A Holistic Approach to Damage Survivability Assessment of Large Passenger Ships

By

Georgios Atzampos

PhD Thesis

Maritime Safety Research Centre

Department of Naval architecture, Ocean and Marine Engineering

University of Strathclyde

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Abstract

A retrospective look at the history of maritime accidents, reveals that the knowledge of how to build safe ships is based predominantly on experience which, in turn, stems from "trial and error", but "errors" in this case imply disasters at sea. Lessons from sea catastrophes materialised in rough recommendations on suitable proportions and dimensions of the vessel hull and its construction, which in turn, would cater for stability. One paramount example in this direction was the establishment of SOLAS after the capsize event of Titanic. Thereafter, the whole history of SOLAS conventions has been linked to disasters at sea.

The face of maritime safety is changing rapidly and, as a result, SOLAS struggles to keep pace with technological and scientific developments. Contemporary developments, such as Safe Return to Port, Risk-Based Design and Alternative Designs and Arrangements are aiming at enhancing the safety level and stability standards of passenger ships. However, in this quest, many principal aspects have been overlooked: A survivability factor that does not differentiate between ships types and has been developed merely on the basis of RoRo vessels; absence of alternative and more efficient ways of survivability estimation of passenger ships in waves; lack of consideration of actual operational profiles in damage stability assessment; inadequate consideration of the actual operational wave environment at the operating location on survivability; accident databases addressing cargo and passenger ship accidents in the same vain and finally, permeability values that do not reflect the actual permeable volume of different rooms, while their impact on damage survivability is unknown.

The aforementioned present a few of the pitfalls that surface and exhibit allegedly the Achilles heel of passenger ships, namely damage stability. To this end, this thesis aims to overcome these shortcomings as well as identify any emerging potential drawbacks in the way SOLAS 2009 and subsequently SOLAS 2020 have been constructed. Even though the application of the common survivability assessment practices is wide in the passenger ship industry, it lacks some rationalisation, while, the integration of actual data is absent. Therefore, the thesis proposes and aims to develop viable alternatives that will constitute more accurate means in assessing damage survivability of large passenger ships

(L≥120m) and more particularly modern cruise liners in a holistic manner considering actual and ship-specific data.

In this line, a framework for a holistic damage survivability approach is provided, which entails development, use and comparison between statistical (traditional) and direct (modern) approaches to damage survivability pertaining to actual operational and ship-specific data and parameters. This involves the development of a cruise ship-specific survivability factor numerically and with a new systematic approach and consideration of wave statistics and operational data in the development of ship-specific methodologies and formulations in order to more accurately account for survivability of this type of vessels.

This is a unique and novel development, particularly addressing the use of modern tools as a means of direct assessment of damage survivability in waves as well as providing the requisite data for the development of a statistical approach, the main emphasis being on cruise ships, unlike any of previous development, where the focus was on cargo and RoPax vessels. Hence, the kernel of the PhD thesis "Holistic Approach to Damage Survivability Assessment of Large Passenger Ships", more specifically large cruise vessels.

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Nomenclature and abbreviations

A	Attained Subdivision Index
A_{GZ}	Area under the GZ_{φ} curve
CDF	Cumulative Distribution Function
CLIA	Cruise Lines International Association
DAMHULL	Damaged hull considered in NAPA calculations
DGMOVE	Directorate General for Mobility and Transport
EMSA	European Maritime Safety Agency
eSAFE	enhanced Stability After Flooding Event
EU	European Union
FBe	Effective freeboard
FLARE	Flooding Accident Response
FLOODSTAND	Integrated FLOODing control and STANDard for stability and crises management
FSA	Formal Safety Assessment
FSI	Flooding Survivability Index
GM	Metacentric height (m)
GOALDS	GOAL based Damage Stability
GZ	Righting lever or arm
GZ_{max}	Maximum value of the righting lever (m)
HARDER	HARmonisation of DEsign Rationale
Hs_{crit}	Critical significant wave height (m)
IMCO	Inter-Governmental Maritime Consultative Organization
IMO	International Maritime Organisation
JNWEP	Joint North West East Project
KG	Vertical centre of gravity (m)
LLH	Long Lower Hold
LSA	Life Saving Appliances
MC	Monte Carlo
PDF	Probability Density Function
R	Required Subdivision Index
RANGE	Range of positive stability of the GZ_{φ} curve (degrees)
RoPax	Roll-on/Passenger vessel
RoRo	Roll-on/Roll-off vessel
SA	Stockholm Agreement
SAFEDOR	Design, Operation and Regulation for SAFEty
SEM	Static Equivalent Method
SLF	Sub-Committee on Stability, Load lines and on Fishing vessel safety
SOLAS	Safety Of Life At Sea

SRtP	Safe Return to Port
STABHULL	Intact hull considered in software NAPA calculations
TTC	Time To Capsize
UGD	Univariate Geometric Distribution
WoD	Water on Deck

Chapter 1

Introduction

1.1.Opening remarks

Titanic (1912) and Costa Concordia (2012); two ships built almost a century apart and two accidents, deriving from very different causes but of similar nature. However, ship technologies in 1912 and 2012 are altogether different to the extent that are not comparable. In fact, one can question the underlying factors that make the two major maritime accidents seem identical despite the fact that the pace of technological advancements has been unprecedented. Pertinent factors can range from human and organisational levels to the actual accident investigation itself and the response from shipping companies, the managerial and organisational regime and regulatory authorities. Considering the later, history has proven that the traditional way of response to maritime accidents relates to rule compliance and development and introduction of stringent measures and advanced technologies.

The two accidents initiated numerous discussions and led to a new generation of accident causation models, rules and technologies to avoid and prevent potential fatalities. However, entrusting new technology can sometimes have a negative effect and subsequently create a false sense of safety and confidence leading to unanticipated consequences. One predominant example in this direction is the navigation system on board Costa Concordia that despite the fact that given course, location and speed, future positions were predicted at sea, the vessel was grounded, while in this case, the operator argued that the probability of encountering such event is insignificant (Schroder-Hinrichs et al., 2012).

Due to dynamic technological advancements, dependence on experience has dramatically declined and proven insufficient. In the field of shipping in particular, this is demonstrated by past marine catastrophes (e.g. Titanic, Herald of Free Enterprise, Alexander Kielland, Costa Concordia and so on) that have resulted in huge loss of lives and assets with adverse effects on the environment and society.

This being the state of affairs, rules and regulations are being updated and improved reactively after each major accident with the introduction of higher requirements or alternative standards without the justification by any scientific or technical means.

Building on this, special merit should be given to the rule-making side of the coin. But here a significant differentiation between technical rules and standards shall be made. In a generic context, technical rules define the minimum applicable requirements necessary to assure public wellbeing and safety along with environmental and property assurance. On the other hand, technical standards target facilitation of a common ground of interchange and fulfilment of the requirements. However, the later has been rather treated as a "black box" than a rational and well organised aspect (Huss, 2010).

The two different purposes cannot fit under the same regulatory regime and this is evident in the face of fast-paced technological progress. Advanced technology and higher safety requirements do not abide and are cumbersome to handle under the same prescriptive regime based on existed technology. The situation, however, is gradually changing. First principles and performance-based approaches are now actively considered in the regulation-making process and developments.

The Goal-based Standards (Hoppe, 2005) represent a rational step ahead in a new regulatory regime that keeps up to pace with changing requirements, while it can retain the experience and knowledge acquired and developed in the past. The main objective of the Goal-based Standards relates to the formulation of objectives and solutions independently from the utilised technology. This separation, in turn, can aid in the validation of the existing standards and will facilitate the adoption of alternative and more innovative solutions.

1.2. Addressing the problem in the passenger ship damage survivability assessment framework

The harmonised standards on damage stability of passenger ships, as adopted in SOLAS 2009, represent the end of a century of prescriptive requirements relating to longitudinal and transverse subdivision of passenger vessels, following the margin line and floodable length concepts. These, in turn, introduced a metric translating to percentage of the ability of surviving all possible damage scenarios in a probabilistic manner. Also in this line, the focus of naval architecture has changed altogether and shifted from a hull focus to total-ship focus. The concept of margin line has disappeared and designers delve into watertight subdivision with a view to identifying and distributing spaces to ensure high survivability in extreme damage cases.

The intention to provide a qualitative assessment of safety, this being a Safety Index, might have been enough back when the probabilistic standards were conceived and introduced but today this is not adequate. With the advent of the Design for safety (Konovessis, 2001) and Risk-Based Design approach as shown in Figure 1 (Vassalos, 2009a, Vassalos and Fan, 2016), the quantification of safety is a prerequisite to treating safety rather as a primary design objective. This means that the level of detail embedded in the method used to assess safety carries more weight. Bearing this in mind, the calculation of survivability in the passenger ship stability framework constitutes a very important parameter, which includes a series of unjustifiable compromises and assumptions, which are inadvertently creeping in during the regulation development process. Nonetheless, what is of high significance is the fact that there is little consistency between performance-based survivability and this stipulated by the probabilistic regulations in place.

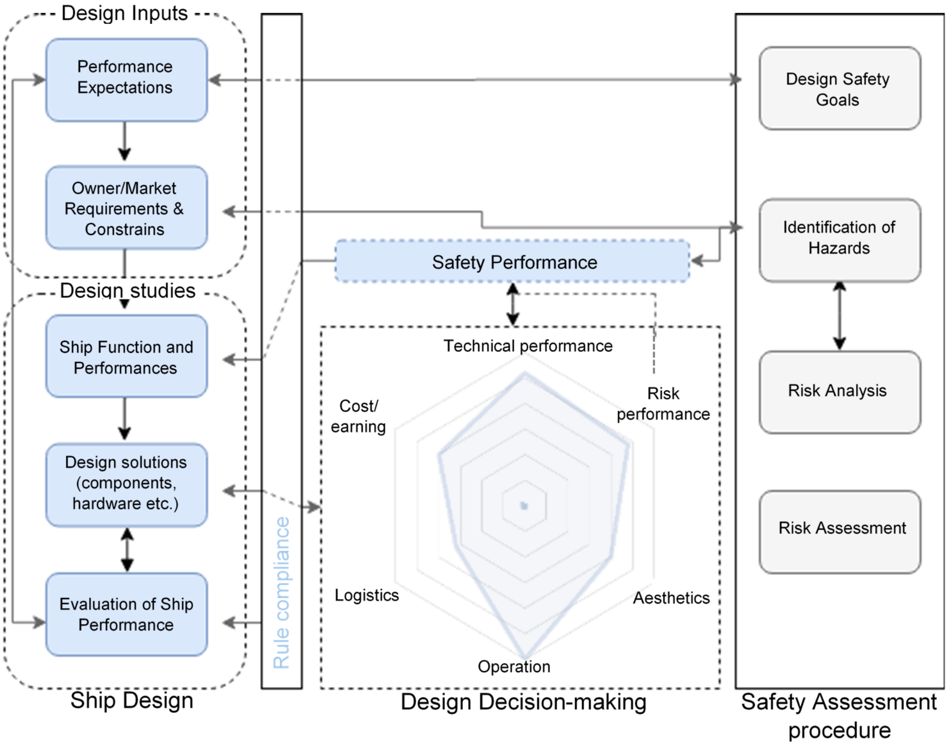


Figure 1: High level Risk-Based design framework (Modified from (Vassalos, 2009).

Building on the above, we are currently facing a two-directional shift; from prescription to performance and from deterministic to probabilistic standards, which in turn can be seen as goal-based standards. The major objective of SOLAS 2009 was not to change and define a new level of safety, but instead, to harmonize damage stability assessment in a unified and rational approach from a situation where two fundamentally different approaches were applied in parallel. The twofold principles made any comparison of the safety level impossible. In fact, SOLAS 2009 has not achieved a full harmonisation but instead changed the mandatory regime for passenger ships (Huss, 2010).

Deriving from the above, the better survivability is understood and more accurately calculated, the better we can separate between decisions on safety level from technical solutions. Therefore, emphasis on the thesis is placed on the development of accurate means of assessing survivability when focusing on damage stability of large passenger ships and more particularly cruise vessels.

Traditionally, damage survivability of passenger ships is assessed by using the statistical approach (probabilistic framework for SOLAS 2009). This is based on rational statistical analysis of historical accident data in combination with statistical information and data (Papanikolaou, 2010). A number of damages, which are typically assessed following probabilistic calculations, are sampled from historical data. This entails a fast and computational effective approach with implementation ease. The calculation of damages can take from seconds for RoPax to minutes in the case of cruise ships pertaining to a large amount of design features, with the main emphasis being placed on statutory compliance.

Nevertheless, this approach is subjected to a number of shortcomings in addition to the aforementioned. Conceptually, the method involves a large number of parameters and probabilities which, in turn, complicate the process and most of them pertain to large number of conservative assumptions and irrational generalisations. Also, the statistical method, as further elaborated in chapter 3, does not account for actual and data, while it does not differentiate between ship types. Finally, the statistical approach does not ascertain the impact of the time element, which is very important in the case of survivability assessment.

In the past, many studies (Vassalos et al., 1999, Vassalos et al., 2005, Vassalos and Guarin, 2009) have indicated the existence of equivalent and more efficient routes to the establishment of the safety level of passenger ships through time-domain numerical simulations. This relates to the Direct Approach to damage survivability. The Direct Approach is very flexible in the way it can accommodate for modern, actual and more accurate data trough Monte Carlo sampling. This, in turn, can be applied to more realistic scenarios addressing accurately modelling of the geometry and the physical phenomenon, along with the floodwater mechanisms. Such approach can provide a handful of information relating to design vulnerabilities to the designers and operators at early stages of the design spiral and during operation. However, this comes at the cost of being computationally intensive when a large number of damage scenarios are considered.

With direct influence, from regulations, and because of the level of effort that is still needed to implement Risk-Based Design (RBD) in full, the real innovation attributable to RBD is currently witnessed mainly at local level. The Direct method can be potentially applied in the same respect in the form of “Approval of Alternatives and Equivalents” as described in MSC.1/Circ.1455 (IMO, 2003a). This is using the principle of equivalent safety to consider alternative design and arrangements other than those supported by SOLAS legislation.

Deriving from above, the thesis is oriented towards developing, applying and comparing the two methods to damage survivability assessment of large passenger ships in a holistic manner. This is achieved pursuing every available avenue to address damage survivability today, following two available approaches, namely the statistical (traditional probabilistic framework) and the direct approach. The first corresponds to rules and the latter to simulations (first principles) for the prediction of survivability. Even though, the availability of utilising high fidelity tools (e.g. CFD) for verification purposes will exist in the future, currently it is still embryonic and under development, hence for this reason is not included in the scope of the thesis.

The two available methods address survivability through generating and assessing whole-ship damages, which differ from those stipulated by the concepts of the WoD and SRtP. The latter address partial damages deterministically following single room flooding (representing approximately 1% of available span of damages), which, in turn, diverge from the aim of the thesis. Additionally, the utilisation of actual and ship-specific data can have a profound effect on survivability. In this line, wave statistics and operational data including permeability constitute elementary components of the conceptual development and practical implementation of the two available damage survivability approaches. These, in turn, as investigated in the thesis, forming the input domain of a holistic approach to damage survivability assessment for large passenger ships, and more specifically cruise ships.

Cruise shipping is a booming ship industry. The fast-growing cruise ship passenger demand rate, which has resulted to a total of 176 million passengers over the recent past while almost 70 per cent cruised between years 2005 and 2016 (Wang et al., 2016a). Yet, considering the economies of scale in physical and engineering basis, currently cruise line companies are planning to building dozens of large capacity ships within the next few years (CIN, 2018).

Even though extensive emphasis has been placed on reducing cruising cost, improving waste-disposal systems and fuel efficiency, improving market revenue, itinerary optimisation and so on, little focus has been placed on improving the stability standards or developing standards with sole consideration of modern cruise liners. Due to the immense societal impact that potential accidents involving large passenger ships ($L \geq 120m$) and particularly cruise ships would have, this safety critical category of ships has been selected with a view of demonstrating the rationale and methodology followed in the thesis. The next section aims at highlighting some of the main aforementioned aspects with reference to the flooding process of ships involved in collision and grounding accidents.

1.3.Flooding process and vulnerability of passenger ships

In a generic context, when a vessel is damaged following collision or grounding can lose the watertight integrity, entailing flooding in internal spaces. In this case, the vessel attains a new equilibrium position in order to account for the accumulated floodwater causing reduced floatability (ability to achieve condition of weight upright equilibrium) and transverse hydrostatic stability (ability to return to a state of upright equilibrium after disturbances), which exacerbate further in the presence of waves.

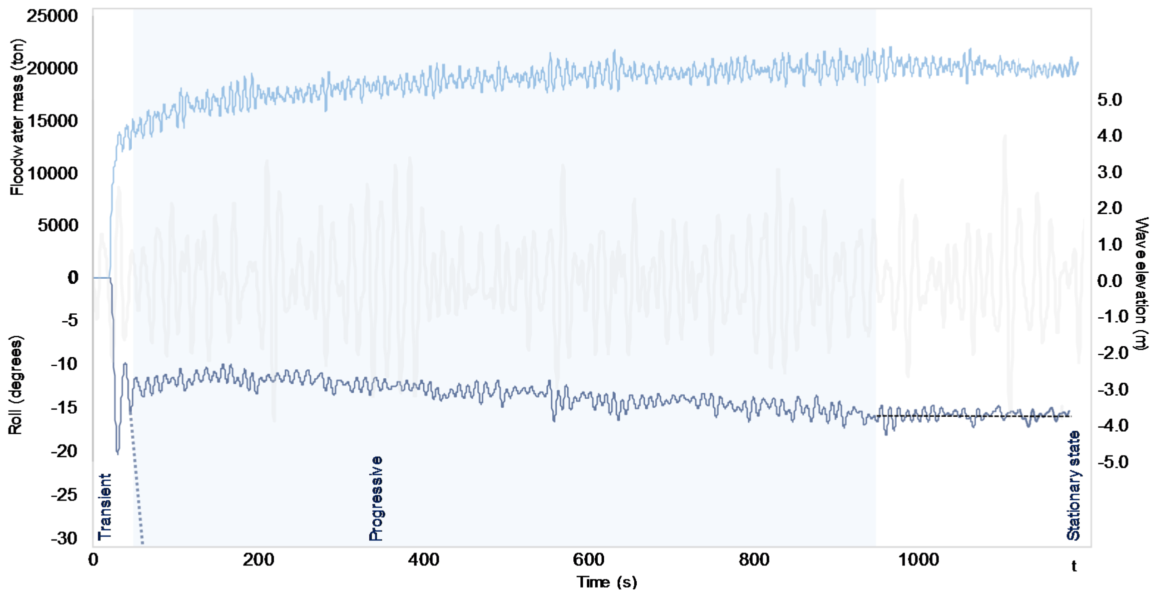


Figure 2: Flooding modes for a large cruise ship with a 3-comparment damage in waves. Indication of floodwater accumulation, wave elevation and roll motion as a function of time.

The ***loss of floatability*** occurs when the total floodwater mass, accumulated through the presence of an opening, equals the residual buoyancy of the vessel sailing in a specific loading condition. On the other hand, the ***loss of stability*** constitutes transverse stability requirement failure, while, the vessel might eventually capsize or sink. Notwithstanding the aforementioned, the vessel might not be subjected to direct loss. A ship is considered to ***sink*** when it submerges from the surface of the sea, while, it ***capsizes*** when it physically turns over ($\theta_r > 90\ degrees$) and hence it cannot recover to its initial/intact equilibrium position.

The flooding process in the wake of damage opening can be described through three different phases (IMO, 2003c); the transient flooding, progressive flooding and stationary state respectively. As it can be demonstrated through figure 2 for a sample flooding case, in the first phase, that of **transient flooding**, water rushes into the ship through the damage opening, which may cause large rapid transient heel to the damaged side in fractions of time shorter than the vessels natural period with possible eventual capsize. This capsize is the so-called **transient capsize** with the vessel heeling, following inrush of floodwater, and never regains equilibrium. In the case of cruise ships, this phenomenon is exacerbated by accumulation of water in higher decks, which can intensify the situation with the presence of multiple free surfaces (MFS effects) (Vassalos, 2012).

Nonetheless, the complexity of structures inside symmetrical compartments can delay the equalization of the floodwater. In this respect, the transient heeling can be diminished allowing cross-flooding to a compartment in the undamaged side of the ship. One important element is the increased air pressure due to compression which can be proven detrimental in the early phases of transient flooding. That is to say for a rapid flooding progress where the ventilation level of the compartment is reduced leading to excessive air compression which in turn delays the process of flooding (Ruponen, 2007).

Following transient flooding, the flooding process usually becomes more quasi-static increasing steadily with time (usually taking from minutes to hours), based on the subdivision and openings layout of the vessel (Ruponen, 2007). **Progressive flooding** is the sequential flooding of adjacent compartments, which takes place before the vessel has reached the **stationary state** (Jasionowski and Vassalos, 2004). An indicative case of a large cruise ship is provided in figure. Progressive flooding can be initiated due to wave-induced and floodwater-induced motions of the vessels. This is further intensified in the case of large passenger ships, which involves complex spaces that allow floodwater to be governed by hydrostatic forces in calm water. A **stationary state** implies that the statistics pertaining to water ingress and egress (st. deviation, mean, etc.) remain constant for a given set of sea states and loading conditions (see figure 2 for t>940s). In this sense, the heel is ascribed a quasi-stationary character resembling a constant oscillatory process as described by (Jasionowski and Vassalos, 2004).

In the case of large passenger ships, the phenomena are amplified by the insufficient protection of openings or when higher decks (above the watertight bulkhead deck) are submerged, allowing flooding through openings in the vessel's central service corridor if available. Furthermore, the floodwater pressure can cause leakage through closed doors or in severe conditions can bring about collapsing of non-watertight structures. In fact, cruise vessels exhibit significant vulnerabilities to transient and progressive stages of flooding (Vassalos et al., 2004). This, however, can be controlled through the positioning of semi-watertight doors on decks susceptible to multi free-surface effects and progressive flooding. Additionally, asymmetric flooding is compensated by enabling utilisation of the cross-ducts in order to reduce the heeling angle. In a similar manner, controlled down-flooding can be allowed for the reduction of the vertical centre of gravity when higher decks are damaged. The stochastic behaviour of water accumulation is less pronounced for the case of cruise ships as opposed to RoPax. For the latter, this is mainly due to the large undivided spaces causing large free surface effects.

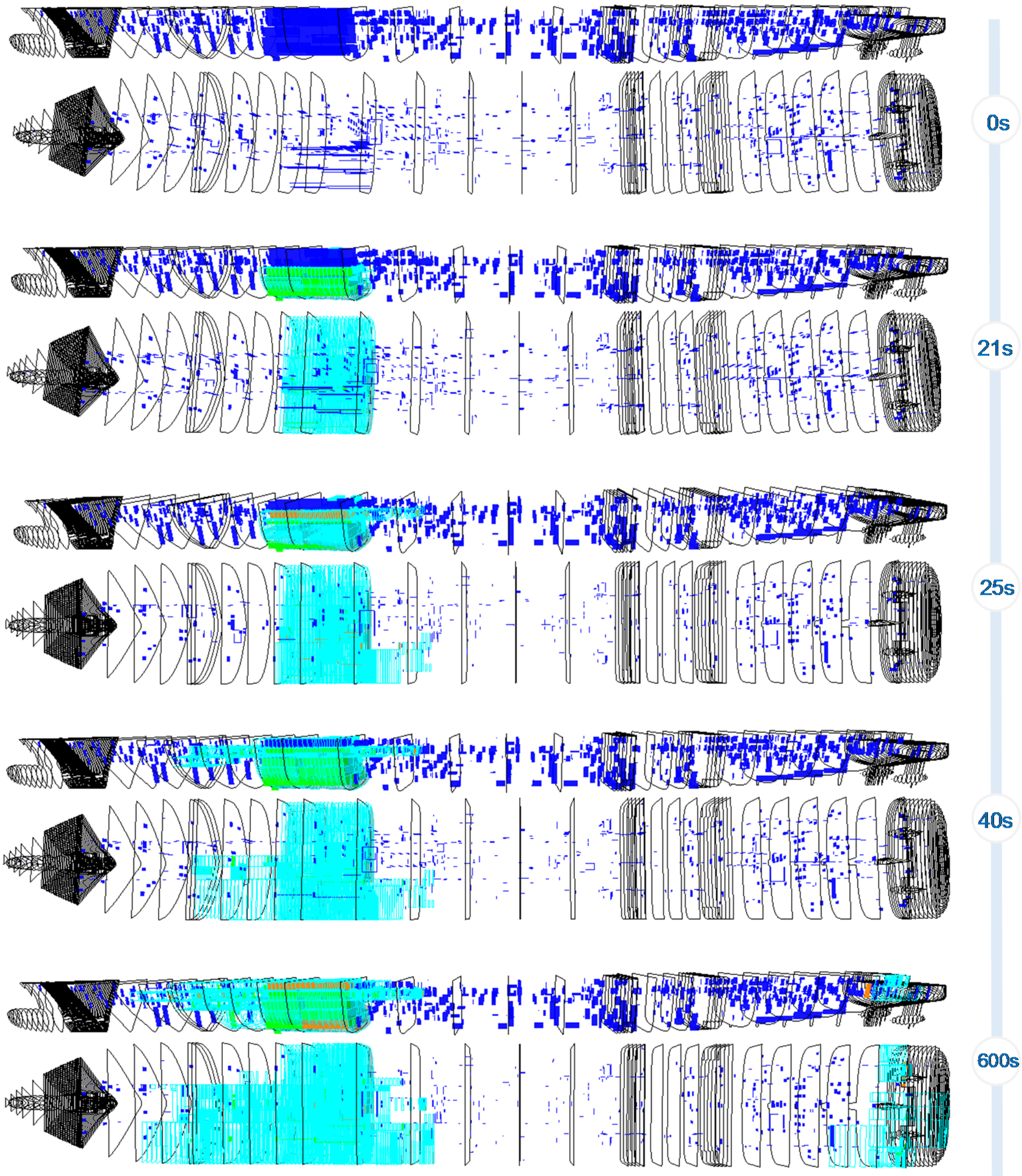


Figure 3: Progressive flooding in a typical 2-compartment damage of a large cruise ship with high degree of internal detail and architecture.

