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Process, methods and tools for ship damage stability and flooding risk assessment

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ABSTRACT

Development of damage stability as a scientific subject, specifically in damage ship hydrodynamics and, generally, flooding risk assessment, has evolved primarily by inquisitive academics with support by people with vision and passion towards maritime safety enhancement from industry and Government, the latter in the wake of serious accidents. Notwithstanding this, the subject has seen remarkable development in a short period of time in terms of understanding process, and developing methods and tools for practical implementation of such developments. The stage has now been reached where large-scale EC and industry-funded projects are bringing all requisite knowledge and experience together towards implementation by end users with the view to institutionalizing such developments. The paper critically traces and presents key developments starting from basic concepts to a complete framework for performing numerical simulations of ship survivability in operational conditions in the seaway, leading to flooding risk assessment with application potential for new and existing ships with focus on the design phase but with operation potential in ship operation, the latter involving emergencies.

1. Introduction

The approach followed by many ship designers concerning the assessment of ship damage stability tends to be deterministic and is governed by empiricism. Such an approach, even though admissible for small craft and cargo ships, is not suitable for passenger ships, especially for modern vessels carrying thousands of passengers onboard. The need for a reliable estimation of flooding risk associated with a serious accident requires treatment of damage stability as a scientific subject, in the process abandoning empirical approaches in favour of using first principles-driven methodologies. In fact, pitfalls in using generalised formulations for damage stability assessment can be overcome by a thorough understanding of the underlying mechanisms leading to vessel capsizing or sinking post-flooding accidents, with potential loss of life, and hence, to the identification of governing design and operational parameters to target flooding risk reduction cost-effectively. Such an ambition necessitates the development of advanced methods, tools and techniques capable of meaningfully addressing the physical phenomena involved. Having said this, it was not until the 1990s when damage survivability, pertaining to ship dynamics in a damaged condition in a seaway, was addressed by simplified numerical models, (Jasionowski and Vassalos, 2002; Vassalos and Turan, 2002; Vassalos and Letizia, 1995a,b; de Kat, 1996; Zaraphonitis et al., 1997). However, the adoption of high-fidelity techniques, such as CFD, EFD and combinations thereof, is still not practicable from a design perspective, due to extremely high computational effort. This gives rise to the need for a detailed guideline for researchers and designers concerning the steps needed to assess with sufficient accuracy the flooding risk onboard passenger ships (Guedes Soares et al., 2009).

The present work critically traces the basic concepts needed to perform a flooding risk assessment onboard of passenger ship employing first-principles methodology, focusing on three main processes:

1. Damage stability/survivability assessment: employment of first-principle tools to evaluate the probability of surviving an accident

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in an irregular sea environment and the evaluation of time to eventual capsize.
2. Evacuation analysis: identification of potential loss scenarios where it is essential to perform evacuation simulations to evaluate the time needed to abandon ship under specific environmental and damage conditions.
3. Flooding risk assessment: combination of the first two assessments to feed a process capable of evaluating the flooding risk.

Starting from a detailed and critical discussion of the basic concepts leading to the use of first-principles tools in Section 2, the paper describes the processes of ship survivability and evacuation analysis (Section 3), with the description of an assessment process that concludes with the determination of flooding risk assessment (Section 4). The resulting process is not only applicable to the design phase of the ship but also to the operational stages, including emergencies, thus increasing the usability of the process for designers and operators.

2. The evolution of direct methods in damage stability assessment

The study of damaged ship survivability in waves received considerable attention following the tragic accident of Estonia, namely by assessing the vessel performance in a given environment and loading condition based on first principles. Such effort was also motivated by the compelling need to understand the impact of the parallel introduction of probabilistic damage stability regulations on the design of cargo and passenger ships, leading to a growing appreciation of problems embedded in the new regulatory framework and the consequent harmonisation process. In this state of affairs, the EC-funded project HARDER (1999–2003) guided a thorough evaluation and re-engineering of the probabilistic framework. In this respect, the HARDER project became a vehicle for IMO to encourage and promote the regulation development process, fostering international collaboration at its best. This has contributed greatly to the eventual success in achieving harmonisation and proposing a workable framework for damage stability calculations in IMO SLF 47. The fundamental and applied levels of development in this project integrated with other concurrent EC-funded projects, such as NEREUS (1999–2002), ROROPROB (1999–2002), SAFENVSHIP (Jasionowski, 2005) and parallel international collaborative efforts (work by the Stability in Waves Committee at the International Towing Tank Conference from 1996 onwards, e.g., (Papanikolaou, 2001), (Papanikolaou and Spanos, 2008), and more recent benchmark studies, e.g., (Ruponen et al., 2022), thus providing a clearer understanding of damage stability and survivability. The conviction for serious development was also increased by the systematic application and verification of the developing numerical tools, helping raise confidence in the available knowledge to address the physical phenomena involved effectively and with sufficient engineering accuracy. Such a positive experience and effort led to the establishment of Project SAFEDOR (2005–2009), aiming to consolidate contemporary developments on damage survivability, thus also leading to the inclusion of damage survivability attributes even at the concept design stage. The knowledge gained with this novel approach allowed experts to address critically contemporary regulatory instruments and to foster new and better methodologies to safeguard against known design deficiencies, thus enabling consideration of damage stability impact on passenger ship design.

