4. A Novel Solution for Retrospective Enhancement of Passenger Vessel Damage Stability

Donald Paterson[1]

[1]Marine Engineering Technology Department, Sharjah Maritime Academy, Sharjah, United Arab Emirates. donald.paterson@sma.ac.ae

Abstract: Ship flooding and inadequate damage stability remains the greatest risk to life in the maritime industry today. To address this problem, increasingly stringent damage stability regulations have been introduced at the international level, most recently SOLAS 2020. However, these apply only to new vessels, leaving the majority of the global fleet under older, more lenient regulations. In fact, the effect of these regulatory changes won't be fully realized for 30-40 years, when older ships are phased out, and that is a long time to wait. The challenge lies in the difficulty and cost of retrofitting older ships to meet modern standards. Adding to the problem is the tendency for the stability of vessels to deteriorate over time, meaning the situation is liable only to get worse. At the heart of the issue has been an overreliance on subdivision as the primary method of controlling flooding, which is exceedingly hard to retrofit in older ships and has diminishing returns with increased application. This highlights the need to seek alternative means of improving damage stability for both new and existing vessels. The research presented in this paper proposes a novel solution to this problem, namely the use of high-expansion polyurethane foam as a means of reducing vessel permeability and enhancing survivability. The system is easy to apply, making it suitable for both new and, more importantly, older ships. The paper provides an overview of the development process to date and presents a methodology for implementing the solution on ships, culminating with promising results from a recent impact assessment conducted on an existing RoPax vessel.

Keywords: Damage stability; Risk-based design; Flooding risk; Passenger vessel safety; Ship survivability

1. Introduction

Despite considerable advancements in ship design and safety, inadequate damage stability remains the greatest singular risk factor within the maritime industry. Observing casualty statistics over the past nine years highlights that ship flooding is responsible for over 50% of all reported losses (Allianz, 2025), indicating that this one risk factor accounts for more casualties than all other significant contributing factors combined. This alarming trend has rightfully prompted international regulatory bodies to implement more stringent safety standards, most recently adopting the SOLAS 2020 amendments (IMO, 2020). However, the efficacy of these new regulations is inherently limited by their scope, as they apply exclusively to newly constructed vessels. This creates a significant and ever-widening safety gap between new build designs and the substantial population of existing ships (Cichowicz et al., 2016;

Dankowski and Krüger, 2011; Person, 2019; Vassalos et al., 2016). Vessels designed and built to previous, less stringent stability standards, may reasonably expect to remain in active service for another 30 years or more (Dinu and Ilie, 2015). Consequently, the full, transformative impact of modern regulatory improvements will not be truly realized until these older vessels are gradually phased out of operation.

Compounding this challenge is the often-overlooked reality that ship stability inherently deteriorates with age. This degradation can generally be attributed to numerous modifications and upgrades undertaken throughout a vessel's operational life. Such alterations, particularly those involving the addition of weight high within the vessel structure, invariably lead to an increase in the vertical center of gravity (VCG) and a subsequent reduction in metacentric height (GM). This often means that older vessels not only fail to comply with current, more demanding stability regulations, but are also at genuine risk of falling out of compliance with the more lenient regulatory frameworks in force at their inception.

Figure 1 illustrates a compelling example of the lifecycle weight growth, presenting a time history of a cruise ship's weight as recorded during successive lightweight surveys from its launch date through to its most recent survey in 2020. This data clearly highlights a significant increase in the vessel's lightship weight, rising from an initial 49,700 tonnes to 51,470 tonnes. This substantial growth demonstrates the considerable potential for weight accumulation over a vessel's operational lifespan.

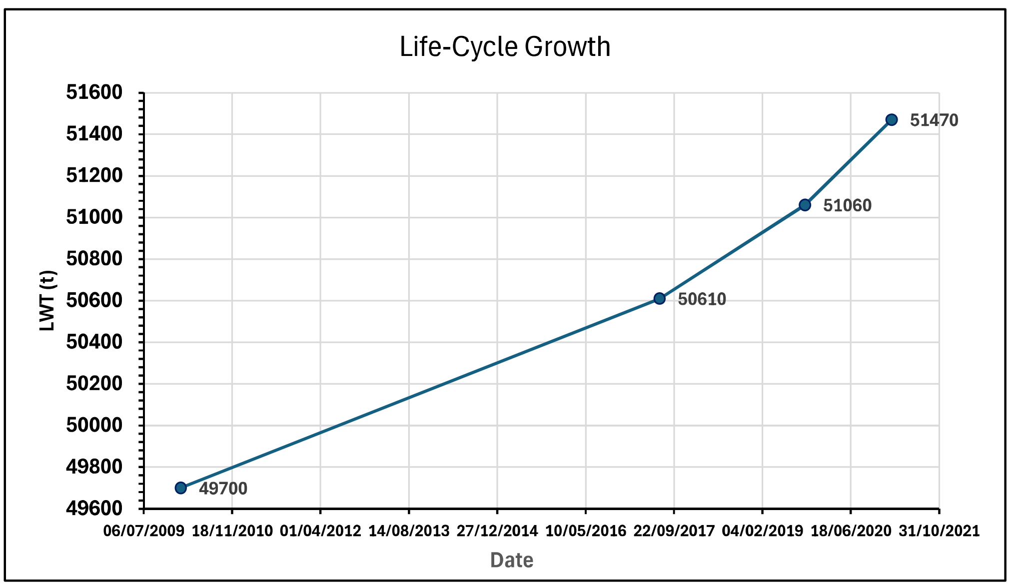

Figure 1: Life-Cycle Growth Example for a Large Cruise Vessel

Figure 2, presented below, provides a critical insight into how this additional weight directly impacts the vessel's vertical center of gravity (VCG). Following the same time history and derived from inclining tests conducted concurrently with the lightweight surveys, the figure reveals a rise in VCG from 19.8 meters to 20.0 meters. While this 20 cm change might on the surface appear small, it is tremendously significant in the context of ship stability, often translating into a considerable reduction in metacentric height (GM) and, consequently, a substantial decrease in the vessel's stability margins.

