufficient residual stability to recover equilibrium without exceeding other criteria. Therefore, to avoid considering those cases as true capsizes, the threshold has been increased to a "real" capsize.

It is convenient to visualise the preliminary dynamic analysis results by means of graphs reporting the failure criteria of each breach, identifying the damage cases as a function of the location X_M and

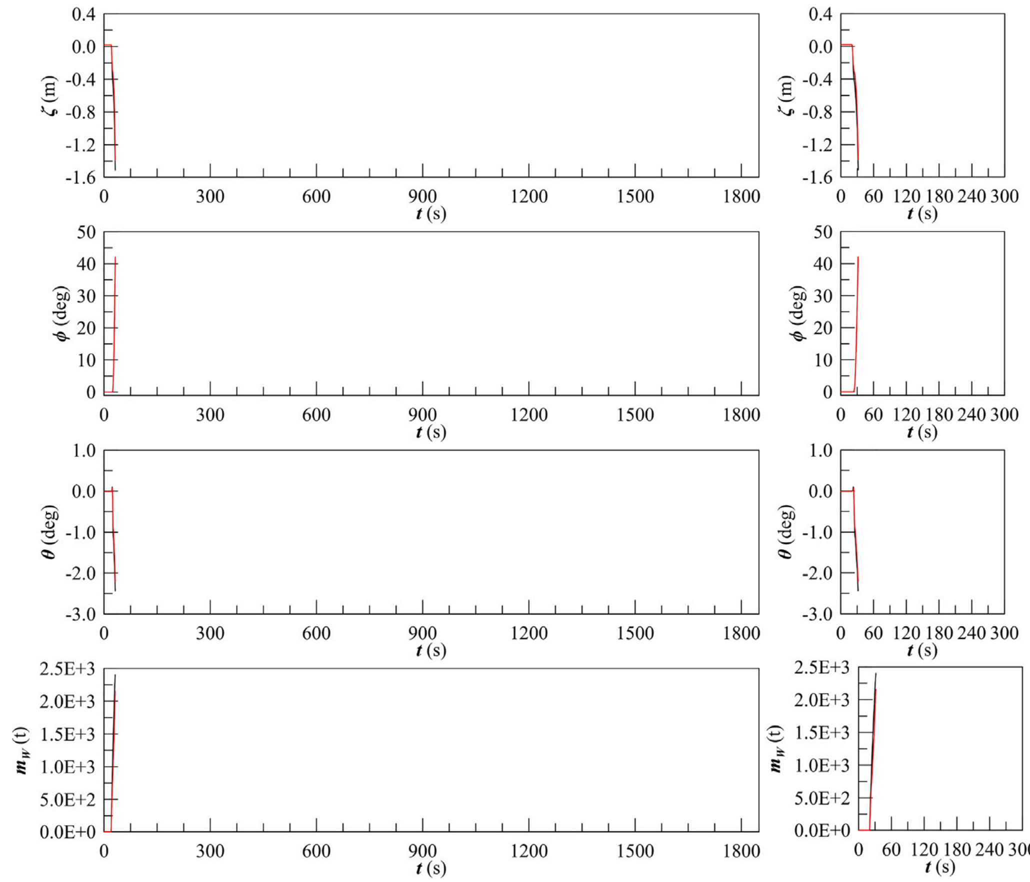


Fig. 18. Comparison between box-shaped (*black*) and eSAFE-shaped (*red*) modelling for damage B2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

longitudinal length L_x. Such a representation allows to clearly visualise the potential critical areas for survivability along the ship (Mauro et al., 2022b) and, consequently, compare different calculation results. Fig. 13 shows the differences between the critical cases detection, during the preliminary dynamic analysis, between eSAFE-shaped and box-shaped damages. Both damage models identify a true capsize for the same case. However, the identification of the critical scenarios is changed between the two cases. Some cases increase their criticality level by one whilst others decrease it, but without substantial changes to the global amount of criticality or its level. Table 3 shows the amounts of criticality detected for the eSAFE and box-shaped modelling of collision breaches. Considering this macroscopic analysis, the differences between the two damage geometric models seems to be negligible, as the global criticality on the vessel is almost unchanged. However, Ship A is a particular case not presenting a lot of critical cases for capsize. An analysis on a different case is therefore necessary to effectively identify the macroscopic differences between the two geometrical models, and Ship B is used for this purpose.

