Ships and Offshore Structures

ISSN: 1744-5302 (Print) 1754-212X (Online) Journal homepage: www.tandfonline.com/journals/tsos20

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To cite this article: Dracos Vassalos (29 Dec 2025): From the Titanic era to the AI era: a rational framework for life-cycle damage stability and flooding risk management of passenger ships, Ships and Offshore Structures, DOI: 10.1080/17445302.2025.2603415

To link to this article: https://doi.org/10.1080/17445302.2025.2603415

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Published online: 29 Dec 2025.

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SHIPS AND OFFSHORE STRUCTURES
https://doi.org/10.1080/17445302.2025.2603415

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From the Titanic era to the AI era: a rational framework for life-cycle damage stability and flooding risk management of passenger ships

Dracos Vassalos

Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, UK

ABSTRACT

Maritime accidents involving passenger ships have long influenced industry approaches to ship design, emphasizing resilience and fail-safe performance following flooding events. Consequently, regulatory frameworks have focused predominantly on damage containment and emergency response rather than on accident prevention. This emphasis is reinforced by largely rules-based regulations that apply mainly to newbuildings and reflect legacy assumptions that have not kept pace with modern technological advances. As a result, many existing ships operate under comparatively lower safety standards, with limited means to sustain or enhance safety during operation. Meanwhile, progress in accident prevention has been modest, failing to capitalize on contemporary developments that could offer cost-effective and transformative safety improvements. There is a clear need for a paradigm shift from post-accident protection toward proactive accident prevention, with the ultimate objective of eliminating loss of life at sea. This paper proposes such a shift and outlines the essential elements required to design and operate fundamentally safer ships.

ARTICLE HISTORY
Received 24 November 2025
Accepted 8 December 2025

KEYWORDS
passenger ship safety; damage stability; flooding risk management; life-cycle framework; risk-based approach

1. Introduction

Damage stability failure represents 90% of the risk to human lives in maritime accidents, affecting over 2 billion people who travel on passenger ships each year and around 100,000 commercial vessels, operated by 1.5 million crew. Inadequate damage stability has been the cause of 53% of all vessel losses over the past decade and was the primary cause of 65% of losses in 2018 (Figure 1). In particular, for passenger ships, the maximum number of passengers carried by the largest cruise ships each year has risen dramatically, almost doubling to 6,800 in 2019 compared to 1999 (Figure 2). This means that there is now a far greater risk of passenger fatality from any given single accident. Similarly, there are about 1,000 damage stability-linked fatalities per year in the general shipping industry for ships over 550 GT and an astonishing 55,000 fatalities per year, considering just two groups of smaller ship sizes (fishing vessels, 25,000 per year; domestic ferries 30,000 per year).

Analysis of 230,000 marine insurance industry claims with a value of almost $10bn between July 2013 and July 2018 (Clarkson 2019) shows that ship sinking/collision incidents are the most expensive cause of loss for insurers, accounting for 16% of the value of all claims – equivalent to more than $1.5bn over this period (Vassalos and Mujeeb-Ahmed 2021). Most importantly, solving the damage stability problem for ships is the holy-grail in naval architecture with a huge transformational impact on the design and operation of every type and size of ship and the whole maritime industry.

The present paper deleniates the historical development of damage stability and associated flooding risk in more than 30 years of research in the field. Starting from analysing the historical pitfalls in understanding the implications of risk prevention, the paper focuses on defining the way forward for the proper consideration of risk prevention measures in a modern flooding risk management framework.

One of the most important elements is related to the concept of prevention in the whole life-cycle of the ship. To stress this, the paper is articulated in two main sections: the first on the key elements and pitfalls of the existing framework for damage stability, and the second on the way forward needed to be pursued, aiming to improve the current state-of-the-art.