1.4.Thesis outline

The thesis consists of 10 chapters and four interrelated appendices as shown in figure 4. The following section provides a concise outline for each of the chapters, respectively.

Chapter 1: Introduction

The Introduction provides the background and sets the scene for the undertaken research. In particular, it starts with an introduction to the damage survivability assessment stage and overviews and compares the approaches in place, namely the statistical and direct approach, which form the research basis.

Chapter 2: Aim and objectives

This chapter will elaborate on the objectives that will facilitate the achievement of the overall aim of the research. Also, it highlights the primary aim of the research.

Chapter 3: Damage stability framework and survivability of passenger ships

Chapter 3 provides the background and an overview of the state of the art in the related field of research. The chapter identifies and highlights the gaps that will be investigated within the research focus.

Chapter 4: Approach adopted

This chapter sets the fundamental assumptions with regards to the development of the approach for each chapter. It provides a flow chart with description of levels and steps to be considered at a global and individual level.

Chapter 5: Modelling and prediction of damage survivability of large passenger ships

This chapter describes the instruments of assessing damage survivability and the survival state used over the years with regards to their development and scope of utilisation. Furthermore, fundamental relationships are derived between the survival state and residual stability properties of large passenger ships, through numerical simulations, with a view to formulating survivability to cater specifically for large passenger ships using the statistical approach. Also, survivability is assessed with the direct approach using

Monte Carlo sampling from pertinent waves, loading and damage distributions as well as a comparison between the two approaches.

Chapter 6: Impact of wave statistics on ship survivability

Chapter 6 investigates further one of the main elements composing survivability, namely the critical survival height. Available and new knowledge is applied to derive survivability formulations enabled for specific areas of operation. Also, ship-specific trends and tendencies are accounted for through the development of ship-specific accident databases. A sensitivity analysis is performed to assess the impact of the newly derived formulae as opposed to the prevailing ones. Also, a new concept that addresses survivability over the period of a voyage is presented.

Chapter 7: Consideration of actual operational profiles in damage survivability assessment

Chapter 7 describes a new approach that allows the utilisation of actual operational data in order to account more accurately for survivability. Several sensitivity analyses are conducted in order to investigate the impact of different elements of the operational profiles on survivability.

Chapter 8: Impact assessment of permeability on survivability

Chapter 8 presents and discusses the effect of permeability on damage survivability, which is scrutinised with the aid of static and dynamic software tools. This, in turn, will provide the requisite evidence to the argument that the magnitude of permeability is significant when assessing survivability and actual values need to be envisaged during the design phase.

Chapter 9: Discussion

In chapter 9, a thorough discussion of the findings of the research is provided that addresses the way the research gaps are fulfilled, leading to recommendations for related future research.

1.5.Closing remarks

As presented in Chapter 1, the scope of the thesis is oriented towards accurate damage survivability assessment of large passenger ships. This entails the development, application and comparison of the two approaches available with main emphasis placed on cruise vessels accounting for actual and ship-specific data. The next two chapters highlight the thesis's objectives and provide the main review of the damage survivability assessment methods in place.

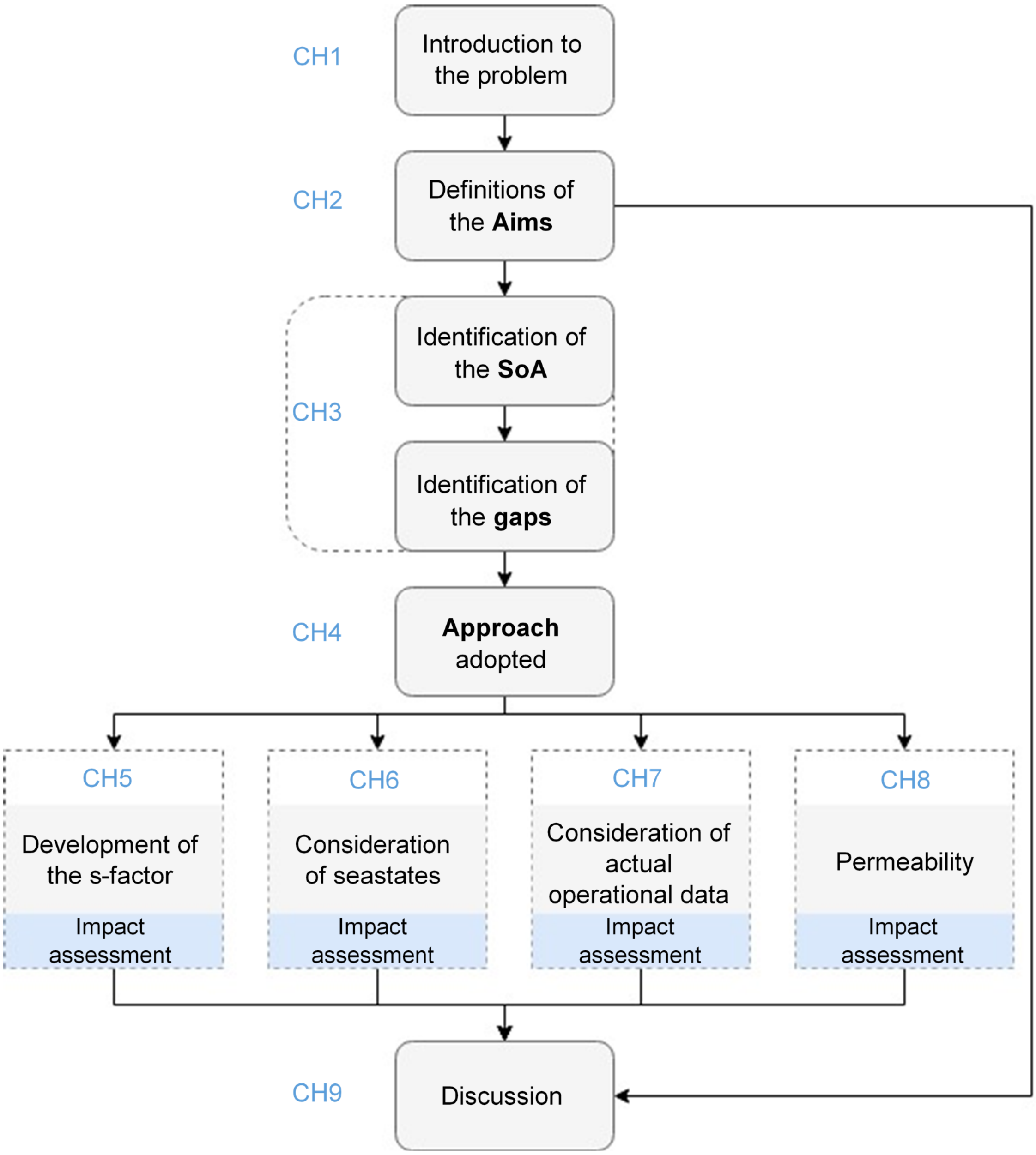


Figure 4: Flow chart depicting the chapters of the thesis

Chapter 2

Aim and Objectives of the Thesis

2.1.Opening remarks

The following section provides the direction of the research topic. The aim and objectives of the research are stated in a concise form that indicates how the concept is devised in latter sections.

2.2.Aim and objectives

The overall aim of the undertaken research is summarised as follows,

〉 To address damage survivability of large passenger ships in a ***holistic*** manner with consideration of actual and ship-specific data.

To this end, specific aspects of the regulatory framework for damage stability of passenger ships (SOLAS Ch. II-B) are reviewed in order to account more accurately for survivability of large passenger ships. The main assumptions, which have been identified within the critical review, are scrutinised with regards to large passenger ships in order to "Fill the gaps" with a view to establishing a regulatory platform that can adopt potentially utilisation of real-time on-board data during each vessel's life-cycle. Even though, the findings cater for large passenger ships in the main, a similar methodology and rationale can be developed and applied to different ship types.

Building on the above, specific research objectives include the following:

〉 Chronological review of the damage survivability assessment methods and framework currently in place to identify the State Of the Art and establish the research gaps presented in the thesis. A comprehensive elaboration is provided to address any presented arguments.

- Development of a survivability factor specifically catering for large passenger ships through the statistical survivability assessment approach, accounting for the probability of survival after collision in waves.
- Prediction of survivability of large passenger ships in waves through the Direct Approach to damage stability accounting for collision and grounding damages. This entails comparison with the statistical approach to survivability.
- Consideration of localised wave statistics in the development of regional critical wave height and survivability factors, accounting for the actual operational environment of vessels and ship-specific data and tendencies of passenger ships using accident data.
- Consideration of the actual operational profile of large passenger ships within the damage stability assessment to cater for existing ships and newbuildings.
- Impact assessment of permeability on damage survivability accounting for different compartment types and quantification of their effects. Attempt to parameterise and formulate the results into an efficient form for future use.

2.3.Closing remarks

The aforementioned section provides clearly the primary aim and the objectives of the research thesis. As it has been highlighted above, the research aims to adopt the utilisation of actual operational data to accurately account for survivability of large passenger ships. The objectives have been formed and derived pertaining to the problems as identified in the foregoing chapter, Chapter 3. This will elaborate on the first objective of the research which will identify the state of the art and pinpoint the research gaps.

Chapter 3

Damage stability framework and survivability of passenger ships

"You cannot understand a system unless you try to change it" – Kurt Lewin, 1939

3.1.Introduction

There have been almost 100 years from Titanic to Costa Concordia with numerous scientific, technological and rule-making developments in between. In our era, even though damage stability is conducted through using robust and computationally efficient tools, the inherent damage stability standards and criteria appear to be more arbitrary than rational. It is a combination of statistical data (historical accident records), along with analytical tools and rationale that render survivability assessment inconsistent. Despite the efforts of the maritime industry to resolve damage stability problems, damage stability remains a dominant risk contributor. With this in mind, the scope of the literature is limited to survivability elements that constitute the main risk indicators as used within the damage stability assessment instruments, albeit in the design phase, of a passenger vessel.

This chapter starts with a historical review of the damage stability framework of passenger ships and the approaches available for survivability assessment. To this end, the established timeline highlights the significant contributions and the events that triggered a series of developments that eventually has shaped the safety culture in damage stability of passenger ships to date. Subsequently, the main aspects of the different survivability assessment approaches available are highlighted starting with the traditional survivability approaches and following with the performance-based approaches.

In this respect, the statistical approach to damage survivability is described first including the main research initiatives and projects that spearheaded a number of developments aimed at accurate survivability assessment of passenger ships. In this attempt, the probabilistic damage stability assessment and the principal survivability components are reviewed. Also, this includes a review on parameters with strong baring on survivability assessment and modelling in the main, such as volume permeability. Following the traditional survivability assessment approaches, the chapter delves into performance-based approaches, which utilise first principles for the derivation of survivability. This entails the direct approach to survivability through using time-domain numerical simulations. The main concepts derived from such techniques are described, including the capsize band and time to capsize.

Having established the state of the art (SoA) in passenger ship damage stability and survivability, a number of methodology shortcomings and implications are addressed, which form a significant basis for the research gaps to be addressed in the thesis. Over the years, a number of papers and documents have been published that shed some light in this direction. These are referenced, as appropriate, in the following paragraphs. Each of the elements is critically reviewed, providing evidence to substantiate the arguments presented.

3.2. Chronological review of the passenger ship damage stability framework

The first Merchant Shipping Act in 1854, which thereafter preceded by the act of 1889 (USG, 1889), was the first legal act of addressing watertight integrity of vessels carrying passengers stating that,

"Ocean-going steam-vessels, which carry passengers, should be additionally protected by having efficient bulkheads, so spaced that when any two compartments be filled with water, the vessels will still remain in a seaworthy condition." – (USG, 1889)

In this era and before the advent of modern aviation, sea passage was the common way across the sea, providing safe passage and avoiding natural risks. However, this does not entirely constitute the safest means of transportation. As of the first decade of the 20^{th} century, the market of passenger ships expanded exponentially while the Titanic and her sisters typifying the modern efficient speed cruise liners and nurturing a sense of resilience and security in the market (Jeremy, 2012).

However, that was not until the Titanic catastrophe in April 1912 when 1,503 people lost their lives. In response to this, the British government devised the first international regulations for the safety of ships namely, the (CSC, 1913), which has not entered into force as it was intervened due to the world war I. The first requirements were addressing safe navigation, watertight and fire-resistance bulkheads and life-saving appliances. In line with this, two subsequent treaties followed in 1929 and 1948 (UKG, 1929, UKG, 1948). In the latter, a series of improvements were achieved with regards to stability standards introducing requirements to watertight arrangement and alternative subdivision methods. According to the standards of 1912 and 1929, the maximum damage longitudinal and transverse extents were 0.02L+3.05 along with B/5, respectively for statutory compliance. Given the slenderness of the cruise ships at the time, asymmetric flooding would seem unlikely and the probability of suffering collision damage was miniscule. However, the pitfalls of the framework were raised eventually (Comstock and Robertson, 1961).

The factorial approach aiding in decision-making with regards to the subdivision was broadly employed with terms such as floodable or permissible length to be of great importance. However, IMO was becoming aware of the shortcomings in place, which gradually weakened the utilisation within the design process and as a result the approach has been withdrawn today. After all, it is important to sustain residual stability than residual buoyancy in a damaged condition. The change in the design trends brought about an increase in the beam of the vessels and therefore the introduction of the first residual stability criteria was inevitable. This was accounted for through the first “Safety of Life At Sea” (SOLAS) convention of 1960 (UKG, 1960) stipulating a minimum residual GM of 0.05 meters. The conventions leading to SOLAS 1960 consolidated the series of requirements for the number and arrangements of watertight bulkheads along with the ship stability following collision damage. Besides, it was recognised that the semi-empirical nature of the deterministic approaches in place required and were driven from the characteristics of formerly known disasters in the industry.

The first probabilistic damage stability rules for passenger ships were derived from the work of Professor Kurt Wendel as presented in “Subdivision of Ships” (Wendel, 1968), and they were introduced in the late 60’s as an alternative to the prevailing at the time deterministic requirements of SOLAS 1960. This, in turn, inspired a series of developments towards probabilistic regulations for subdivision and stability; initially for the case of passenger ships as a proposed alternative to the deterministic regulation of SOLAS (A.265) (IMO, 1974) and later in the 80s for the case of cargo vessels within Part B1 in Chapter II-1 of SOLAS (IMO 2004). The work of Wendel has been the subject of debates through a series of older papers (Robertson et al., 1974, Krappinger, 1961, StDennis, 1962, Abicht, 1989). The IMO resolution A265, or so called Equivalent Passenger ship Regulations, was the first resolution that referred to equivalent safety and safety level as part of a set of explanatory notes. Subsequently, in the same line, the 1974 SOLAS (IMO, 1974) convention accounted for Rahola's proposals following his work (Rahola, 1939). The proposals comprised requirements for the residual stability curve and intermediate stages of flooding based on a deterministic approach. Notably, the amendments followed in 1983 included provisions for lifeboat launching with a requirement of 20 degrees in either ship side and capacity of at least 50 percent of people on-board.

In December of 1987 as shown in figure 5, the RoRo vessel Herald of Free Enterprise capsized in Belgium and as a result 193 passengers lost their lives. It was an accident that shook the foundations of the industry. Consequently, this accentuated the need to address the dynamic phenomena capturing water on deck (WoD). IMO was alarmed and adopted stringent standards for new ships within the convention of SOLAS 1990 (IMO, 1990). These entailed a range of 15 degrees beyond the equilibrium angle, an area of 0.015m.rad, residual GM of 0.05m and a maximum GZ $\geq$ 0.1 meters. The amendments took into consideration passenger crowding on to one side of the ship, survival craft launching on one side of the ship and wind pressure. These, however, incorporated full deterministic elements. It also stipulated that the maximum angle of heel after flooding should not exceed 15 degrees. A series of studies followed (Vassalos and Turan, 1994, Vassalos, 1995, Velschou and Schindler, 1994) assessing the impact of dynamics on RoRo and passenger ships, however utilising only a small sample of ships.

Another major step change in stability standards followed again in 1992 with the introduction of SOLAS part B-1 (Chapter II-1), integrating a probabilistic standard for cargo ships, using the same characteristics as embodied in the earlier 1974 regulations based on the data collated by IMO regarding collisions. For the case of RoRo vessels, further enhancements took place following the Estonia accident in 1994 when 850 passengers lost their life. This lead to the so called “Stockholm Agreement” (SA), which was reached by the North West European Nations as part of the North West European R&D project (JNWEP) in December of 1997, which aimed in rationalising the probabilistic approach. Extensive research in the field indicated that the main cause of the capsize of Estonia was due to excessive water accumulation on the main deck (Jasionowski and Vassalos, 2002).

After that, in 1995, SOLAS 1990 was adopted as a global safety standard of damage stability with provision for water on deck standards. The stability committee adopted a series of amendments to SOLAS 1974 related to the stability of Ro-Ro passenger ships in Chapter II-1, containing special requirements for Ro-Ro passenger ships carrying 400 passengers or more. This was intended to pass out ships built to a “one-compartment standard” and in turn guarantee that ships could survive without sinking with two compartments being flooded following collision damage.

The future direction of rule development set course through the European research project HARDER (HARmonisation of DEsign Rationale) (HARDER, 1999-2003) (see figure 5) with international participation, which was launched in March 2000. The main objective entailed the generation of fundamental knowledge in the underlying relationships and physics of damage stability by systematic research with a view to clarifying implications of the harmonisation task conducted by the IMO-SLF subcommittee. During project HARDER, the new harmonised probabilistic damage stability concept, known as the SLF42 proposal was systematically assessed and an improved proposal was introduced for discussion at IMO, known as the HARDER-SLF46 proposal. Several concerns were raised after the completion of the project in 2003, related to the severe impact of the harmonisation on the design and economic impact of large passenger ships. With this in mind, the proposal was revisited in IMO-SLF47 with respect to the large ships assessment method on the way from the MSC79 to the MSC80, where it was finally adopted. The project set the foundation of SOLAS 2009 through MSC80 committee and it is applied since then on dry cargo and passenger ships (Wilson, 2018).

Later on, safety in the entire life-cycle of cargo and predominantly passenger ships was addressed through the subsequent EU-funded R&D project (SAFEDOR, 2005-2009), representing an effort to foster a radical transition from the current maritime safety regime, via the actions of the thematic network SAFER EURORO ("Design for Safety"). The project demonstrated the potential of risk-based frameworks undertaking a series of high-level formal safety assessments. The related FSA studies on cruise and RoPax vessels indicated that the risk to human life could be significantly reduced cost-effectively by raising the required subdivision index R. In the same manner, cruise ships demonstrated a reduction of risk by 2.1 lives per ship per lifespan (30 years) through increasing freeboard or GM (Nilsen, 2007). However, the FSAs were addressed in high-level and as a result only generic design measures were explored and found to be cost-effective while the consequences of higher subdivision requirements were not addressed. (Eliopoulou et al., 2009).

The adaption of probabilistic assessment methods in the maritime industry had a profound effect, which was achieved via projects HARDER and SAFEDOR, the latter leading to the adoption of Risk-Based and Performance-Based approaches in the safety of passenger ships. The latest marine accidents prompted the industry to become proactive and ensure safety at every aspect, addressing survivability and safety in a holistic way. In this sense, new regulations came into force in 2010 (first draft in 2006) applicable to passenger ships over 120 meters including three and more vertical fire zones. The so-called Safe Return to Port (SRtP) guidelines (IMO, 2010), as per SOLAS 2009, incorporated two new concepts; that of "casualty thresholds" and "safe areas" which eventually formed a stepping stone in naval architecture.

Along similar lines, one of the top-agenda items within IMO was the Goal-Based Standards by targeting in the longer term a broader range of ship types. Passenger ships and especially RoPax vessels were the primary focus while it was becoming implicitly apparent the need of addressing in more detail the damage stability standards of such vessels (Papanikolaou et al., 2010). The EU funded, FP7 project (GOALDS, 2009-2012), (GOAL based Damaged Stability), aimed at addressing the shortcomings of the standards in place by providing state of the art scientific methods, and instruments along with formulation of a rational regulatory framework accurately accounting for the damage stability properties of passenger ships. In particular, the project shed some light into the underlying concepts of the survival probability and eventually of the Attained and Required Subdivision Indices for passenger ships. However, despite the profound importance of grounding accidents, as has brought to attention by the accident statistics in place, there was no provision for grounding damages in the damage stability assessment, which eventually was accounted for through project GOALDS.

In January of 2012, the cruise ship Costa Concordia capsized attempting “A sail by salute” across the Italian coast. This was perceived as a defining moment for the modern cruise history and in the wake of this CLIA and EMSA arranged a series of committees to address critical safety elements (Miller, 2017). Even though the industry had already formed a basic understanding of damage stability of passenger vessels, the missing piece of the puzzle was the understanding of the real safety level after flooding in the case of cruise ships.

One predominant step in this direction was taken by the Joint Industry project eSAFE (enhanced Stability After Flooding Event),(Luhmann et al., 2018a, Luhmann et al., 2018b) funded by the Cruise ship Safety Forum in 2016. The project aimed at enhancing damage stability of cruise ships using modern first principle tools within their early design process. Another attempt (DGMOVE, 2016, Cichowicz et al., 2018a, Cichowicz et al., 2018b) focused in assessing the impact of European stability and survivability standards for RoRo ships and, in turn, it indicated that the risk thresholds need special attention as they do not cater for newly designed ships. Generally, the fundamental requisite is that pertinent risks need quantification most of the time in an appropriate way throughout the life cycle of a vessel, from design and daily operation to crisis situations. This was promulgated within project FLARE (Flooding Accident REsponse), which started in 2019 with an ultimate aim of developing a novel Risk-Based methodology beyond the existing state-of-the-art for ‘live’ safety assessment in line with the IMO high level goals for passenger ships.

Finally, looming SOLAS 2020 (IMO, 2017) as adopted by resolution MSC421(98) is intended to enter force in early January of 2020. This addresses, a new Required Index R, which depends only on the number of passengers on board, new practices in treating local Attained Indices when calculating multiple trims, along with increased range and GZ_{max} requirements in the final stage of the survivability factor. The latter applies only in the case of RoPax ship damages involving RoRo spaces, and as a result, it is not applicable to cruise vessels. Building on this, the shortcomings one could observe in the early

SOLAS 2009 with regards to the survivability formulation and the Attained Index are still present in 2020. Therefore, the emphasis on the literature is placed on SOLAS 2009.