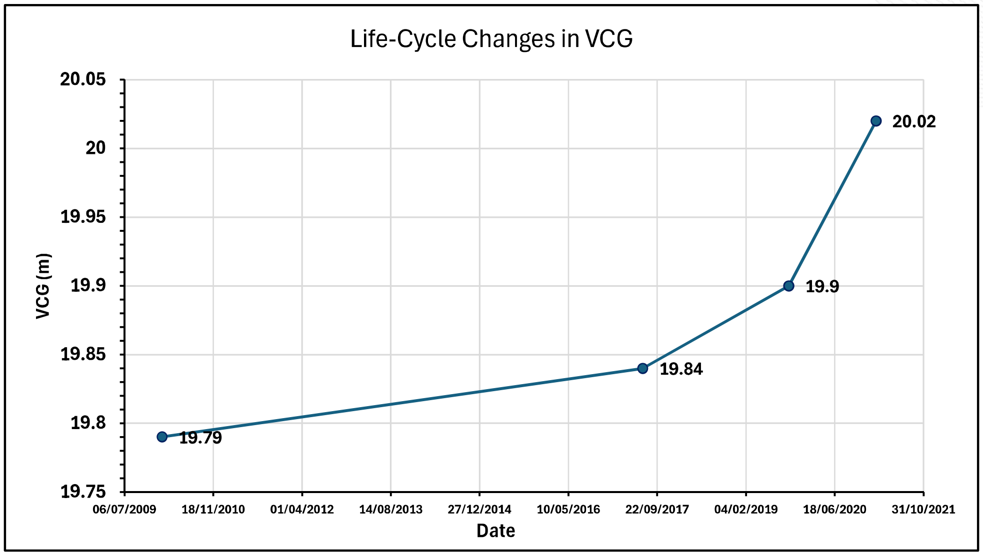

Figure 2: Impact of Life-cycle Growth on VCG

In acknowledgement of the extensive stability deterioration that can occur over a ship's life-cycle, modern passenger vessels are now typically designed with more significant stability margins in an effort to "future-proof" designs against life-cycle growth. Unfortunately, many existing ships were not designed with this foresight, meaning they now require significant and often costly upgrades to remain compliant. These upgrades, while essential for enhancing safety, frequently impact the operability of the vessel and can limit payload capacity, thereby affecting the economic viability of continued operation. The reason for this further derives from the fact that the options available to naval architects and designers in addressing fundamental stability deficits in existing vessels are inherently limited (Bačkalov et al., 2016; Boulougouris et al., 2016; Vassalos and Paterson, 2020). Constrained by the fixed hull form and internal arrangements of a pre-existing vessel design, solutions often resort to brute-force methods such as adding significant quantities of fixed ballast or undertaking extensive and disruptive structural modifications. These interventions are capital-intensive, time-consuming, and invariably impose operational penalties on the vessel as discussed further in the following section.

2. Issues with existing solutions

While the imperative to enhance the damage stability of older passenger vessels is clear, the existing retrospective solutions available are far from ideal. The significant constraints of modifying a pre-existing hull form and internal structure mean that designers are faced with a narrow design space within which to find solutions, and often considerable compromises must be made.

One common approach involves the addition of semi-watertight doors. These doors are designed to be watertight up to a limited head of water, offering a degree of floodwater containment. However, their effectiveness often necessitates the upgrade of numerous doors throughout the vessel, leading to significant installation costs and logistical challenges. Crucially, they demonstrably affect operability, impeding the free flow of passengers and crew and complicating emergency evacuation procedures. Furthermore, their ability to limit floodwater is restricted to relatively low collapse heights, typically around 3 meters water head (Jalonen et al., 2012; Veritas et al., 2009), resulting in only marginal improvements in overall damage stability.

Another option is the installation of sills, either fixed or tiltable, which act as partial watertight barriers to limit the progression of flooding. These are often located at the foot of doorways or around the upper boundaries of stairwells, though they are sometimes found in corridors as well. These barriers are generally limited in height, often only up to 30 cm, rendering them ineffective against significant ingress of water. Their practical utility is further compromised in dynamic sea states where the pumping action of a vessel rolling in waves can easily overcome these low barriers. This highlights a critical disconnect between their theoretical benefit in hydrostatic damage stability calculations (which are inherently blind to dynamic effects) and their actual efficacy in real-world scenarios. Consequently, these measures tend to yield improvements that are questionable in reality.

The use of permanent ballast, whether solid or liquid, is a fairly straightforward method to lower the vessel's vertical center of gravity (VCG). While conceptually simple, adding significant quantities of ballast increases the vessel's overall weight and draft, thereby lowering its freeboard and reducing its payload capacity. Furthermore, there must be the space available to house the ballast. For this reason, it is often viewed as a method of last resort.

The retrofitting of sponsons involves welding additional watertight structures to the stern or sides of the ship to increase its initial stability (GM). While effective in principle (Vainionpää, 2022) (Vassalos et al., 2015), sponsons represent a costly and complex installation, often requiring extensive dry-docking periods. They inevitably increase the ship's weight and can negatively impact resistance, leading to higher fuel consumption and reduced speed. Critically, their presence can paradoxically worsen damage stability in scenarios where the sponsons themselves are breached, creating additional compartments that flood asymmetrically and further compromise the vessel's stability.

Perhaps the most traditional and effective form of flooding protection is the installation of additional watertight subdivision. This can take the form of conventional fixed bulkheads or flood control barriers such as those offered by MacGregor and applied to subdivide Ro-Ro decks. While fixed bulkheads are theoretically highly effective at localising floodwater, their retrospective application is fraught with difficulties (Vassalos and Paterson, 2020, 2021). Gaining accessibility to install new steel plating below the bulkhead deck often necessitates cutting through existing structural elements, a highly disruptive and costly process. Furthermore, the limited free space within an operational ship is a significant impediment; machinery, pipe runs, cables trays and ventilation ducts frequently occupy most available volume, leaving little room to accommodate new bulkheads. These additions also inherently add weight to the vessel and can significantly influence the ergonomics and operational flow depending on their placement, impacting passenger and crew movement. While flood control barriers offer a less invasive alternative for Ro-Ro decks, they do present operational difficulties regarding the loading of the vessel as certain areas of the deck must be kept clear to accommodate the barriers (Santos, 1999).