5.2. Ship B

Ship B is a small cruise vessel used as one of the case tests by designers in project FLARE (Luhmann et al., 2019). The main characteristics of the vessel are listed in Table 4, highlighting the differences with Ship A in terms of dimensions and people onboard. Fig. 14 shows the internal layout of Ship B with the granularity and openings definition suitable for dynamic simulations. The modelling of the internal layout and openings for the dynamic model requires less than one week between implementation and compliance check with the model used for static calculations, as the layout is smaller and less complex than Ship A.

Table 4
Main characteristics of Ship B.

Parameter	Symbol	Value	Unit
Length over all	L_{OA}	128.0	m
Length between perpendiculars	L_{PP}	113.7	m
Subdivision length	L_s	125.8	m
Breadth	B	20.0	m
Calculation draught	T	5.1	m
Calc. vertical centre of gravity	KG	9.584	m
Number of passenger	N_{Pass}	323	–
Number of crew	N_{crew}	155	–
Deadweight	DWT	1250	t
Calculation displacement	Δ	8404	t

This ship was selected by the designers as a test ship for the openings modelling in dynamic simulations and has been then used by designers also as initial reference for the breaches generation in the dynamic simulations environment. Furthermore, the vessel was already used for the Level-1 damage stability assessment and therefore breaches and associated damage cases were available for this ship according to the eSAFE probabilistic model for collisions, bottom and side groundings, together with filtered cases selected for dynamic analyses according to the procedure described in Section 3.3. Therefore, the case is ideal to figure out differences between the box-shaped and eSAFE-shaped damage modelling for the dynamic simulations in the designer-oriented hybrid framework.

The filtering on the Level-1 analyses with the predefined $p(1-s)$ threshold of 2E-4 leads to the selection of a set of 228 collision damage cases, where the breach with the larger lateral projected area has been selected as representative between the group of the same static

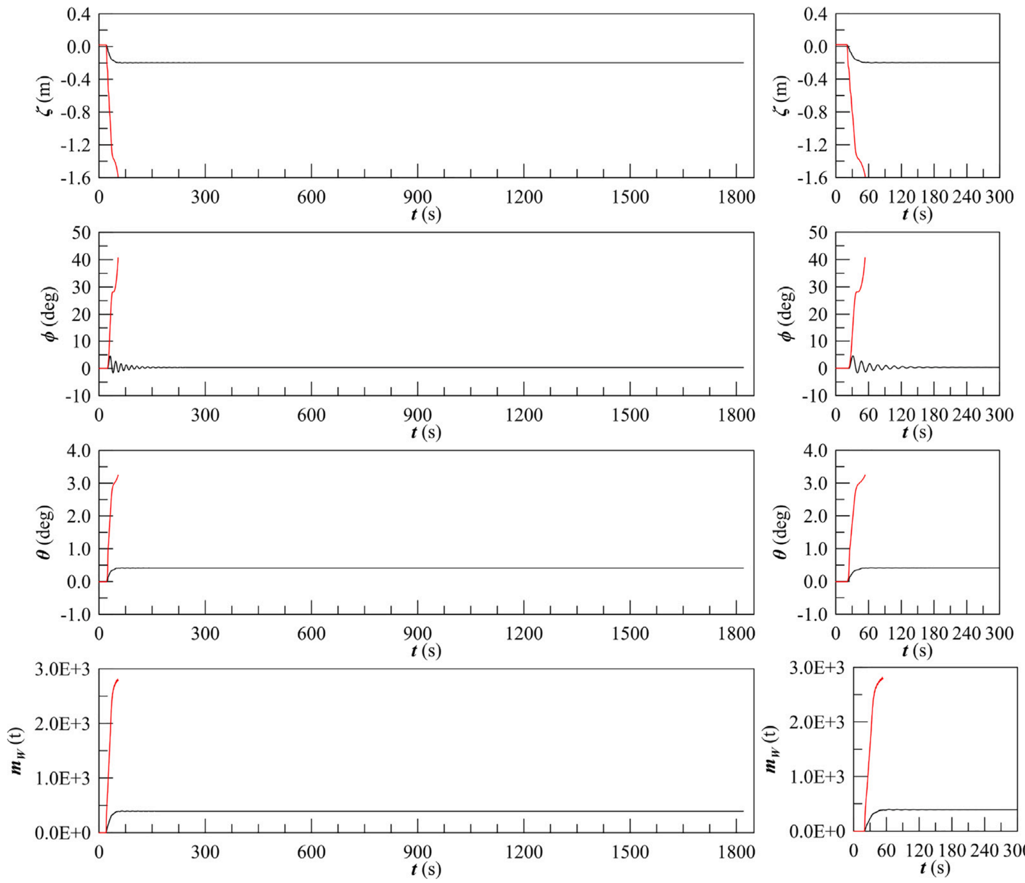


Fig. 19. Comparison between box-shaped (*black*) and eSAFE-shaped (*red*) modelling for damage B3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