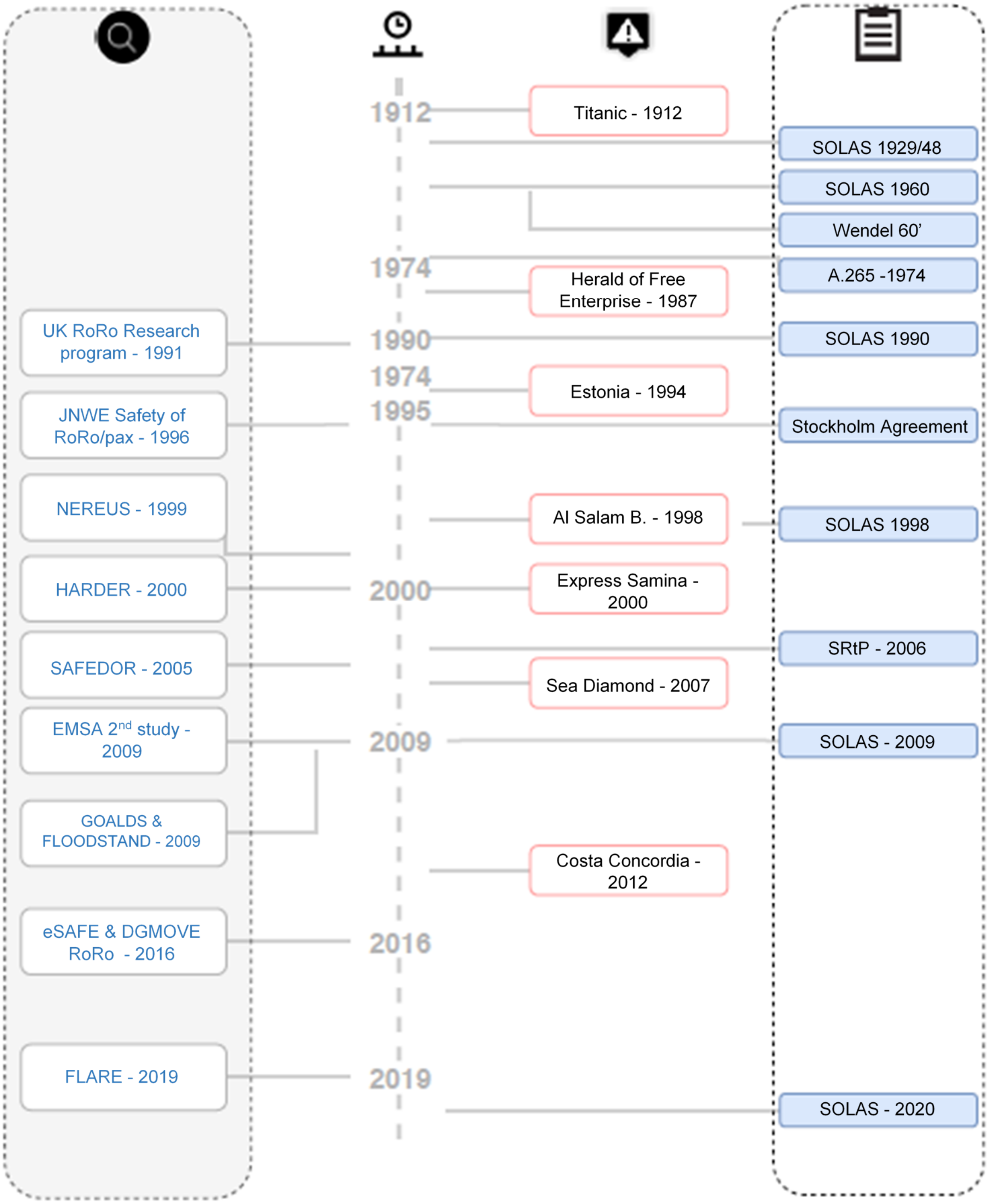


Figure 5: Timeline of accidents that initiated a number of research projects and regulation developments

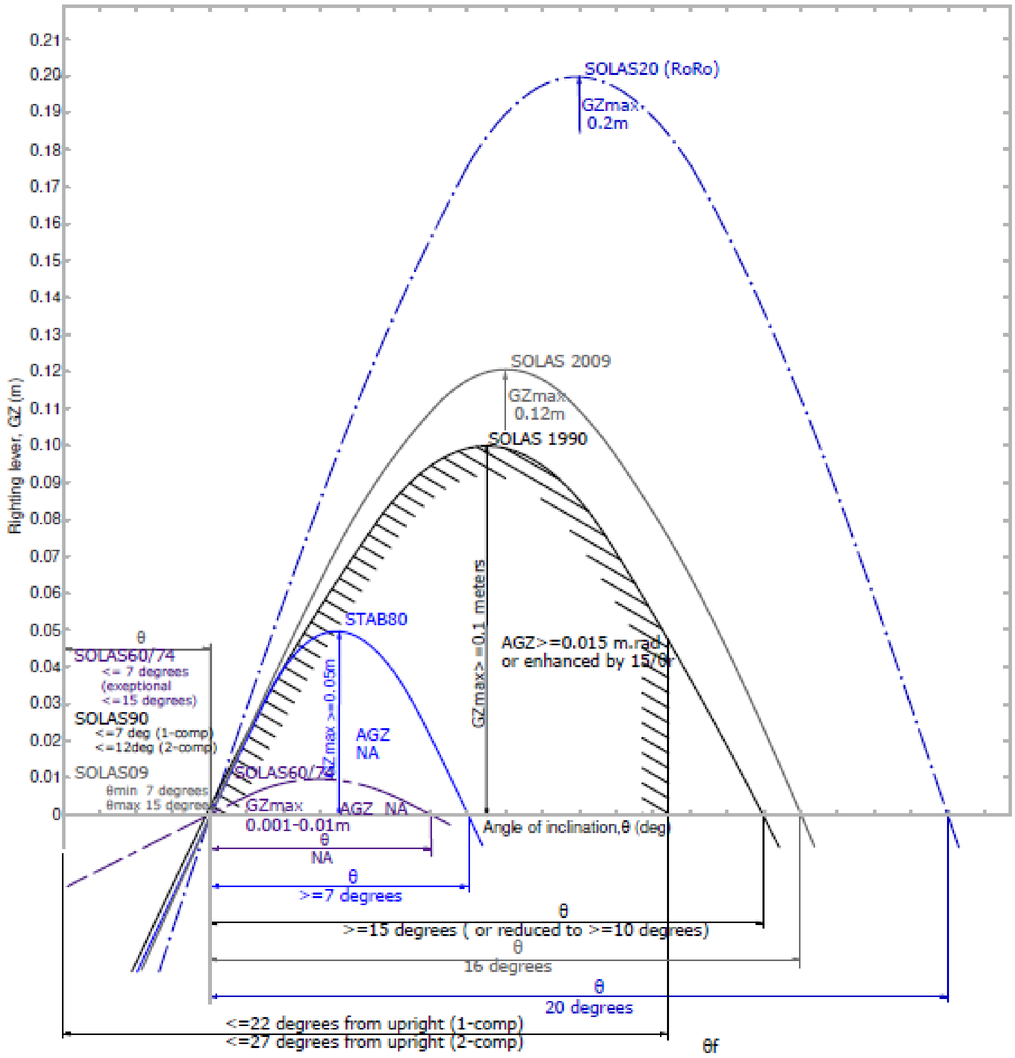


Figure 6: Residual stability standard comparison from 1960 to present.

Table 1: Deterministic damage residual stability criteria 1960 to 2020 and current probabilistic for the final stage of flooding.

	Deterministic				Probabilistic	
Criterion	IMO SOLAS60/74	UK STAB80	IMO SOLAS90		IMO SOLAS2009	IMO SOLAS20
Positive residual righting level (GZ) curve range , θ_{RoS}	NA	≥7	≥15	$15 \geq \theta_{RoS} \geq 10$ (if A_{GZ} is increased by $15/\theta_{RoS}$)	16	20
Area under GZ curve, A_{GZ}	NA	NA	≥0.015	≥0.015 x $15/\theta_{RoS}$	-	
Maximum residual righting lever, GZ_{max}	0.001 to 0.01 (UK)	≥0.05	≥0.100		0.120	0.200
Angle of heel due to unsymmetrical flooding after equalisation, θ_B	≤7 degrees	≤7 degrees	≤7(1 compartment damage) ≤12 (2 compartment damage)		Minimum 7 Maximum 15	
Positive residual metacentric height, GM_T	≥0.05	≥0.05	≥0.05		-	

3.3.Survivability assessment methods

Despite the well-known theoretical differentiation between deterministic and probabilistic terms in risk analysis (Kirchsteiger, 1999), an apparent related separation exists within the damage stability standards and the inherent nature of the survivability concepts (Papanikolaou, 2007). Over the years, passenger ships have indicated very high sensitivity concerning survivability, stemming from the nature of the assessment criteria. Even though the previous deterministic standards have shown to penalise passenger ships, the latest harmonised regulations in place provide some relaxation into the design phase but some pitfalls are still present (Papanikolaou and Eliopoulou, 2008). The foregoing paragraphs provide an insight into the aforementioned criteria.

In more depth, SOLAS 1974 addresses resistance to capsize for one-compartment damages with no provisions on sea states, whilst, SOLAS 1990 addresses resistance to capsize to two-compartment worst damages in a sea environment (approximately 3m for RoRo ships). In the same manner, Stockholm Agreement is applied like SOLAS 1990 but with additional provisions for water on deck depending on residual freeboard and operational wave heights up to 4 meters. Alternative compliance approaches that were sought at the time through model experiments constituted the first Performance-based assessment techniques for verification purposes. Subsequently, SOLAS 2009 provided a step change away from the deterministic methods for passenger ships while 1 and 2-compartment standards eventually disappeared with the appearance of probabilistic elements and Goal-Based standards (Vassalos and Guarin, 2009). However, some determinism still remains within the probabilistic regulations, namely regulation 6 and 8, which stipulate B/10 and 2-compartment equivalent standard. Another distinct differentiation between SOLAS 1990 and SOLAS 2009 is the maximum damage limits. SOLAS 1990 addressed a penetration of B/5 and length 3m+0.03L (or max 11m) whereas SOLAS 2009 a penetration of B/2 and length 0.303L (or max 60 meters). A closer look into the residual stability thresholds applied over the years is provided in the next paragraph.

Figure 6 demonstrates the increase in the residual stability requirements for passenger ships from SOLAS 1960 Convention to date. Even though the nature of the criteria remained the same from SOLAS 1960 to SOLAS 1974, the increased demand from the

UK (MSN, 1998) resulted in a minor increase from 0.01 to 0.05 metres metacentric height GM. The step change from the deterministic SOLAS 1990 was observed with the introduction of Stockholm Agreement after the loss of Estonia. SOLAS 1990 postulated that all 2 - compartment damages do not submerge the margin line, however studies later proved the need to address different damage extents. Following this, SOLAS 2009 introduced an increase to GZ_{max} at 0.12 metres. However, the impact from Water On Deck was omitted for the case of RoRo vessels. Even though the GZ curve criteria for the previous deterministic regulations represent minimum values, which, in turn, must be achieved for every damage scenario as specified by the regulations (e.g. up to B/10 penetration), in the probabilistic method instead, each individual scenario does not necessarily need to achieve a value of GZ_{max} 0.12 metres but the interaction will be captured through the weighted average s-factor. Finally, SOLAS 2020 newly proposed amendments for the case of RoRo ships compensate for the effect of the Water On Deck (Hutchinson and Scott, 2016) through increased requirements linked to the GZ-curve properties. The main concepts underlying survivability and the critical wave height currently in place along with the latest approaches to estimate survivability are provided in the following sections.

3.3.1. Probabilistic damage stability assessment

SOLAS 2009 (IMO, 2009c) uses a comprehensive and advanced instrument for ship survivability assessment, a method constituting IMO's stability requirements currently in place (SOLAS Ch. II-B). This entails a fundamental assumption, within the probabilistic damage stability concept, being that the ship under investigation is damaged with ensuing large scale flooding stemming from hull breach. This can be regarded as the conditional probability of losing ship stability in the wake of a collision event disregarding the nature of the breach. The main focus is placed on the ship being flooded after the occurrence of a collision event. In this sense, the damage stability instrument implies the same level of "safety" irrespective of the mode of operation that can vary depending on ship type, or can involve vastly different consequences and flooding events or different modes of capsize constituting a total level of risk altogether (Vassalos and Guarin, 2009). This being said, all risk-related factors such as size of ship, number of persons on board, lifesaving appliances, subdivision and arrangements are explicitly accounted for by the

Required Index of Subdivision, R. This plays a vital role in the main condition within the probabilistic framework as provided by the inequality expression eq.(3-1) where A is the probability of ship surviving collision damage, namely the Attained Subdivision Index.

$$A \geq R \tag{3-1}$$

The Attained subdivision index as outlined within SOLAS 2009 (IMO, 2009b) is formed from the summation of three probabilities as expressed from eq.(3-2) below.

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \cdot p_i \cdot s_i \tag{3-2}$$

Where,

- j Represents the loading condition under consideration.
- J Represents the total number of loading conditions considered in the calculation of A, usually three draughts covering the operational draught range of the vessel.
- w_j Represents a weighting factor applied to each initial draught.
- i Represents each compartment or group of compartments under consideration for loading condition, j.
- I The total number of all feasible damage scenarios involving flooding of individual compartments or groups of adjacent compartments.
- p_i The probability that, for loading condition, j, only the compartment or group of compartments under consideration are flooded, disregarding any horizontal subdivision.
- s_i Accounts for the conditional probability of survival following flooding of the compartment or group of compartments under consideration for loading condition j weighted by the probability that the space above a horizontal subdivision may not be flooded.

The Attained Subdivision Index represents the conditional "averaged" probability of survival or else put simply the "weighted average s-factor" following the summation of survivable flooding scenarios as depicted from eq.(3-2). Therefore, this can be translated as,

$$A = E(I) \tag{3-3}$$

This means that Index A is the marginal probability for time to capsize within certain time, assuming that the time being considered is sufficiently long for capsize to have occurred in the majority of cases. This is a key observation, as this can be used to derive the flooding risk contribution, as indicated in the following. However, the assumption on time being sufficiently long is significantly critical. Finally, the Required Index of Subdivision, R represents the level of safety associated with collision and flooding events that is deemed to be acceptable by society, in the sense that it is derived using ships that society considers fit for purpose, since they are in daily operation. In line with the standards in place (IMO, 2009c), the Attained Index must be greater than the required R (A>R) and specifically for passenger ships (A≥0.9R) in order to form the limiting GM curves.

With this in mind, one could observe that two ships with different watertight architectures and size altogether, are equally safe if they achieve the same Attained subdivision Index. This, in turn, implies that they will have the same overall capacity to resist flooding following collision which cannot be true under any circumstances.

The fundamental element which describes the probability of surviving collision damages in waves is described by the s-factor as depicted by eq.(3-4), in line with the probabilistic framework of assessing damage stability. This, in turn, is linked to the concept of the critical significant wave height, which constitutes the basis for assessing the impact from the expected wave heights statically. The following sections provide and review the concepts related to survivability in more depth.

3.3.2. Relationship between s-factor and the critical wave height

The relationship between the survivability factor and the critical wave height stems from the consideration of the s-factor as an average probability of survival with the averaging function being the probability density function of the encountered sea states during collision incidents as provided by eq.(3-4) (Jasionowski, 2009b).

$$s = Prob\{Hs \leq Hs_{crit}\} = \int_0^\infty f_c(Hs)P(Hs)dHs \qquad (3\text{-}4)$$

Where,

$f_c(Hs)$ Probability density function of a sea states recorded at the instance of collision

$P(Hs)$ Probability of surviving flooding casualty in sea states for a specific time given the specific loading condition and flooding extent (sometimes it can be regarded as "prime s-factor") (Vassalos et al., 1997, Pawłowski, 2007)

In an abridged manner, it can be assumed that $P(Hs)$ is a unit step function centred at the critical or limiting Hs (i.e. $P(Hs) = 1$ for all $Hs \leq Hs_{crit}$ and 0 otherwise), hence the s-factor can be expressed as follows (Jasionowski, 2009a).

$$s = Prob\{Hs \leq Hs_{crit}\} = \int_0^{Hs_{crit}} f_c(Hs)dHs \quad (3\text{-}5)$$

The above insinuates that in order to evaluate the s-factor, it is necessary to establish the critical (or limiting) sea-state Hs_{crit}, as discussed in the foregoing section.

3.3.3. Determination of the critical sea state

The critical sea state for a specific damage extent and loading condition can be established either with the aid of model test experiments or employing time-domain numerical simulations (first principles). Traditionally, both approaches have been utilised in the past in the course of the development of survivability criteria and verification between the two. Generally, the experiments either of physical or numerical nature are subjected to repeated time trials (usually 30 minutes full-scale) in a random realisation of a specific sea state with the view of deriving the capsize rate at that specific wave height. Subsequently, a distribution $P(Hs)$ can be derived following multiple repetition of tests (Tsakalakis et al., 2010b). Depending on the definition, the critical sea state can be regarded as a wave height at which $P(Hs)$=0.5 or alternatively as a highest sea state with low probability of capsize (e.g. $P(Hs) < 0.05$, as proposed in GOALDS and more in-line with the notion of limiting wave height) according to (Cichowicz et al., 2016b).

Usually the critical wave height is related to the geometrical characteristics of the vessel and its residual stability. These of course can vary depending on the derivation process and design of experiments implemented. Customarily this step is implicitly considered with the s-factor calculations. In this sense, the s-factor eclipses the presence of the critical sea state and instead survivability is expressed directly as a function of ship and stability residual parameters. The following sections provide a comprehensive discussion on the findings of the approaches and state of the art with regards to survivability.

3.3.4. IMO Resolution A.265

The survivability factor adopted in resolution A.265 (IMO, 1976) is based on an extensive research on survivability by (Bird and Browne, 1973). Historically, that was the first time model experiments were conducted on a flooded ship at the time along with previous studies from (Middleton and Numata, 1970). The two research programmes aimed at identifying a set of relationships that address the survival sea state of a damage based on flooded GM and effective freeboard along with the probability of exceeding this sea state. The latter is based on a set of accident historical data with distribution of wave heights (IMCO, 1973). The resultant formulation characterises the survival state as a function of the effective freeboard, metacentric flooded height and ship breadth. Also, the experiments considered the relationship as "a consistent relationship between combinations of initial stability, residual freeboard and sea state" even though there was a lack of inherent confidence for lower survivability (when $s<0.6$, zero value is assigned) (Vassalos et al., 1995). The formulation for the survivability factor as later adopted by IMCO (IMCO, 1973) in a slightly modified approximate format which is provided from eq.(3-6) below.

$$s = 4.9\sqrt{\frac{F_E \cdot GM}{B}} \tag{3-6}$$

Where,

F_E	Is the Equivalent residual freeboard (m)
GM	Initial stability (flooded metacentric height) (m)
B	Breadth of the ship (m)

The process of deriving the s-factor for the given damage condition underlying damage stability calculations in A.265 is illustrated in Figure 7. Simply, for different damaged GMs (one GM is presented below) can provide an approximation on the survival state obtained through the cumulative probability of survival.

The s-factor achieved as part of resolution A265 was part of the first probabilistic provisions in assessing damage location and extent. In the same manner the s-factor models presented in the foregoing sections have sustained the probabilistic elements. However, the intrinsic inaccuracy of the models is based on the limited sample utilised during the development (291 observed incidents recorded between 1946-1967 (Kendrick, 1999)) and the choice of parameters along with the way the relationship between survivability and the ship characteristic is captured, deem the relationships inaccurate and insufficient. Therefore, various attempts followed aiming at enhancing the s-factor models at hand or deriving more robust alternatives. The main attempts in this direction are described in the foregoing sections.

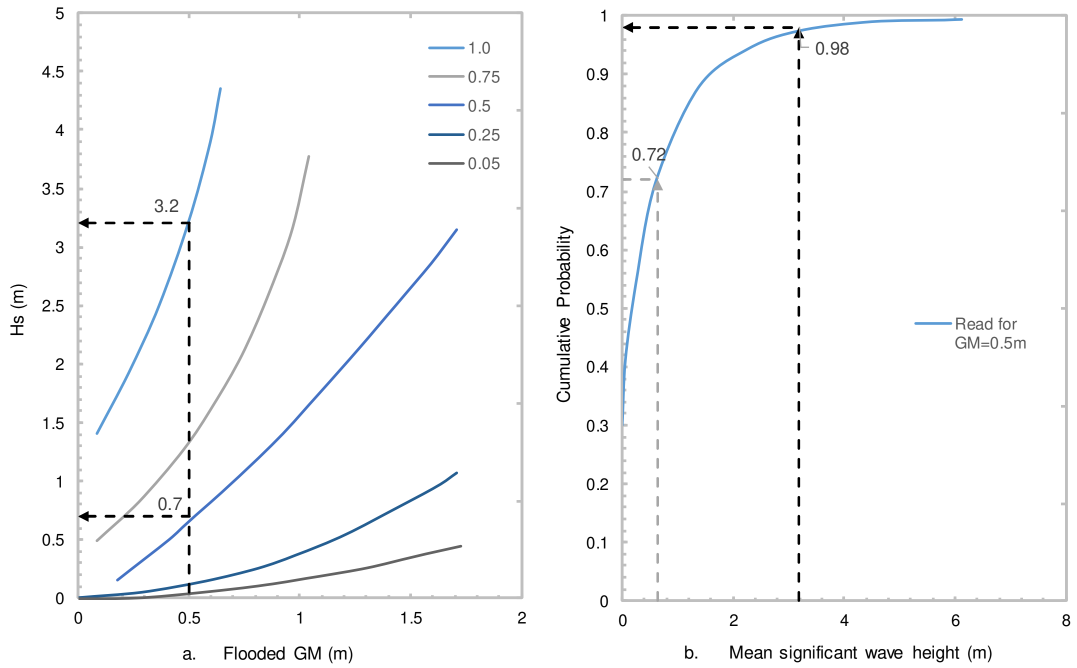


Figure 7 : Method of deriving limiting sea-state and survival index s.

A subsequent study from the UK RoRo research programme provided an alternative relationship incorporating the non-dimensional metacentric height. However, definitions such as the effective freeboard can be peculiar in terms of the subdivision and arrangement they represent and, therefore, cannot be sufficiently generalised as discussed in (Vassalos et al., 1995). Damage stability is regarded as a very complex problem while deductions on a survival boundary would be insufficient based only on two geometrical parameters.

In addition to the observations presented in Figure 6 and Table 1, showing the same GZ curve properties between SOLAS 1960 and resolution A265, one can note two deficiencies as they were clearly noted in (Tuzcu, 2003c). Firstly, the effects of the loading condition and operation of the vessel are not properly accounted for, since only the deepest draft is considered in the model experiments. Also, the resolution overlooked the way different damage extents are considered within the framework since different subdivisions might lead to different damages and flooding pathways.

Many elements of resolution A265 were transferred to the updated version of SOLAS in 1990, which was applied probabilistically on dry cargo ships over 100 meters. Eventually however, a number of concerns started to surface with regards to the proposals taken forward from resolution A265. To begin with, the huge amount of casualty scatter was notable with inconstancies in the trends regarding ship size resulting a cut-off trend at 200 meters. In addition, according to (Kendrick, 1999) the probability of occurrence of collision damages can differ altogether for a cruise liner, ferry and cargo vessel since passenger ships tend to spend more time at costal water where traffic density is higher. In that case, the probability of collision and survivability should cater for different ship types as passenger ships are prone to higher probability of collision.

3.3.5. Static Equivalent Method (SEM)

Historically, SEM is an approach originally recommended following a number of model test observations from (Vassalos et al., 1997). Then, following a number of refinements within project HARDER (Pawłowski, 2007, Pawlowski, 2004, Tuzcu, 2003a) an updated formulation was recommended in order to be applied in assessing survival probability for passenger ships (Pawłowski, 2017). Based on the findings from HARDER, it was suggested that SEM should be used for the estimation of survivability of waves of RoRo ships while the conventional s-factor should be used for the estimation of survivability of cargo ships.

Notably, as mentioned in (Tagg and Tuzcu, 2002) the SEM methodology was developed on the basis that the traditional survivability methods (GZ_{max} etc.) do not adequately estimate survivability of RoRo ships. At the time, a distinction was made between low freeboard Ro-Ro vessels and non-RoRo vessels, because of the observed differences in their mechanisms of capsize. The original SEM method linked the critical sea state to the dynamic elevation of floodwater (resulting from action of waves) on the vehicle deck, h, can be provided by the boundary stability curve as follows (applicable only to RoRos with large undivided spaces like vehicle decks),

$$Hs_{crit} = \left(\frac{h}{0.085}\right)^{\frac{1}{1.3}} \tag{3-7}$$

Where both the Hs_{crit} and h are taken as median values of the respective random quantities. The critical significant wave height can be then used in the s-factor formulation adopting the cumulative distribution of waves from IMO.

In project HARDER, the formulation was updated following a statistical relationship between dynamic water head (h), the freeboard (f) and the critical heel angle and the mean significant survival wave height. This turned out to overestimate survivability at the lower end of the 3D surface.

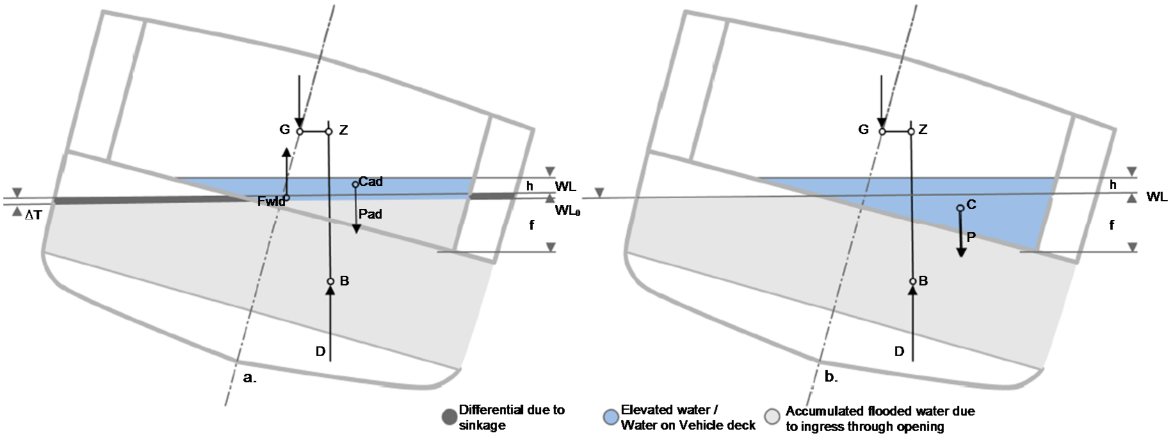


Figure 8: (a) Depiction of SEM parameters with water elevation in the vehicle deck at the Point of No Return (PNR) - case of RoRo ship. (b) Normal method employed by damage stability software considering the floodwater volume as a total water on the vehicle deck inside an undamaged tank.

Based on (Tagg, 2014) the SEM method, accounting for the probability of capsizing considering water on deck effects, was used as a replacement, which in the case of low freeboard RoRo passenger ships aiding in retaining consistency with SOLAS95 North European standards and eventually stringent Stockholm Agreement. Also, (Pawlowski, 2010a) performed a comparison between SEM and SOLAS s-factors on a ferry. According to the author, the pre-HARDER formulation underestimated significantly the critical wave height providing a formulation independent from ship-type loading condition, subdivision and so on. The results indicated a large insensitivity of the SEM method on the damages and that was merely due to the sole dependence on the elevation of water at the critical heel angle.

According to (Jasionowski et al., 2002), SEM was initially applied to derive the survival time but it was inadequate due the insufficient sample of physical model experiments used in deriving and quantifying the survival band generating generalisations of the ship behaviour. SEM deals only with the (stationary) steady state mean water accumulation ignoring the element of the flooded volume. To this end, (Bulian, 2008) extended the method quasi-static equivalent method accounting for the effect of accumulated water and presence of multiple number of compartments. The findings of SEM formed the precursor to the subsequent approach namely Stockholm Agreement for RoRo damage stability assessment. A brief discussion is provided in Appendix A.

3.3.6. SOLAS 2009 survivability

Survivability in SOLAS 2009 is calculated based on the findings of project HARDER by means of the s-factor as a metric of the safety level for statutory compliance. It is known that the s-factor depends upon a number of parameters which are related to stability, floatability, evacuation and operability of the vessel after flooding incident while depending on the damage stage (final or intermediate). Figure 9 below shows all the related parameters, which are involved in the calculation of the s-factor according to SOLAS II-1 §7-2. The final step is related to the calculation of Attained subdivision Index based on three damage stability loading conditions and the associated weightings.

The relationship between the stability parameters and the critical significant wave height is discussed previously by (Tuzcu and Tagg, 2002). Although the final recommendation of HARDER aimed in the adoption of SEM (see §3.3.4) for passenger ships, it was finally decided by the IMO to adopt the model, which was initially intended for cargo ships as presented in Figure 9. The coefficients of 0.12 meters and 16 degrees are regression parameters, usually referred to as targeting values TGZ_{max} and TRange, respectively. As in the case of resolution A.265, the probability of survival of a flooding event after a collision damage involving one or more compartments is currently defined in SOLAS Ch.II-1 Regulation 7-2 through the s-factor. The formulation of the s-factor is based on the concept of critical significant wave height HS_{crit}, as derived from HARDER project (Tuzcu, 2003a).