The common theme among these existing retrospective solutions is their fundamental inadequacy. They are often highly invasive, impose significant operational penalties, are financially burdensome, and ultimately offer only limited enhancements to a vessel's overall damage stability performance. This pervasive lack of truly effective and practical options underscores the urgent and growing need for the maritime industry to actively seek and develop novel and alternative solutions to address the critical safety gap for its aging passenger vessel fleet.

3. Proposed solution

In light of the limitations in conventional retrospective damage stability enhancements, this paper proposes a novel and non-invasive solution, namely the strategic filling of high-risk void spaces within existing vessels with high-expansion polyurethane foam. This approach targets spaces that are typically inaccessible or unused, such as cofferdams, double bottom tanks, and other structural voids, thereby ensuring that the solution does not heavily impact the day-to-day operation of the vessel, nor rob the utility of any actively used spaces. Similar approaches have been proposed over recent years, originating with a suggested system that would actively deliver the foam to the damaged compartment following a breach (Vassalos et al., 2016). This was further developed into a passive system whereby empty void space(s) were permanently filled within foam material (Valanto, 2022; Vassalos and Paterson, 2020, 2021; Vassalos et al., 2022).

The fundamental principle behind the foam's effectiveness lies in its ability to significantly reduce the permeability of the targeted void space. In a damage scenario, instead of floodwater being allowed to fully enter and occupy the compromised volume, the foam mass effectively blocks and displaces the ingress of water. This contrasts sharply with traditional subdivision, which primarily seeks to contain water once it has already entered the vessel. By preventing the initial entry of a substantial volume of floodwater, the solution inherently limits lost buoyancy and minimizes free surface effects that are detrimental to stability. Moreover, the foam itself acts as a buoyant volume, providing additional floatability and enhancing the residual stability of the vessel following damage. This innovative approach offers a promising pathway to retrospectively enhance damage stability without incurring the severe operational and financial penalties associated with conventional methods.

The specific properties of the high-expansion polyurethane foam are critical to its efficacy. This material is produced by mixing a resin and a hardening agent, which initiates an exothermic reaction resulting in rapid foam expansion. The foam utilized in this proposed solution boasts an impressive expansion ratio of 1:40, meaning it expands to 40 times its original liquid volume, effectively filling large void spaces from minimal initial quantities. The resultant solid foam possesses a remarkably low density of approximately 25 kg/m³, minimizing any significant weight addition to the vessel. Crucially, the foam is characterized by its closed-cell structure, rendering it non-porous and thus near impermeable to water, as outlined later within the paper. Furthermore, the material is inert and not subject to deterioration over time, ensuring its long-term effectiveness as a passive flood protection measure.

4. Methodology

The research methodology applied within this paper is primarily focused on verifying the efficiency and suitability of high-expansion polyurethane foam as a retrospective damage stability enhancement. This verification process involved a comprehensive series of experimental investigations into the foam's material properties, followed by a detailed numerical case study on an existing RoPax passenger vessel.

Firstly, to address the crucial question of the foam's resistance to water ingress, a series of water absorption tests were conducted. Specimens of the foam material were immersed in water, and their weight was monitored over a period of 30 days. Any detected weight increase was directly correlated to absorbed water mass, thereby allowing for the determination of the foam's permeability. Recognizing that floodwater can exert significant hydrostatic pressure on the foam mass within a damaged compartment, these tests were performed at varying external pressure, firstly at atmospheric pressure, and subsequently within a pressure vessel at 0.5 bar, 1 bar, and 1.5 bar, respectively. This comprehensive pressure regime accounts for potential water columns up to 15 meters, providing a realistic assessment of the foam's integrity under flooding conditions.

Figure 3: Foam test specimen shown left, pressure vessel shown right.

Next, the adhesion and cohesion properties of the foam were ascertained to determine its ability to remain securely in place when subjected to the dynamic forces associated with a flooding scenario. A stud pull test, as detailed in Figure 4, was performed on foam specimens formed directly onto both bare and painted steel plates, mimicking typical shipboard surfaces. This test provided valuable data on the bond strength between the foam and structural elements, which is vital for ensuring it will not be displaced from its installation position.

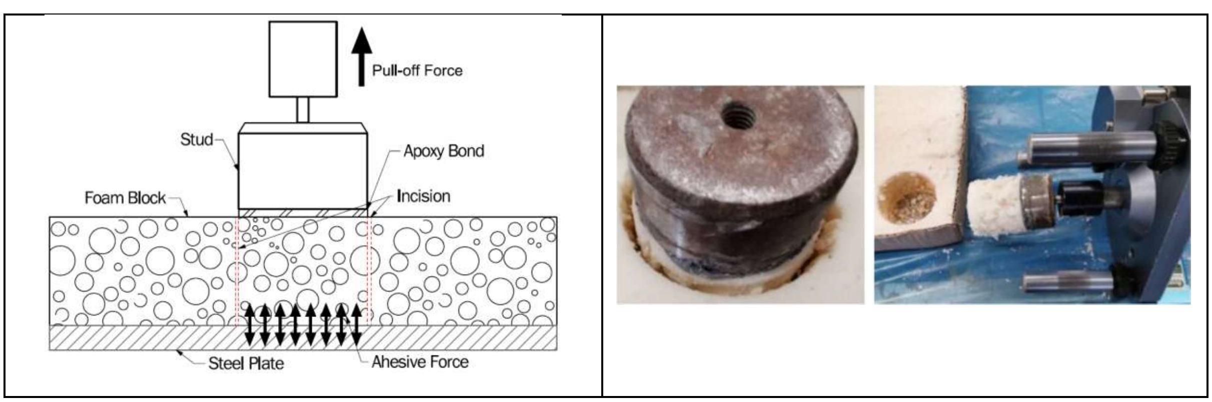

Figure 4: Outline of stud pull test

The potential for the foam to be compressed by the hydrostatic head of floodwater was investigated through compression testing, as illustrated in Figure 5. Foam specimens were subjected to axial loading in a universal testing machine to generate the material's stress-strain curve. This characterization allowed for a direct comparison between the foam's compressive strength and the expected compression forces it would experience following a flooding event, ensuring that the buoyant volume provided by the foam would not be significantly diminished under pressure.