Interestingly, IMO prescriptions introduced a notable influence on stability and safety matters, with goal-setting-performance-based approaches becoming the new face of safety. What is known as Safe Return to Port (SRtP) of SOLAS 2009, enforceable on every passenger newbuilding vessel and special-purpose ships over 120m in length or having three or more main vertical zones, has paved the way for holistic approaches to risk, specifically fire and flooding risks. These regulations represent a step change from the deterministic methods of assessing ship subdivision and damage stability, in general. The old deterministic stability concepts like floodable length, criterion numeral, margin line, 1 and 2 compartment standards and the B/5 line have disappeared from new building projects, which now adopt a more holistic approach to addressing damage stability and survivability. Moreover, such considerations cover the vessel's life cycle, targeting cost-effective safety as a primary design objective, alongside other conventional design objectives (Vassalos, 2012).

Assessment of ship performance in terms of damage survivability in waves, however, is not an easy task to perform. In addition to the complexity of predicting ship behaviour in waves by employing techniques derived from intact ships, further non-linear phenomena of water ingress-egress through the breach open to the sea and the consequent ship-floodwater interaction and water sloshing further inhibit accurate behaviour prediction (Vassalos and Letizia, 1998), (deKat, J, 1996), (Vassalos and Jasionowski, 2002), (Spanos and Papanikolaou, 2012) and (Ruponen, 2014). Such behaviour, in turn, depending on compartment geometry, dimensions and position with respect to the axis of rotation, amount of floodwater, and amplitude and frequency of motion (Van den Bosh and Vugts, 1966), displays a behaviour ranging from small-amplitude short waves formation and non-linear standing waves to highly non-linear hydraulic jumps or combinations of all these (Hamlin et al., 1986). The dynamic pressures exerted on the compartment walls are also non-linear as they comprise both non-impulsive loads related to fluid transfer and impulsive localised loading. Such dynamic-mutual effects of fluid motion on the ship response have been extensively studied since the late 1960s, mostly focusing on roll stabilising tanks, water trapped on deck, tank sloshing in LNG carriers and related problems, all these with the amount of fluid mass in the tank/compartment assumed to be constant. However, the issue of a ship undergoing progressive flooding entails additional degrees of freedom and complexity arising from fluid mass variation, which renders all related processes not only non-linear but also non-stationary.

Published research on the subject exhibits tremendous variety in levels of sophistication and type of approaches used to solve these problems, even though simplified quasi-static approaches are still being developed for fast calculation time (Dankowski, 2013; Ruponen, 2014; Braidotti and Mauro, 2020). However, such methods are too simplified to be considered as direct methods for ship survivability assessment. Therefore, developed approaches can be broadly classified into two categories: simplified numerical methods based on rigid-body theory and using a Bernoulli-based mechanism for modelling water ingress-egress and techniques employing high-fidelity Computational Fluid Dynamics (CFD). Studies on coupled ship motion and water sloshing based on the latter approach have been reported by (Mikelis et al., 1984; Francescutto and Contento, 1994; Bass and Cumming, 2000; Daalen et al., 2000; Faltinsen and Timokha, 2009; Gao et al., 2019). In these studies, the exciting internal fluid behaviour due to tank/ship motion is dealt with by coupling the solution of RANS (Reynolds-averaged Navier–Stokes) equations with the simultaneous time-domain solution of equations of intact ship motions, treating the fluid forces as external input. Further, (Veer and Kat, 2000), presented an attempt to predict, in a similar manner, the effects of water ingress with the rate of flooding itself estimated from Bernoulli's equation. In addition, water sloshing coupled to a 6-DOF ship motion prediction model, (Woodburn et al., 2002), led the way to representing water ingress/egress and damaged ship dynamics in a more sophisticated (albeit still simplified) manner, allowing for direct coupling between external and internal fluid domains. Intermediate approaches model the sloshing inside the compartments according to the shallow water equation (Valanto, 2006; Santos and Guedes Soares, 2008; Janβen et al., 2013), reducing the computational effort compared to RANSE by employing potential theory but still remaining linked to the Bernoulli equation for the evaluation of water ingress/egress.

Even though addressing the problem of intact and damaged ship dynamics with water sloshing at the most fundamental of levels, these techniques are plagued with practical solution setbacks, deriving from two reasons: the very large fluid domains required and the presence of free surfaces. The applied numerical solution schemes proposed, such as the VOF (Volume Of Fluid) method, suffer from a notorious inability to conserve the fluid mass with time marching, due to fluid diffusion near the free surface, which is severe, especially in the presence of wave fields. Highly refined space discretisation must be used, which increases grid density, thus rendering computation excessive and unaffordable. Additionally, for the case of bodies undergoing motions, the grids must be instantaneously adapted to the new fluid geometry, which is a non-trivial numerical problem, adding to the complexity of using even the most advanced general-purpose CFD tools available today. This prevents methodological application for routine studies on damage survivability in waves. It is envisaged that, presently, the use of these tools will be applied to address many basic problems, such as higher-order effects of waves diffraction upon encountering a ship with a breached hull, highly turbulent (rotational) and locally 3-dimensional flows at the damage opening or non-linear floodwater behaviour inside the ship compartments coupled with effects of instantaneous water ingress/egress on ship hydrodynamics. More methodological treatment of such tools, leading to knowledge-intensive models (for example, response surfaces) paved the way as far back as the early 2000s, for example, in the EC-funded IP project VIRTUE (2005–2009). Other than some gains attributable to higher computing power, no significant advance is noted in this direction as concluded in Project eSAFE (Luhmann et al., 2018). However, such numerical treatment of damage stability is deemed to evolve into a viable alternative to physical model testing. This also forms part of Project FLARE (2019–2022) where in addition to validating numerical tools for routine evaluation of damage stability and survivability in waves (Ruponen et al., 2022), high fidelity numerical tools are utilised for verification and validation of the numerical methods to be used routinely in the design process. Such developments are elaborated in the following starting from basic concepts and leading to risk assessment methodologies.