CONTACT Dracos Vassalos d.vassalos@strath.ac.uk Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, UK

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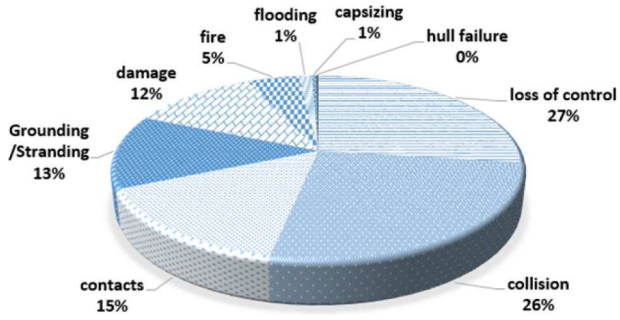

Figure 1. Casualty events for ships in the period 2011–2019.

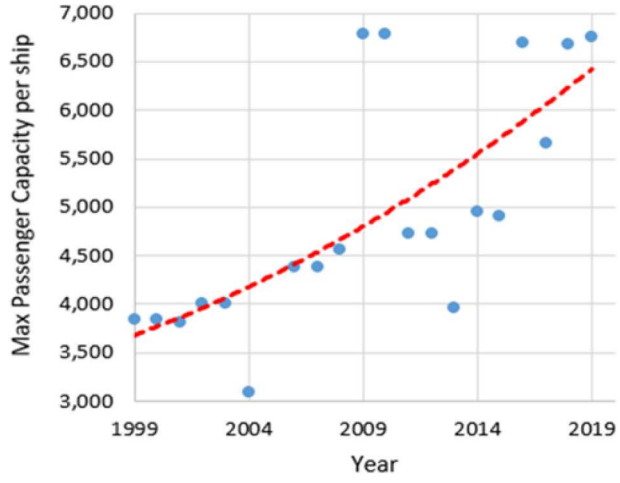

Figure 2. Trend on capacities of largest passenger ships by year.

2. Key elements and pitfalls of the current framework

Overcoming the Titanic Syndrome: 'If it is made of steel, it can sink,' (Figure 3) is the cornerstone of all development ever since. This dictates total emphasis on resilience in ship design to ensure that should an accident happened, the ship will fail safe, but what happened to an ounce of prevention is a pound of mitigation? Given this, why not ensuring that an accident will not happen in the first place?

2.1. Paving our way through an archaic regulatory framework

Presently, damage stability assessment is based on key performance indicators with unclear risk content (A and R-Indices). More specifically, indices focussing and reflecting one aspect of ship design, namely subdivision below the bulkhead deck.

The area of operation, reflected through the s-factor is generalistic, i.e. 4 m of significant wave height H_s, not representing the specific area of operation and based, more latterly, on RoPax model tests (SOLAS

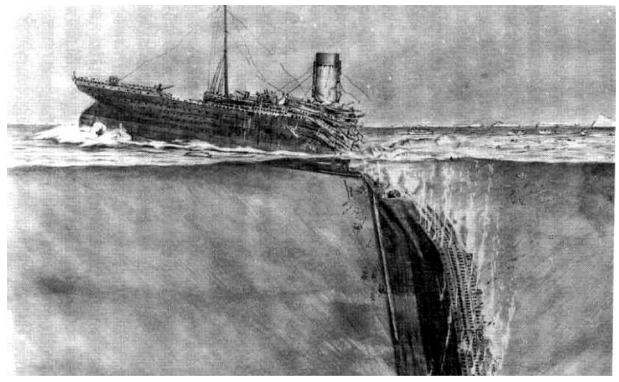

Figure 3. The sinking of Titanic.

2009), with only one cruise ship bring involved in its derivation (Figure 4). Moreover, the p-factor is based on accident accidents involving cargo ships and tankers of a bygone era. Interestingly, based on numerous applications, static assessment of survivability has been shown to be too conservative for passenger ships, as depicted in Figure 5.

2.2. Sustained research and development but limited focus leads to limited progresses

Sustained research for over 25 years by experts from Industry, Government and Academia helped develop the subject of damage stability to standards comparable with any other transport industry. Despite this, limited focus (internal subdivision) leads to limited progress, thus depriving the shipping industry of cost-effective solutions to meet the ever-increasing demands for higher safety of passenger ships. Some of the key projects, paving the way and leading to Project FLARE, are listed in Table 1.

