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Editorial

Damage Stability of Ships

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1. Introduction

Ensuring adequate damage stability of ships is essential in ship design and directly contributes to their safe operation. In an accident, where a ship's hull may be breached and the ship is flooded, the ship must have sufficient internal watertight subdivision to limit flooding progression, as well as sufficient residual buoyancy and stability to withstand environmental loads, and thus, avoid capsizing and sinking. Over the centuries, the development of methods and regulations for improving the damage stability of ships has been slow [1]. The disastrous sinking of the *Titanic* in 1912, in which more than 1500 people lost their lives in the icy waters of North Atlantic, reinforced the urgency of addressing the risk of flooding on ships. However, several decades passed before significant scientific and regulatory developments were made [2]. During the last three decades, especially after the tragic capsizing and sinking of the passenger ferry *Estonia* in 1994 in the Baltic Sea (with 852 victims), the assessment of damage stability of ships has been revolutionized, moving from the calculation of a limited number of deterministic damage scenarios to a probabilistic framework based on damage statistics and involving numerous feasible damage scenarios [2]. While there is strong evidence based on recent accident statistics, that grounding is the most frequent accident type, particularly for passenger ships, the latest IMO (International Maritime Organization) regulations for the Safety of Life at Sea (SOLAS) [3] still only consider collision damage when evaluating the probabilities of the studied damage scenarios. The urgent need to update the present SOLAS Part B, referring to ship damage stability, was recently reinforced by the findings of the EU-funded project FLARE [4]. Increased computing capacity, in terms of both hardware and software tools, has enabled more advanced assessment of damage stability. Time-domain flooding simulation tools have already been available for some time [2]. In addition, Monte Carlo sampling of the damage cases and the non-zonal approach, considering, besides collision, also bottom and side grounding damages [5], have been introduced, but until now, only as an alternative to a limited extent in SOLAS. Furthermore, in recent years the trend has been towards wider use of direct numerical simulations for the assessment of the survivability of the damaged ship, e.g., [6]. These tools are especially suitable for use in the design of large passenger ships, where high survivability is crucial.

Various numerical codes for time-domain simulation of the flooding process and of the motions of damaged ships have been introduced during the past two decades, and now appear advanced enough to have various practical applications. However, recent benchmark studies on the flooding and motions of damaged RoPax and cruise ships [7,8] have indicated that more research is still needed to more accurately capture the flooding process of ships, both in calm water and in waves.

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2. Overview of Contributions

This Special Issue contains six contributions covering the latest research from different fields on damage stability. In the following overview, the most notable findings and conclusions of each contribution are briefly presented.

2.1. Statistical Analysis of Accidents

Eliopoulou et al. [9] present a detailed analysis of passenger ship accidents in the last two decades (2000–2021). Interestingly, when two notably disastrous accidents where the ships clearly did not comply with the existing safety regulations were excluded from the statistical sample, the estimated fatality rate was reduced by about 50%, although the effect on accident frequency was minimal. Thus, statistics of fatalities should be always carefully analysed, and their consequences properly assessed. Furthermore, the results confirmed that grounding and contact accidents dominated the statistics for all types of passenger ships. Consequently, it was recommended that the present SOLAS regulations should be revised to include side collision and grounding events as the primary contributors to flooding risk.

2.2. Regulatory Damage Stability Calculations

Krüger [10] presents a practical approach to introducing the non-zonal method, in connection with Monte Carlo sampling, to the regulatory SOLAS damage stability calculations. Since the current regulations rely on the zonal approach, additional methods are necessary to evaluate the associated probabilities for each individual damage case when the Monte Carlo-based non-zonal approach is used instead. Moreover, Krüger discusses the possibility of using the same approach of directly calculating the attained subdivision index under the real operational loading conditions of a RoPax ship as an alternative to applying a limit curve for the minimum allowed GM (metacentric height), thus improving the flexibility of operation, especially at lower draft values.

2.3. Advanced Simulation Methods

The current standard practice in flooding simulation is to apply the quasi-static Bernoulli equation for the calculation of flow rates through the breach and the internal openings. Two contributions dealt with the more advanced approaches, while also considering the effects of floodwater inertia.