3. Damage stability first-principles assessment concepts

The principal aspects for ship damage stability/survivability assessment comprise the evaluation of the following characteristics of the damaged ship:

1. Survivability: the ability of the damaged vessel to survive in a specific sea environment and initial loading conditions, i.e. the determination of safe, unsafe and uncertain region (capsize band).
2. Time to capsize: evaluation of the average time of occurrence of a capsize event in a specific sea environment and loading condition.
3. Time to evacuate: estimation of the time needed to evacuate passengers or in general people on board after damage in specific environmental and loading conditions.

The next sections provide an exhaustive discussion of the above-mentioned characteristics concerning the use of first principles methods for their evaluation.

3.1. Survivability and capsize band

While assessing the ability of a ship to survive a damage case in an irregular, hence random, wave environment, it is important to determine the probability of survival or capsize in each sea state and, thereafter, the time that it takes for this to happen. The stochastic nature of the irregular sea waves does not allow for the execution of a single calculation to establish the probability of survival for the damage event; this is possible only in calm water. Therefore, it is necessary to perform a significant number of repetitions N_r to evaluate the final probability p of survival in the selected case. The clear identification of the survivability cases was not straightforward until the mid-1990s (North West European Project) when the capsize band concept (Vassalos et al., 1997; Vassalos et al., 1998; Tsakalakis et al., 2019) offered the basis for a credible answer. In simple terms, the capsize band describes the transition of sea-states from those at which no capsize is observed (lower boundary with survival probability $p = 1$) to those at which the probability of capsize equals unity (upper boundary with survival probability $p = 0$). This is a region outside which capsize is either unlikely to happen or certain, thus where $0 < p < 1$. The capsize band is usually visualised in two ways: through the variation of the KG or, more likely, the GM for different sea states. One schematic example of the latter is provided in Fig. 1.

The extension of the capsize band reflects the variation of the damage characteristics and ship loading conditions leading to potential capsize. Even though the capsize band looks like a confidence interval, it is clearly not. The band itself, can be interpreted as a measure of capsizes dispersion, which in turn, relates to separate sea states for which the capsize probability (i.e., the conditional probability of capsize or, in a more simple form, the number of registered capsizes in the N_r repetitions) is very low from those in which the probability is very high. Allied to this, the capsize band signifies that there is no distinct boundary that separates safe from unsafe sea states, but instead, a transition zone within which capsize is possible. Although there are sea states where the vessel always survives and sea states where the vessel will inevitably always capsize, the lower and upper capsize/survival boundaries can be represented by means of limits. Here, this asymptotic behaviour requires the use of threshold values of the conditional probability outside of which the occurrence of capsize will either be impossible or practically certain.

Fig. 2 represents a sample of capsize bands for various simulation times considering only one loading condition. In this case the asymptotic transition between fully safe and fully unsafe regions is modelled with a sigmoid shape distribution. The probability of capsize is dependent upon the time of observation (i.e., the simulation time) and, in the limiting case of infinite exposure, the capsize probability dependence on significant wave height will converge to a unit step function, as indicated in Fig. 2 for increased simulation times. In this vein, for low capsize probability, the corresponding significant wave height will remain the same (with only a minor difference) with the time of observation. In other words, a sea state corresponding to a small capsize rate can be established on the basis of relatively short-time simulations and would remain valid for longer observations. Such property is of utmost

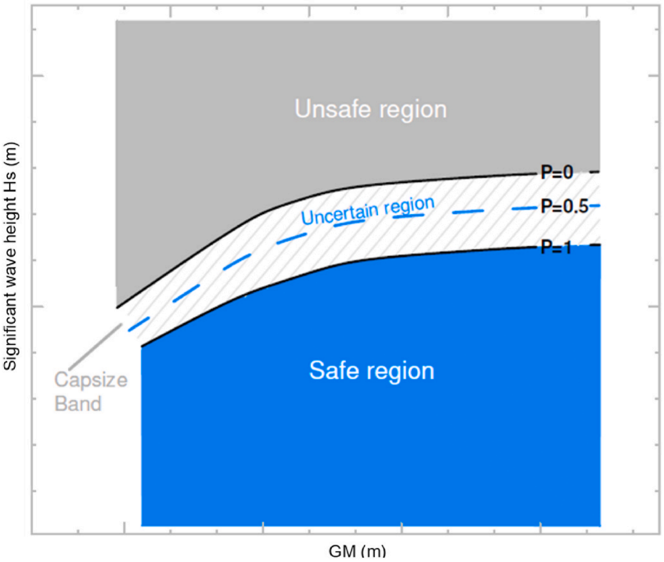

Fig. 1. Capsize band for one damage scenario and different loading conditions and sea states.