Figure 5: Pictorial image of foam compression test

Given the organic nature of polyurethane, its combustibility is a critical safety consideration. Adhering to the principle of not resolving one problem by inadvertently introducing another, the foam technology was subjected to a rigorous series of fire tests, some out which are illustrated in Figure 6. Many of these tests were conducted in accordance with the IMO FTP Code (IMO, 2012) at an approved, independent laboratory, DMT in Germany. These comprehensive assessments included thermal decomposition tests, smoke and toxicity tests, thermal conductivity tests, and overpressure testing, all aimed at evaluating the foam's fire performance and ensuring its compliance with maritime safety regulations. Though not further elaborated upon within this paper, further details of the fire testing procedures that have been conducted on the foam technology may found in (Vassalos et al., 2022).

Figure 6: Visual results from foam thermal decomposition test (left), over pressure testing apparatus (right).

Finally, to evaluate the practical efficacy of the proposed solution, an existing RoPax vessel design was utilized as a detailed case study. This vessel was subjected to probabilistic damage stability calculations in full accordance with the current SOLAS 2020 regulations (IMO, 2020). An initial damage stability calculation was first conducted on the as-designed vessel to establish a baseline. Subsequently, a risk-profile was generated by mapping the flooding risk across the vessel's various compartments. This detailed profile served as the basis for strategically determining the optimal placement of the foam solution, targeting areas identified as having heightened vulnerability to flooding. The foam solution was incorporated into the stability model by representing it as a reduction in space permeability within the relevant compartments. The optimal volume of foam to be employed was then determined through a sensitivity analysis, investigating the incremental increase in vessel survivability relative to the volume of foam installed. The derived optimum foam volume was then used to conduct the final damage stability analysis, from which the potential benefits and overall enhancement in vessel safety attributable to the proposed solution could be quantitatively gauged.

5. Foam testing results

5.1 Determining foam permeability

The water absorption tests conducted to ascertain the permeability of the foam material yielded unexpected yet significant findings. Surprisingly, the largest degree of water absorption was observed when the foam specimens were tested under atmospheric pressure conditions, with 2.7% of the volume being occupied by water following 28 days exposure, as shown Figure 7Figure 7.

Conversely, when subjected to the overpressure conditions (0.5 bar, 1 bar, and 1.5 bar) also analyzed, an interesting phenomenon was observed. The outer layer of the foam material underwent a structural collapse of its surface bubbles. This collapse, rather than leading to increased absorption, acted to form a protective "shield" or barrier, effectively preventing any further water absorption. This self-sealing characteristic under pressure is a highly advantageous property for a flood mitigation material.

A considerable effort was dedicated to optimizing the foam formula to achieve an ideal balance between low density and its propensity to absorb water. It was consistently found that lower-density foams, while offering the benefit of reduced weight, exhibited a higher permeability, which unfortunately offset the advantages of a lighter material. Furthermore, these lower-density formulations also displayed negatively affected compressibility properties, meaning they were more prone to unwanted volume reduction under hydrostatic pressure. This extensive material science investigation was crucial in developing a foam variant that maximizes both buoyancy and resistance to water ingress while minimizing weight implications.

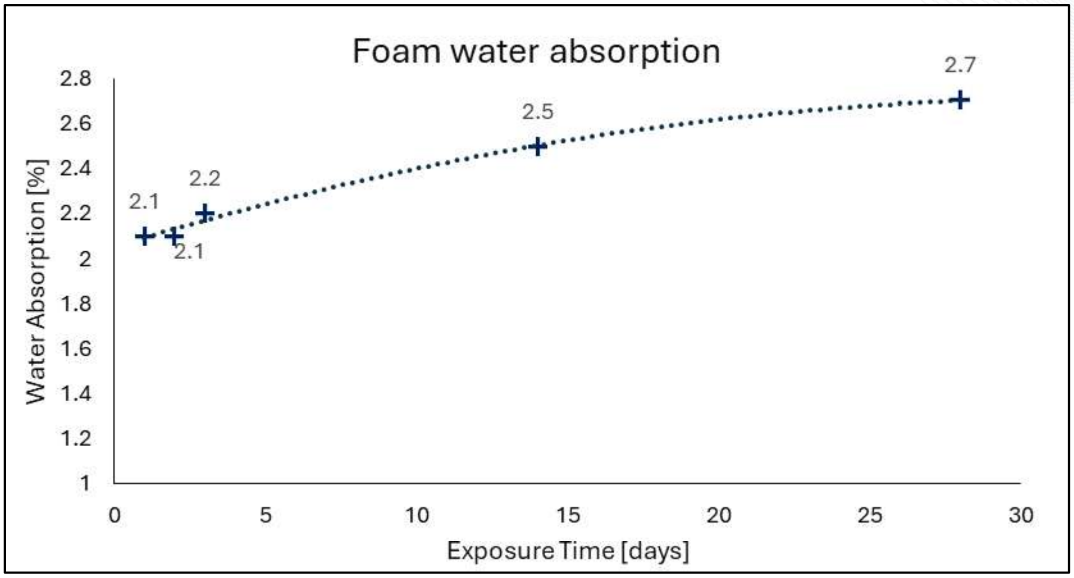

Figure 7: Foam Water Absorption Test Result at Atmospheric Pressure

5.2 Foam adhesion & cohesion properties

The crucial aspect of the foam's ability to remain securely in place during a dynamic flooding event was assessed through a series of adhesion and cohesion tests. The results of these experiments were highly encouraging, demonstrating robust material properties. Cohesion, which represents the internal strength of the foam itself, was consistently found to be higher than its adhesive properties. The measured values were:

- Adhesion: 0.13 MPa
- Cohesion: 0.19 MPa

To put these figures into a practical context, these results mean that a force of approximately 13 tonnes would be required to separate a segment of foam with a 1 m² contact area from a steel surface. Such magnitudes of force are far beyond any expected to act upon the foam in a real-world flooding scenario. Therefore, these tests provide strong assurance that the foam will remain firmly in place within the void spaces, offering continuous buoyant support and floodwater exclusion even under the most severe conditions.