A number of these projects addressed flooding risk directly, accounting for all flooding hazards, including methodologies for risk estimation and management being submitted to IMO. However, political compromises led to continuing focus on indices and to adopting significantly lower safety levels than those demonstrated in the aforementioned research projects (Figure 6). More importantly, reliance on a framework offering only subdivision as a key risk control option for flooding risk, led to saturation of such measures, thus depriving the wider profession of cost-effective solutions to reduce, mitigate and control flooding risk (Figures 7).

2.3. Evolution of passenger ship hazards

Most importantly, with SOLAS focussing on collision only and with attention by ship designers on protection

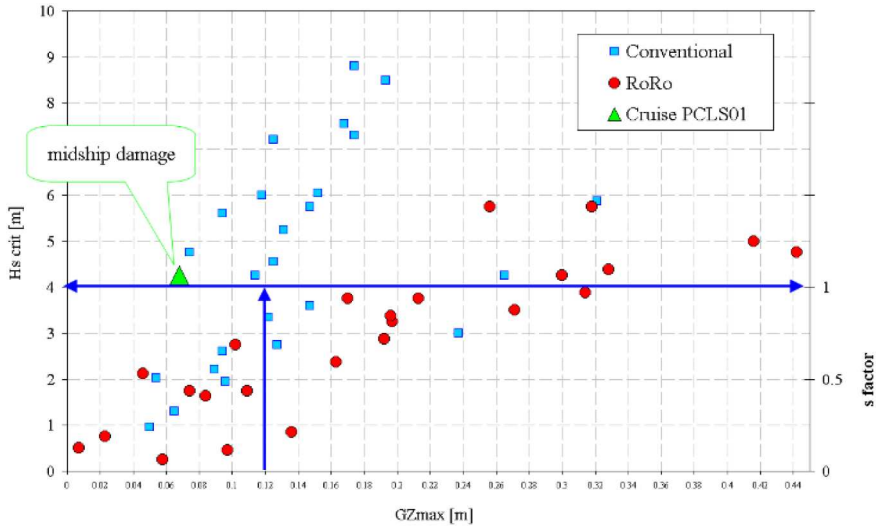

Figure 4. Derivation of the s-factor for passenger ships.

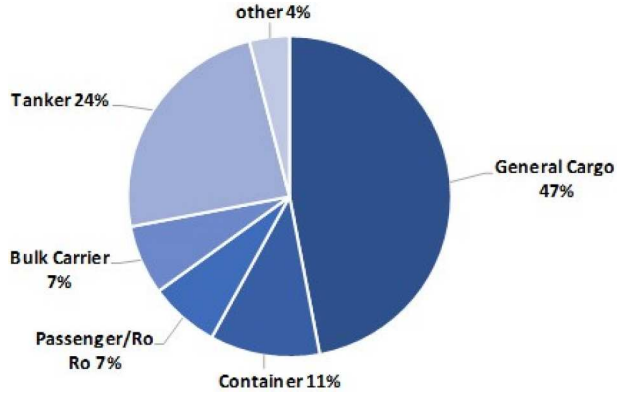

Figure 5. The p-factor is based on accident accidents involving cargo ships and tankers of a bygone era.

Table 1. Sustained research and development in damage stability and flooding risk.

Project	Achievement highlights
HARDER (1999–2002) (HARDER 2002)	Harmonisation of damage stability regulations for cargo and passenger ships – probabilistic concept.
SAFEDOR (2005–2009) (SAFEDOR 2009)	Risk-Based Design; update of accident data; detailed risk models for collision and grounding.
GOALDS (2009–2013) (GOALDS 2013)	Improved probabilistic models for collision and grounding; proposals to IMO for revision of the required subdivision index.
EMSA III (2013–2016) (EMSA 2016)	New required index R for passenger ships (SOLAS 2020) for collision, results from grounding used to support political decisions.
eSAFE (2018–2019) (eSAFE 2019)	Combination of collision, bottom and side grounding hazards; safety metric for combined analysis of collision and grounding events.
FLARE (2019–2023) (FLARE 2023)	Life cycle (design, operation and emergencies), flooding risk assessment and management to enhance passenger ship damage stability cost effectively.