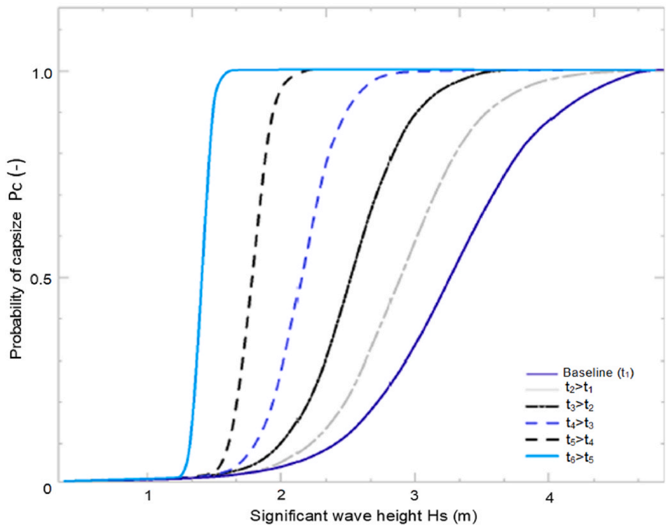

Fig. 2. Change in shape of the capsize band with increasing significant wave height for a single damage and loading condition with increasing exposure time t_1 for the baseline scenario (dark blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

importance for the identification of extremely rapid capsizes (transient cases), which are the most dangerous and severe in terms of possible fatalities. For more details on this concept and various interpretations of the associated probabilities, refer to (Tsakalakis et al., 2019).

3.2. *Time to capsize (TTC)*

The Time to Capsize is used to identify those flooding scenarios where damage survivability is compromised (loss scenarios), given the time it takes for the vessel to capsize/sink. The process is not significative for single damage, thus it involves the generation of many flooding scenarios by sampling the random variables comprising loading conditions, sea states and damage characteristics (location, length, height, penetration) according to damage statistics adopted in the IMO probabilistic regulations in SOLAS, using crude Monte Carlo (Kruger and Dankowski, 2019; Bulian et al., 2020, Ruponen et al., 2022) or, better, Randomised Quasi-Monte Carlo sampling (Mauro and Vassalos, 2022). Each damage scenario is then simulated using explicit dynamic flooding simulation, e.g., PROTEUS3, (Jasionowski, 2001), aiming to identify potential loss scenarios, Figs. 3 and 4. Other relevant references on this matter, worth mentioning, are those of (Palazzi and de Kat, 2002) and (Spanos and Papanikolaou, 2012).

The results of the flooding simulations allow the vessel survivability to be determined, by considering the ratio of cases survived to cases lost. This is a time-conditional value, depicted as the cumulative distribution function of Time to Capsize (TTC), shown in Fig. 5 for a cruise vessel. Here, the probability of vessel capsizing can be observed with respect to time. The complement of this value then represents the vessel probability of survival, or *Survivability Index*, conditional on exposure time. In addition, through observation of the shape of the CDF, one can learn a great deal about the modality of the loss scenarios giving rise to the capsize risk (transient loss or progressive flooding loss). The CDF of a vessel with a higher propensity for transient capsize will demonstrate a sharp increase within the lower time range, after which only a gradual increase in capsize probability will be observed. Alternatively, a vessel with a higher propensity for progressive flooding will possess a CDF with only a slight increase within the lower time range, following which the curve will take on a much sharper incline towards longer exposure times. In addition, the CDF is also shown with 95% confidence intervals. to account for statistical uncertainty and provides an upper and lower bound for the Survivability Index.

3.3. *Time to evacuate (TTE)*

The Time to Evacuate is the measure of the time required for an orderly evacuation of passengers and crew in any given flooding emergency scenario, identified in the estimation for TTC, which pertains to the last line of defence following flooding and fire ship casualties, namely the evacuation (mustering + abandonment) process, as depicted in Fig. 6.

3.3.1. *IMO evacuation analysis*

The statutory requirements pertinent to evacuation of passenger ships are shown in Table 1, (Ilus, 2019), the main reference for evacuation being IMO MSC (2016) – MSC.1/Circ. 1533 concerning revised guidelines for evacuation analysis of new (after 01/01/2020) and existing passenger ships. Such guidelines still relate to simplified day and night scenarios, without explicitly considering the additional hazards related to the presence of floodwater and motions of the damaged ship. Hence, the identification of pertinent flooding scenarios and their impact on evacuation analysis needs to be properly considered.

3.3.2. *Advanced evacuation analysis*

In MSC.1/Circ.1533 (IMO MSC, 2016), the term ’advanced’ in the evacuation analysis indicates the use of direct simulations where each person is modelled individually, rather than using the ’simplified’ approach. However, as indicated in the foregoing, such analysis is still performed on simplified day and night scenarios without explicitly considering the impact of flooding (and fire) hazards, see for example (Guarin et al., 2014).