5.3 Foam compressibility properties

The compression tests conducted on the foam material provided critical insights into its structural integrity under simulated floodwater pressures. The results demonstrated that the elastic deformation region of the foam extends up to 0.22 MPa. Beyond this point, plastic deformation is realized, occurring at approximately 5% volumetric compression, Figure 8.

Significantly, the expected compression resulting from exposure to the hydrostatic pressure in a flooding scenario is conservatively estimated at 0.1 MPa. This anticipated pressure would lead to a compression of approximately 3%. This level of compression is well within the foam's elastic range and, crucially, does not jeopardize the buoyancy offered by the foam to any significant degree, affirming its ability to maintain its volume and provide effective support even when subjected to the substantial forces of floodwater.

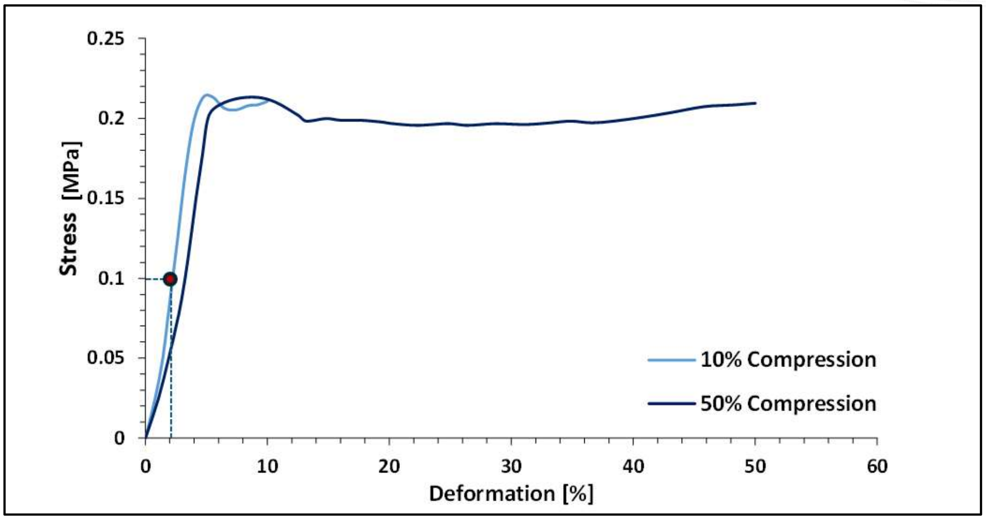

Figure 8: Foam Compressibility Results at 10% and 50% compression

6. Impact assessment – RoPax vessel case study

6.1 Overview of case study vessel properties

To evaluate the practical applicability and efficacy of the proposed foam-based solution, a detailed case study was conducted on an existing large RoPax vessel. This particular vessel, approximately 15 years in age, was designed and built in accordance with the SOLAS 2009 regulations, making it a representative example of the older passenger fleet that faces increasing damage stability challenges. The vessel has a substantial passenger capacity of approximately 2,400 persons and features three Ro-Ro decks, one of which is a mezzanine deck. Its internal volume is subdivided into 17 watertight compartments.

The vessel hull form is illustrated in Figure 9 and the key properties of the subject vessel are detailed in Table 1.

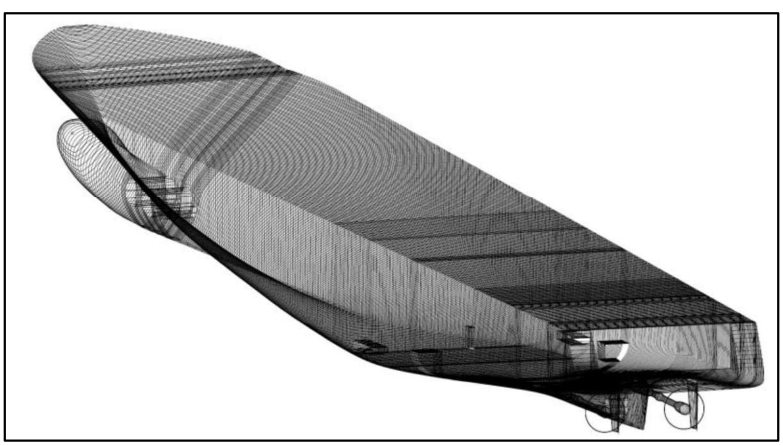

Figure 9: Stability Model Calculation Sections

Table 1: Vessel Particulars

Principle Particulars	
Length OA	≃210 m
Length BP	≃195 m
Length WL	≃200 m
Breadth, molded	≃25 m
Draught, design	6.55 m
Draught, scantling	6.70 m
Draught, subdivision	6.70 m

6.2 Assessment of as-built damage stability performance

6.2.1 Statutory damage stability analysis results

An initial damage stability assessment was conducted on the case study RoPax vessel to establish a baseline performance against the regulatory framework under which it was originally designed and built, namely SOLAS 2009 (IMO, 2009). The probabilistic damage stability calculations were performed in accordance with the methodologies prescribed by these regulations.

The results of this baseline assessment are presented in Table 2 which details the partial Attained Subdivision Indices for each of the three calculation draughts, along with the final Attained Subdivision Index (A) calculated as the weighted sum of these partial indices.

Table 2: As-Built Damage Stability Results in Accordance with SOLAS 2009

Draught (m)		Intact GM (m)	Trim (m)	Partial Indices		Attained Index	
Dl	5.807	1.78	-0.35	Al	0.793	0.2	0.1586
Dp	6.343	1.905	0.00	Ap	0.796	0.4	0.3184
Ds	6.700	2.26	0.00	As	0.792	0.4	0.3171
Required Subdivision Index R							0.7911
Attained Subdivision Index A							**0.7943**

As demonstrated by the results in Table 2, the vessel marginally surpasses the Required Subdivision Index (R) under SOLAS 2009, achieving an Attained Index (A) of 0.7943 against a Required Index of 0.7911. As expected, this indicates that the vessel meets the minimum damage stability criteria of its applicable regulatory period.