from this hazard, the risk from unattended hazards such as bottom and side groundings has now become dominant for both RoPax and cruise ships (Bulian et al. 2019). Recent damage statistics as portrayed in Figure 8 indicate that the frequency of grounding hazards for both cruise ships and RoPax accounts for 80% for both categories of ships whilst the flooding risk attributed to groundings has grown to 75% for RoPax and an astounding 95% for cruise ships.

2.4. Old ships vs new ships

The shipping industry is very old and, consequently, very traditional. Damage protection in the form of watertight bulkheads was the first risk control option proposed in 1854, but it has taken many more accidents and significant loss of life, with the Titanic driving this effort, for it to be internationally adopted as SOLAS 1929. It is more than likely that the delay was primarily due to the fact that the industry was keenly aware that serving safety will compromise functionality and earnings, ultimately the viability of business, and this contrast and conflict continues to this day. This is clearly obvious in that new regulations for damage stability apply only to new buildings (Grandfathers Clause). Hence, assuming a 5% constant growth of the industry over the years, this leaves the majority of ships (existing ships) with an inferior damage stability standard and damage protection, a gap that widens progressively to the extent that SOLAS becomes less and less relevant. The only way that this 'landslide' will be arrested is if cost-effective active damage control measures are made available, thus incentivising the industry to adopt these for life-cycle flooding risk management.

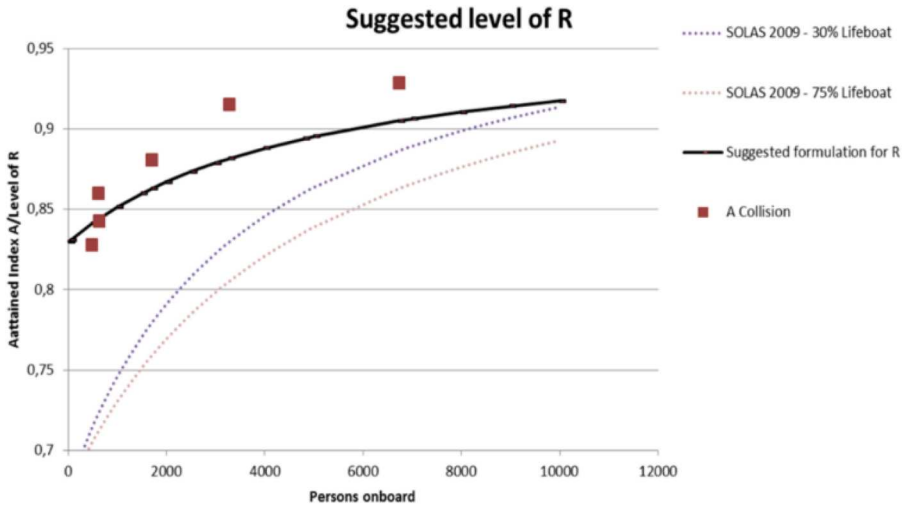

Figure 6. Proposed to IMO (red squares) and adopted (black line) safety levels for damage stability (Index R).

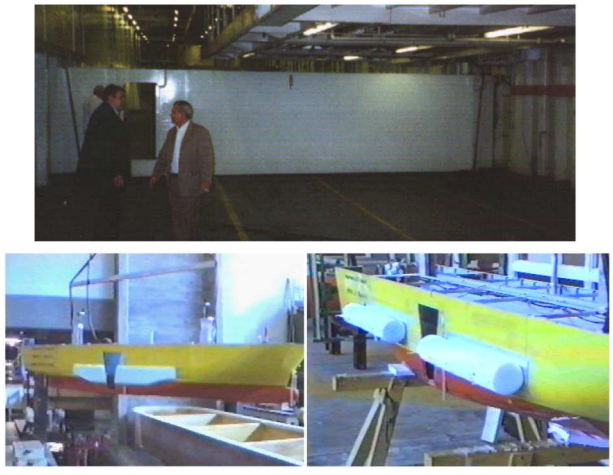

Figure 7. More subdivision, more volume, more complexity.