Valanto [11] studied the flow through a damage opening in a ship in calm water and in waves. The traditional quasi-static Bernoulli equation (BE) and the so-called dynamic orifice equation (DOE) were used. The latter was modified and extended to account for the horizontal motion at the damage opening on the side of the ship. This equation takes into account the inertia of the floodwater in the damage opening. The DOE approach was also combined with shallow water equations method for floodwater in the compartments. Experimental data from dedicated model tests were used as a reference, and different simulation approaches were compared. In general, simulations using DOE provided better results than the commonly applied simple BE method, although there were still notable differences between simulation results and measurements from the model tests. Valanto emphasizes that further studies on floodwater inertia and effects of ship in motions on flooding are necessary for more reliable simulations of damaged ship survivability in waves.

Van't Veer et al. [12] presented development of a so-called unified internal flow model (UIF), which they had incorporated into a generic in-house time-domain ship motion simulation environment. Flow and mass conservation were solved based on a time-dependent network of "virtual pipes", which were connecting "nodes", either on a free surface in a flooded room or at the location of an opening. The virtual pipe network was then used to determine the cell-averaged momentum to account for the fluid inertia effects. The developed method was demonstrated using four different test and validation cases, including a cruise ship flooding benchmark case [7]. The dynamics of an oscillating water column device were especially well captured, indicating that the approach has good potential for assessing the dynamic stability of ships in waves.

2.4. Counter-Actions for Risk Mitigation

Two contributions to this Special Issue dealt with the operational aspects of damage stability, namely, risk mitigation with counter actions in the event of a flooding accident.

Valanto [13] investigated counter-actions to mitigate the consequences of flooding in a modern RoPax design, using both numerical simulation and model tests, in calm water and in irregular beam seas. The studied counter actions were counter-flooding, the recovery of lost buoyancy by displacing floodwater in a damaged compartment, and the deployment of a watertight barrier to prevent floodwater spreading over the large open trailer deck. The mitigation methods improved ship survivability in the two tested damage cases. For low wave heights, mitigation is often not needed, and for higher wave heights, the effects were not always sufficient to ensure survival. However, for moderate wave heights, all the tested mitigation efforts considerably increased ship survivability.

Lee et al. [14] performed a detailed study on the application of a Buoyancy Support System (BSS) to mitigate the risk of sinking or capsizing as a consequence of flooding. The system is based on carbon dioxide-filled chambers that can rapidly reduce the effective permeability of the flooded compartments. Consequently, less water will flood in, and the survivability of the damaged ship will be improved. A practical example of the application of this system in a small passenger car ferry was presented, demonstrating that it could prevent the ship from capsizing and sinking, provided that the system worked, and the chambers could be rapidly inflated. The authors also mentioned that a prototype of the studied BSS concept was already installed onboard, and a detailed description of the system was presented.

3. Summary

Major ship accidents with numerous fatalities have continued to occur in recent decades, despite the fact that stricter requirements for damage stability have been introduced into international regulations. However, these accidents are mostly, if not exclusively, related to ships that do not comply with current design and operational safety regulations. It can be expected that such accidents will continue to happen in the future.

Research on the survivability of damaged ships is essential, and more advanced analysis methods will help in the design of safer ships, as well as in developing safer operational practices to minimize the consequences of accidents. The contributions to this Special Issue represent current research topics relevant to the field of damage stability of ships. Based on this work, and other recent relevant literature, the following research trends can be identified:

- Greater emphasis in the investigation of (bottom and side) grounding damage;
- Monte Carlo simulation for the generation of damage cases;
- The development of more advanced flooding simulation tools that account for floodwater inertia;
- Studies on active counter-actions to mitigate the effects of flooding onboard damaged ships.

It is also noteworthy that the cruise ship industry, which now operates numerous mega cruise ships, has been deeply involved in recent research, thus paving way for the adoption of more advanced tools to proactively improve passenger ship safety, with designs and operational practices that go beyond the minimum requirements of international regulations.