However, it is critically important to note the implications of evolving safety standards. This vessel, designed to SOLAS 2009, would not meet the more stringent requirements of SOLAS 2020, which mandates a significantly higher Required Subdivision Index of 0.845. This stark disparity clearly highlights the "safety gap" between existing older vessels and newly constructed tonnage, underscoring the pressing need for retrospective solutions to enhance the damage stability performance of the older fleet.

6.2.2 Vessel risk profile

Building upon the initial damage stability assessment, a flooding risk profile for the RoPax vessel was generated. This profile provides a graphical depiction of flooding risk distributed along the entire length of the vessel. In Figure 10, the X-axis denotes the damage longitudinal center, while the Y-axis represents the calculated flooding risk, defined as the probability of damage multiplied by the complement of ship survivability (i.e. capsize probability).

The analysis of this risk profile clearly indicates that the vessel exhibits areas of heightened risk in its aft and fore shoulders. This observation aligns with typical findings for passenger vessels, where the geometry and internal arrangements in these regions often contribute to a greater susceptibility to critical flooding. Consequently, compartments located within these high-risk zones should be specifically targeted for the application of the foam solution, contingent upon the operational nature and accessibility of the spaces within these areas. This risk informed approach ensures that the retrospective enhancement is applied where it will yield the most significant improvement in overall vessel safety.

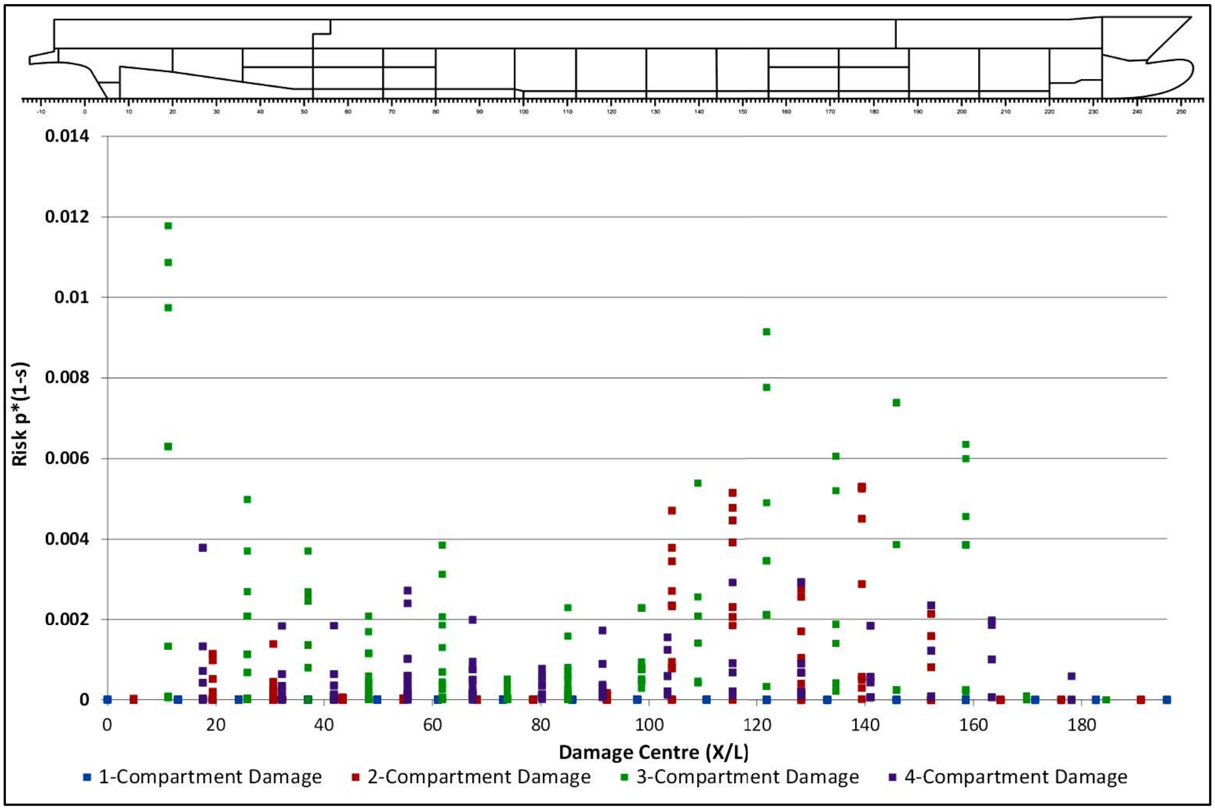

Figure 10:As-Built Risk Profile

6.2.3 Selection of spaces for foam application

Using the insights gained from the vessel's risk profile, the identification of suitable void spaces for foam application proceeded. Fortunately, the areas previously determined to have heightened flooding risk, specifically the fore and aft shoulders of the vessel, also contain a number of dry tanks and other void spaces. These spaces are ideal candidates for the proposed solution as their utilization for foam filling will not interfere with the vessel's operational areas or passenger amenities.

In total, three void spaces have been strategically targeted for foam application: two spaces situated around the vessel's fore shoulder and one space located within the vessel's aft shoulder.

Figure 11 highlights the location of these selected compartments within the vessel's general arrangement, shaded in blue. This targeted approach ensures that the foam is deployed in locations that offer the maximum benefit in enhancing the vessel's damage stability performance.