2.5. Passive vs active protection

In the quest for damage stability improvement, design (passive) protection has traditionally been the only means to achieve this in a measurable/auditable way (SOLAS 2009, Ch. II-1). However, it is undeniable that the consequences from inadequate damage stability can also be reduced by operational (active) measures, which may be very effective in reducing loss of life (the residual risk). As a matter of fact, active and passive measures for damage control have co-existed almost from the outset. One could imagine that in the absence of decks, old seamen would have had to use buckets, later on pumps and other means to empty floodwater from ship hulls, plug holes with any matter of means, adjust sails, and so on. More latterly, safety equipment, LSA, drill teams, Safety Centres, Safety Masters, and all active damage protection measures have been progressively introduced, most in the wake of accidents.

Given this, why is this myopic and uncompromising focus only on passive protection? There are two reasons for this. The first relates to the traditional understanding that operational measures safeguard against erosion of the design safety envelop (increase of residual risk over time). The second derives from the lack of measurement

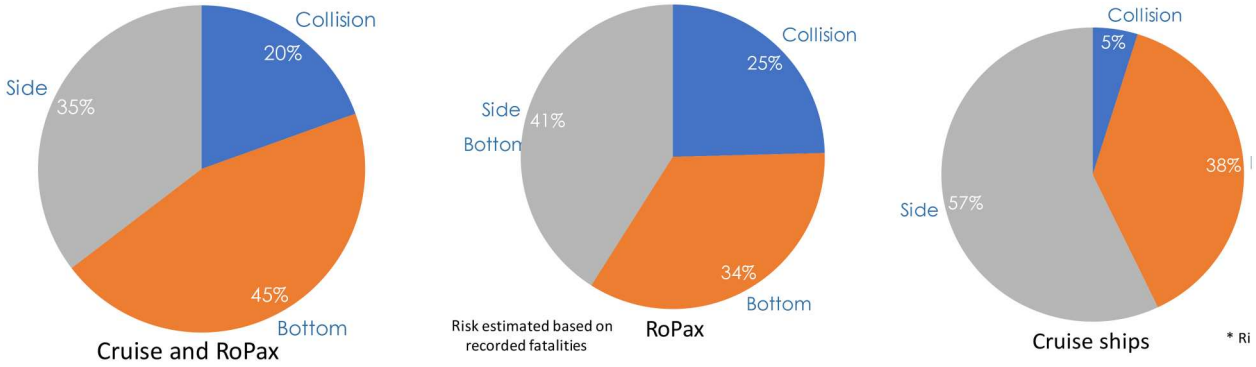

Figure 8. Unattended flooding hazards.

and verification of the risk reduction potential by any active measures. Notwithstanding this, the exact contribution of active measures to safety has never been considered, even as a discussion topic in industry and at IMO, irrespective of how effective these might be as damage protection control options. The dogma that 'if it cannot be measured, it cannot be improved' has gone a step further in the maritime industry to become 'if it cannot be measured, it cannot be regulated.'

Hence, all these options, however cost-effective and safety-effective they might be, they are not being considered as a means of damage protection, in the same way that passive measures are. For example, for passive protection, we have indices of subdivision, indices for damages, indices for survival, indices for everything. There is some refreshing new ground on passenger evacuation metrics, but this is still highly general (some say arbitrary) and incomplete. Novel Technology Qualification (risk assessing and de-risking the novelty) offers a portal for introducing active means of damage protection and modern tools offer enhanced capability to estimate flooding risk over the life cycle, even live-risk onboard ships. This is the requisite platform to facilitate change and Project FLARE facilitated a systematic and structured way to account for such developments.