damage cases for the dynamic analyses (see Section 3.3). Prior to performing calculations, a global check has been carried out to compare the compartments hit by the damages according to the eSAFE-shaped modelling, highlighting the congruence of the developed tool for breach definition with the Level-1 damage cases. Afterwards, calculations in calm water have been performed considering both the box-shaped and the eSAFE-shaped damage models, considering the initial conditions for Level-2 analyses of the hybrid framework reported in Section 3.4 (considering in this case also the suggested simulation time of 30 min instead of the 1.5 h use for Ship A). With the simulations mainly oriented to visualise the global effect of the different models on survivability, the same representation provided in Section 5.1.2 for Ship A is here used, considering the dynamic failure criteria as an indicator of the difference between box and e-SAFE shaped models. Fig. 15 shows the differences between the two damage geometry modelling for Ship B, with the same representation method used for Ship A. Compared to the case of Ship A reported in Fig. 13, more differences can be figured out for Ship B at a macroscopic level. It is evident that the damages in fore part of the ship result in potentially more critical cases employing the eSAFE-shaped geometry instead of the box-shaped one, essentially because the modelling of the waterline affects more compartments. The same can be visualised also for the aft part of the ship.

Considering the entity of the criticalities, Ship B presents more exceptions to dynamic criteria and “true” capsize cases than Ship A, even though the distribution of the filtered collision damages is representative of an area excluding the largest damages, due to the adoption of eSAFE distributions. Such phenomenon has been observed by Mauro et al. (2022b) comparing the results provided for Ship A and a Ro-pax vessel of shorter dimensions, highlighting how the statutory probabilistic distribution of damage length L_x for relatively shorter vessels leads to higher critical damage lengths for sorter vessels than for the larger ones (also because of the limitations of the maximum L_x to 60 metres). A more detailed overview of the differences of detected criticalities is reported in Table 5, where the number of the single cases exceeding each criterion is reported for the two damage modelling options.

Table 5
Critical cases according to eSAFE-shaped and box-shaped collision damages for Ship B.

Criteria	Box-shaped	eSAFE-shaped
True capsize	92	79
Final floodwater	0	0
ITTC average roll	47	69
ITTC maximum heeling	87	89
SOLAS maximum heeling	193	185

Table 6
Capsize cases categorisation for eSAFE-shaped and box-shaped collision damages for Ship B.

Criteria	Box-shaped	eSAFE-shaped
Transient capsizes	79	48
Capsizes	13	31
No capsize (survived)	136	149

As the amount of capsizes is considerably higher compared to Ship A, it is here possible also to compare between different kinds of capsize that may occur between the reported damage cases. In fact, it is possible to distinguish between different capsize modes, depending on the following flooding states (Spanos and Papanikolaou, 2012; Ruponen et al., 2019; Vassalos et al., 2022c):