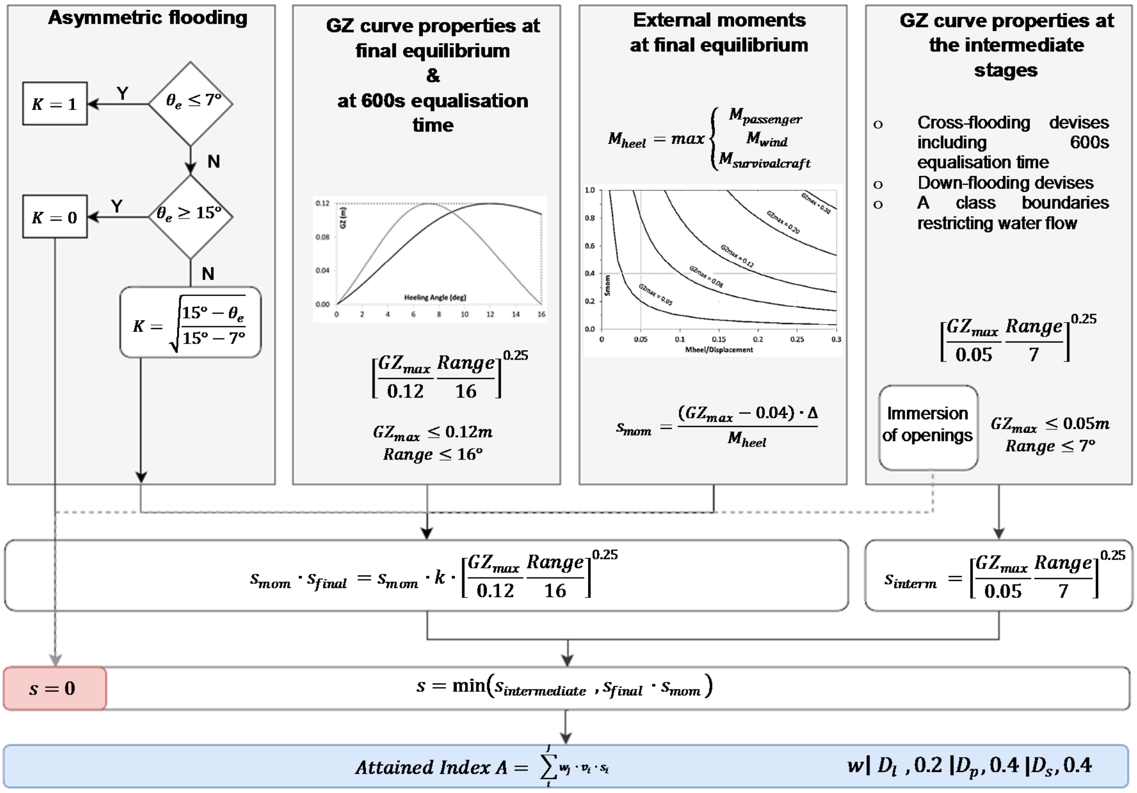


Figure 9: Calculation process of s-factor as per SOLAS 2009 accounting for external moments at final and intermediate stages of flooding.

$$Hs_{crit} = 4\frac{GZmax}{0.12} \cdot \frac{Range}{16} = 4s^4 \leftrightarrow s = \left(\frac{Hs_{crit}}{4}\right)^{0.25} \tag{3-8}$$

It is noteworthy to mention that the survival factor established through harmonisation produced a survival probability relating to the dynamic effects of encountering waves only when the vessel had reached final equilibrium after damage. Deriving from the definition of the survivability factor, a number of pitfalls surface which are the result of compromises and assumptions. To begin with, one of the main assumptions lies with the conditional probability of loss of stability itself. The current framework does not account for the cause of the breach (grounding or collision), modes and progressive flooding sequence or the circumstances that led to it. In this sense, the same safety level can be assigned irrespectively of the mode of ship operation, which inherently depends on the ship type (Vassalos et al., 2005). This is crucial in the case of passenger ships and especially cruise ships as they operate in areas with very high traffic density and low proximity to ports where the risk to life and likelihood of accident will be higher.

Moreover, examining the sample of ships considered during the modelling of survivability in project HARDER (see Appendix A) one could observe that while 7 ship models (3 RoPax, 2 RoRos and 1 cruise ship) were considered in the project, the formulation of the s-factor is based merely only on the two RoRo ships and on 25 data points out of 51. Given the very well-known differences between passenger and conventional cargo ships with regards to their capsize mechanisms and the intricate internal architecture of the former, one could agree that the s-factor in place is not appropriate and robust for the case of passenger ships. But here again, a serious different ion shall be made between cruise ships and RoPax vessels, which are currently assessed under the umbrella of passenger ships. According to the study conducted by (Jasionowski, 2005) on three cruise ships and 33 different damage cases, it was demonstrated that one third of the cases capsized within 2 hours yielding an s-factor equal to zero. Here, the fundamental problem is that the s-factor and the critical wave height is based on experimental data derived within 30 minute exposure. At the time, the critical wave height was perceived as the wave height at which there is 50% probability of survival with exposure time of 30 minutes.

Building on that, the s-factor provides the wave height value up to which the vessel has 50% probability to survive for 30 minutes at least and little else, and consequently any deduction for survivability of cruise ships will be misleading. Also, this cannot be helpful for the SRtP requirements relating to 3 hour floatability and residual functionality of critical systems. Traditionally, the GZ curve properties cannot capture accurately the behaviour of a damaged cruise ship pertaining to intricate internal watertight architecture and subdivision presenting different loss mechanisms. That is justified because of the abundance of openings, which when immersed truncate the GZ curve leading to small GZ_{max} and Range values. The high degree of cruise ship internal detail subjects survivability sensitive to local details, which in turn, renders survivability of large passenger ships in waves incapable of capturing the global phenomenon pertaining to the involved dynamics.

Therefore, the current s-factor does not represent the average resistance of cruise ships to capsize after a collision damage, leading to flooding (Vassalos et al., 2007). This is further exacerbated by the presence of Multiple Free Surface (MFS) phenomena in the case of complex subdivision ships, which are not captured by any flooding stage, based on the framework adopted. Adding to this, the s-factor in place does not account for the transient flooding process, which according to literature from (Vassalos et al., 2005) they can impose significant limitations to ships with intricate watertight architecture.

Allied to this, according to (Vassalos and Jasionowski, 2011) the cruise ship used in the experiments of project HARDER was able to survive wave heights higher than 4 meters and therefore the formulation underestimates survivability of cruise ships. This is not the case for RoRo vessels where it was found that survivability is overestimated and as a general statement provided by the authors, the bigger the vessel the larger the deficiency of the s-factor. The s-factor represents a conservative nature itself as it provides an approximation of the distribution of probability for sea states encountered in collision incidents, redistributing probability weight mostly towards higher sea states. In particular, there is a 30% probability that a collision damage will occur in calm water, whilst, 90% of all collisions occur in 2 metres or lower wave height. Moreover 99.9% of collisions have been encountered in lower than 4 metres significant wave height. In this respect, a vessel can withstand 4 metres wave heights in damaged condition and as a result it can survive 99.9% of collisions with a probability of survival of 99.9%.

However, the problem is related to the assumption that if GZ_{max} is equal to or larger than 0.12 m then the vessel can survive 4 metres wave height and this can only be true in the case of non-RoRo vessels. Looking into the assumption underlying MSC216, which relates GZ_{max} to 0.12 meters to the critical sea state of 4 metres for a specific flooding case on any ship type, a RoRo ship only survives a sea state of 4 metres after flooding, if GZ_{max} in this flooding case approaches a value of 0.25m or above. In light of the aforementioned, the need to address survivability for cruise ships, RoPax and cargo ships independently is highlighted.

Another drawback, which was brought to attention by later studies (Spanos and Papanikolaou, 2011) is the limitations of the wave distribution considered in SOLAS 2009. The survivability factor constrains the maximum encountered significant wave height to 4 meters, which represents a 99% probability. This, in turn, is averaged across all the accidents encountered in the accident database presented by (Heimvik, 2001). The accident database comprised a total of 3,000 records out of which only 389 collision cases, incorporating the recorded incidents from resolution A265, (excluding collisions on rivers and channels) are included for the purpose of regression.

Notably, an important element is that the accident database included every ship type. While most of the accidents recorded in coastal waters and with close proximity to ports there is some uncertainty on the 5 cases (Hs>4m) with the highest wave height, as these were reported to be in the vicinity of a port or a harbour (Heimvik, 2001). Indicatively, based on the wave height distribution obtained, there is 1.5% probability based on the marginalisation process to encounter environments with wave heights higher than 4 metres, which is considerable. The statistics suggest that almost 50% of collisions occur in calm water where the induced dynamics are neglected, whereas another 50% occurred in waves.

Building on the above, the s-factor does not account for different ship types and ship tendencies or patterns between passenger ships and cargo ships. Also, based on studies from (Jasionowski, 2009a) it is indicated that survivability is underestimated when the HS_{crit} is between 1 and 4 meters, while it overestimates cases for significant wave heights less or equal to 1 metre in the case of RoPax ships and cruise ships can survive higher sea states than 4 metres. More evidence was presented (Vassalos et al., 2007) that the framework focuses only on conditional safety independently of the nature of collision risk. Adding to this, the regulations in place require the same safety level without the consideration of the area of operation and thus neglecting the actual operational wave environment of ships.

With this in mind, the consideration of localised wave statistics and their impact on survivability would help ascertain the actual risk of ships subjected to specific areas of operation with pertinent wave limitations. An attempt in this direction was performed by (Spanos and Papanikolaou, 2011) considering the operational wave profile in the prediction of survivability to provide a ship-specific solution. However, the method lacks inherent confidence as it includes multiple intrinsic uncertainties pertaining to the correlation with the critical wave height and its determination while the concept appears limited in terms of applicability and verification. Also, (Pawlowski, 2010b) emphasised the importance of localised wave distributions in the calculation of the critical significant wave height as it would potentially provide "regional deviation" in the s-factor calculations.

Furthermore, at the heart of the probabilistic framework is the Attained subdivision Index (an "aggregated" statistic), which can be regarded widely as a rigorous model for assigning the marginal probability of survival, "averaged" over all the external pertaining parameters, which set the level of ship stability as discussed by (Jasionowski, 2009b). In this sense, the A-Index reflects the average survivability of vessels following a collision damage and therefore an accurate calculation of this metric is of significant importance to damage stability assessment. Regulating the level of ship stability by relying on the Attained subdivision Index, provides the designer with adequate freedom and flexibility in setting the watertight architecture arbitrarily, without the regulation stipulating a set of solutions that will ensure compliance, as for example the B/5 bulkhead.

On the other hand, the Index A is the first comprehensive probability within the standard that considers all feasible damage cases, and not a fraction of the cases being flooded that will be analysed before compliance. A problem, however emerges, when looking at the product of the marginalisation process since probability A considers the loading conditions through the introduction of probability relating to loading conditions or else weighting w. The introduction of probability w derives from the assumption that the ship's loading condition is a random variable, which cannot be true. The weighting factors in the case of passenger ships are derived based on a draft triangular distribution ranging between the lightest and deepest draft vanishing towards the end representing the time spend in each loading condition as originally described in (IMCO, 1973).

However, one can question the degree that these values reflect the actual loading drafts and operational profiles of the passenger vessels currently in operation. In fact, the aforementioned contradicts what has been known over the past years in the practices of monitoring loading limits for a range of drafts whose GM limits are used in order to define and attain a constant level of stability. In line with this, the drafts have been considered to a known range at every time within the vessels life cycle, while it is a known parameter at every instant of ship operation, implying that a draft is never a random variable in real life. Even in the case of intact stability with regards to the limiting criteria applied on the GM curve, the drafts have never been assumed as a random variable, but instead as a known range. When looking into the damaged limiting curve and compliance with the inequality of A≥0.9R for every draft, the weighting w can compensate for worst stability in the case of one draft and better stability for another, leading to an overall probability A that is lower than expected, if the actual frequency of operating at the deepest draught is actually higher than the assumed weighting. The calculation of the overall Attained index can be very sensitive in the case of cruise ships (Tagg, 2014) and therefore this will need to be subjected to scrutiny in future developments of the regulation-making processes.

3.3.7. EMSA 2009

The study led by EMSA in 2009 on the investigation of survivability of different ships (Jasionowski, 2009a) focused on the impact of the different probabilities of the framework. As indicated in the previous section, the regression of the model in project HARDER is subject to considerable uncertainty, leading to an inefficient spread between the predicted values and the measurements (see Appendix A). All critical sea states established for cases selected for model experiments in this study proved to be higher than the calculated values. Although there is no robust justification for the huge scatter between all the data, these experimental results must be viewed together with all existing data. In this case, a proposed a conservative approximation with view of establishing accurately the critical sea state to at least as high as to that of the measured data during experiments.

In this sense a new formulation is not proposed but instead a recommendation is brought forward to change the SOLAS targeting values for GZ_{max} and Range to 0.25m and 25 degrees, respectively. This recommendation aimed at ensuring that the s-factor does not underestimate survivability in 9 out of ten cases of RoRo ships (Jasionowski, 2009b).

Also, in a study presented by (Tsakalakis, 2012), the impact of the new recommendations on the Attained index had a miniscule effect. In particular, according to the author, the minor impact is caused by the distribution of damage cases and their inherent nature along with the dependency on the required index and the probability of survival of each damage case scenario. Despite the attempts of the EMSA study to address an accurate survivability factor, the drawbacks of the formulation are not diminished and therefore a call for further improvements will appear in the research project GOALDS.

In the same vain, the EMSA study addressed the impact from the draft distribution as the concerns started to be raised post-HARDER with regards to the validity and robustness of the predominant three "unrealistic" draft weightings. Based on the comprehensive sensitivity conducted by (Jasionowski, 2009b) it was suggested to remove the w factor altogether from the calculation of the Attained Index. Particularly, the sensitivity was performed on a vessel in two ways; using one constant draft, which provided an index of 0.712 and using three weightings (0.05, 0.4 and 0.55) based on one actual operational distribution providing a lower Attained index. Even though the impact of the recommendation was obvious, the effect of the actual operational data in the damage stability assessment has not been captured in the full extent accounting for a range of real operational profiles. That can prove important, especially in the case of cruise ships as the current framework has been proven to underestimate survivability for these ships (Vassalos, 2015a).

In the past, an attempt was performed as part of the JNWER project (Rusaas et al., 1996) with a study on a limited data from RoRo ships providing three weightings based on the intact draft of the vessels at the time of the accidents. Unfortunately, little can be found from literature on the origin and nature of the data. The intact draft distribution demonstrated that the ships operate mostly at the upper half of their draft range between the lightest and deep subdivision drafts. Particularly, the highest draft frequencies lies within the 70-80% interval while above 80% the draft frequency is halved.

3.3.8. GOALDS Project (2009-2012)

In spite of the long-drawn-out efforts of the industry to neutralise the surfaced implications of the survivability approaches in place, survivability calculation based on SOLAS appears to be conceptually inadequate for the case of cruise liners and RoPax ships and further research is necessitated (Turan and Tuzcu, 2003, Vassalos and Jasionowski, 2011).

One initial step in this direction was taken by (Tsakalakis et al., 2009b) , in line with the EMSA study, proposing a new survivability factor for RoPax ships. The proposed formula is based on the existing HARDER data set for RoPax ships and the same formulation is used as basis but with different GZ_{max} targeting value (0.25m), while

TRange remains the same as the related sample is well reflected through the existing values. This philosophy has also been suggested by (Scott, 2011), which according to the author is an accurate and conservative solution.

On this basis, survivability seemed to be captured accurately but still the problem of omitting cruise ships and a significant stability area for RoPax ships was profound. In this line, within the EU-funded project (GOALDS, 2009-2012) an attempt was made to propose an alternative to HARDER's survivability formulation that caters for passenger ships whilst accounting for the main differences between RoPax and cruise ships. The research revisited all the major concepts related to survivability (e.g. accumulation of water on deck, capsize band, relationship between stability parameters and survivability, time to capsize).

Based on (Papanikolaou et al., 2011), the GOALDS accident database comprised 1,587 casualties, incorporating the existing HARDER database, with casualties encountered between 1944 and 2009 (HARDER database spans between 1944-2000). Also this entailed a differentiation with regards to the nature of the accidents (1016 collisions, 472 groundings and 39 contacts in total). Even though different ship types were accounted for, it was deemed appropriate to consider all types within the statistical analysis of damaged extents for two reasons. Primarily, based on the statistical samples, the same damage patterns and trends were noticeable across the different ship types and secondly, only a limited number of passenger ship casualties (7%) was available at the time (Papanikolaou et al., 2013).

Yet, according to the authors, passenger ships with length over 200 meters constituted a high uncertainty due to the scarcity of the data at hand. In addition to this, the s-factor is based on the concept of the critical significant wave height following project HARDER and the cumulative distribution of critical wave heights was based on the sample of sea states for collision damages accumulated from before providing an updated exponential regression formula. To this end, one could agree that the shortcomings of the HARDER formulation are still present despite the aforementioned efforts.

As part of the project, 20 RoPax damages and 2 cruise ships were subjected to parametric investigation numerically (Cichowicz et al., 2016a) for the establishment of survivability whereas, tank experiments were conducted on two RoPax and two cruise ships respectively, for verification purposes only in the case of collision damages. The collision damages were derived based on the worst SOLAS 2-compartment damage across ±35%L amidships, whilst, in the case of cruise ships, which exhibited high resistance to capsize, 3-comparment damages were used for the derivation of the survivability boundary. Based on the presented results (Papanikolaou et al., 2013), the cruise ships demonstrated adequate survivability and deductions on the capsize rate were impossible for the case of one cruise ship.

As a result, the survivability boundary of the cruise ships was derived by either opening the semi-watertight doors above the bulkhead deck in extreme scenarios or by increasing KG and reducing erroneously GM. This indicated the high survivability of cruise ships in severe scenarios, which resulted in only one point in the data available for regression (2 points in total, one from HARDER).

The study presented by (Cichowicz et al., 2016a) concluded that the two stability parameters in the current survivability formulation, namely GZ_{max} and Range are insufficient and incapable of capturing the relationship between the critical wave height and residual stability and, as a result, an additional element is required that reflects the ship size. This has been previously noted according to literature from (Tagg, 2014, Scott, 2011) where the authors believe that the GZ_{max}, range and heel is a simplistic approach to the problem and this might have been resolved by the introduction of the residual freeboard or accumulation of floodwater. Currently, the framework focuses on the residual GZ curve but the problem reappears when looking at the Attained Index. The TGZ_{max} is insensitive to survivability as a large proportion of damage cases are equal to zero or unity and there is no penalty when s=0 as long as the inequality A≥R is correct even if the ship sinks without reaching equilibrium.

Allegedly, the size of the ships (watertight subdivision, volume, main dimensions etc.) plays a vital role in the statistical correlation with the critical wave height. The significant scatter in the results is attributed to the “effects of scale”, which are the result of the small range and maximum GZ values, which in turn impose great limitations to survivability. In this sense, in order for two ships of different size to achieve the same critical significant height, their residual stability properties (GZ_{max} and Range) would vary and differ significantly. This is mainly attributed to the difference in floodwater volume accumulation in the damage compartments, which results a disparity in the residual stability parameters. In this respect, an attempt is presented by (Cichowicz et al., 2016a, Tsakalakis, 2012) providing a measure, that of the centroid of the residual volume as a function of the vertical centres of intact and damaged compartments divided by the draft of the intact condition, in order to compensate for the size parameter.

Even though the correlation is satisfactory, the relation is inadequate for two reasons. Initially, the approach is based on a regression formula, which could be rather impractical for other ship sizes than those utilised in the regression. Secondly, the formulation is based merely on the GZ curve properties (GZ_{max} & Range) and is subjected to truncation in the presence of openings. As a result, the values are restricted to the immersion of openings and their topology and this allows for a significant positive area/stability of the GZ curve to be omitted. This can be very detrimental in the case of cruise ships with intricate watertight architecture, subdivision and excessive number of openings above the watertight bulkhead. Conceptually, this would mean that survivability is restricted to local details without consideration of the physical properties of the vessel in an operational environment. Therefore, a survivability factor that would account for the global details of the vessel would be essential for the definition of the problem. This, in turn, will allow for consideration of the size of the vessel and main residual stability properties.

To this end, one more rational recommendation comprised the proposal to associate the critical wave height with the highest sea-state at which no capsizes are observed, which in a sense would make the HS_{crit} time-independent as provided by the following model (Cichowicz et al., 2016b).

$$Hs_{crit} = \frac{A_{GZ}}{0.5 \cdot GM_f \cdot Range} \cdot V_R^{\frac{1}{3}} \tag{3-9}$$

Where,

A_{GZ}	Represents the area under the GZ curve (un-truncated)
GM_f	Represents the flooded GM
Range	Represents the range of positive stability
V_R	Reflects the residual volume of the watertight envelope (i.e. excluding compartments within the damage extent)

A number of parametric studies (Puisa et al., 2012) (Zaraphonitis et al., 2012) have been performed to assess the impact of GOALDS and SOLAS 2009 survivability factors (and critical wave height) on passenger ships. The first, through a quantitative statistical analysis demonstrated that the GOALDS formulation yields a higher Attained Index when compared to the SOLAS counterpart, while, it was proven more sensitive to design alterations related to subdivision. According to the authors, the introduction of the residual volume in the formulation of the critical wave height constitutes a very critical and influential element as it accounts for the effects of ship size. However, the residual volume depends on the way the ship is subdivided and the topology of the bulkheads and watertight deck. This, in turn, implies that a higher positive stability can be attained (through the increase of the GZ_{max}) when the volume is distributed higher above the bulkhead deck and as far from the centreline as feasible. Based on observed trends, the position of the bulkhead deck on cruise ships exacerbates or enhances stability and that is solely depended on the VCG of the vessel. In other words, the residual volume is a reflection of the vessels reserved buoyancy, that being the available buoyant volume above the vessel equilibrium waterline. This is a good indicator of the vessel's dynamic stability of their volume available to generate the vessel's righting lever when distributed from its equilibrium position by only excitation forces. The higher and the wider the volume is distributed, the larger the restoration couple GZ formed between the centre of gravity and centre of buoyancy.

However, this is not the case with RoPax ships as the difference between the two formulations appears to be minor and this entirely accounts for the impact and the presence of a long lower holds (LLH) (Puisa et al., 2013). Nevertheless, the LLH RoPax ships entail different loss mechanisms (margin line immersion and rapid capsize/sinking in calm water) in contrast to ships designed with transverse subdivision below the vehicle deck and this will require further attention in the future.

Notwithstanding the above, according to (Vassalos, 2012, Cichowicz and Murphy, 2016) the formulation accounts adequately for the water on deck, scale of ship, and interfaces to the SRtP philosophy through the concept of Hs deriving from a very good correlation with the experimental data. Nonetheless, there is a number of drawbacks despite the accuracy derived when compared to the HARDER counterpart. Particularly, survivability is based only on two points for cruise ships, while the rest of the points represent SOLAS90 RoPax ships. The later have a simplified configuration and internal watertight arrangement and, as a result, the calculation of flooding progression following collision can be easily estimated, which cannot be the case for large passenger ships. Also, the model presents a "counterintuitive" nature because of the presence of GM and Range, which implies strict physical significance (Cichowicz and Murphy, 2016). Building on the above, the GOALDS survivability formulation is an inadequate means of damage stability verification for modern cruise liners and RoPax vessels and as a result further study in the field would be essential.

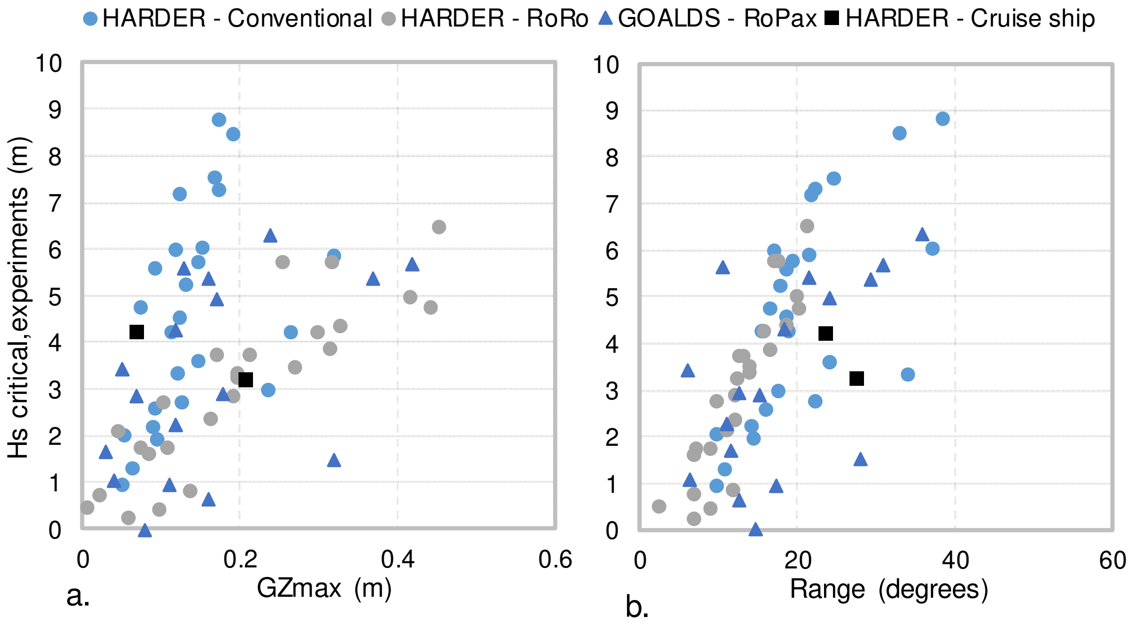


Figure 10: Hs critical obtained via model experiments versus a) GZmax b) Range

Touching upon the design of the formulation, in order to reflect the "epitome" of passenger ship survivability, it would be essential to compose an s-factor (or Hs_{crit} formulation) engaging a number of governing parameters. Initially, as it has been indicated through the aforementioned, the geometry of the vessel (size, volume, characteristics) needs to be accounted for considering the influence of scale. This is very important in the case of cruise ships pertaining to complex architecture. One predominant geometrical characteristic is the residual freeboard, which has been used previously in resolution A265. However, for operation in waves, the residual freeboard can be negative, thus leading to large Range and GZ_{max} requirements.