This, in turn, will change the maritime safety agenda and its evolution. In simple terms, what is needed is the means to account for risk reduction by operational (interventional) means as well as measures that may be taken during emergencies. Such risk reduction may then be considered alongside risk reduction deriving from design measures. Therefore, new measures for risk reduction (operational and in emergencies) should be considered in addition to design measures. What needs to be demonstrated and justified is the level of risk reduction and a way to account for it, the latter by adopting a formal process and taking requisite steps to institutionalise it.

2.6. Prevention vs mitigation

'One ounce of prevention is worth a pound of cure.' This is almost a dogma in most fields of safety science and engineering. There are, however, two aspects worth considering from a different perspective. The first is residual risk, which for large passenger ships is so excessive that reducing this must be a priority. For example, consider the largest ship built to date, which is a 10,500 People On Board (POB) ship. In the IMO FSA for cruise ships, it has been proposed that Risk Control Options for ship safety enhancement will be costed against the propensity of society to spend towards saving one life, which for the western world is approximately $8M.

With the A-Index of this ship being approximately 0.9, according to IMO SOLAS 2009 and assuming that a collision has taken place, the residual risk is worth €8.4B, a few times over the worth of the ship. The second relates to the feasibility of preventive Vs mitigating measures. For effective preventive measures, we should be searching far into the left of the fault tree, where the emphasis lies on sociotechnical, organisational and safety culture matters, which will require long-term investment and effort to identify and bring to fruition effective RCOs. Mitigation measures, on the other hand, are linked strongly to technological innovation, where the strength currently lies. Hence, solutions are likely to be of shorter term but, more than likely, cost-effective.

Therefore, mitigation still remains a key target. In this respect, the prevailing situation can be drastically improved through an understanding of the underlying mechanisms leading to vessel loss and to identification of governing design and operational parameters to target flooding risk reduction cost-effectively. This, in turn, necessitates the development and institutionalisation of appropriate methods, tools and techniques capable of meaningfully addressing the physical phenomena involved, one key target of the EU Project FLARE (Mauro et al. 2023).

Considering that 80% of flooding scenarios in passenger ships (90% considering older ships) refer to transient flooding, current measures of flooding protection fail catastrophically. Hence, prevention is the only credible way forward.

In this respect, a risk-based approach opens new routes for passive and active flooding protection. Emphasis to date has been placed on improving damage survivability, namely increasing factor-s and hence mitigating measures. Little attention has been focused on the p-factor and, hence, on damage prevention measures. A summary of such measures for both prevention and protection is

Table 2. Protection/prevention measures for damage stability and flooding risk.

s-factor (Passive/active Protection)	*p*-factor (Prevention)
- Protection of critical openings - Protection of critical spaces (WT/ semi-WT doors, Deployable Foam barriers) - Seals (Stairwells) - Sponsons (external modifications) - Flooding control, counter ballasting - Permanent ballast - Additional WT protection (mainly WT bulkheads) - Static (passive) foam - Connection between starboard and port compartments	- Safe navigation (capability today to target zero tolerance in maritime accidents) - Structural Crashworthiness - Static (passive) foam

shown in Table 2 (notable that prevention is evolving but still in embryonic state).

3. The way forward

3.1. The first keyword is 'lifecycle'

The realisation that risk is inextricably linked to operation and a derivative of exposure has driven the industry to life-cycle considerations for effective flooding risk management. Key to life-cycle flooding risk management is the understanding that both the operational phase (monitoring and management of residual risk) as well as emergencies (emergency response) depend crucially on having identified during the design phase pertinent design vulnerabilities, which lead to critical accident scenarios in pre-specified loading and environmental conditions and, on the basis of this, having taken appropriate measures to ensure damage protection and control to satisfy adopted tolerable levels. We normally refer to these measures as recovery control measures or mitigating and controlling measures (barriers are another term, Figure 9), which as indicated and explained in the foregoing, traditionally have focussed on passive measures of damage protection after the flooding incident accident has occurred.

However, safety affects everything in the lifecycle of a ship and is, in turn, affected by everything, so why focussing singularly on design (passive protection) and ignoring any interventional (active) measures during normal operation and in emergencies?