In advanced evacuation analysis, it is suggested that the total evacuation time of a passenger is to be calculated following the procedure

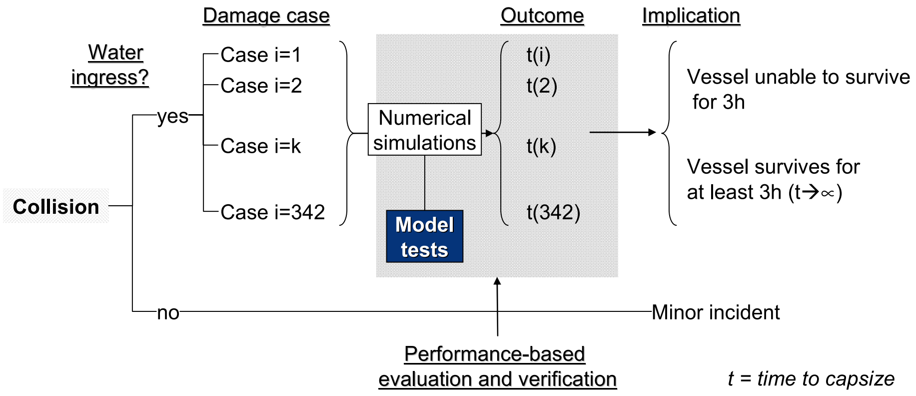

Fig. 3. Monte Carlo simulation scheme – collision.

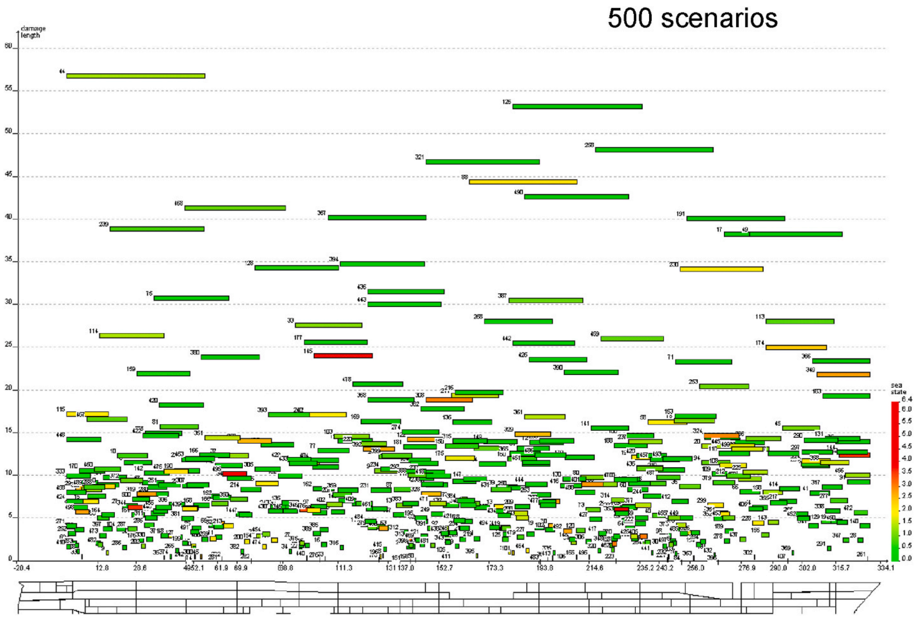

Fig. 4. Monte Carlo simulation set up – collision, Vassalos (2020).

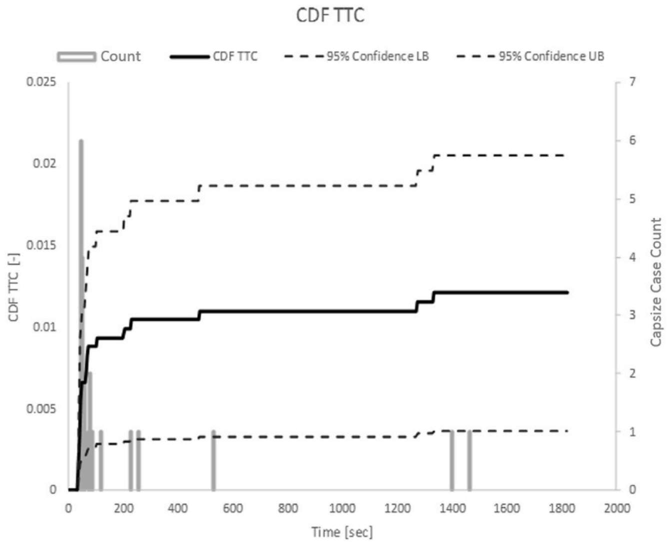

Fig. 5. CDF for Time to Capsize (TTC) with double side 95% confidence interval.

shown in Fig. 7, at least 50 repetitions are recommend to account for the random elements involved in the analysis (e.g., passenger distribution within the ship relevant to the scenario being considered, reaction times, etc.), Fig. 8.

The evacuation analysis prescribed by IMO for new cruise and existing passenger ships allows for assessment at the design stage of passive safety (in-built) of the ship evacuation systems only. Operational

Table 1
Summary of relevant regulations on flooding and evacuation of passenger ships.

Statutory document	Relevant topics
SOLAS Ch. II-1 Part B-1, and SOLAS Ch. II-1 Part B-2 (after 01/01/2020 incl. SOLAS amendments from MSC 98th session)	Stability, i.e., damage stability Subdivision, watertight & weathertight integrity
SOLAS Ch. II-2 Part D	Escape, esp. Reg. 13: Means of escape
SOLAS Ch. III (after 01/01/2020 incl. LSA code amendments from MSC 98th session)	Life-saving appliances & arrangements
MSC.1/Circ. 1533 (after 01/01/2020 mandatory for all passenger ships)	Revised guidelines on evacuation analysis for new and existing passenger ships
FSS Code: MSC.98 (73) Annex Ch. 13 Part 2 Passenger ships	Definition of benchmark scenarios, i.e., pax/crew distributions Requirements concerning stairways, doors, corridors, evacuation routes & means of escape plans