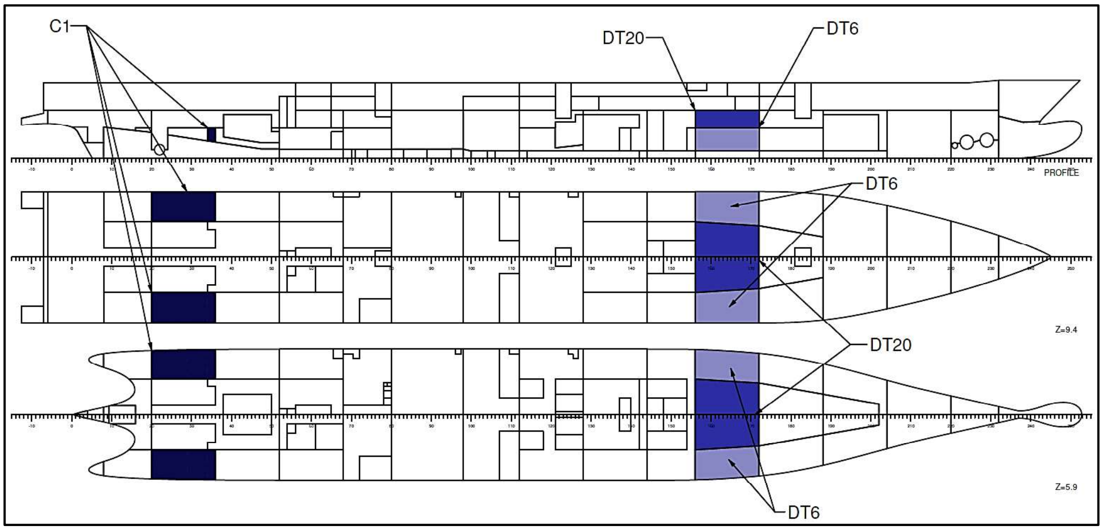

Figure 11: Spaces Targeted for Foam Application

6.2.4 Implementation of foam application

A critical step in the implementation of the proposed solution involved identifying the optimal foam volumes to be introduced into each of the three targeted void spaces. This was achieved through a comprehensive sensitivity analysis for each compartment, where the decrease in vessel flooding risk was evaluated against varying percentages of foam fill.

As an illustrative example of this process, Figure 12 demonstrates the results of the sensitivity analysis for one of the selected spaces. This figure clearly indicates a trend of diminishing returns in terms of increased survivability beyond approximately 70% of the space being filled with foam. This threshold suggests that beyond a certain point, the marginal benefit of adding more foam becomes less significant relative to the increased cost and weight.

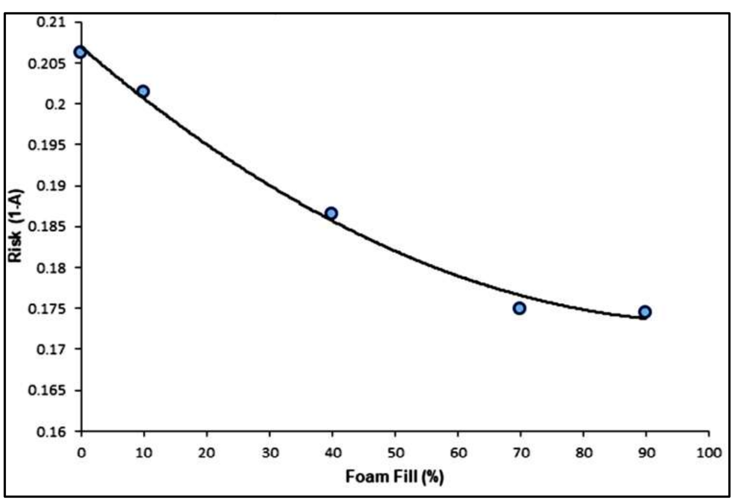

Figure 12: Sensitivity Analysis of Foam Volume and Flooding Risk Reduction

Following this analysis for each of the three targeted compartments, the optimal foam volumes were determined, ensuring the most efficient and impactful application of the solution. These optimal volumes for each space are summarized in Table 3 below.

Table 3: Summary of Optimal Foam Volumes

Compartment ID	Foam Volume (m^3)
C1	560
Dry Tank No 6	900
Dry Tank No 20	400

7. Evaluation of foam solution impact on survivability

With the optimal foam solution identified and modelled, the vessel's damage stability performance was reassessed to quantify the impact of the proposed enhancement. Probabilistic damage stability calculations were conducted once again, incorporating the reduced permeability in the foam-filled void spaces.

The results of this re-assessment are presented in Table 4, showing the partial Attained Subdivision Indices for each of the three calculation draughts, along with the updated final Attained Subdivision Index.

Table 4: Damage Stability Results with Foam Solution in Accordance with SOLAS 2009

Draught (m)		Intact GM (m)	Trim (m)	Partial Indices		Attained Index	
Dl	5.807	1.78	-0.35	Al	0.793	0.2	0.176
Dp	6.343	1.905	0.00	Ap	0.796	0.4	0.348
Ds	6.700	2.26	0.00	As	0.792	0.4	0.341
Required Subdivision Index R							0.791
Attained Subdivision Index A							0.865

The results demonstrate a significant improvement in the vessel's damage stability. The Attained Subdivision Index has risen from its previous value of 0.7943 to 0.865. While this numerical difference of approximately 0.07 might appear small, in the highly sensitive domain of damage stability, this represents a tremendous enhancement in survivability.

Crucially, and perhaps most significantly, the vessel would now comply with the rigorous requirements of SOLAS 2020, as its new Attained Index of 0.865 comfortably exceeds the required value of 0.845. This outcome underscores the potential of the foam solution to bridge the safety gap for older passenger vessels, offering a viable and effective means of retrospective compliance with modern damage stability standards.

To further illustrate the profound impact of the foam solution, a side-by-side comparison of the vessel's risk profiles, both pre- and post-application of the foam, is presented in Figure 13. Here, it can be observed that the high-risk areas previously identified in the vessel's aft and fore shoulders have undergone a significant reduction in flooding risk. In several instances, the risk has been effectively eradicated in these targeted zones. This underscores the ability of the foam solution to directly mitigate the most critical vulnerabilities within the vessel, transforming areas of high susceptibility into zones of considerably enhanced safety.