On the other hand, a small Range (truncated), which is the result of rapid immersion of openings, can yield a high flooded GM, which will result in a ship sensitive to high accelerations and motions. The flooded GM is a good candidate since it reflects the excitations when the vessel is damaged but this is inherently connected to the area under the GZ curve and its properties. In the case of calm water, the predominant prerequisite is to attain positive residual buoyancy, considering positive area under the GZ curve A_{GZ}. This, however, is dependent on the properties of the GZ curve, namely Range and GZ_{max} which have to be not truncated in order to capture the global characteristics of the vessel. Theoretically, the aforementioned parameters namely, A_{GZ} of flooded ship, flooded GM, residual freeboard and residual buoyancy are necessary in the formulation and conceptually they are interrelated but this is hard to put it into practice.

In light of GOALDS (Bulian and Francescutto, 2011), it was demonstrated that bottom groundings follow a semi-empirical analytical approach employing "semi-empirical s-factors" being hardy applicable to real passenger ships as the method was initially based on "box-shaped" vessels and therefore, according to the authors, it was important to use Monte Carlo simulations in order to generate breaches in future applications. Based on previous work from (Lutzen, 2001, Lutzen, 2002), collision damage distributions, p and v factors were generated providing what is now implemented in SOLAS 2009 as a basis for assessments.

However, the element of grounding is absent in SOLAS. In fact, bottom groundings (only vertically) are considered through regulation 9 (IMO, 2009c), which stipulates minimum requirements for double bottom height based on accident statistics (Heimvik, 2001). In a similar context, for the case of dry cargo ships, MARPOL (IMO, 2003b) specifies a non-analytical method for the assessment of oil outflow performance and double bottom requirements. In this line, this was addressed following the work from (Kehren and Kruger, 2007), which proposed a MC direct approach for oil outflow with the potential of utilisation in survivability assessments.

When scrutinizing the "Zonification" approach in SOLAS 2009 (IMO, 2009c) one could agree that it constitutes a fast and accurate method, however, it is impractical to use in the case of collisions since a number of explanatory notes is required for the consideration of complex compartments with unsymmetrical shape (that is because the derivation is based on simple "box shapes"). This cannot be the case of groundings and especially large passenger ships. After GOALDS, a complementary study performed as presented in literature (Zaraphonitis et al., 2013, Bulian et al., 2016, Bulian et al., 2015) suggesting a new approach that accounts for grounding damages (bottom and side) in survivability assessment using a direct non-zonal approach for the generation of p-factors. The p-factors are renormalized for an adequate number of damage cases in order to represent survivability. The model can be easily updated in the availability of new damage distributions and statistics as opposed to the previously analytical expressions.

Additionally, SOLAS does not account for the distribution of damages below the waterline of the vessel. This is currently approached using the conservative "worst case approach" technique (IMO, 2008), which combines v-factors and minimum s-factors but it underestimates actual ship survivability (Bulian et al., 2018). Currently, the generation of damages is based on the waterline of the ship in consideration, while the breaches extent the waterline with the lower limit being below, but it was found that the v-factors underestimate the occurrence of damages below the waterline (Bulian et al., 2018).

Furthermore, the GOALDS database provided a good confidence of the v-factors in probabilistic assessment. Based on this, (Bulian et al., 2018) presented a simplified "u-factor" to account for the cumulative distribution of damage extents below the waterline, which can be used as complementary to the SOLAS framework. One case study on a large cruise ship indicated that the introduction of the new factor raises the Attained Subdivision Index considering a passable amount of damages below the waterline. However, the aforementioned solution requires further purifications and verifications in order to form a robust implementation instrument for future application in the passenger industry.

3.3.9. Parameters with strong bearing on survivability

Over the past decade, a number of studies have revealed a multifarious number of governing parameters when flooding and survivability are concerned. Watertight subdivision, openings, watertight/semi-watertight doors, wave environment, damage extent, ship design and so on are explicit, while some implicit factors pertaining to survivability are essential; permeability is one of them.

The values of permeability that have been widely applied in the maritime industry cater for passenger and cargo ships. They were first introduced in 1912 (CSC, 1913) and they have remained unchanged during the course of the years regardless of the technological and scientific developments taking place across the industry. Currently, damage stability of passenger ships is assessed utilising values as descripted in SOLAS 2009 CHII part B reg. 7 (IMO, 2009c) designated to a limited range of specific compartment types. However, the origin and the basic rationale behind the established values remains unclear. The values have been adopted and used deterministically in the assessment of damage stability but one can question the extent to which the values reflect accurately permeable space in related ship compartments. This is also the case for tanker ships as it has been brought to attention by (Tagg and Letizia, 2009) when looking deeper into their respective damage stability framework, namely MARPOL reg. 24.4.2 (IMO, 2004). According to the authors, the values can be arbitrarily changed to comply with the desired statutory compliance standard when assessing stability and in this respect there is inconsistency. As a result, they recommend the adoption of realistic values to account accurately for structural and flooding permeability that address the physically inconsistent and incorrect calculations. This, however, applies to every ship type and size.

Undoubtedly, two of the most influential factors on flooding are the discharge coefficient and permeability. Extensive research has been conducted to assess the effects of the discharge coefficient (Vassalos et al., 2000, Stening et al., 2011, Vassalos and Letizia, 1998) on different arrangements along with numerous experiments (Smith and Walker, 1923, Ruponen et al., 2010, Hearn et al., 2008) in calm water to address the flooding rate through orifices and prediction of discharge coefficients by accounting for different orifice sizes and geometries (Wang et al., 2016b, Li et al., 2013). However, the aforementioned research does not consider the effects of the waves in damage ship motions, which has been accounted for by (Wood et al., 2015, Lobrowski et al., 2015) through carrying out model test experiments in three different wave heights. There, the results showed that the discharge coefficient reduces with increasing wave amplitude and height. Notwithstanding the above, it is obvious that the effect of permeability is not subjected to adequate scrutiny when assessing motions in waves.

In the past, numerous researchers have focused on the effect of damaged ship motions but a few examples are provided below that consider closely the element of permeability. For example, (Santos et al., 2002) indicated that water accumulation exacerbates when considering permeability to adjacent compartments with simulations conducted on a Ro-Ro shaped barge. This, in turn, causes excessive transient heel, which becomes dominant when the area of the opening increases geometrically. In the case of large damage sizes/breaches and when the ro-ro deck is located close to the waterline, excessive heel immerses the waterline and leads to ensuing accumulation of water through the deck. (Ruponen et al., 2010) demonstrated that when real permeabilities values are implemented in the assessment, the results tend to diverge in terms of correlation. This is justified due to the dependence and sensitivity upon the size of the damage. The damage considered was small and, therefore, the results are more sensitive to the attributed discharge coefficient.

Yet, (Veer et al., 2002) investigated the time to sink criteria, as it has been discussed in earlier sections, based on capsize criteria performing 125 time-domain numerical simulations on a single damage case for a range of wave heights spanning from 2.5 to 15.5 metres. Permeability was captured by detailed modelling of the ship arrangement with a few simplifications to facilitate numerical simulations. The results indicate that the ships can survive wave heights lower than 5.5 metres wave height with a time to sink of 10 hours while the ship becomes unsafe above 6.5 metres. Despite the fact that permeability is known to have impact on ship motions, the impact of varying permeability in specific spaces has not attracted significant attention.

In this direction, (Domeh et al., 2015) performed model experiments on a specific single damage for a model scale Leander class frigate. The impact of three permeabilites (70, 80 and 100%) has been investigated at zero and forward speed of 18 knots in high regular wave heights. The authors conclude that permeability does not appear to have a significant effect on the pitch and heave responses at zero speed, which may be justified considering the massive inertias in heave and pitch as compared to roll motion. While comparing the motions of damaged and intact ship with other research (Korkut et al., 2004), it is shown that the heave and pitch motions are similar.

The findings of the above research were extended in (Domeh and Lartey, 2015) where it is demonstrated that the model in consideration is highly susceptible to failure when damaged with 100% permeability and 80% permeability at zero and forward speeds respectively , while, it is less vulnerable to failure when in intact condition, which of course is unrelated to permeability. However, when considering the peak period, the model is highly susceptible to failure when damaged with 70% and 100% permeability at zero and forward speeds respectively.

The results of these studies are discussed by (Ruponen et al., 2016). The authors regard permeability as a crucial stability variable, which needs special attention and further research. However, the effects on the draft, and especially on the likelihood of up-flooding to bulkhead deck, may be crucial and therefore it needs to be addressed. This is achieved in a more recent study when assessing the impact of the non-watertight doors on progressive flooding (Ruponen, 2017). According to the authors, the impact of permeability on the leakage and collapse parameters of closed doors need to be addressed in future research as they dictate the process of flooding. Consequently, more research is deemed appropriate in order to improve the reliability of damage stability calculations, both for design and regulatory calculations, as well as for decision support on-board a damaged ship and this can be addressed accurately only through employing real permeability values.

In this view, (Ruponen et al., 2010) presented actual but very rough estimations of permeability values applicable to a small naval vessel with a view to providing realistic distributions in transverse and longitudinal directions. A variable permeability is sometimes required in vertical direction in order to model the fact that most of the equipment is not usually evenly distributed. The authors present values for side tanks, equipment, pump rooms and stores while, a comparative study is undertaken with a stability software where it is found that the real permeability of the flooded compartments can differ notably from the model test arrangements, where impermeable blocks are often used to model the large equipment, such as the main engines.

In a similar manner, another study conducted by (Santos and Soares, 2009) utilised numerical simulations to examine parametrically factors that have a bearing on survivability in waves for a Ro-Ro ship. These comprise the vertical centre of gravity, wave spectrum, wave height, roll damping and discharge coefficient. A two-compartment SOLAS mid-ship damage is assessed in irregular waves, accounting for different wave spectra and for sea states spanning from 3.5 to 5 metres. Here, the main engine room is assigned a permeability of 0.7, which according to the author accounts for the effects of the volume of the main engine whereas, the rest of the rooms are assigned a value equal to 1. The consideration of internal impermeable blocks facilitates the thorough examination of physical properties and transient phenomena during flooding progression. The results demonstrate that long-crested waves decrease survivability while, there is large initial transient motions and water flowrates into the compartments below the main deck leading to large heel angles.

Another study from (Mironiuk, 2012, Mironiuk, 2013) provided the calculation of a permeability curve that depicts the change of permeability as a function of the main engine room height. A detailed CAD drawing of the main engine room of a naval combatant is utilised for this purpose. The results indicated that the average value corresponds to that suggested by SOLAS for machinery spaces (0.85). A varying permeability that changes with respect to height can significantly aid in the prediction of floodwater accumulation and propagation through permeable spaces for different time steps. This is tackled in a later study performed by (Ruponen et al., 2016) using level sensor data to gauge the floodwater level inside the damaged rooms of a large passenger ship when the vessel operation is considered. Based on this, it is noteworthy to mention that large passenger ships have intricate watertight architecture and subdivision as opposed to naval vessels, which entails a significant effort to capture and derive actual permeability values accounting for every aspect of the equipment.

Over the years, a number of research projects and concepts have been developed that utilised permeability as modelling means of assessing survivability. Particularly, (Vassalos et al., 2016b), and (Atzampos et al., 2018b) presented an innovative damage stability recovery system, which ejects expandable foam reducing the available flooding volume in high risk compartments, and thus increasing survivability. The optimum system arrangement is selected assessing survivability statically and by reducing permeability with the aid of a trade-off analysis of protected compartment's permeability, risk is reduced significantly as a function of foam volume.

Another example of such research is the implementation of a number of active system concepts with the view of enhancing survivability and restoring water-tightness in wake of damage for a RoPax vessel as presented by (Illario, 2014). Systems such as counter ballasting, internal blisters into the side shells and high expandable foam are modelled by varying permeability homogeneously and accounting only for the size of the systems in a static manner. Survivability is investigated for 12 different damage cases dynamically in waves via the concept of capsize band (Jasionowski et al., 2007) and employing time-domain numerical simulations (Jasionowski, 2001) for 30 minute simulation runs. Although, in most cases the increase in the critical significant wave height is substantial, the numerical sample is limited to size and type, whereas, permeability is assessed solely for fixed values and in that way the variation is uncaptured. Also, the modelling procedure was unable to account for the change in permeability as a function of time, which potentially can be proven to be dramatic.

In the same spirit, a study led by EMSA in 2009 evaluated the impact of permeability on the car deck of a conventional ROPAX ship (Spanos, 2009). One two-compartment standard mid-ship damage is identified as critical through the SOLAS damage sample. The permeable volume and buoyancy is distributed homogeneously across the car deck taking two values of 0.9 to 0.92, while, the side casings are assumed to be intact with a permeability of 0. Survivability was addressed using time-domain numerical simulations (Spanos, 2002) in waves with increments of 0.25 metres. This entailed the identification of the survival wave height and maximum GZ curve properties as main means of assessment. The results indicate that lower permeability (0.9) results in higher survival wave heights and on the contrary, higher permeability improves stability by increasing the vanishing angle and the maximum GZ values of the damage. The author concluded that despite the aforementioned compromise, the value of 0.9 as currently assigned by SOLAS (CHII-1, reg. 7-3.2) (IMO, 2009c) to car decks improves physically survivability.

The findings of this study are also discussed by other parties (Jasionowski, 2009b). The consideration of 90% permeability of car deck might be unrealistic since the area of significant relevance to stability occupies only 0.3 to 0.5 m of the vehicles deck surface which is essentially covered with wheels and in this way the space is not entirely filled. The effect of permeability on survivability can be prominent but this research did not expend adequate effort to assess the impact on overall survivability. Finally, (Jasionowski, 2009b) recommends that such sensitivity studies should be considered as part of the typical approval and statutory compliance process.

Deriving from the above, it is oblivious that further research is required in the direction of assessing permeability and the relevant impact captured from dynamics. That is the case for large passenger ships where overall survivability might impose significant risk to life. Addressing the impact from varying permeability can demonstrate how potential actual values in critical locations can contribute to the safety level of the passenger vessels.

3.4.Performance-Based approaches to damage survivability assessment

The primary focus of the maritime industry over the last few years has been oriented towards survivability assessment pertaining to a time variable, which can therefore be used to assess the ship in a life-cycle manner. In this direction, there is significant work conducted by (Vassalos et al., 1999) and also (Jasionowski and Vassalos, 2004) in order to represent survival criteria as a function of time. This is further investigated in later studies and based on the promulgated concept by the IMO that of the “Safe Return to Port” (SRtP) (IMO, 2010), which promotes that a ship suffering casualty below a given threshold should either remain upright and afloat for three hours allowing for adequate evacuation time or if the threshold were exceeded to retain functionality of main powering systems, enabling the ship to return to the nearest port (IMO, 2004a, IMO, 2006b). Therefore, the aforementioned concept, in principle, renders the ship a lifeboat emphasising the importance of the time to capsize and time to evacuate in damage stability assessment of passenger ships.

In addition, (Vassalos and Guarin, 2009) highlighted the safe transition from deterministic to goal-based safety through the utilisation of performance-based approaches. The catalyst in this is again the concept of “Safe Return to Port” with main emphasis on the flooding survivability analysis. According to the authors, transient and intermediate flooding should be addressed with time-domain numerical simulations as opposed to static calculations since survivability might be interpreted incorrectly.

Performance-based approaches are divided in a twofold manner; analytical and numerical simulations (first principles tools). The latter is broken down into three categories namely, numerical simulations, model tank experiments (Experimental Fluid Dynamics - EFD) and Computational Fluid Dynamics (CFD). However, the scope of literature is only limited to numerical simulations and the way they are used to address damage survivability in waves.

Analytical approaches

The main benefit of using the analytical models in assessing survivability is the time-efficiency provided by such instruments. In this regard, the first approach is related to the Attained subdivision Index, as it has been described in earlier sections, assessing damage stability by means of statuary compliance as specified within SOLAS 2009 (IMO, 2004b). Related literature can be found in (Pawlowski M, 2017) where, despite their computational efficient nature, there is one main element missing which is necessary in the calculation of survivability; time-dependence. To this end, the survival time is accounted for through the time-based analytical model, namely Univariate Geometric Distribution (UGD), which was initially developed in the EU funded project SAFEDOR (Jasionowski, 2006) and it was further evaluated in the consecutive project FLOODSTAND (Jasionowski, 2012a) being subjected to significant improvements. The concept provides a comparison basis to the typical s-factor with an assigned time to it. It derives from the main assumption that the process of observing capsizes in a number of trails is related to that of the so-called Bernoulli trial process using statistical inference (Jasionowski and Vassalos, 2004). The basic equations that represent the improved model from (Jasionowski, 2012a) are provided below.

$$F_{cap}(t_{cap}) - 1 - (1 - p_f)^n = 1 - (1 - p_f)^{\frac{t_{cap}}{t_0}}\ ,\ t_0 = 30min \tag{3-10}$$

$$p_f = \phi\left(\frac{H_s - (H_{crit,i,j,k} - \varepsilon)}{0.061 \cdot (H_{crit,i,j,k} + \varepsilon)}\right) \tag{3-11}$$

$$F_{cap}(t|d_{i,k}, T_j, Hs) = 1 - \left[1 - \phi\left(\frac{H_s - (H_{crit,i,j,k} - \varepsilon}{0.061 \cdot (H_{crit,i,j,k} + \varepsilon)}\right)\right]^{\frac{t}{t_0}} \text{ for } Hs \geq 0, H_{crit} \geq 0 \tag{3-12}$$

Where, H_{crit} is provided from eq.(3-8) and it represents the 50th percentile of significant wave pertaining to a subjected flooding scenario d_i as derived in project HARDER (Tuzcu and Rusaas, 2003),(Tagg and Tuzcu, 2002).

Put simply, a specific damage flooding scenario in given constant loading condition and draft j is represented by the cumulative probability of the time to capsize F_{cap} in a single sea state considering 30 minute duration tests. The prerequisite assumption of this concept is that the critical significant wave height Hs_{crit} for the single damage case in consideration is known. This, in turn, aids in the calculation of the capsize band following a normal distribution, which is denoted with p_f as represented by the function approximation eq.(3-11).

The concept has been extensively evaluated over the years with a number of studies, which aimed in verifying the robustness of this analytical approach. However, the model is subject to a number of uncertainties based on its inherent generic nature. To begin with, the prediction of the critical wave height formulation is depended on two parameters namely GZ_{max} and Range, which implicitly makes the formulation ship type-dependent. Saying this, the applicability of the concept is proven only for the case of small RoRo ships and it inherits the uncertainties originating from the concept of the critical wave height too.

In addition, the statistical sample of experiments used initially to regress the data using linear regression is narrow (Tuzcu and Tagg, 2001a, Tuzcu and Tagg, 2001b) and it therefore fails to characterise the stochastic nature of the capsize occurrence based on the derived cases. This directly calls into question the validity and size of the experiments in terms of ship size, ship type, loading condition and sea state. The author of a later study on a RoPax vessel (Jasionowski, 2012a) stated that the solution is questionable when applied to cruise vessels as it is well-known that the process of capsizing of cruise ships differs altogether from RoPax ships with regards to water propagation through openings and a simulations time of 30 minutes might be insufficient. A subsequent work conducted by (Tsakalakis, 2012) and (Tsakalakis et al., 2009a) demonstrated that in the case of two RoPax vessels the Attained subdivision Index is within the 99^{th} confidence interval of the conditional probability of capsize for a single damage. This study however, was not sufficient to substantiate the validity of the approach given the limited study cases and the absence of cruise ships from the sample.

Furthermore, the model is utilised for vulnerability screening aiding in decision making and crisis management during operation by evaluating the impact of watertight doors on one RoPax vessel (Jasionowski, 2010). According to the author, the uncertainties within the model range and vary in both aleatory and epistemic types. In the same vein, (Chen, 2013), (Chen, 2012) identified and quantified a number of inherent uncertainties relying on the above performance-based approaches.

Time-domain numerical simulations and Monte Carlo sampling

The maritime industry is gradually stirring towards performance-based criteria in addressing stability while considerable effort has already been expended in the advancement of dynamic numerical simulation instruments that can accurately predict the dynamic behaviour of damaged ships in waves.

Generally, the dynamic behaviour of damaged ship in random waves is a complex process, which should be investigated in a time-domain manner. In this respect, theoretical-numerical models enable a time-based prediction of the nonlinear motions of the vessel and eventually the flooding process. In this direction, using predefined damage case scenarios, the probability of capsizing and respective time to capsize (TTC) can be measured by scrutinising the time series of ship motions and related quantities (e.g., floodwater mass, elevation and subsequently behaviour in flooded compartments).

The availability in the industry of cutting-edge advanced codes that capture the flooded ship-wave interaction and address survivability in waves is very limited and those available are subject to dissimilarities since their development took place independently. To this end, the ITTC Stability in Waves committee performed 3 consecutive benchmark studies in assessing their performance with regards to the dynamics of damaged ship in waves, the floodwater-ship interaction and the values of different semi-empirical coefficients for damping, openings and discharge coefficients. Four different codes namely, PROTEUS (Jasionowski, 2001, Letizia, 1996), FREDYN (Veer and DeKat, 2000), CAPSIM (Spanos, 2002) and IST (Santos and Soares, 2003) were subjected to scrutiny through a parametric study on a 2-compartment SOLAS90 worst damage for the case of RoRo/passenger ship. In view of the findings of the third benchmark study, as discussed in (Papanikolaou and Spanos, 2008), discernible differences exist in the estimation of survival boundary indicating a sensitivity on the wave periods while significant concerns are raised regarding the viscous roll damping. Finally, based on the comparison of the results obtained through numerical codes and model experiments (ITTC Benchmark study and project FLOODSTAND), the effects of air compressibility applied on the later, on the considered damages were found to be minimal on survivability for large passenger ships.

The numerical models for simulating the behaviour of damaged ships in waves presented briefly in earlier paragraphs integrate four basic elements: a model of the ship geometry including subdivision, a model of the sea environment, a model of the flooding process and finally a model of damaged ship dynamics in waves. The in-house code PROTEUS has been utilised in the work presented in the thesis and a description is provided in Appendix A. The availability of the code and the results obtained through various past studies (Vassalos & Letizia, 1998, Vassalos et al, 1999, Vassalos et al 2005) render the utilisation of the code a sufficient means of assessing damage survivability of large passenger ships.

The numerical simulation tools are used to derived properties such as Time To Capsize (TTC) as explained later. The time to capsize is a random variable, thus only known as a distribution determined through probability methods. Moreover, survivability dependents upon a number of governing parameters (e.g. loading condition, sea state, damage extent, shape and location of damage) all of which are also random in nature. In this respect, accounting only for the damage case scenarios implicit in SOLAS 2009 (normally over 1,000 for a typical passenger ship) and considering the 3 loading conditions, also implicit in these regulations, and some 10 sea states per damage case for estimating capsize rates, it becomes readily obvious that some form of simplification and reduction will be meritorious.

To this end, one of the most efficient ways, entails a process using Monte Carlo sampling of distributions of pertinent random variables (damage extents, loading conditions, sea states, etc.) to generate damage scenarios and perform numerical time-domain simulations. The latter, accounts accurately for the physical phenomena of ship-floodwater-wave interactions as function of time, providing robust indication on which of these scenarios would lead to ship capsize/sinking and the TTC. In this manner, any assumptions and approximations inherent in the probabilistic elements of SOLAS damage stability regulations are diminished or minimised (Atzampos et al., 2019).

Typically, the random input concerning wave data is considered of Gaussian form whilst, the output data of the intact ship are regarded as stationary ergodic (Veer et al., 2002). In this manner, long-time averages taken on any arbitrary time-history records will bring about results with statistical equivalence on the related ensemble averages over a large number of records. Therefore, single simulations with sufficient time can be proven adequate in order to produce spectral properties. Nevertheless, this is not the case for the damaged ship. Damaged ship simulations entail transient random data, which require sufficient number of simulation repetitions of similar conditions in order to derive reliable data. Therefore, with a given damage scenario and sea state defined by a significant wave height Hs, a peak period Tp and a spectral shape, the random phasing of the spectral components can provide the required variation in sea state realisations. Typical numbers of runs per damage case scenario with pertinent wave heights vary from 5 to 10 or 20 based on previous work (Chen, 2013).

Concepts deriving from first principles

One of the main elements, which can be derived from the characteristics of the damaged ship is the capsize band. The capsize band was first introduced in the North West Research European Project as a result of a number of systematic studies (Vassalos et al., 1997, Vassalos et al., 2000) triggered by the disaster of RoRo Estonia. The capsize band can be depicted in two ways; through the variation of the KG for different sea states or the variation of the GM for different sea states. One example of the latter is provided in Figure 11. The capsize band indicates the range of sea states within which a transition from unlikely (P_s=1/ P_c=0) to certain capsize (P_c=1/Ps=0) can be observed. The width of the capsize band reflects the variation of the damage characteristics and ship loading conditions. Even though the capsize band is depicted in the form of confidence intervals, in fact it measures the dispersion of capsizes, which in turn relates to separate sea states for which the capsize rate (i.e. the conditional probability of capsize) is very low from those in which the rate is very high, respectively. 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 that vessel always survives and sea states that the vessel will inevitably always capsize the lower and upper capsize/survival boundaries can be represented by means of limits. In this case, this asymptotic nature requires the use of threshold values of the conditional probability outside of which the occurrence of capsize will either be impossible or practically certain.