Utilising the IMO probabilistic damage stability framework, the provisions for AD&A and Goal-Based Standards and Safety-Level Approach, a Life-Cycle Flooding Risk-Based Regulatory Framework will enable and support a continuous evolution of regulations, ensuring the risk level is ALARP (As Low As Reasonably Practicable) whilst providing a sound platform for benchmarking alternative/novel ship and system designs and operating procedures for new and existing ships. To this end, a fundamental requisite is that pertinent risks need to be quantified, in many cases almost in real time throughout the life cycle of the ship, from design and daily operation to crisis situations. Consequently, there is a clear need for a wider consideration of measures of flooding risk mitigation and control, namely active as well as passive measures of flooding protection, in a way that every measure is assigned a risk metric and is accounted for in such risk assessment.

3.2. The second key word is 'holistic'

The gap in the aforementioned framework at the end of Project FLARE will still be that emphasis on prevention will have been only cursory with strong emphasis once again on damage limitation, post-accident (Vassalos et al. 2023; Mauro et al. 2024). Therefore, the scope need not only be 'life-cycle,' addressing active and passive means of damage mitigation and control, but also 'holistic,' addressing both prevention and mitigation/control measures through a 'Holistic, Risk-Based Regulatory Framework for Damage Stability.' A typical formulation of the flooding risk will be in the form:

$$R_f = P_f \cdot P_{b/f} \cdot P_{sc/b} \cdot P_{loss/sc} \quad (1)$$

Namely: Flooding Risk = Probability that a flooding event has occurred times Probability of hull breach, conditional

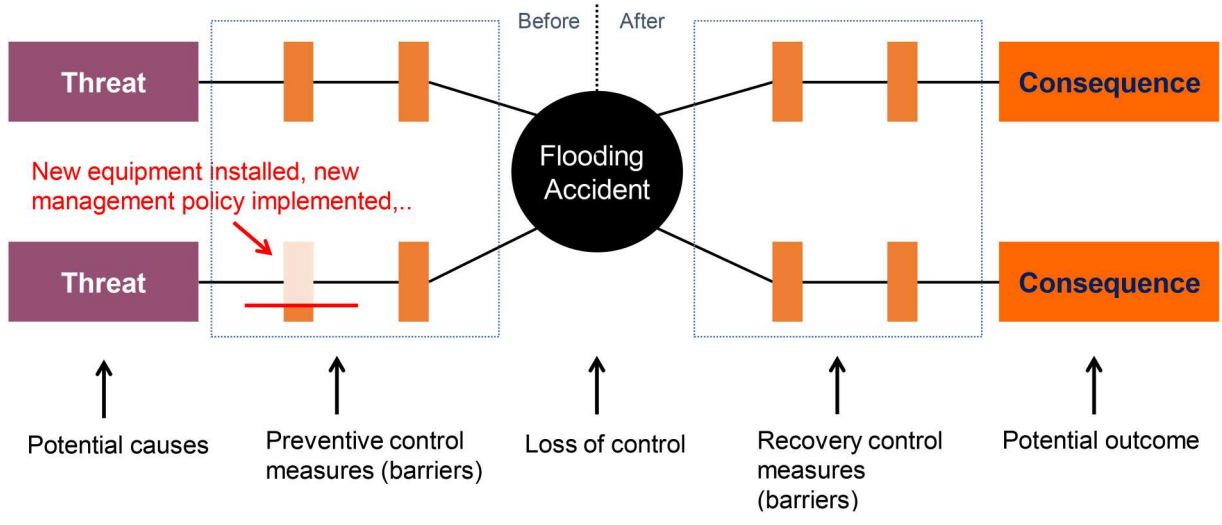

Figure 9. Life-cycle flooding risk management.

Table 3. FLARE innovation and impact.