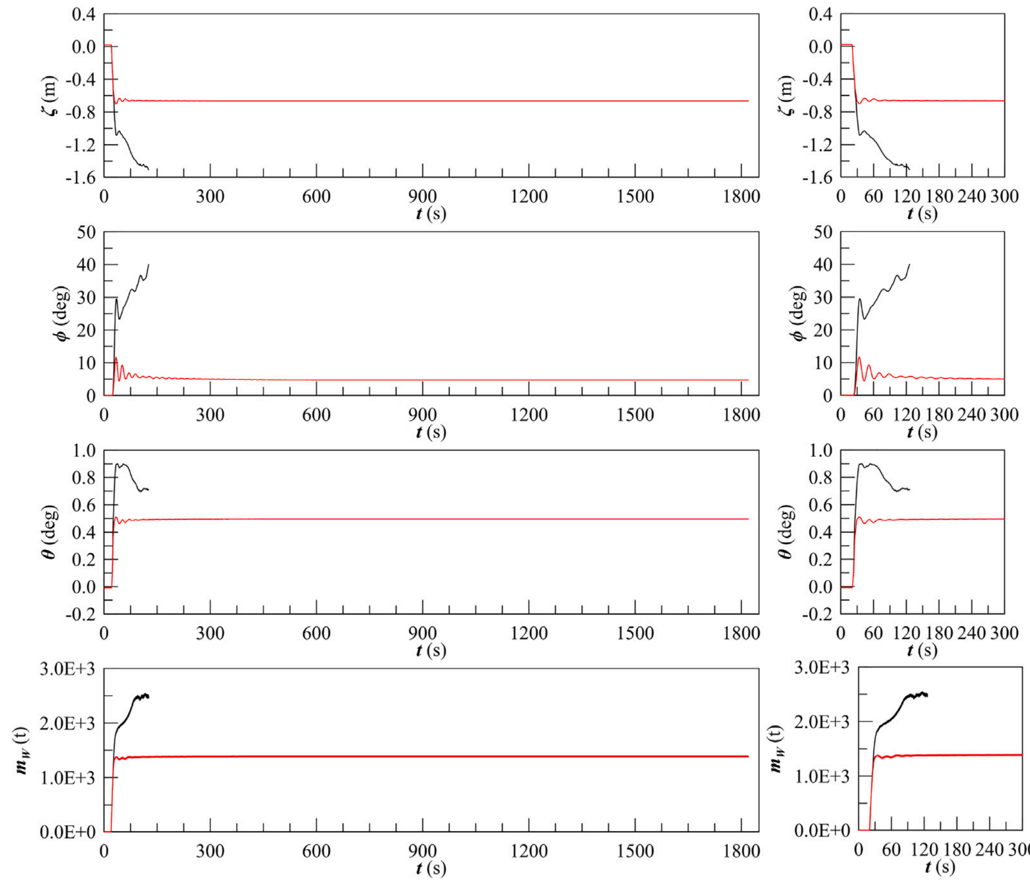


Fig. 20. Comparison between box-shaped (*black*) and eSAFE-shaped (*red*) modelling for damage B4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

– *Transient*: the capsize occurs in the first instants of the flooding process, generally with oscillations shorter than the ship natural roll. However, in this study, the transient capsize is intended as a fast capsize with a time to capsize TTC shorter then 3 min.
– *Progressive*: the capsize occurs while the flooding process is still ongoing. The capsize event may occur after minutes or hours, depending on the breach dimensions, vessel stability and the external environment.
– *Stationary*: the capsize occurs when the flooding process is finished and the vessel has reached an average equilibrium in flooded conditions. Thus this capsize is determined by the external loads only (i.e. wave action).

As the simulations performed on Ship B have a maximum simulation time of 30 min, it is difficult to really distinguish between progressive and stationary capsize cases. Therefore, the comparison is presented distinguishing between transient capsize, general capsize (progressive + stationary) and survived cases. Fig. 16 shows the comparison between the capsize modes considering the eSAFE-shaped or the box-shaped modelling, adopting the X_M, L_x representation of the previous graphs. It is interesting to observe the differences between the two cases, with the eSAFE-shaped damages detecting less transient cases in the aft-ship, but detecting more capsizes in the fore part of the ship, as already highlighted before. Table 6 gives an overview of the amount and type of capsizes observed with the two damage models. The obtained results show that the macroscopic global effect of the two damage modelling on the dynamic simulations is not negligible, and that the homogenisation of the damage geometry between the Level-1 and Level-2 simulations is mandatory for a hybrid multi-level framework.

On Ship B, also a detailed analyses has been performed on the single damages, identifying the differences in the time traces during the simulations. In the following, only four damages are reported, showing cases where the two damage types produce comparable or opposite dynamic behaviours in calm water. The reference damages are named and defined as follows:

Damage B1 : is a starboard collision damage located at 50.7 metres from aft perpendicular, thus in the aft shoulder, with a longitudinal extension of 29.4 metres, a penetration of 2.2 metres a vertical extension of 12.4 metres and a lover vertical limit at 0.12 metres.

Damage B2 : is a port collision damage located at 13.5 metres, thus in the aft-ship, with a longitudinal extension of 33.3 metres, a penetration of 2.5 metres a vertical extension of 8.1 metres and a lover vertical limit at 1.6 metres.

Damage B3 : is a port collision damage located at 91.9 metres, thus across the fore shoulder, with a longitudinal extension of 26.6 metres, a penetration of 0.8 metres a vertical extension of 9.7 metres and a lover vertical limit at 1.1 metres.

Damage B4 : is a port collision damage located at 61.7 metres, thus between midship and the fore shoulder, with a longitudinal extension of 21.1 metres, a penetration of 0.7 metres a vertical extension of 7.4 metres and a lover vertical limit at 1.7 metres.