Another concept intrinsically linked to the capsize band is the capsize rate. Figure 12 represents a sample of capsize rates for various simulation times. The capsize rate follows always a sigmoid shape distribution. The rate of observed capsizes is depended upon the time of observation and in case of a limiting case of infinite exposure the capsize rate distribution will turn into a unit step function as indicated in Figure 12 for increased simulation times. In this vain, for a small number of the capsize probability, the corresponding significant wave height will remain the same (minor difference) when the time of observation is increased (GOALDS (Papanikolaou et al., 2013)). In other words, a sea state corresponding to a small capsize rate can be established on a basis of relatively short simulations and would still remain valid for longer observations.

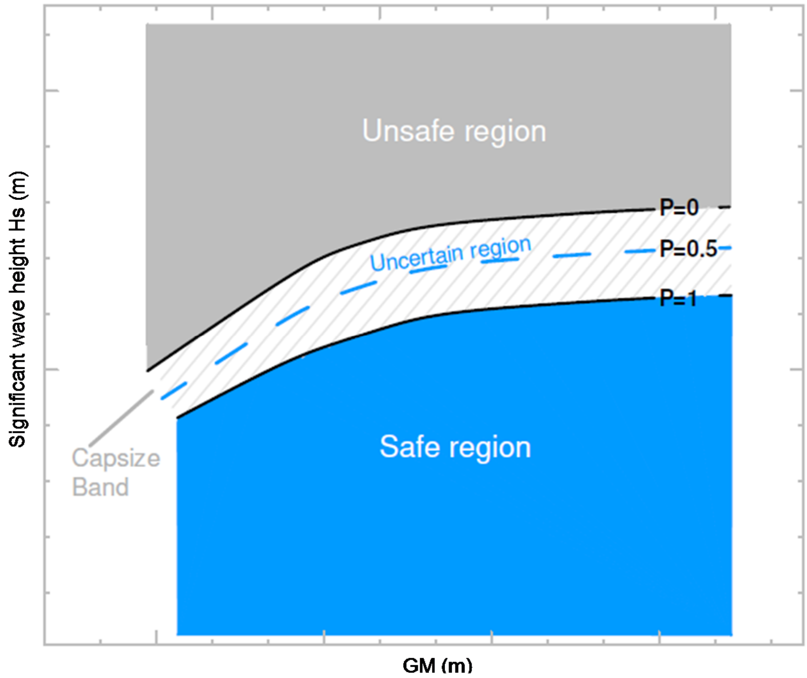


Figure 11: Capsize band with indication of safe, uncertain and unsafe regions. The capsize band represents one damage case for different loadings conditions and sea states.

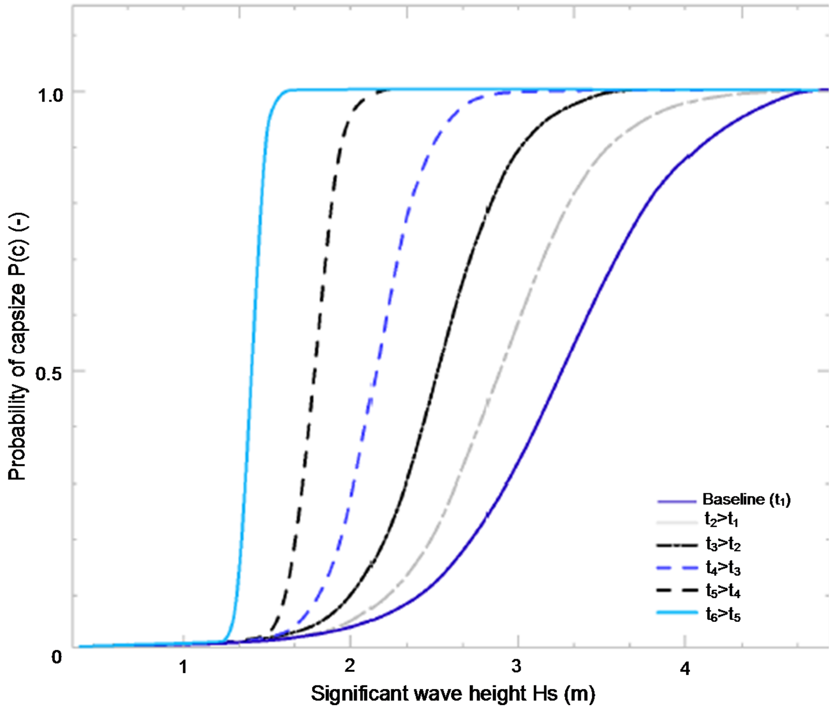


Figure 12: Indication of change in shape of the capsize band with the increase of the exposure time t1 for the baseline scenario (dark blue line). The capsize rate is derived for one damage, one loading condition and various significant wave heights.

Another element of significant contribution is the critical significant wave height, which is derivative of the capsize band. As it has been mentioned in earlier sections, originally, during HARDER (Tuzcu, 2003c) the s-factor was linked to the critical significant wave height as the sea state at which a ship exposed for half an hour (30 minutes) to the action of waves would have a 50% chance of capsize and 50% of survival (alternatively the abscissa of the inflection point of the sigmoid curve). This however, based on observations at the time raised concerns and therefore an attempt was made later in project GOALDS (Tsakalakis et al., 2010a) with the view of improving the accuracy. In view of these findings, it was concluded that when the simulation time increases, the capsize band contracts towards its lower boundary. In this respect, if someone would assume infinite observation time, then the sigmoid distribution would be simply reduced by a step function. In light of this observation, it was deemed appropriate to change the definition of the Hs_{crit} to that of the highest sea state at which no capsizes are observed within half-hour exposure. For practical reasons, the Hs_{crit} was assigned to the sea state of a capsize probability or else rate of 5%. In this respect, the critical significant wave height forms a boundary curve below which a damaged vessel is unlikely to capsize, whereas exposure to sea states higher than Hs_{crit} will eventually lead to a capsize event (P_c=1).

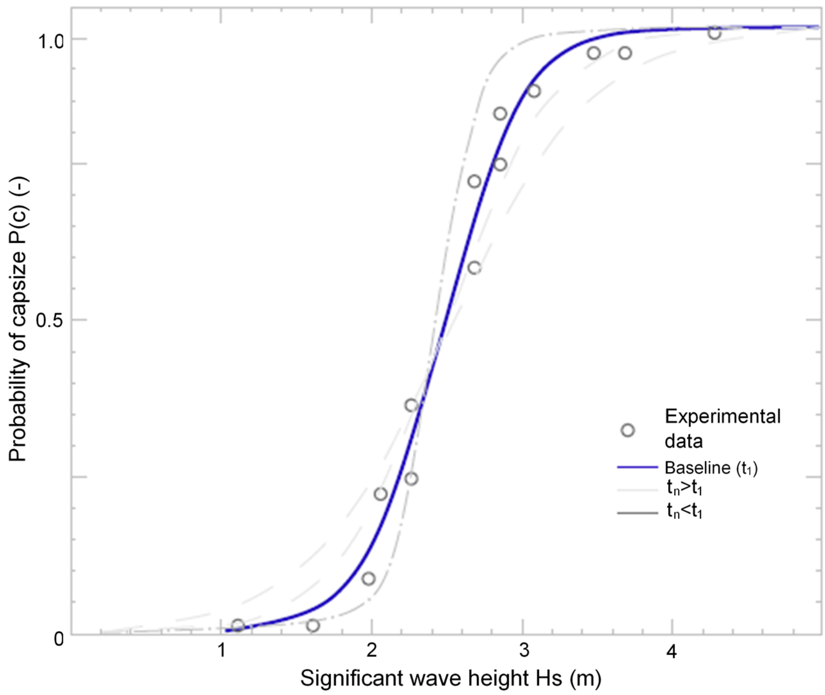


Figure 13: Indicative capsize rate transition from baseline with fitted on experimental data curve with increase or decrease of observation time.

Irrespectively of the differentiation between passenger ship types, capsizes of damaged vessels are the result of accumulation of floodwater in the spaces open to the sea of the vessels. The problem of the Water on Deck for the case of RoPax ships in particular is more pronounced and it is ascribed to a stochastic and non-ergodic pattern of the flooding process which can result in a computational intensive calculation. Saying this, the calculation of the WoD can be predicted from the properties of the capsize band even for cases outside of the lower survival boundary where the capsize band typically contracts. Therefore, the critical significant wave height can be represented by a limiting sea state above which the flooding process changed to progressive ensuing loss of floatability. On the contrary, for lower sea states than the critical expected wave height, even though the floodwater mass fluctuates instantly, on an averaged basis it is the same.

Based on findings from (Cichowicz et al., 2016a), it is difficult to detect capsize on the basis of time histories, however, the end result of the simulation is merely based on the floodwater accumulation which remains constant. This was approached in a different way in project GOALDS (Papanikolaou et al., 2010). Particularly, at various peak periods the maximum values were recorded obtaining a critical significant wave height at the upper confidence limit. Deriving from the achieved results of the project, two significant observations were made at the time. Initially, the reference curve did not have a horizontal boundary, which indicated that some of the surviving runs will result in capsize when they are subjected to longer simulation times. In a second manner, the survival cases those above the critical significant wave height would be within the confident limits of the baseline curve regardless of the change in the wave height.

Another important notion, which derives from the capsize band is the so-called time to capsize (TTC). Even though the time to capsize remains a random number, it can be predicted with the aid of the cumulative probability distribution of the various time to capsize across a number of damage case scenarios, Monte Carlo sampled.

Several studies in the past have revealed the significance of the time element in survivability. (Jasionowski et al., 1999) investigated the survival time (aka capsize time or time to capsize) based on a limited range of experimental data. Despite the lack of available data the concept was proven robust and adopted the survival band with the association of the survival time. Later, (Jasionowski et al., 2002) introduced a new approach that employs as basis the SEM methodology. The authors considered individual waves or groups as an integral element of the capsizing process. The capsize event was identified from the presence on the incidence of the critical groups and survival time was predicted conducting a statistical analysis on the results. (Veer et al., 2002) referred to the term "time to sink" and "time-to-reach" specific static criteria based on SOLAS framework (maximum roll smaller than 30 degrees, mean roll angle smaller than 20 degrees within 3 minutes, mean roll angle smaller than 12 degrees). Finally, an alternative term namely, "Time to flood" presented for the first time in a study on a large passenger vessel (IMO, 2006a). The time to flood represented the time spanning between initiation of water ingress and steady state ensuing progressive flooding.

Normally the time to capsize decreases with the increase of the encountered wave height. In fact, the time to capsize is inversely proportional to the difference between the actual and the critical sea state. The rate of decrease of the time to capsize depends upon the residual stability properties of the vessels, their size and of course the degree of complexity of their internal architecture. This is higher in the case of RoPax ships than in the case of cruise liners. The difference emerges from the dissimilar watertight subdivision of the vessels and specifically from the presence of large undivided spaces typical of RoPax ships (Vehicle decks).

The concept of the Time To Capsize can be used to form a time-depended survival/capsize boundary as it is illustrated in Figure 14 below. An identical concept has been proposed in the past by different studies (Veer et al., 2002, Spanos and Papanikolaou, 2007) and the principle is similar to the one presented in Figure 11 earlier. Below the limiting wave height (denoting the survival limit) the time to capsize is infinite, whilst above this value, the time to capsize converges asymptotically to the limit. This is distinguished from the survival boundary, which in turn forms the lower boundary of the transition space between unsafe and safe conditions. The required rescue time stipulated by the standards can define upper limit of the calculations obtained through longest achieved survival simulation times. In essence, the time to capsize is estimated through the overall probability function of survival limited by the rescue time.

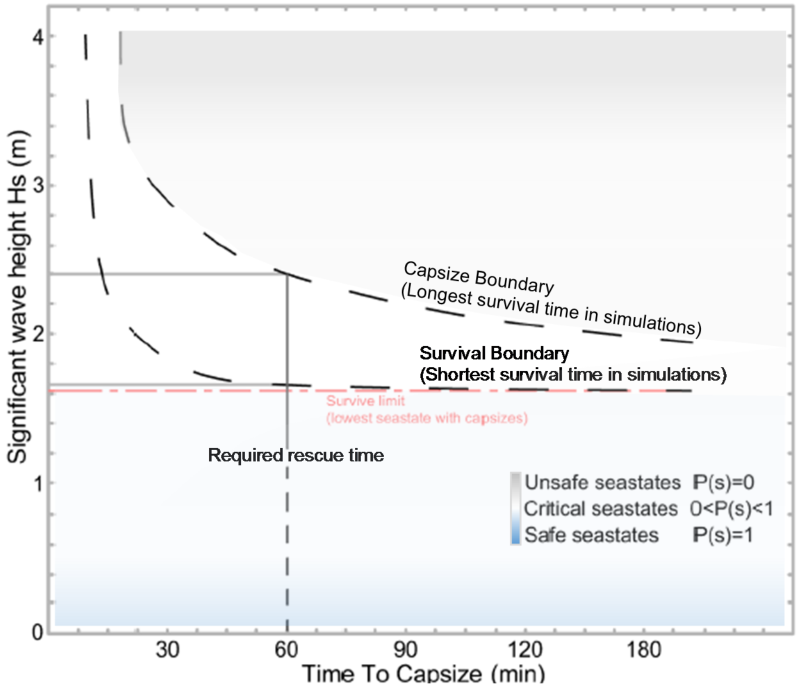


Figure 14: Capsize and survival boundary concept with indication of the safe and unsafe regions with respect to change of the Time to Capsize as a function of the significant wave height.

A number of points are highlighted in the aforementioned for the concept of time to capsize in collision damages.

- Survival time (aka TTC) is a random quantity and its distribution is based on probability P which respectively depends on a variety of factors (sea state, damage, loading etc.).If the significant wave height varies then the average survival time varies too. In the capsize band when p=1 the survival time is infinities whereas for lower probabilities it depends on the capsize rate. That implies that for all cases that survivability equals to 1, the time to capsize should be infinite in case of wave heights equal or smaller to 4 meters.
- The time to capsize is the same across a damage case repeated infinite number of times in the same wave environment but with random realisations. In this respect, the probability of survival is the same as it depends on the significant wave height and capsizal is attributed on the random nature of water accumulation only. This probability however varies in the case of progressive flooding. For this process, Bernoulli trial process is implemented keeping a constant probability over the number of segments employed.

- The time to capsize is distributed as a function of significant wave height exponentially varying from zero to infinity.
- The Time To Capsize in the design aspect is addressed through the utilisation of the probability of survival (s-factor). There, in case of collisions the survival time is equal or greater than 30 minutes which derives the averages probability of survival A Index. The prerequisite for this is an accurate survivability factor that captures well the capsize mechanisms.
- The probability of survival can be segmented into equal time spans considering that probability equals to unity every 30 minutes (t_0=30 minutes). A formulated version of this statement is provided by (Pawlowski, 2008, Pawloswki, 2007) as follows,

$$F = P^n \tag{3-13}$$

  Where n=t/ t_0 the fraction of time from the completion of flooding. For example, for the case of 1 hour simulation time, the probability of capsize in the second segment is derived from P_2=P (1-P).
- Building on the above, there is a differentiation between the marginal and conditional distributions concerning the connection to subdivision Indices.
  - For a single sea state and flooding case the conditional probability depends on the probability of survival (conditional distribution) within 30 minutes.

$$CDF(t) = 1 - P^n \tag{3-14}$$

    Where, $n = t/30$ represents the variation in time t.
  - The "Local" CDF represents the marginal distribution of the time to capsize based on the averaged probability of capsize during all sea states for one single flooding scenario. The added element here is the survivability factor which represents the averaged survivability in sea states.

$$CDF(t) = 1 - E(P^n) = 1 - s_n \tag{3-15}$$

    Where, s_n represents survivability for cases run for longer times
  - The "Global" CDF represents the marginal distribution of the time to capsize based on the averaged overall probability of capsize during all sea states for all the generated flooding scenarios.

$$CDF(t) = 1 - E(s_n) = 1 - A_n \tag{3-16}$$

    Where, A_n is the Attained Index for survival Sn in longer test runs

The TTC is therefore interpreted from the complement of the A-I to one. That represents the probability of capsizing within 30 minutes when the actual Attained subdivision Index is considered.

For longer simulation runs the impact on the s-factor will be minor and the higher the Attained Index is, the greater the number of cases with infinite time. This has been brought to attention by (Pawlowski, 2008, Vassalos and Jasionowski, 2011).

The concept of the capsize band is directly associated with the survival probability and subsequently the s-factor. As mentioned in earlier paragraphs, the capsize band is derived on the basis of one loading condition (KG, GM) and one damage case which form the baseline capsize band curve. Nevertheless, the translation of the capsize band (as indicated in Figure 12) backwards to smaller critical significant wave heights, reaching a steep shape, is not depended only on simulation time but also the loading condition and GM. In this sense, new derived curves can be the product of variations in GM. This philosophy can be accurately captured with the utilisation of one accurate s-factor that accounts for the size of the vessel and merely it captures the variation in the GM or KG. However, having identified the shortcomings of the s-factor in earlier sections it is obvious that this element is currently not being addressed conscientiously.

The effects of the Time to Capsize on survivability have been addressed in the past through the use of Monte Carlo simulations in a number of instances. (Santos and Soares, 2005) performed MC numerical simulations on a large passenger RoRo vessel in order to assess survivability on the basis of the SEM methodology employing actual damage distributions, loading conditions and sea states. For the later the authors used sea state distributions of actual accidents (75% below 1m) and winder season North sea distributions for comparative reasons. As expected, the results presented low number of capsizes using the IMCO distributions, whereas very significant numbers in the case of North Sea waves. (Dankowski and Kruger, 2010) performed numerical simulations on two RoPax ships using wave statistics sampled with MC based on SOLAS. The damages are based on HARDER distributions for both SOLAS90 and SOLAS09 standards. The main aim was to gauge the impact on the safety level of the vessels providing a consistent comparison basis through the “Safety Index”. The results indicated that SOLAS2009 underestimated the safety level of the vessels when compared to SOLAS90.

(Spanos and Papanikolaou, 2012) performed MC sampling and numerical simulations using the distribution of sea states from HARDER, distributions of damages and distributions of loading conditions from SOLAS (0.2, 0.4, 0.4) for one cruise ship (SOLAS09) and one RoPax (SOLAS74). Based on the obtained results, the ships were subjected to capsize within 15 minutes. This indicated that the resulted times are significantly shorter than the threshold that of 3 hours (IMO, 2007b) for orderly abandonment of the passenger ships same as in the case of the 1 hour for evacuation process (IMO, 2007a).

Therefore, according to the authors, the orderly abandonment appears infeasible, while optimistically, it might be only partially accomplished for the ships in consideration. In the same manner, (Spanos and Papanikolaou, 2007) performed in the past MC simulations on a 2-compartment damage (worst SOLAS90 damage) of a RoRo passenger ship. In order to adequately gauge the effects on the TTC, the authors conducted parametric studies varying properties of the RoRo/passenger ship such as the length of the damage opening, vertical centre of gravity, fixed pitch (cancel dead water on deck) and reduction of freeboard. In this study it was found that the survive boundary is not subjected to any radical changes.

(Ruponen et al., 2019) accentuated the need of first principles in deriving accurate survivability. In this effort the authors performed Monte Carlo simulations on a large cruise ship using the quasi-static flooding tool NAPA for a number of damages. A constant wind velocity is assumed similarly to the calculation of the typical s-factor, while a simplified approach was employed in order to calculate the wave elevation. The latter simulated the pumping effect of waves on the progressive process through an instantaneous wave elevation using distributed amplitudes. The results indicated that wave pumping model is conservative in high waves while for smaller than meters wave height the effects on survivability are marginal.

Notably, the aforementioned studies have been performed in the past concerning the effects of collision hazards derived from collision damage statistics (IMO, 2009c) only. Therefore, the effect of other flooding causes such as groundings need to be addressed in the future to complete the research for the time characteristics of the sinking large passenger ships due to eventual flooding as it has been highlighted by (Spanos and Papanikolaou, 2012).

3.5.Closing remarks

In light of the aforementioned discussion on the available damage stability and survivability approaches the following gaps are identified.

- An accurate survivability factor accounting for the differentiation in internal watertight layout, ship size and loss mechanisms of different passenger ship types. In this line, an adequate number of data sets will be required for the development of a robust and rational methodology. The main emphasis should be placed on cruise ships since the risk to potential loss of life is higher and little effort has been exerted in the past in this area.
- Survivability can be derived on the basis of the statistical approach (statutory Attained Index) and direct approach through the use of numerical time-domain simulations (hydraulic models). A comparison between the two is necessitated with the view to acquiring in-depth understanding on survivability between statics and dynamics.
- Investigation of the effects of collision and grounding damages on large passenger ships through numerical simulations and Monte Carlo sampling of pertinent higher sea states than those stipulated by SOLAS 2009. This stems mainly from the fact that cruise ships operate in global wave environments, which entail exposure to sea states higher than 4 meters as derived through project HARDER. This is also supported by the high resistance to capsize of large cruise ships in lower sea states as demonstrated in past research projects. In this respect, the effects on time to capsize and wave height will be quantified.
- Consideration of localised wave statistics into the derivation of accurate survivability factors following the GZ-based approaches devising formulas that can be easily implemented complementary to SOLAS2009/SOLAS2020. The deviation from SOLAS of using actual wave statistics, rather than wave statistics pertaining to sea states at the time of the incident, is based on the argument that it is essential to estimate the risk of exposing ships to all operating sea states and not just those wave characteristics at which accidents have taken place in the past.

- The latter can be further investigated through the creation of ship-specific and specifically passenger-specific accident databases encompassing only related type of accidents with consideration of the wave heights at the exact time of collision and grounding incidences.
- Investigation of operational patterns and loading conditions of large passenger ships with view of developing accurate inputs in the calculation of the averaged survivability in waves during both operational and design phases.
- Assessment of the effects of permeability on survivability for large passenger ships employing static and dynamic damage stability assessment tools. A parametric study will demonstrate the need of actual permeability values in the damage stability framework of SOLAS for future assessments.

Chapter 4

Approach Adopted

4.1.Opening remarks

The following chapter presents an overview of the approach followed in the thesis, which aims in clarifying and underlying the methodology adopted within every phase of the undertaken research. Also, there is a provision of the implemented framework along with the structure of the consecutive chapters as indicated in figure 16.

Based on the aforementioned, the prevailing instrument for damage stability assessment uses the Attained subdivision Index and the survivability factor as indicators of the safety level. These, in turn, are explicitly linked to the loading conditions considered and the critical wave height as it has been described in previous chapters. As a result, the following section aims to construct the methodology and findings in the same manner, starting with the survivability factor and continuing with factors that have a bearing on survivability and the safety level. Damage survivability is addressed holistically, as shown in figure 15, using and developing the two methodologies available with consideration of actual data. In this manner, the approach is divided into the assessment and input domain comprising the main elements of the two methodologies (wave statistics, operational data, and permeabilities).

Every phase of the delineated approach adopted follows two steps. The first step is the methodology itself along with all the necessary assumptions, which constitutes the main body of the research. This entails an overview of the methods used in the past in order to acquire any relevant knowledge which can embraced by the new one. A second essential part is the validation of the findings of each section with implementation studies. These are accompanied by a sensitivity study that aids in pinpointing the limitations of the methodology. The validation study provides a thorough comparison with the standards currently in place, which can form the basis for the conclusions in the later sections. Every primary chapter is presented in a "self-contained" system, introducing the argument, which substantiates the need to address the presented gap and following with the methodology and the results. In this way, each chapter traces back to each relevant critical review and the research gap identified. This leads to a smooth transition to the construction of the concluding remarks. The following flow chart (see figure 16) depicts the applied methodology presented in a local level along with the interconnection between each individual aspect. The foregoing sections provide a brief description of the adopted methodology.