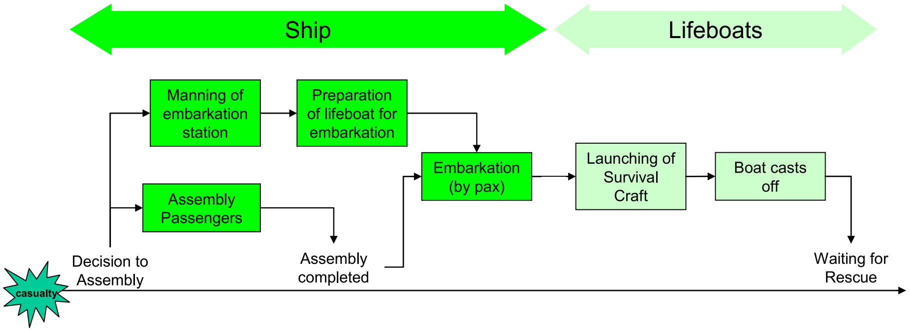

Fig. 6. Different stages in the evacuation process.

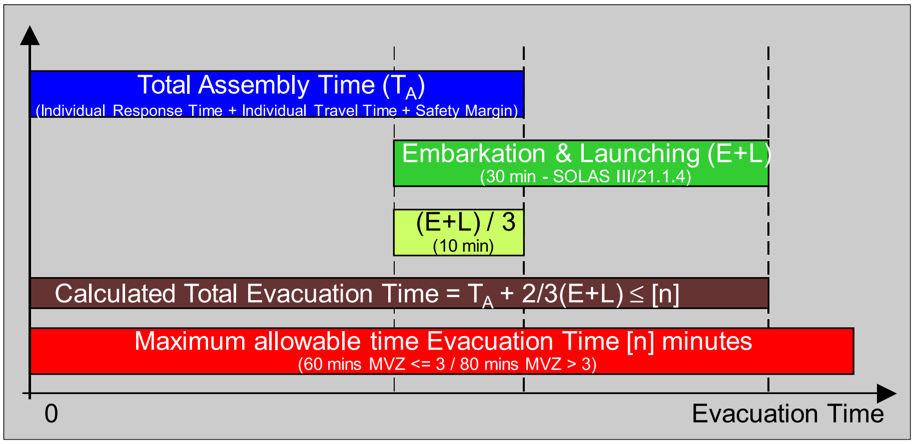

Fig. 7. "Advanced" evacuation time (IMO MSC, 2016) – MSC.1/Circ. 1533.

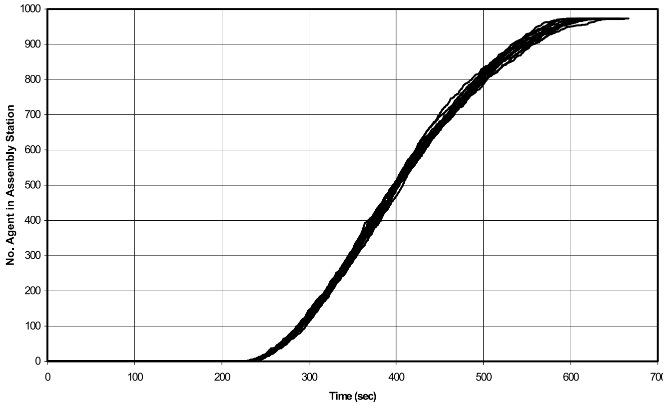

Fig. 8. Typical evacuation completion curve (analysis repeated 50 times).

safety, pertaining to any measures to enhance emergency preparedness and to better manage the crisis in case of an emergency, is only dealt with by means of an empirical safety factor. The IMO evacuation scenarios purely consider only the layout and availability of primary evacuation routes as well as passenger distribution and response times. These, however, do not reflect any real emergencies and hence the need to prepare for such through better planning, training, and decision support, all related to the functionality of the crew onboard, a factor as crucial to passenger mustering and abandonment as a good layout of the escape routes. The Class Notation developed in (Dogliani et al., 2004) assesses the effectiveness of crew functionality by a comparison of the evacuation performance of a ship in several specific scenarios (in addition to the 4 IMO scenarios), pertaining to social events, ship at berth and owner-specified scenarios to reflect real emergencies with and without crew assistance. This new approach increases the relevance of evacuation analysis providing a novel "means" for enhancing passenger evacuation performance as well as incentivising passenger ship owners to improve emergency procedures. Stemming from these developments, evacuation analysis in emergency situations through numerical simulations could be undertaken more meaningfully using advanced evacuation tools, especially when such analysis is fused with technological developments to reduce uncertainty in crisis situations, Project SAFEPASS (2019–2022).

Notwithstanding these developments, use is already made of advanced evacuation simulation software developed specifically for the marine environment and in particular for large passenger ships such as, for example, EVI (Vassalos et al., 2001, 2002; Dogliani et al., 2004; Guarin et al., 2004). Hence, such tools easily transform traditional bidimensional accommodation layouts (as for example in.DXF format) into a 3D VR (Virtual Reality) environments. EVI software is based on mesoscopic multi-agent modelling, accounting for behavioural and environmental characteristics and their interaction and can handle any passenger/crew/sea scenario. For this purpose, the term Evacuability has been coined to identify the ability of passengers/crew to evacuate a ship environment within a given time and for given initial conditions, as portrayed by the following expression:

$$E=f\{\text{env},\text{d},\text{r(t)},\text{s}[\text{evacplan, crew},\text{mii}(\text{g},\text{y},\text{hci})];\ \text{t}\} \tag{1}$$

Thus, Evacuability is a function of a set of initial conditions: ship environment (env), passenger distribution within the ship (d), passenger initial and in-situ response, r(t) and evacuation dynamics, s(ni), pertaining to evacuation plan, crew functionality, passenger mobility characteristics (mii) related to gender(g), age(y), and mobility impairment depending on various handicaps (hci), as depicted in Fig. 9.