The simulations results for the four cases are shown in Figures from 17 to 20, comparing the time series for the heave ζ, roll ϕ and pitch θ, together with the mass flow m_W entering or leaving the ship.

As for the damage cases reported for Ship A, a scope with the first 300 s of simulation is reported. Also in this case the ships start the simulation in intact conditions and breaches are opened after 20 s.

Fig. 17 shows damage case B1 where both damage models lead to a capsize, but with two different TTCs. The box-shaped damage lead to a capsize in around 200 s, but considering the initial time to opening, the TTC is lower than 3 min, thus a transient capsize according to the used categorisation. The eSAFE shaped damage has a different behaviour, leading to a capsize with a larger TTC, in this case longer then 3 min. Damage case B2 presents different characteristics, as shown in Fig. 18 where both models lead to an immediate transient capsize, thus without significant differences between the simulations. On the other hand, the remaining two cases show two opposite simulations behaviours between the two damage models. Fig. 19 shows damage case B3, where the original box-shaped damage embedded in PROTEUS3 was not leading to a capsize in the first 30 min of simulation. On the contrary, using the eSAFE-shaped modelling, the calculations show a transient capsize. Damage case B4, shown in Fig. 20 has an opposite trend compared to damage case B3, thus with the eSAFE-shaped damage not leading to a capsize and the original box-shaped damage leading to a transient capsize.

It is not possible to draw out general guidelines to identify the direct consequences of the different geometrical modelling of damages, as the complexity of the flooding path may lead to opposite consequences (i.e. capsize or survive) just changing one flooded compartment or the breach opening area. What can be observed is that the fore and aft extremities of the vessel (starting from the shoulders) are more affected by the geometrical modelling change, because of the reference waterline form. It is, therefore, mandatory for an homogeneous results between Level-1 and Level-2 calculation to model the damage shape according to the same geometrical model; as, for dynamic simulations, the damage shape has an impact both on the global and detailed results of flooding simulations. This is more evident for the global survivability especially for smaller ships as Ship B, where more differences have been detected in this study, but on a detailed level differences are highlighted also for large cruises as Ship A.

6. Towards a full direct approach

The definition of the hybrid FLARE framework has allowed designers to start dealing with rigid-body flooding simulations, thus exploring the capabilities of dynamics for damage stability assessment. However, the didascalic hybrid multi-level framework developed to match and fulfil designers necessities and concerns is far away to be the end point for the establishment of a calculation framework for damage stability in the design phase.

The process is subject to many assumptions aimed to reduce calculation time, thus simplifying the complexity of the physical problem and the conditions to be taken into account for the calculations. The following sections summarise the main points that, according to the didascalic framework analysis, should be further studied in deep to pursue the aim towards a full direct approach to damage survivability of ships.

6.1. The filtering process

A first concern on the hybrid framework is on the damage filtering process. As highlighted in Section 3.3, the selection of critical damage cases is performed considering the results of the Level-1 static calculations on the total damage cases, considering a threshold of 2E-4 on the $p(1-s)$ value. Such an assumption intrinsically identifies all the unfiltered cases as "non critical" for a damage stability assessment.

However, advanced filtering methods fully based on direct approaches (Mauro et al., 2022a) demonstrate that it is possible to identify with a low calculation effort the region where, for instance, critical collisions are located along the ship. This is something that the static filtering proposed in the hybrid framework cannot ensure.

As an example, for the collision damages reported on Ship B, additional calculations have been carried out in calm water on all the unfiltered damage cases with a damage length $L_x \geq 10$ metres. Fig. 21 shows the criticalities of the damage cases, with reference to the same criteria identified and reported for the dynamic simulations in Section 5. It can be observed that there are a lot of unfiltered cases that still present criticalities, especially, for the case of Ship B, in the aft ship. To have an idea concerning the effect of waves on those unfiltered damages, three cases exceeding at least two dynamic criteria have been selected to be analysed in irregular waves.

To take the stochastic nature of irregular waves into account, 10 repetitions have been carried out for each set of selected wave heights (from 0.5 metres in step of half a metre). Fig. 21 shows on the right side the time traces of roll angle ϕ for the wave height H_s where all capsizes for the repetition have been recorded. The foremost damage is capsizing with an $H_s = 2$ metres while the other two cases register immediate transient capsizes with the lower wave height.