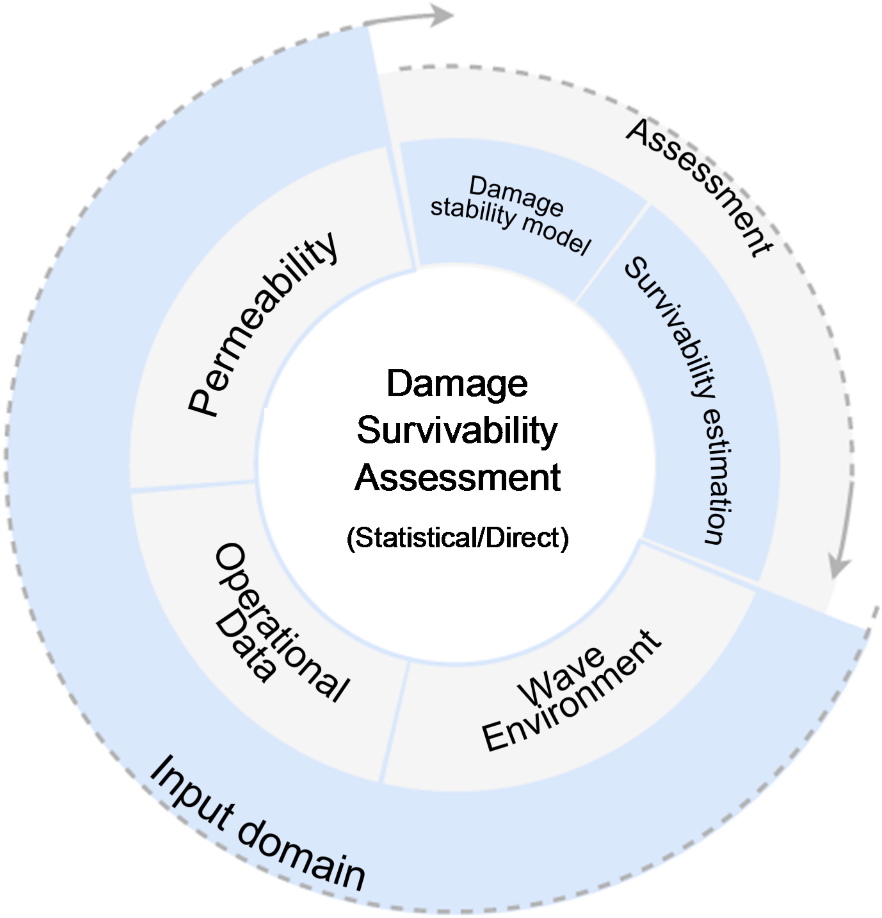


Figure 15: Holistic approach to damage stability assessment via the statistical and direct approaches

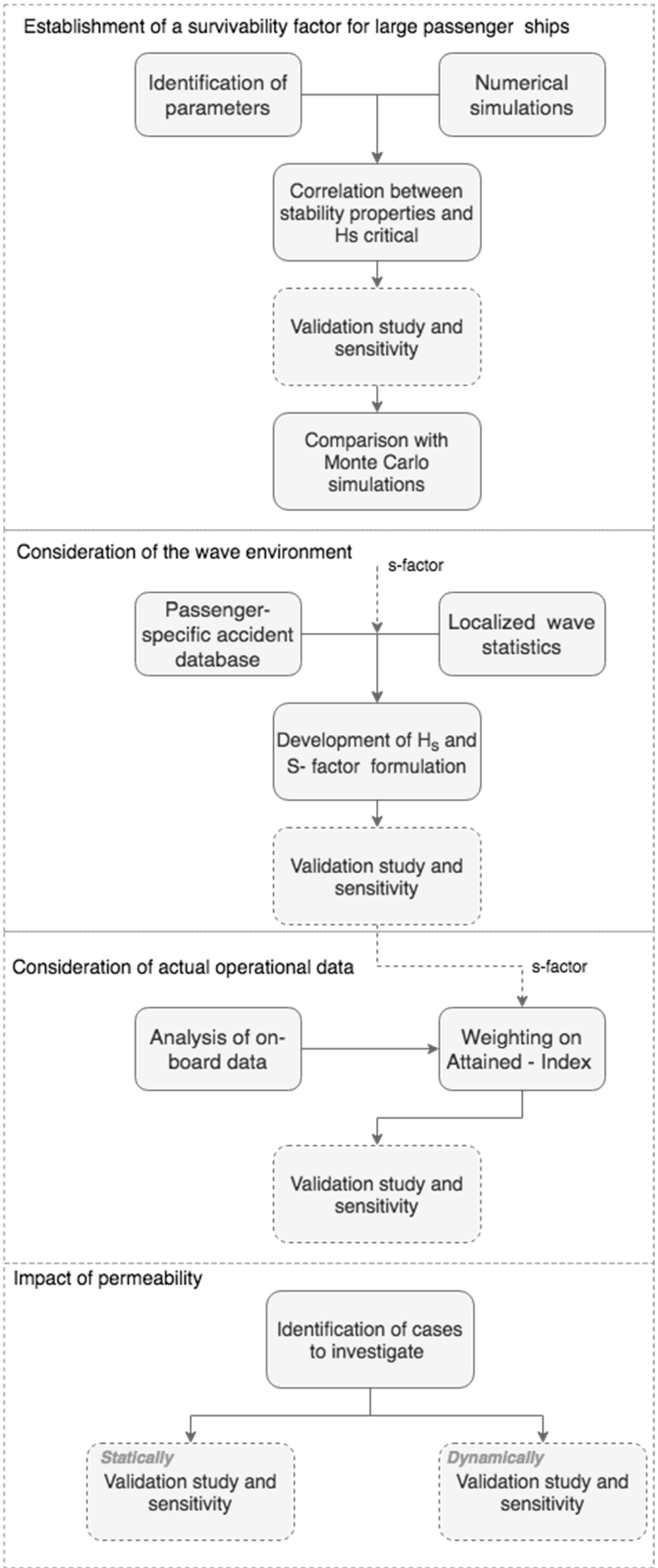


Figure 16: Flow chart for adopted methodology

4.2.Prediction and modelling of survivability for cruise ships

Over the years extensive studies have been carried out in the field of damage survivability of passenger ships. This being the case, it is deemed appropriate to provide an overview of the previous techniques and adopt elements that can potentially aid in the development of a new approach that caters for specific ship types. The first step towards the development of robust survivability formulation is to identify pertinent parameters as candidates for the new survivability formulation. Various parameters that affect ship damage stability are considered in the first instance, namely GZ_{φ} curve properties but these are reviewed at later stages. The stability properties, in turn, are correlated with the results from the numerical time-domain simulations, which are performed on a number of large passenger ships, carefully selected for the purpose of the research. As opposed to similar past studies, experimental tests are omitted not only because of their excessive cost, but also because of the modelling detail degree offered by numerical time-domain simulations. The key to producing accurate and adequate numerical simulation results is the development of a technique for damage case selection. Having obtained the numerical results, an approach to correlate residual stability properties and the critical sea state is sought. The selection of the appropriate residual stability properties is relied upon the best regression fit of the data set obtained. A critical significant wave height and survivability formulation is established through regressing the data.

As it is shown in Figure 16, the resultant s-factor is validated for the purpose of comparison between different ship sizes and standards (new vs SOLAS 2009/2020). A sensitivity study is performed to assess the applicability of the approach and its limitations. To this end, the formulations are also benchmarked against the direct approach which utilises Monte Carlo simulation runs for a number of vessels from the sample set. The Flooding Survivability Index from numerical simulations is derived pertaining to collision and grounding damages as an alternative to survivability prediction. A comprehensive description of the methodology is provided at the beginning of the relevant chapter along with discussion and conclusions.

4.3.Other factors which have bearing on survivability

The prediction of survivability is based on the calculation of the averaged critical significant wave height at the time of collision accidents at sea. A number of factors affect implicitly or explicitly the evaluation of the safety level of a vessel. These are examined in the next sections.

4.3.1. Consideration of the wave environment

In the same manner as before, previous techniques used in the area are discussed in order to highlight specific elements that can contribute to the new methodology. The wave environment is accounted for in survivability studies by employing two methods. In the first, localised wave statistics are utilised for different key trade regions. Following analysis of the statistics, the data are regressed to yield respective localised survivability factors and critical significant wave height equations. With regards to the second method and in line with previous work conducted in the past (Heimvik, 2001, Tagg and Cantekin, 2002) a ship-specific accident database is constructed encompassing data only from passenger ships. In an identical manner to that used previously to address experimental data, the numerical results are regressed, leading to a formula that reflects the averaged values from the accident database. The second part of the method is related to the validation of the techniques that took place in the first stage. Here, important knowledge can be transferred from implementation to the design of the formulation. A number of ships are subjected to sensitivity analysis and comparison of the derived formulations with the former ones.

4.3.2. Consideration of the actual operational data

A number of actual operational data are collated from a range of large passenger ships. A statistical methodology is sought to account for the patterns in the operational profiles of the large passenger ships. This takes the form of a normalisation and sensitivity process, which is further explained in the respective chapter. Following the analysis and having derived weightings, which will represent the time spent in each of the respective cases, the additional terms are applied on the formulation of the Attained subdivision Index. The new formulation leads to two forms, based on the nature of the undertaken analysis; the first is a generalised formulation representing all the ships and the second, ship-specific leading to trends that can address both operational and design stages of the lifecycle of the vessels in the fleet. On the same basis as before, a validation is conducted to assess the primary terms of the loading conditions with a detailed sensitivity analysis on a range of sample ships.

4.3.3. Impact assessment of permeability

The effect of permeability on survivability assessment is assessed meticulously, following a sensitivity analysis that caters for static and dynamic influences, the latter using time-domain numerical simulations. In this sense, permeability is varied for a number of rooms. An attempt to parameterise the resultant impact will be presented following a simple regression technique. With regards to the static analysis, a range of ships of different length are compared using their Attained Subdivision Index as a measure of comparison. The results will be obtained for the three different damage stability drafts and comprehensive commenting will follow on the observed differences. As far as the dynamic sensitivity is concerned, aspects other than the impact on survivability are explored such as the impact on motions of damaged ship and flooding rates for specific damage case scenarios. This is achieved through engaging the direct approach MC simulations and varying permeability for specific room groups.

4.4. Sample ships

A number of sample cruise ships are considered within the thesis for analysis, validation, and utilisation in the methodology, as shown in Table 2. Further remarks on the sampling and selection of the sample ships used (specifically chapter 5, 6, 7 & 8) are provided in each individual chapter.

Table 2: Sample cruise ships considered (SOLAS 2009)

	Length Loa (m)	Beam (m)	Displacement volume at deepest draft (m^3)	Gross Tonnage	PoB	Chapter
Ship A	293.13	35.8	51286.8	99100	3820	5,6,8
Ship B	311.13	38.6	65196.4	138279	5020	5,6,8
Ship C	325.33	39.7	71278.8	145655	6536	5,6,8
Ship D	128	20	8668.3	11800	478	5,8,
Ship E	61.05	12.5	1915.9	1610	48	8
Ship F	241.49	31.2	32844.8	58250	1600	8

Table 2 provides some of the particulars for 6 SOLAS 2009 ships used in the analysis through the thesis. For confidentiality reasons not all the data or drawings are available for publishing. The considered sample ships represent the operational fleet with regards to main dimensions and capacity of people on board. Also, the sample ships are subjected to and account for a high degree of internal geometry detail (openings and watertight subdivision), which is required in order to develop methodologies and formulations catering for this type of vessels, as mentioned in earlier sections. Furthermore, the current developed formulations in SOLAS 2009 are based on SOLAS 1960 or SOLAS 1990 ships, thus they are subjected to large variations in their designs. In response to this, SOLAS 2009 ships are used. In addition to this, all the sample ships represent operating ships in key trade regions including the Mediterranean, South East Asia and Caribbean in order to compare the developed methodologies addressing the effect of operational environment and profiles of such vessels, which is one of the aims of the thesis. Finally, specific ships are used in some chapters, while they are excluded from specific tasks of other chapters because the sample used in order to undertake each task is adequate in proving and developing the methodology and rationale pertaining to each of the gaps.

4.5.Closing remarks

Chapter 4 presented the rationale and the adopted methodology relating to a global and local levels of survivability assessment. The foregoing chapters follow the methodology of the aforementioned section and elaborate further, including presentation and discussion of the ensuing results.

Chapter 5

Modelling and Prediction of Damage Survivability of Large Passenger Ships

5.1.Opening remarks

The current probabilistic damage stability concept, as outlined within SOLAS 2009/2020 for passenger ships, expresses survivability with a generic passenger ship formulation and this can cause problems. However, there is a large differentiation between passenger ship types in a manner that ships capsize or sink following a flooding event. Specifically, complexity in the internal watertight architecture and details in the local geometry of cruise ships play a vital role in progressive flooding, which is the cause for eventual sinking and capsize. Flooding of cruise ships can be inherently uncertain since there are multiple paths to same end state, while, the time to capsize becomes hours rather than minutes as in the case with RoPax vessels. To date, very little effort has been expended on research for damage stability and survivability of large cruise ships in particular. Within the following chapter, a new s-factor is presented catering specifically for cruise ships that accounts more accurately for survivability whilst capturing the physical phenomena of damaged ship behaviour in waves. A number of simulations are conducted on varying size cruise ships with the view to deriving a relationship between the critical significant wave height and the residual stability properties in line with previous studies, namely projects (HARDER, 1999-2003, GOALDS, 2009-2012). This, in turn, attempts not only to establish a survivability factor that addresses survivability of cruise ships accurately but it can also allow for a solution allied to the current damage stability framework. An alternative survivability derivation is sought namely using the Direct approach to damage survivability estimation through utilising numerical time-domain simulation tools. The simulations are performed with the view to gauging survivability in waves, linked to collision and grounding damages for two large sample cruise ships. On this basis, a comparison is conducted between the statistical and direct approach results, leading to drawing specific conclusions between the two techniques.

5.2. Statistical approach to damage survivability assessment of cruise ships in waves

Survivability in the scope of this thesis is derived on the basis of the concept of the capsize band and in line with previous survivability established approaches (see §3.3.6 and §3.3.8). This entails the concept of the critical significant wave height implicit in the formulation of survival.

Touching upon the description given in chapter 3, the critical sea state for a specific damage extent and loading condition can be established either with the aid of model tests or by employing time-domain numerical simulations based on first principles. Traditionally, both approaches have been utilised in the past in the course of developing damage stability criteria, including comparisons between the two (HARDER, 1999-2003, GOALDS, 2009-2012) on specific individual cases. Generally, both physical and numerical experiments refer to repeated trials (usually corresponding to 30 minutes full-scale (Cichowicz et al, 2016)) in a specific random sea with the view to deriving capsize rate at a specific significant wave height. However, this is the first time that a derivation of pertinent formulations for damage survivability in waves is solely based on numerical experiments.

In this respect, one of the main elements, which can be derived from the characteristics of the damaged ship is the **capsize band**. This indicates the range of sea states within which a transition from unlikely (Pc=0; Ps=1) to certain capsize (Pc=1; Ps=0) can be observed. Another concept intrinsically linked to the capsize band is the **capsize rate**. The capsize rate follows always a sigmoid shape distribution (see §3.4). Following previous studies, the concept of the s-factor is linked to the critical significant wave height. Originally, during the EU project HARDER (Tuzcu, 2003c) the s-factor was linked to the critical significant wave height of the sea state at which a ship exposed for half an hour (30 minutes) to the action of waves would have a 50% chance of capsizing. However, based on subsequent observations in project GOALDS (Tsakalakis et al., 2010a), it was found that when the simulation time increases, the capsize band contracts towards its lower boundary, with the capsize probability becoming a step function of Hs.

Generally, the s-factor is a measure of the probability of survival of a damaged ship in waves given from the following relationship (Cichowicz et al, 2016).

$$s = \int_0^\infty f_{Hs|coll}(Hs) \cdot F_{surv}(Hs)\, dHs \quad (5\text{-}1)$$

Where,

$f_{Hs|coll}(Hs)$ Represents the probability density distribution of the expected encountered sea states during collision incidence.

$F_{surv}(Hs)$ Probability of survival in the sea state represented above when exposed to a specific flooding scenario.

Deriving from the aforementioned capsize band section, the probability of survival represents in fact the conditional probability given from eq. (5-2) below.

$$s(t = 30m) = \int_0^\infty f_{Hs|coll}(Hs) \cdot F_{surv}(t = 30m|Hs)\, dHs \quad (5\text{-}2)$$

In addition to this, following the aforementioned observations, the probability $F_{surv}(Hs)$ is given by a step function centred on the critical sea state.

$$F_{surv}(Hs) = \begin{cases} 1 \leftrightarrow Hs \leq Hs_{crit} \\ 0 \leftrightarrow Hs > Hs_{crit} \end{cases} \quad (5\text{-}3)$$

$$s = \int_0^{Hs_{crit}} f_{Hs|coll}(Hs)\, dHs = e^{\left(-e^{\left(0.16-1.2\cdot Hs_{crit}\right)}\right)} \quad (5\text{-}4)$$

Where, Hs_{crit} is derived from project HARDER (Tuzcu, 2003a) as follows,

$$Hs_{crit|30min} = 4 \cdot \left(\frac{\min(GZ_{max}, 0.12)}{0.12} \cdot \frac{\min(Range, 16)}{16}\right) \quad (5\text{-}5)$$

$$Hs_{crit|30min} = 4 \cdot s(t|30min)^4 \quad (5\text{-}6)$$

Thereafter, following the observations within project (GOALDS, 2009-2012), in line with project HARDER, an alternative survivability factor was introduced to serve for the limiting assumption on survival time, which accounted adequately for the effect of water on deck and effects of ship and damage size through the concept of critical significant wave height. Specifically, the formulation utilised the area under the GZφ curve, GM, Range and the residual volume of the damaged vessel (Cichowicz et al., 2016a) as provided by eq.(3-9) and (5-7) below. The latter was introduced in order to account for the effects of the ship size which is characterised as key characteristic to modern cruise liners. However, the residual volume solely depends on the way the ship is subdivided and the topology of the bulkheads and watertight deck. This, in turn, implies that a higher positive stability can be attained (through the increase of the GZ_{max}) when the volume is distributed higher above the bulkhead deck and as far from the centreline as feasible.

$$s(Hs) = \begin{cases} e^{\left(-e^{\left(0.16-1.2\cdot Hs_{crit}\right)}\right)}, \forall\ (AGZ, V_R, Range, K>0) \\ 0, otherwise \end{cases} \tag{5-7}$$

Even though the GOALDS formulation provided a good correlation to experimental data as explained, in earlier sections comprehensively, when compared to the current SOLAS 2009/20 s-factor, its derivation has been exclusively depended upon sample data of either RoPax or solely cargo RoRo ships. Adding to this, the one cruise ship for which experimental data have been obtained, demonstrated significant resistance to capsize. This leads to the following observations:

〉 The s-factor cannot relate to cruise ships based on the initial sample set used and the ensuing formulation.

〉 The s-factor in place does not reflect the survival resistance of cruise liners.

In order to overcome this, the described concept has been utilised on the basis of a number of numerical simulations conducted on a total of four cruise vessels of varying sizes for the derivation of the cruise ship-specific s-factor. The simulations have been conducted according to the worst case three-compartment damage, lying within 1/3 of the subdivision length about midships and across a range of loading conditions. The dynamic behaviour of each vessel in the damaged condition has been assessed under a range of wave environments characterised by varying significant wave heights, using a JONSWAP spectral distribution. For each damage scenario assessed through simulation, the critical significant wave height has been identified and a relationship between the residual stability properties of each vessel and Hs_{crit} has been derived. Based on this information a new cruise ship-specific formula for predicting the Hs_{crit} has been derived on the basis of GZ properties through regression of the simulation results. Following this, a new s-factor formulation that accounts more accurately for cruise vessels has been proposed using a regression formulation of the significant wave height distribution at the time of the accident with respect to the critical significant wave height.

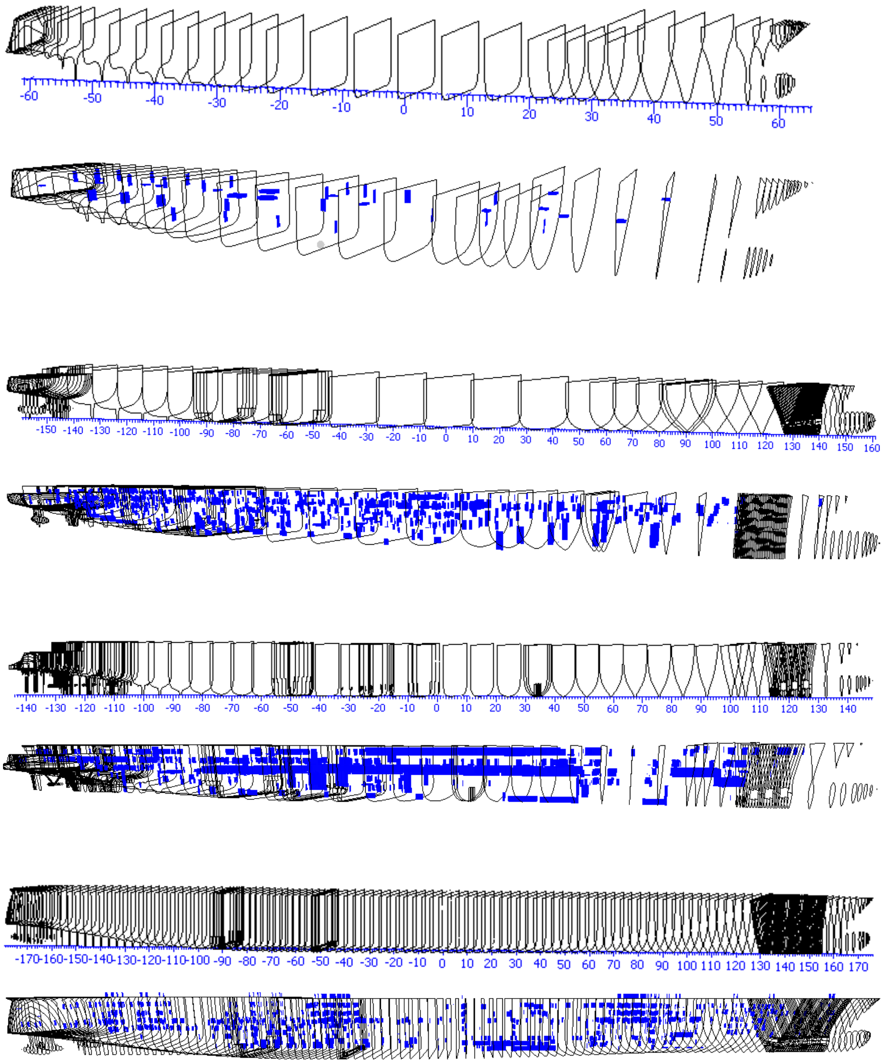
Following the description of the methodologies available as described in chapter 3 (see §3.4), survivability in the presented work is derived solely on the basis of numerical time-domain simulations for a number of reasons. Initially, the watertight architecture of cruise vessels is very complex and this would necessitate excessive cost and time. Recent studies (Ruth et al., 2019, Niotis et al., 2019) have demonstrated the application of CFD and conducted comparison with time-domain numerical simulations in damage stability proving their respective application implications.

Numerical time-domain simulations can capture a high degree of internal detail pertaining to rooms and openings and this is merely based upon the considered level of subjected detail of the simulation geometry models. Additionally, as mentioned in earlier sections, cruise ships do not necessarily capsize instantly but instead follow progressive flooding. Such dynamic effects following the progressive flooding process are demanding and hard to model through employing tank experiments but instead they can be easily captured with time-domain numerical simulations. In light of the aforementioned, the time- domain numerical simulations form a capable means of predicting survivability.

5.2.1. Numerical simulation methodology and establishment of pertinent formulations for damage stability of cruise ships

Cruise ships considered

Four varying size ($128 \leq L_{OA} \leq 359$ meters) cruise ships have undergone numerical time-domain simulations and modelling in PROTEUS (Jasionowski & Vassalos, 2001). The numerical simulation geometry models used in the simulations are provided in the figures below along with their main particulars in size order.



	Ship D	Ship A	Ship C	Ship B
Loa (m)	128	294	324.9	359
B (m)	19.5	35.4	38.7	41.2
T (m)	5.3	8.25	8.3	9.3
Dis. (ton)	8885	49508	73061	95218
GM (m)	1.47	2.4	2.24	2.4

Figure 17: Numerical simulation models with openings in PROTEUS for the four cruise ships along with their main particulars

Modelling assumptions

The four sample ships presented in Figure 17 are modelled in PROTEUS, including hull/compartmentation, geometric subdivision and detailed openings. The simulation models are subjected to modelling alterations in order to improve computational efficiency and allow for the adoption of the non-zonal approach. This included simplification of the geometries and internal compartmentation with regards to reduction of knuckle points on sections. In particular, large damages include a large number of damaged rooms and thus a large number of geometrical groups (sections and points). This number of simulation geometry groups is reduced by decreasing the number of sections on specific rooms and points that subsequently can provide a simplified simulation model. This does not have any bearing on the accuracy of the spaces in terms of volumes and their centres. The stability geometries are modelled to capture meticulously detail following the actual general arrangements of the vessels in consideration. Two characteristic examples are provided in Figure 18 for two different decks demonstrating the additional degree of detail.

This leads to detailed modelling of all the openings (down flooding points, all type doors, hatches, and cross-flooding openings) which in the case of cruise ships is essential for vulnerability studies. For example in the case of cruise ship C a total number of 1044 openings have been modelled in PROTEUS indicating the large magnitude of the entailed complexity. The main inputs of such openings comprise length, width, connected compartments, direction, opening type, opening coordinates, collapse pressure, time to open, time to close, leak height and leak ratio. Water progression is assumed only through openings and doors, while, pipes and ventilation trunks have not been included while the status of the door follows the respective damage control plans. The opening definition follows guidelines from the FLOODSTAND D2.2b report (Ruponen and Routi, 2011) for modelling door and boundaries for flooding simulations. This involved the guideline values for collapse heads and leak rates of each different type of door modelled in PROTEUS.

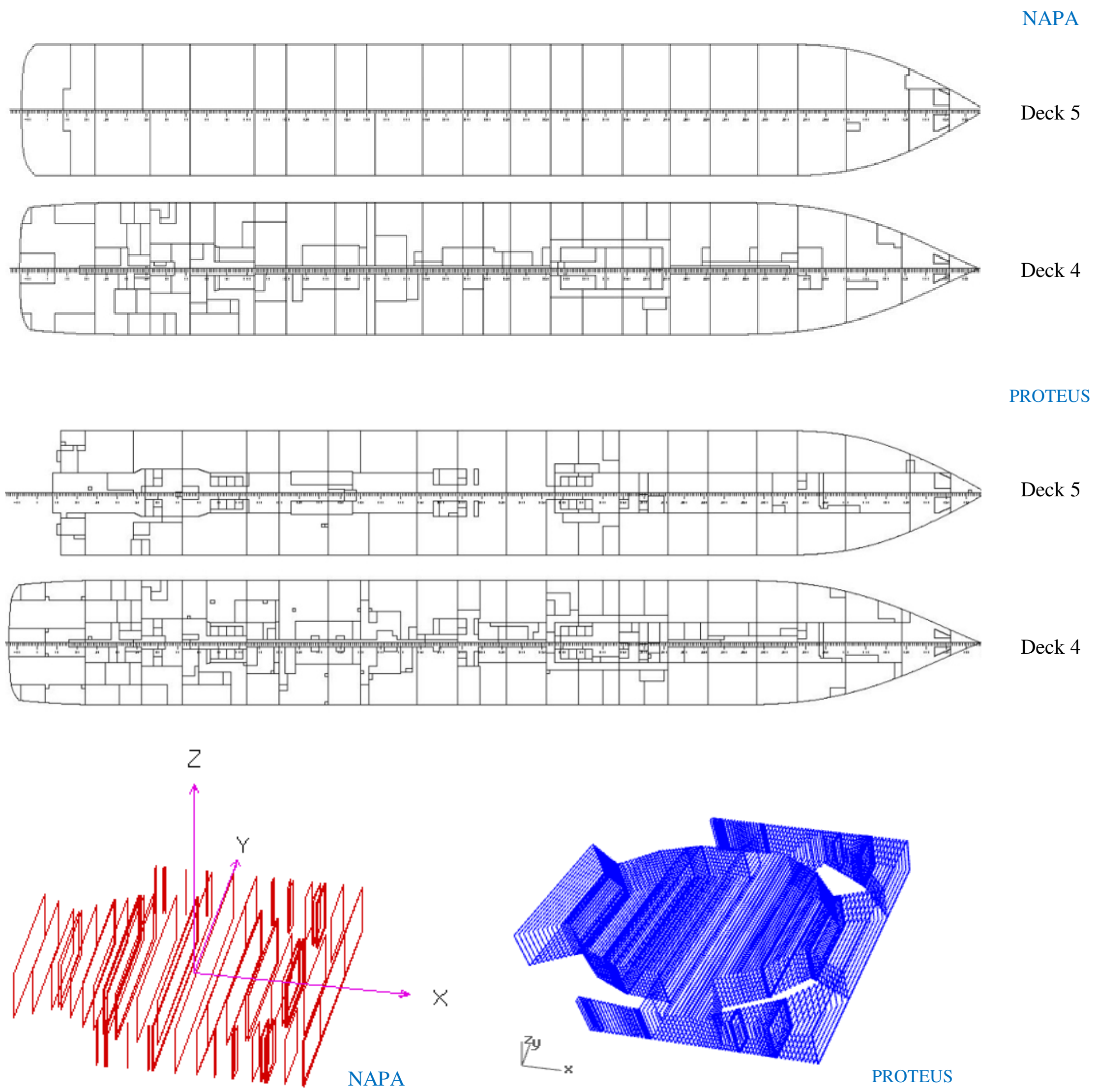


Figure 18: Indicative room modelling in PROTEUS and NAPA respectively for two decks and sections for one public space above the watertight bulkhead.