Evacuability analysis provides a probability measure of passenger evacuation in a ship-sea environment, namely at passenger, group or ensemble level P(TTE $<$ TTC) deriving from the sample of cases, informed by simulations, i.e., synonymous with the flooding risk (Vassalos et al., 2002). More importantly, EVI uniquely incorporates the capability to estimate the effect of flooding in the evacuation process. In pertinent flooding loss scenarios, data from PROTEUS are imported into the EVI evacuation simulation environment, in the form of time series, as additional semantic information for the agents (evacuees). The agent model considers human behaviour in an evacuation according to a small set of crucial characteristics, such as speed and awareness. A hazard within the evacuation environment will, therefore, affect these characteristics, changing the performance of the agents. More specifically, floodwater data from PROTEUS can be imported in EVI, incorporating information pertaining to the flooding scenario being considered, which is translated in a deck inclination to the horizontal (level) position. Using inclination, a correction factor is then applied to the walking speed of the evacuee (agent) based on the results of research undertaken in the MEPDesign project, which describes a parabolic relationship between walking speed and inclination. This has been discussed in detail in (Vassalos et al., 2002). Thus, flooding data are used to affect the awareness and walking speed of agents (Dogliani et al., 2004; Guarin et al., 2004), reducing it as they become affected by (walking in) floodwater, as described below:

- Deck inclination: asymmetric flooding will cause the ship to heel, making it more difficult for evacuees to walk, thus reducing the speed of the agents.
- Ship motions: ship motion will affect people orientation and movement; consequently, agents will advance more slowly, make wrong decisions, or fall over.

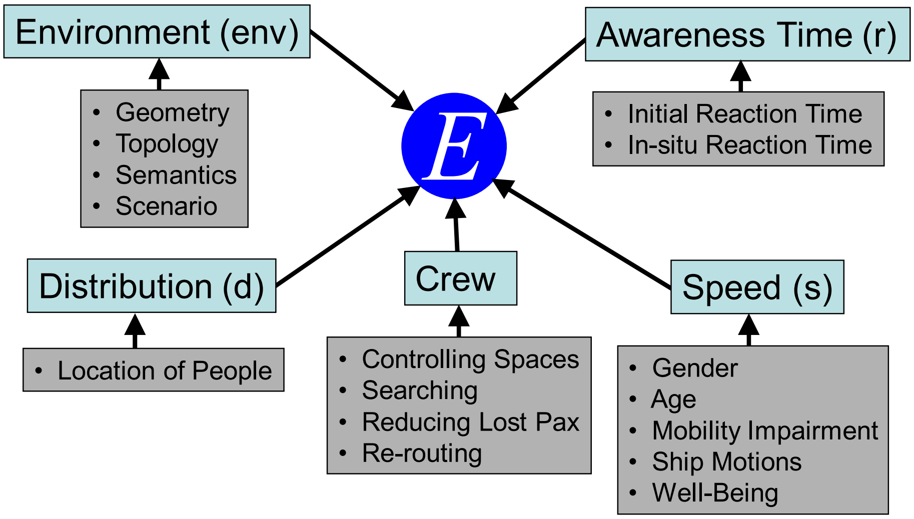

Fig. 9. Parameter set for the advanced evacuation simulation software EVI.

- Inaccessibility: flooding renders some areas of the ship inaccessible; this entails that for people on lower decks, certain evacuation routes may become unavailable, and this will impact evacuation completion time. Fig. 10 shows an example floodwater effect, where an evacuee has to walk in water and the speed reduction factor is provided as a function of the level of water (immersion) that the evacuee has to walk through.

For each loss scenario identified as described in the foregoing, evacuation simulation determines in a direct way the time to evacuate (TTE).

There have been some attempts addressing flooding in time domain, whilst linking the problem with the time for abandonment, for example, (Spanos and Papanikolaou, 2014), (Valanto, 2006) and (Bulian, 2008).

4. Flooding risk assessment

Deriving from the foregoing, Fig. 11 illustrates the evaluation of flooding risk in terms of the Potential Loss of Life (PLL) through advanced passenger evacuation simulation tools, taking as input the available Time To Capsize (TTC) deriving from flooding simulation analysis for a given flooding scenario, as described above.

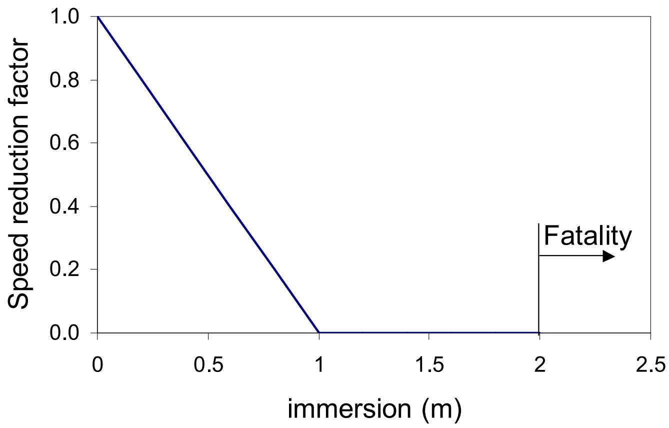

Fig. 10. Walking speed reduction factor when an evacuee walks through water with given water level (immersion).