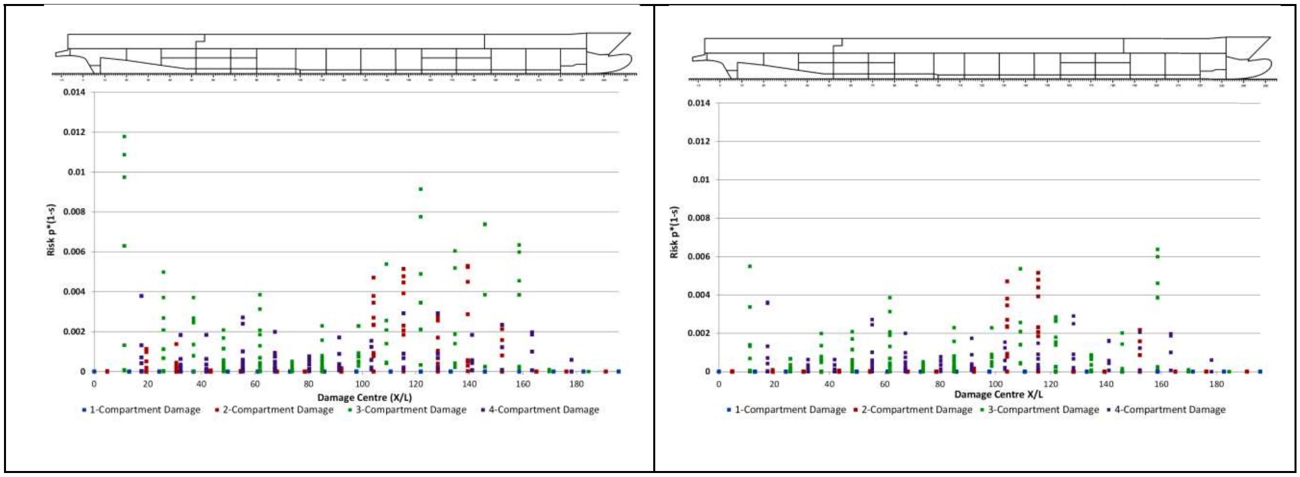

Figure 13: Comparison of Risk profiles, as built design shown left, modified design shown right

8. Conclusions

In conclusion, the application of high-expansion polyurethane foam in targeted void spaces offers a compelling and effective retrospective solution for enhancing the damage stability of existing passenger vessels. This innovative approach addresses the shortcomings of traditional methods by providing substantial safety improvements without compromising operational utility, payload capacity, or incurring prohibitive costs. The verified material properties and the successful case study demonstrate the significant potential of this technology to bridge the growing safety gap in the global legacy fleet, contributing to a safer maritime future.

References

Allianz. (2025). Safety and Shipping Review 2025.

Bačkalov, I., Bulian, G., Rosén, A., Shigunov, V., & Themelis, N. (2016). Improvement of ship stability and safety in intact condition through operational measures: challenges and opportunities. *Ocean Engineering*, *120*, 353–361.

Boulougouris, E., Cichowicz, J., Jasionowski, A., & Konovessis, D. (2016). Improvement of ship stability and safety in damaged condition through operational measures: Challenges and opportunities. *Ocean Engineering*, *122*, 311–316.

Cichowicz, J., Tsakalakis, N., Vassalos, D., & Jasionowski, A. (2016). Damage survivability of passenger ships—Re-engineering the safety factor. *Safety*, *2*(1), 4.

Dankowski, H., & Krüger, S. (2011). On the safety level of the SOLAS 2009 damage stability rules for RoPax vessels. *Marine Systems & Ocean Technology*, *6*(2), 87–96.

Dinu, O., & Ilie, A. (2015). *Maritime vessel obsolescence, life cycle cost and design service life* (Vol. 95). https://doi.org/10.1088/1757-899X/95/1/012067

IMO. (2009). *The International Convention for the Safety of Life at Sea*. International Maritime Organisation. https://doi.org/doi:10.20935/AcadBiol6023

IMO. (2012). *2010 FTP Code*. International Maritime Organization. https://doi.org/https://doi.org/10.62454/KC844E

IMO. (2020). *The International Convention for the Safety of Life at Sea*. International Maritime Organization. https://doi.org/https://doi.org/10.62454/KG110E

Jalonen, R., Ruponen, P., Jasionowski, A., Maurier, P., Kajosaari, M., & Papanikolaou, A. (2012). FLOODSTAND–overview of achievements. *Spyrou et al*.

Person, J. L. (2019). Evolution of the SOLAS Subdivision and Damage Stability Regulations. SNAME Maritime Convention,

Santos, T. A. (1999). *Time Domain Simulation of Accidental Flooding of RoRo Ships*. University of Glasgow (United Kingdom).

Vainionpää, O. (2022). Optimization of retrofit sponson-ducktail for improved passenger ship stability.

Valanto, P. (2022). Active Flooding Mitigation for Stability Enhancement in a Damaged RoPax Ship. *Journal of Marine Science and Engineering*, *10*, 797. https://doi.org/10.3390/jmse10060797

Vassalos, D., Boulougouris, E., & Paterson, D. (2016). *An alternative system for damage stability enhancement*.

Vassalos, D., & Paterson, D. (2020). Reconfiguring Passenger Ship Internal Environment for Damage Stability Enhancement. *Journal of Marine Science and Engineering*, *8*(9), 693.

Vassalos, D., & Paterson, D. (2021). Towards unsinkable ships. *Ocean Engineering*, *232*, 109096. https://doi.org/https://doi.org/10.1016/j.oceaneng.2021.109096

Vassalos, D., Paterson, D., Mauro, F., Atzampos, G., Assinder, P., & Janicek, A. (2022). High-Expansion Foam: A Risk Control Option to Increase Passenger Ship Safety during Flooding. *Applied Sciences*, *12*, 4949. https://doi.org/10.3390/app12104949

Vassalos, D., Stoumpos, S., & Boulougouris, E. (2015). Stability upgrade of a typical Philippine ferry. *STAB2015*, 521.

Veritas, B., Neuilly-Sur-Seine Cdx, F., & Oy, S. F. (2009). FLOODSTAND–Integrated Flooding Control and Standard for Stability and Crises Management.