FLARE research	Current state and SOLAS practice	FLARE innovation and impact
Ship Geometry	Geometry definition lacks granularity	New guidelines for modelling ship geometry and internal arrangements.
Operational data	Old cargo ship data	Permeability, drafts, traffic data for passenger ships and area of operation.
Accident data, frequencies and breach distributions	Old cargo ships, ship structure unaccounted	New accident database, flooding risk model, frequencies and non-zonal breach distributions for collisions and groundings. Influence for crashworthiness accounted.
Benchmarking of numerical tools	Static stability analysis for collision, benchmarking by academia, RoPax.	Model experiments for ship survivability in calm water and in waves (0,2,4 and 7 metres Hs),(1:40 models, cruise ship and RoPax), two model basins (MARIN and HSVA); transient and progressive flooding scenarios. Benchmark studies for quasi-static and dynamic flooding simulation tools, FLARE partners and worldwide.
Situational awareness	Simplistic methods based on statics.	First-principles approach and inference, using AIS data, response-surfaces based on crash analysis, survivability and evacuation assessment and flooding severity assessment.
Ship stability and survivability analysis	Static stability and vulnerability screening for collision only	Physics based survivability analysis and forensics for specific sips, operational environment and conditions, new methods for vulnerability assessment and flooding severity assessment.
Flooding risk assessment (design, normal operation and emergencies)	A & R indices offering no explicit risk content and limited choice RCOs	Direct estimation of flooding risk (Potential Loss of Life (PLL)), with a multi-level approach. Application by shipyards in FLARE to 7 cruise ships and 2 RoPax (one existing ship) showed practicability and potential for use in normal design practice. Demonstrator developed for flooding risk estimation before and during emergencies.
IMO proposals	Collisions,indices. Bottom grounding, partly by deterministic requirements.	Shortcomings identified, proposals made to address these. Introduction of non-zonal approach for damage breach sampling, grounding hazards (bottom and side groundings); new holistic evaluation framework for passenger ship damage stability. Guidance for the assessment of novel RCOs for damage stability enhancement.

on the flooding event times Probability of sinking/capsize, conditional on hull breach times Probability of human life loss, conditional on ship sinking/capsizing.

The current framework addresses only part of the 2nd term in Equation (1) (namely, probability of hull breach, conditional on a collision event, p-factor) and part of the 3rd term (namely, the complement of the probability of capsize/sinking as a result of collision only). Therefore, flooding events as a result of side and bottom groundings are not considered and neither is the probability of having a flooding event. Adopting such a framework will bring together every aspect of risk prevention, mitigation and control, targeting a balance of all credible RCOs and leading to the most cost-effective means of flooding risk management.

The 'Towards Zero Maritime Accidents' initiative, coupled with the efforts made in FLARE will provide the maritime industry with a 'Holistic, Risk-Based, Life-Cycle Regulatory Framework for Flooding Risk Prevention, Mitigation and Control,' offering the requisite flexibility to address flooding risk ontologically and methodologically, thus catalysing a transformative improvement in maritime safety. The contribution to all the above from project FLARE is summarised in Table 3.

4. Conclusions

The present paper describes the current framework for flooding risk management, highlighting the pitfalls and the assumptions on the base of its development. Starting from a digression on the different research studies that lead to the definition of the framework in force by SOLAS, the paper describes the enhancements provided by the recent developments in project FLARE, where, for the first time, the effective focus was on the applicability of first-principle tools for the flooding risk estimation on passenger ship through the whole ship lifecycle.

Bearing in mind the above, the paper proposes a way forward for further developments in the field of flooding risk assessment and management, urging focus of attention on risk prevention primarily, with protection measures reinforcing rather than preceding or unitarily being addressed. In fact, the enhancements introduced by project FLARE together with the more advanced technologies that can be employed onboard to ensure safe navigation, allows for effectively considering prevention as a primary measure to reduce risk. Such an approach should be studied carefully, with a dedicated focus on the applicability of novel technologies and knowledge acquired by research as well as experience in operating ships. This will lead to reshaping the classic methodologies of design currently in use by shipyards in developing new projects, with safety being addressed cost-effectively, particularly concerning flooding risk over the life cycle of passenger ships.

Author contributions

CRediT: **Dracos Vassalos:** Writing – original draft.

Disclosure statement

No potential conflict of interest was reported by the authors.

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