Starting with the premise that risk is probability x consequences, and considering flooding risk at scenario level, results in the simplified expression of equation (2) (Vassals at al., 2022), with hazard frequency results taken from (Mujeeb-Ahmed, M.P. et al., 2021) and the fatality rate as illustrated in Fig. 11.

$$PLL_A[1/year] = hazard\ frequncy \times breach\ frequncy \times sea\ state\ probability \times capsize\ probability \times fatality\ \ rate \times POB \tag{2}$$

A similar concept can also be applied in the case of fire scenarios. For estimation of the fatality rate in a single loss scenario, Fig. 11 presents schematically what has been described in the foregoing, with all other parameters, easily determined from standard ship stability software (e.g., PROTEUS in the context of damage survivability in a random wave environment) and breaches from sampling pertinent SOLAS accident statistics for collision or grounding hazards from work in EU Project FLARE (FLARE, 2019-2022; 2022) as well as environmental conditions from pertinent distributions.

Pertinent rules are also now in place to fuel further development and application in ship design and operation and encourage further development and validation, with real-life applications, as in the EC-funded Project SAFEPASS (2019–2022). The main focus is on expanding and verifying such concepts with application to passenger ships, considering both flooding and fire casualties whilst introducing technological innovation to enhance situational awareness for evacuees and render this last line of defence in an emergency much more effective with practical implementation as a key objective.

5. Concluding remarks

The paper demonstrates that a clear trend from static, deterministic instruments to dynamic, probabilistic concepts is being witnessed by the maritime industry, fuelled in some cases by accidents, as usual, but fundamentally by the need to develop a regulatory framework that embraces and encourages positive change and innovation with regulatory instruments that reflect real ship design and operational experience.

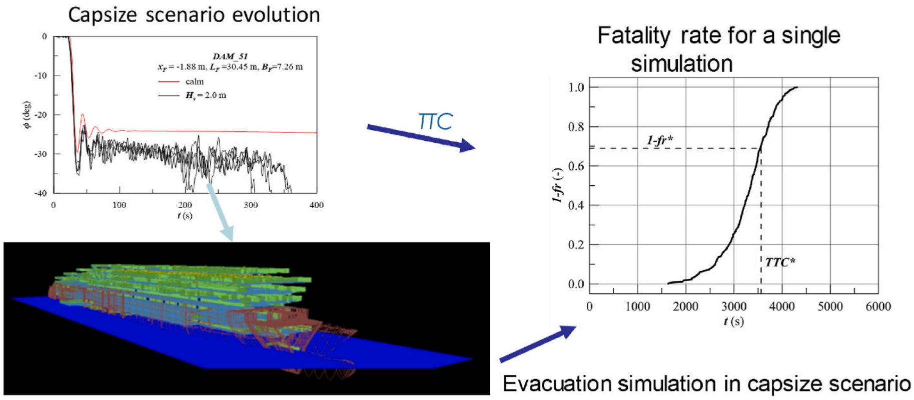

Fig. 11. Fatality rate estimation for a single loss scenario after a flooding casualty.

In response to this need, the paper portrays the painstaking evolutionary development in the subject of ship damage stability and survivability in waves that is leading to unprecedented scientific and technological changes at an ever-increasing pace which, despite all the simplifying assumptions still embedded in the available "tool-set", facilitate step changes in addressing the main contributor to loss of life at sea, namely flooding risk.

A primary future effort should be in support of regulations at IMO, driving a shift from experiential to risk-informed regulations and rational decision making on safety matters in ship design and operation.

This effort is culminating in recent large-scale projects funded by the EC/Maritime Industry, with a focus on damage stability and flooding hazards, in a series of unique developments addressing current gaps at IMO (e.g., focus only on the hazard of collision) and paving the way for a new regulatory framework where all hazards are addressed as well as developing design and operational measures to contain, control and mitigate flooding risk with application to new and existing ships.

To this end, deviating completely from the current practice at IMO of using Indices as measures of damage stability and passenger ship safety, a methodology has been described for addressing directly flooding risk in the form of Potential Loss of Life (PLL).

Such methodology has been recently applied to sample ships, involving all major yards building passenger ships in Europe, to demonstrate that the developed methodology could readily be implemented in daily design work, following significant efforts by all parties involved, and that it leads to meaningful results in line with expectations, current knowledge, and best practice.

This is a first step in the transformational process of risk-based damage stability, being driven by the maritime industry. Engagement with the wider industry, Government and Academia is key to instigating and promoting the requisite cultural shift in maritime safety for any positive change, particularly from the regulator to be duly addressed.

Credit author statement

D. Vassalos: Conceptualization, Methodology, Writing – Original draft, Writing – Revised paper. D. Paterson: Methodology, Writing-Original draft. F. Mauro: Methodology, Writing – Revised paper. P. Mujeeb-Ahmed: Writing-Original draft. E. Boulougouris: Writing – Revised paper.

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

No data was used for the research described in the article.

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Appendix A. Supplementary data

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