Such a result indicates that the filtering process actually implemented in the hybrid framework is ineffective for the identification of critical cases in irregular waves, as, the selected damage cases have occurrences also higher than cases filtered by the hybrid process. This is underlining the importance of considering static results as fully indicative for critical dynamic conditions. Therefore, the direction for future studies should adopt a filtering process closer to the full direct methods developed by Mauro et al. (2022a), actually not implemented in the hybrid framework.

6.2. The initial conditions

Another issue is on the selection of initial conditions for the Level-2 (dynamic) calculations. The actual selection is reflecting the common practices used by the solver PROTEUS3, without considering non-standard settings. Considerations concerning the wave environment to be used for the assessment in irregular waves are nowadays empirical and based on the assumption of maximum values observed in old collision databases (Ventikos et al., 2018). Furthermore, with the aim of designers to go towards operational seagoing conditions for damage stability assessment (Luhmann et al., 2017), appropriate discussion should be opened also on the representative sea areas to be considered and the possibility to evaluate tailored survivability indices (Mauro and Vassalos, 2022a).

The recent benchmark campaign of flooding simulation codes performed within FLARE project (Ruponen et al., 2021, 2022b,a) highlighted substantial differences between the outputs of different available software, concerning the modelling of external and body forces and the input settings. Therefore, substantial studies have to be carried out on an harmonisation of initial inputs to time-domain flooding simulations. A substantial agreement on the geometrical modelling of internal surface has been found within FLARE (Guarin et al., 2021; Vassalos et al., 2022a), however a complete alignment within different codes is nowadays impossible and will require continued collaborative studies between parties interested in building a harmonised calculation framework for damage stability.

6.3. The damage definition

The present work highlights how the differences in damage geometry could strongly influence the results of dynamic simulations, especially for irregular waves simulations and, in case of relatively small vessels, in calm water. To this end it is essential to figure out what a reliable geometrical definition of a damage is. Probably the box-shaped assumption is the easiest geometry to implement and to be used in an automatic process for breach generation. On the other hand, the eSAFE shaped model, compliant with statutory Level-1 static