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References

1. Francescutto, A.; Papanikolaou, A.D. Buoyancy, stability, and subdivision: From Archimedes to SOLAS 2009 and the way ahead. *Proc. Inst. Mech. Eng. M J. Eng. Marit. Environ.* **2011**, *225*, 17–32. [CrossRef]
2. Papanikolaou, A.D. Review of damage stability of ships—Recent developments and trends. In Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS), Houston, TA, USA, 30 September–5 October 2007.
3. IMO. *Safety of Life at Sea (SOLAS), Part B Subdivision and Stability, Consolidated Edition 2020*; International Maritime Organization: London, UK, 2020.
4. Vassalos, D.; Luhmann, H.; Cardinale, M.; Hamann, R.; Papanikolaou, A.; Paterson, D. A Multi-Level Approach to Flooding Risk Estimation of Passenger Ships. In Proceedings of the SNAME Maritime Convention, Houston, TX, USA, 26–29 September 2022. [CrossRef]
5. Bulian, G.; Cardinale, M.; Dafermos, G.; Eliopoulou, E.; Francescutto, A.; Hamann, R.; Lindroth, D.; Luhmann, H.; Ruponen, P.; Zaraphonitis, G. A Framework for Probabilistic Damage Stability Assessment of Passenger Ships Considering Collision, Grounding and Contact Accidents. In *Contemporary Ideas on Ship Stability. Fluid Mechanics and Its Applications*; Spyrou, K.J., Belenky, V.L., Katayama, T., Bačkalov, I., Francescutto, A., Eds.; Springer: Cham, Switzerland, 2023; Volume 134. [CrossRef]
6. Mauro, F.; Vassalos, D.; Paterson, D.; Boulougouris, E. Evolution of ship damage stability assessment—Transitioning designers to direct numerical simulations. *Ocean Eng.* **2023**, *268*, 113387. [CrossRef]
7. Ruponen, P.; Valanto, P.; Acanfora, M.; Dankowski, H.; Lee, G.J.; Mauro, F.; Murphy, A.; Rosano, G.; van't Veer, R. Results of an international benchmark study on numerical simulation of flooding and motions of a damaged ropax ship. *Appl. Ocean Res.* **2022**, *123*, 103153. [CrossRef]
8. Ruponen, P.; van Basten Batenburg, R.; van't Veer, R.; Braidotti, L.; Bu, S.; Dankowski, H.; Lee, G.J.; Mauro, F.; Ruth, E.; Tompuri, M. International benchmark study on numerical simulation of flooding and motions of a damaged cruise ship. *Appl. Ocean Res.* **2022**, *129*, 103403. [CrossRef]
9. Eliopoulou, E.; Alissafaki, A.; Papanikolaou, A. Statistical Analysis of Accidents and Review of Safety Level of Passenger Ships. *J. Mar. Sci. Eng.* **2023**, *11*, 410. [CrossRef]
10. Krüger, S. Statutory and Operational Damage Stability by a Monte Carlo Based Approach. *J. Mar. Sci. Eng.* **2023**, *11*, 16. [CrossRef]
11. Valanto, P. On Boundary Conditions for Damage Openings in RoPax-Ship Survivability Computations. *J. Mar. Sci. Eng.* **2023**, *11*, 643. [CrossRef]
12. Van't Veer, R.; Berg, J.v.d.; Boonstra, S. A Unified Internal Flow Model with Fluid Momentum for General Application in Shipflooding and Beyond. *J. Mar. Sci. Eng.* **2023**, *11*, 1175. [CrossRef]
13. Valanto, P. Active Flooding Mitigation for Stability Enhancement in a Damaged RoPax Ship. *J. Mar. Sci. Eng.* **2022**, *10*, 797. [CrossRef]
14. Lee, G.J.; Hong, J.-P.; Lee, K.K.; Kang, H.J. Application of Buoyancy Support System to Secure Residual Buoyancy of Damaged Ships. *J. Mar. Sci. Eng.* **2023**, *11*, 656. [CrossRef]