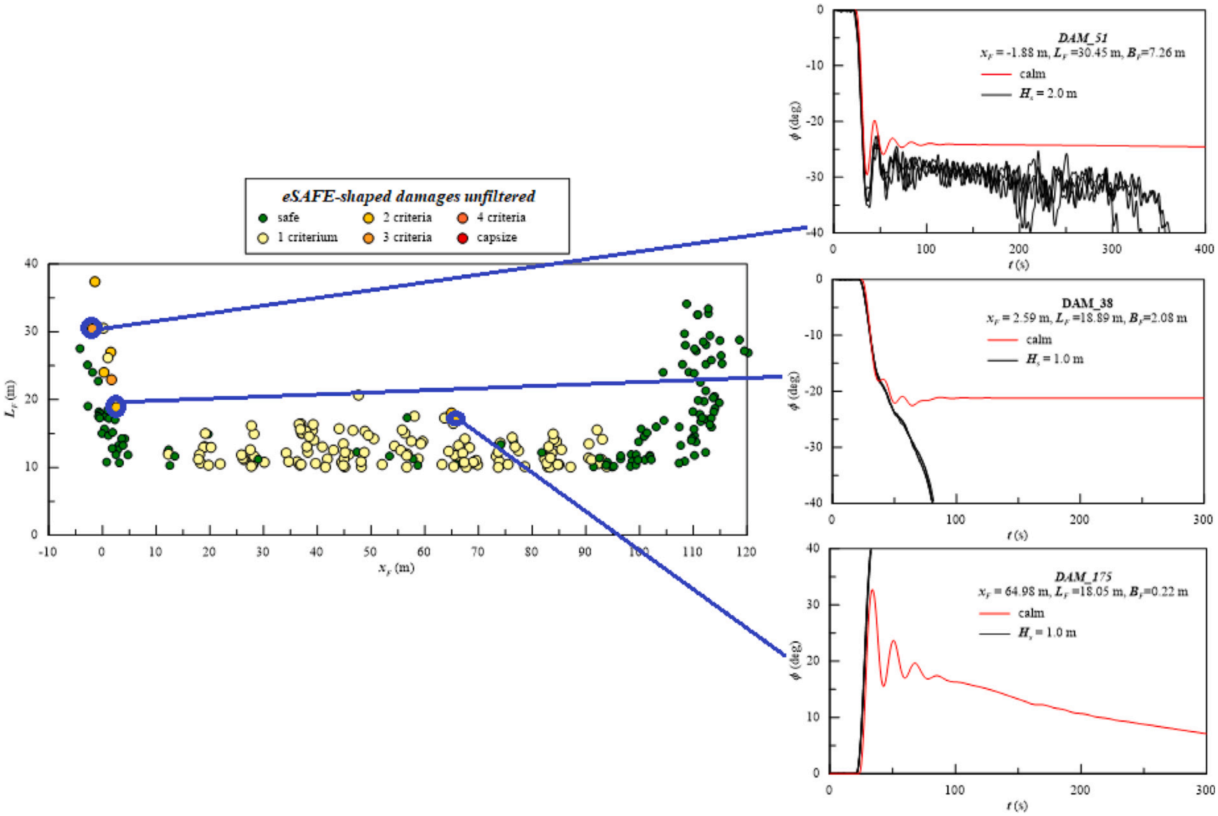


Fig. 21. Criticalities of unfiltered collisions for Ship B in calm water, with analysis in irregular waves for three selected cases.

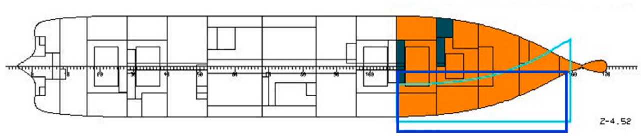


Fig. 22. Example of eSAFE-shaped damage (*light blue*) crossing both vessel sides. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

calculations, is not straight forward to reproduce in dynamic calculation, even though now it is possible thanks to the tool developed in the FLARE project.

However, eSAFE-shaped damages have sometimes unrealistic shapes, as they refer to the geometry of the waterline at a given z^* depending on the damage type. Especially for side groundings, where the z^* often lies under the design draught, this is an issue, as the typical twin-screw propeller shape of the waterline in the aft-ship generates non-convex shapes leading to strange geometry for the internal shape of the damage. Furthermore, the adoption of the waterline also in the collisions, generates damages that may cross the centre-line or also go outside the hull on the opposite side, especially on the bow (see Fig. 22). It is therefore essential to focus part of the future research efforts to determine a new realistic damage shape, to be used in both Level-1 or Level-2 analyses. Such a necessity can be fulfilled only by means of extensive collisions and groundings analyses by means of high fidelity crash simulation codes (Kim et al., 2022), thus applying a direct approach for the damage generation.

Also the definition of the side groundings should be put in discussion, as, the damage model definition for this kind of damage type (Bulian et al., 2020; Mauro and Vassalos, 2022b) allows for the development of a damage entirely above the calculation waterline. Such an assumption is acceptable for static calculations, as criteria related to opening and connections between compartments could make such cases critical considering stepped flooding processes. However, in a dynamic simulation, the damage case will remain always safe as no water is entering in calm water and only in waves there will be the probability of flooding some damaged compartment. Fig. 23 gives an overview of calm water Level-2 calculations on side groundings for Ship B, where it is possible to observe the effect of the above-mentioned issue. In fact, of the 262 filtered cases according to the $p(1-s)$ threshold, 30% were entirely above the waterline, resulting in a high number of 'safe' cases compared to the collision analyses given in Section 5.

In conclusion, the harmonisation of damages generated with a direct methodology between Level-1 and Level-2 calculations should then take in discussion the current damage definition of statutory damages, and consequently a redefinition of the in-force probabilistic damage stability framework.

6.4. The calculation of risk

Furthermore, the most recent developments ongoing in project FLARE (Mujeeb-Ahmed and Vassalos, 2022; Vassalos et al., 2022e), suggest to going beyond the survivability issues for the damage stability assessment of a passenger ship, introducing the adoption of the potential loss of lives (PLL). Such a definition evaluate the risk in its standard definition, hence the multiplication of a probability times its consequence. In the specific case of PLL, the following generalisations have to be considered:

Probability : is the total probability of a flooding event, intended as the joint occurrence of a hazard, a sea state, an encounter condition (meaning an "extended" p factor) and the associated probability to survive at that event (thus the $1 - s$ factor).

Consequence : the consequence of the event is measured as the multiplication of the fatality rate of an event and the people onboard

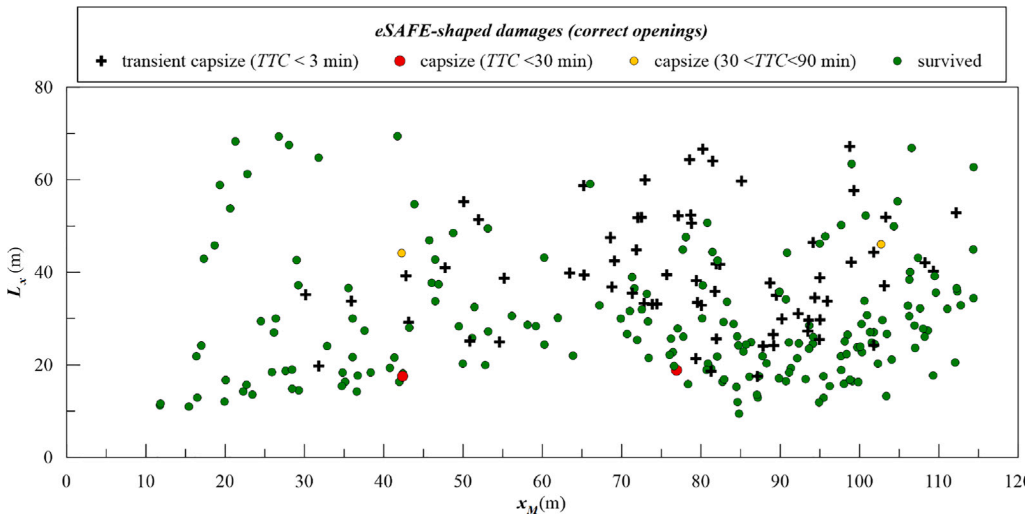


Fig. 23. eSAFE-shaped side grounding damages in calm water for Ship B.

the ship. The fatality rate is a function of the time to capsize and the time to evacuate the ship. Thus the risk intrinsically implies the execution of evacuation analyses.

Such a transition to risk-based assessment implies the integration of an additional aspect of damage stability, that is the evacuation of passengers. It can be foreseen that also for the inclusion of evacuation the first inclusive steps will be simplified, but aiming towards a direct application of evacuation analyses in the survivability assessment of passenger ships.

7. Conclusions

The present work presented an overview of the evolution of survivability concept in damage stability across the last decades of research in the field. Such an analyses highlighted a gap between the vision of researchers, more oriented to apply direct physic-based methods, and designers, more inclined to statutory calculations. The mediation proposed in the initial and intermediate phases of project FLARE led to the definition of a multi-level hybrid framework, mitigating researcher and designers visions on damage stability. The framework gave the opportunity to designers to directly approach and experiment with dynamic calculations for damage stability, both in calm water and irregular waves environment.

The designers vision provides a positive effort in the identification of incongruences between consolidated practices in the disassociated static and dynamic analyses for damage stability, highlighting how the adoption of an hybrid multi-level approach necessitates the harmonisation of damage modelling between Level-1 (static) and Level-2 (dynamic) analyses. Such an observation and the resolution of the designer request allows also to improve the breach modelling inside the dynamic simulation program used in the framework.

In any case, the didascalic framework provided for the designers is still subject to simplifications and empirical assumptions, thus it is far away to be a complete and rigorous approach to damage stability assessment but it is a step forward through the active adoption of direct methods by designers. Furthermore, the analyses and studies provided jointly by researchers and designers in FLARE allow for identifying future focal points for improvements in the damage stability assessment, namely:

– Filtering of critical cases.
– Selection of initial and environmental conditions for dynamic analyses.
– Damage shape definition with direct methods.
– Use risk instead of survivability as damage stability performance indicator.

The latter of the mentioned points, meaning risk, is going to be fulfilled by the last developments within FLARE project, and has been already started to be disseminated through the scientific community. However, the remaining points trace out some future research path in the damage stability field, potentially leading to new research projects and a strict collaboration between researcher and designer towards a full application of direct methods in damage stability. Furthermore, to make the direct framework even more attractive to designers, a step forward should also be performed concerning the calculation time of a single dynamic calculation, improving the performance of the dynamic simulation. However, calculation time should not be interpreted as the main key performance indicator of a process, especially comparing Level-1 and Level-2 predictions. The amount and fidelity of information available with a direct method is much higher than static calculations, necessitating higher computational time that can be efficiently reduced by code optimisation.

Besides the definition of a consistent framework for damage stability assessment based on direct calculations, additional work is also needed to gain acceptance of the methods by regulatory bodies. Some of the assumptions of the provided framework, like the reduction of calculation draughts (from three as prescribed by SOLAS to two), are not yet part of the regulatory framework, and further studies are needed to check the validity of the proposed approach. After fixing the main point figured out in this paper, and with a broader application of direct methods by designers, it could be possible to consider the updated version of the proposed framework suitable for statutory calculations.

CRediT authorship contribution statement

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

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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