5.2.2. Simulation methodology

In order to facilitate the derivation of a cruise-vessel-specific s-factor and Hs formula, the initial basis ships were subjected to a number of numerical simulations in pre-specified damage scenarios in increasingly higher sea states with the aim to identify the relationship between important stability parameters (GZ_{max}, A_{GZ}, Range, FB etc.) and the critical significant wave height. The simulations account for 'equilibrium mode' tests where the vessel was allowed to equalize (ramping) before being subjected to the action of the waves and have been conducted using the worst case three-compartment damage within a range spanning one third of the subdivision length amidships (1/6 on either side of midship). The damage was located in this manner in order to ensure critical damage geometries (floodwater accumulation) and to remain in line with the approach taken in previous studies aimed at the derivation of s-factors such as in project HARDER.

Following work from projects HARDER (Tuzcu, 2003b) and GOALDS (Papanikolaou, 2012) midship damages were also explored. A damage extent spanning three-compartments (spaces separated by watertight bulkheads, not zones) in length was selected on account of the fact that no two-compartment damage scenarios led to capsize in any of the vessels subjected to assessment, which meet SOLAS 2-compartment standard. To this end, following the same fashion as before, two sample ships, namely ship A and C are the best candidates in order to identify, following static damage stability assessment, critical damages that are representative and can form a comparison basis as explained in later paragraphs. The initial conditions for each vessel were also defined based on criticality with respect to the three SOLAS 2009 initial loading conditions. Firstly, the draft was selected as that associated with the worst post-damage stability properties in accordance to SOLAS. Each vessel's initial KG was then selected based on the limiting KG value such that no three-compartment damages capsized statically (in calm water).

Damage simulations are then conducted for each vessel, firstly according to the initial conditions described above and then at incremental reductions in KG allowing for the influence of KG and thus the vessel stabilities properties on the critical significant wave height to be determined. Each KG value (initial condition) is subjected to five simulation runs and the critical significant wave height is defined as the highest significant wave height in which no capsizes were observed. The number of runs per case is based on previous studies (Jasionowski, 2006, Chen, 2012, Chen, 2013).

(Papanikolaou et al., 2010) presented that cruise ships exhibit high resistance to capsize as observed in project GOALDS for the two cruise ship damages used in the experiments. There however, one damage failed to capsize with reduction of GM which subsequently was achieved using brute force of opening the semi-watertight doors above the watertight deck (Papanikolaou et al., 2010).

Notwithstanding the above, the described approach is a change of direction from the approach taken in the model tests upon which SOLAS 2009 is based, in which only two-compartment damage scenarios were considered on cargo vessels and the critical significant wave height was taken as the significant wave height were the capsize probability was 50% as indicated in Figure 19 for a sample case. To this end, damage lengths (longitudinal or transverse) are not limited and that in fact can cater more accurately for larger damage lengths which can potentially facilitate the applicability of the approach to large scale grounding damages.

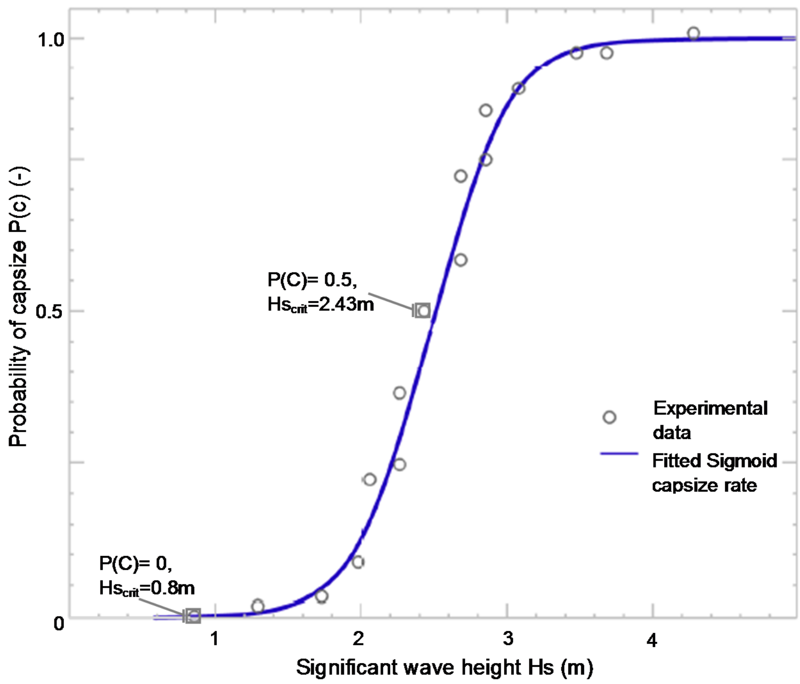


Figure 19: Example of critical significant wave height based on the new approach, based on the highest significant wave height in which no capsizes were observed and HARDER as the significant wave height were the capsize probability is 50%.

5.2.3. Step scheme identification of critical damages

The following steps describe the process of identifying a damage case for subsequent damage stability assessment through simulations.

1. Performance of a static damage stability assessment (calm water) at each of the three SOLAS 2009 draughts.
2. Use of the same GM value for each draught (based on SOLAS 2009).
3. If no three-compartment damage case capsized, GM was decreased until such point that one does, thus enabling the definition of the critical GM for three-compartment damages.

4. If at step 2 there are three-compartment damage cases that capsize, the GM is incrementally raised until such time that no three-compartment damage case capsized, again identifying the critical GM value.
5. If the most critical three-compartment damage case, that being the case that fails first due to decreasing GM, is within 1/3Ls amidships then this damage case should be selected for subsequent simulations.
6. If the most critical three-compartment damage case is located out width the aforementioned range then GM is reduced further until the first three-compartment case capsizes within the 1/3Ls amidships.
7. If step 6 is necessary, the GM value used in subsequent simulations is the value such that no three compartment damage case failed and the limiting GM value such that the damage case amidships capsizes.
8. In the case that there is little variation between the criticality of draughts, the subdivision draught shall be used, as cruise ships have been shown to operate primarily around this draught.

The following flow chart illustrates the critical damage identification process and simulation methodology.

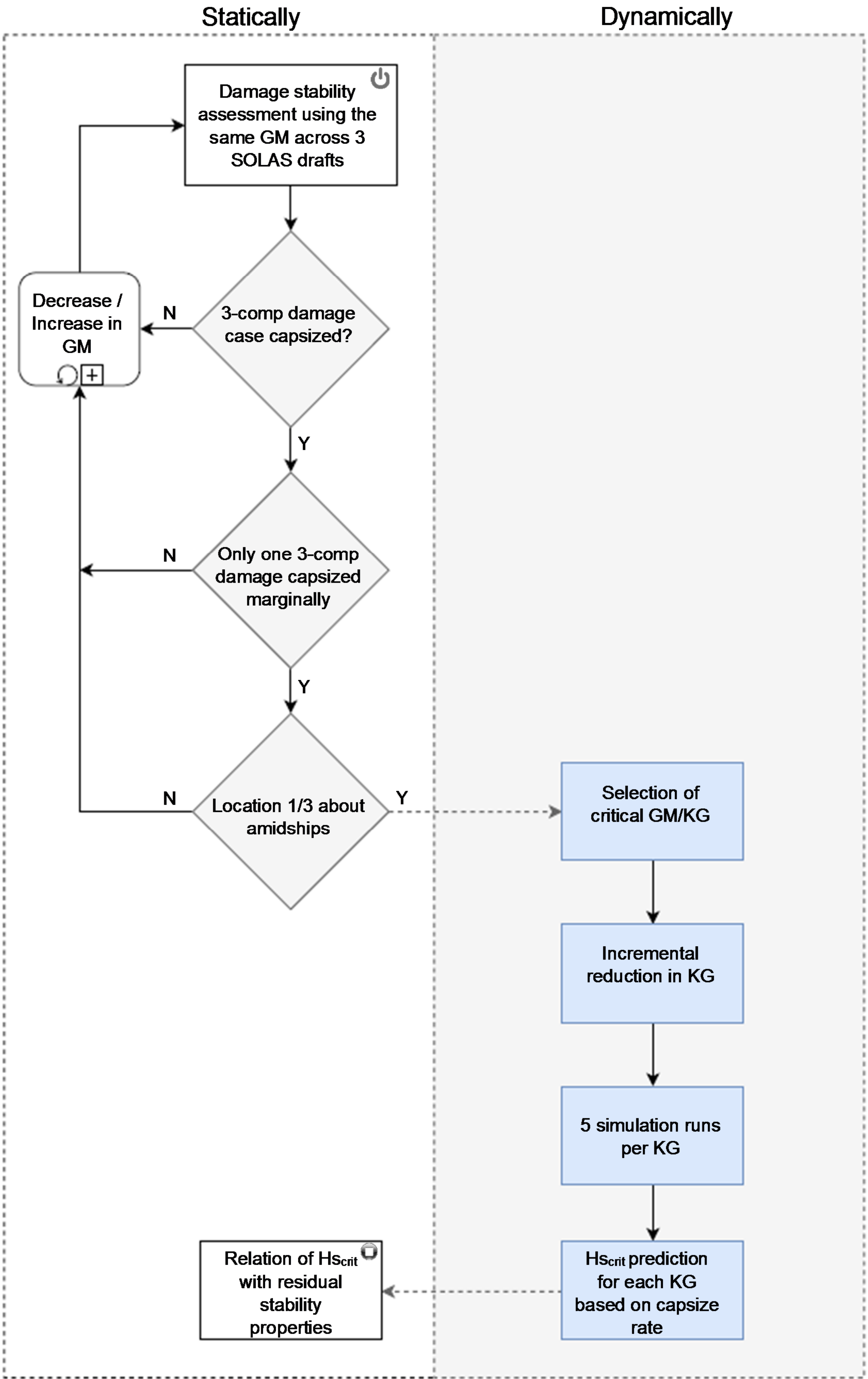
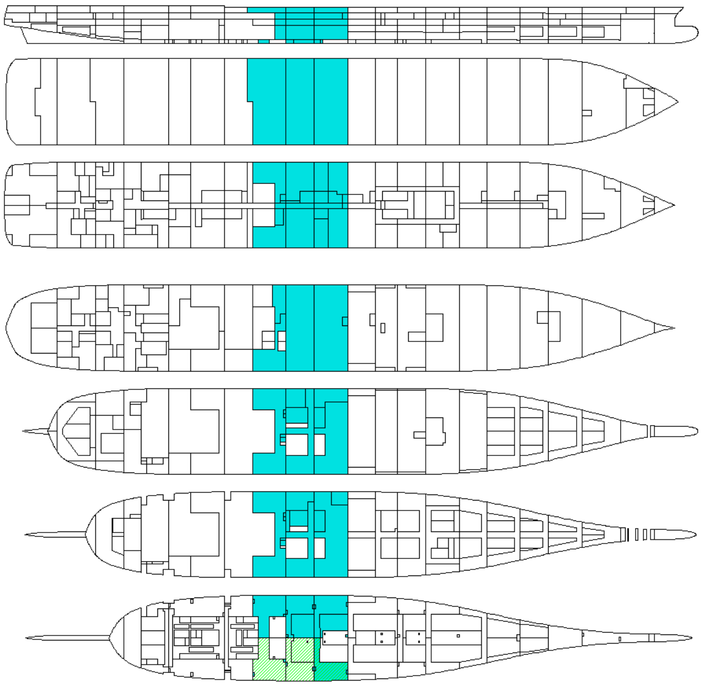


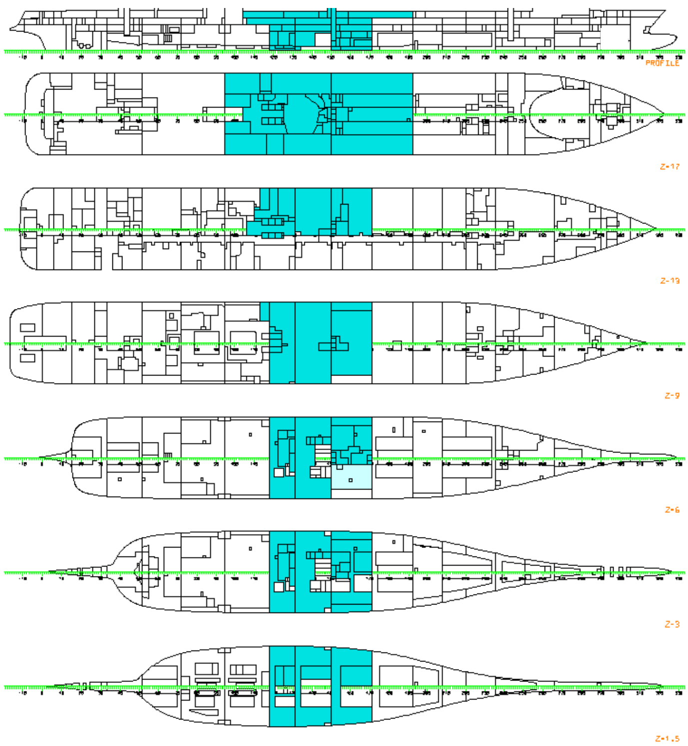
Figure 20: 3-compartment damage identification using static and dynamic assessment instruments

5.3.SOLAS collision damage characteristics

The characteristics of the extent and location of each of the midship SOLAS collision damage cases can be found in the following tables along with their damage visualisation.



Damage	D1-Ship A
X1	115.8
X2	149.38
Adjacent zones	3
Floodwater volume (ton)	10668



Damage	D1-Ship C
X1	99.7
X2	144.4
Adjacent zones	3
Floodwater volume (ton)	12809

Figure 21: 3-compartment collision damages and particulars for ship A and C.

5.4.Prediction of survival state for cruise ships in waves

The critical significant wave height is derived in line with the concept of the capsize band. The capsize bands (significant wave height versus vertical centre of gravity) are depicted for the two damages shown in Figure 21. Generally, each capsize band is formed for a number of loading conditions. The identification of the critical significant wave height pertaining to each different loading case (KG/GM) is based on the capsize rates (probability of capsize versus significant wave height) as demonstrated below.

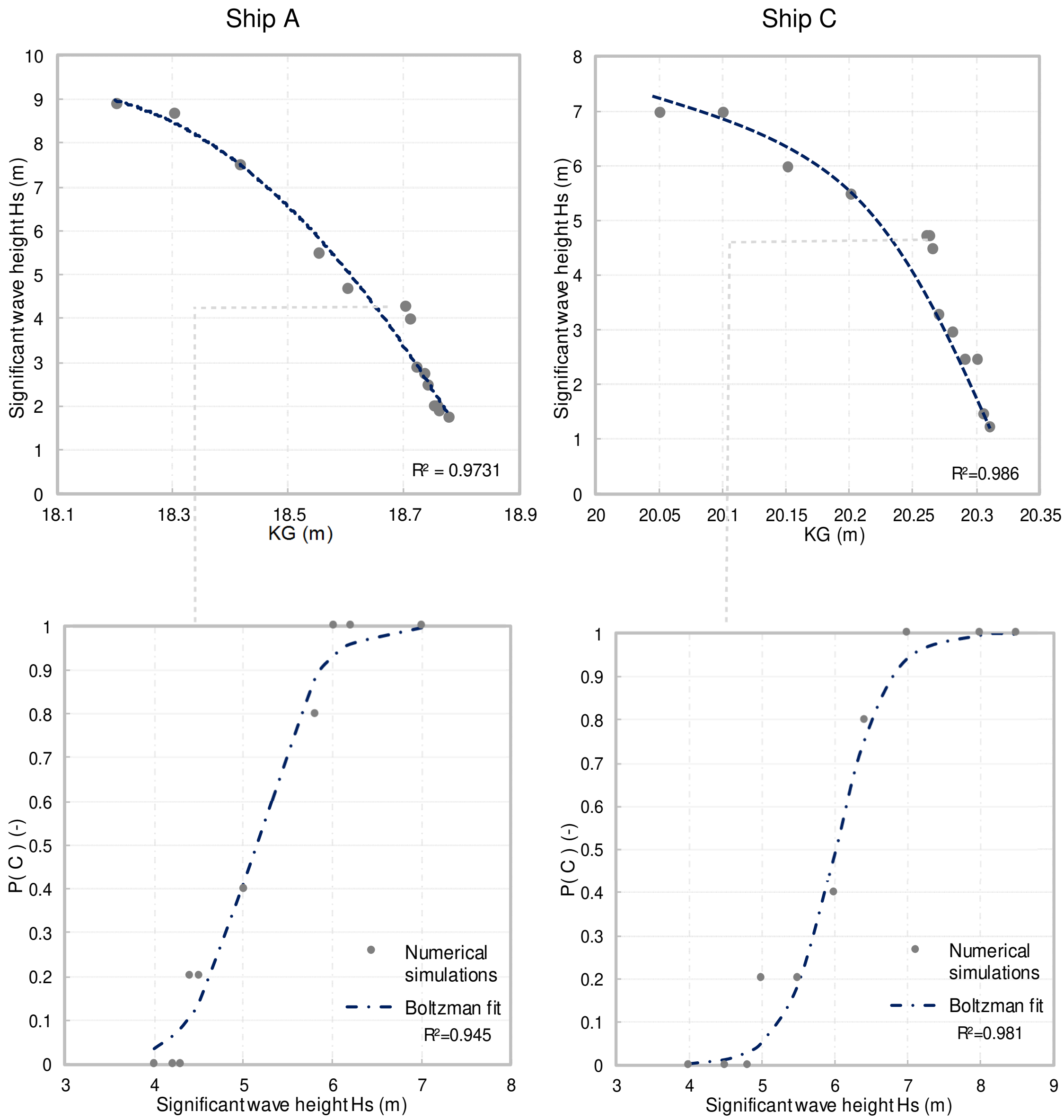


Figure 22: Capsize bands and capsize rates for 3-compartment midship damages for ship A and Ship C. The capsize rate graphs indicate the derivation of a critical wave height of 4m for ship A and 4.8 meter for ship C respectively.

The foregoing results are provided for the two initial damage collision cases for ship A and ship C as presented in the previous section. The primary failure mode witnessed across all simulations was capsizing (physical capsize). In the following graphs the relationships are shown with regards to the un-truncated damaged Range and GZ_{max} meaning that these values have not been limited to the angle at which unprotected openings are immersed but instead only the angle where the righting lever becomes zero. Such characteristics (openings) relate to local details in the ship geometry that cannot be easily captured by global parameters such as the residual stability properties. In the case of cruise ships, two ships can have the same size but can entail different opening arrangement, which in turn, implies that the presence of different openings which are immersed would result very different residual stability properties for two ships.

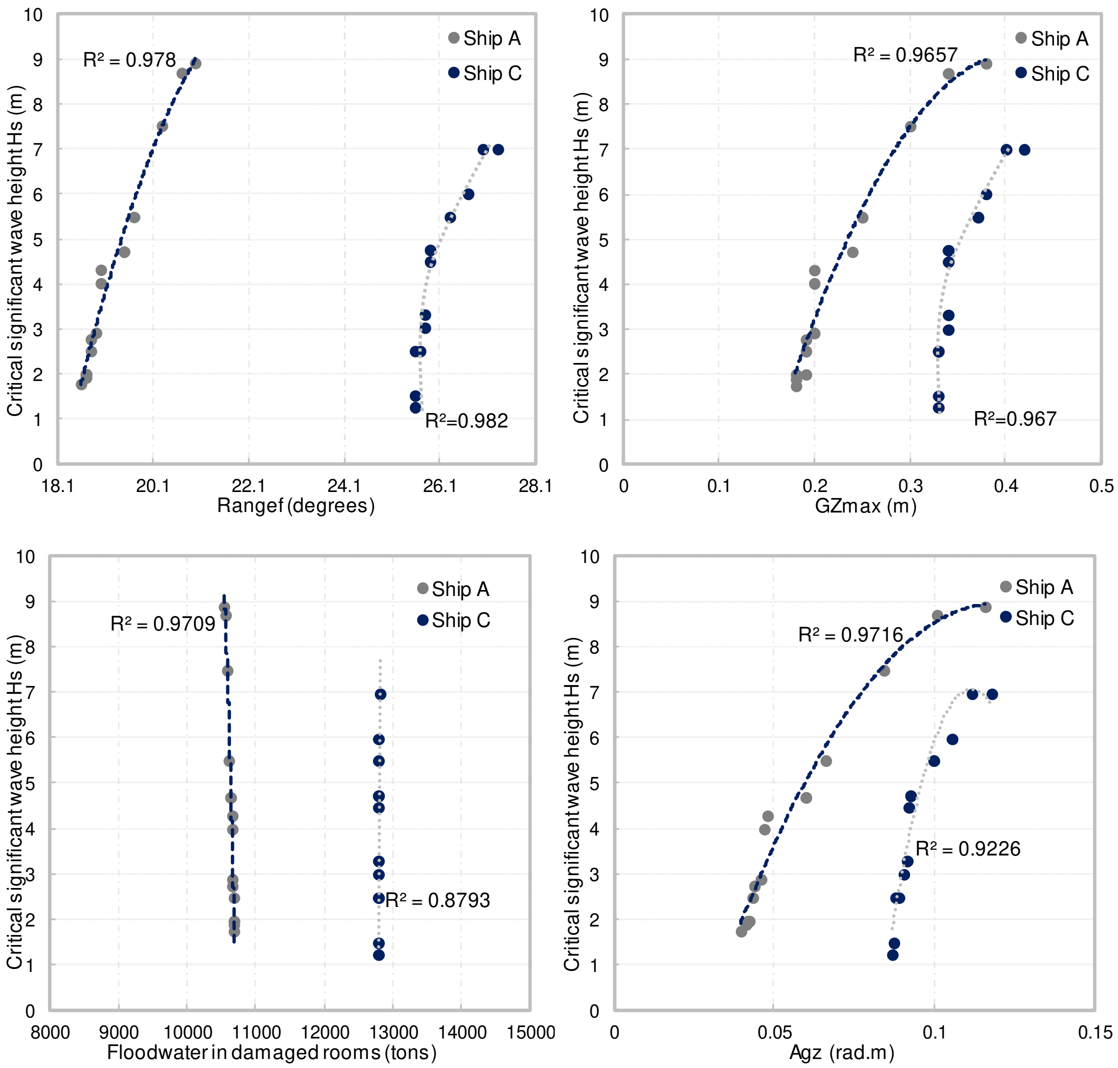


Figure 23: Relationships of derived significant wave height from simulations and residual stability properties for the two damages.

5.4.1. Scaling effects

Having collated the results from the initial two vessels, a disparity in the stability properties required in order to achieve the same critical significant wave height was observed. This exacerbated any efforts in achieving any form of the data that would aid in the derivation of statistical analysis. This was attributed to the difference in scale in both the size of each vessel and the volume of accumulated floodwater associated with each of the vessel respective damage case. It was, therefore, considered necessary to find an appropriate scaling factor. In this effort, several parameters were investigated including the residual freeboard and residual volume. However, the most suitable scaling parameter was found to be the "Effective Volume Ratio"; a parameter which accounts for both the ship and damage size and the volume of floodwater. The EVR is calculated according to the following formula,

$$\text{Effective Volume Ratio} = \frac{V_{residual}}{V_{flooded}} \tag{5-8}$$

Where, the residual volume $V_{residual}$ is given from the following formulae,

$$V_{residual} = V_{WTE} - V_{Displacement} - V_{flooded} \tag{5-9}$$

Where, specifically:

V_{WTE}	Weather Tight Envelope is the real weathertight extent and refers to the total volume of all rooms contained in the area spanning from the base line up to and including the deck at which weather tight structure spans vertically. This reflects the physical properties of the vessel (m^3).
$V_{Displacement}$	Represents the volume of displacement of a given vessel (m^3).
$V_{flooded}$	Represents the volume of the water in the flooded compartments at the final stage of flooding based on static calculations (m^3).

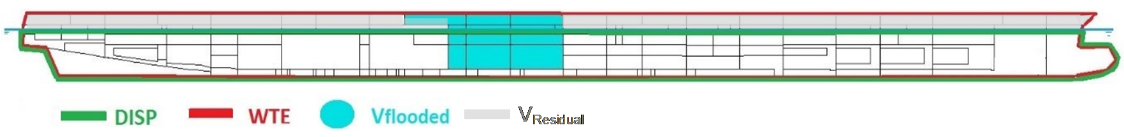


Figure 24: Sample cruise ship, example of definitions

Notably, the scaling factor is explicitly depended on the Effective Volume Ratio of the damage case (constituting it damage-specific) since the flooded volume ($V_{flooded}$) will always change based on the specific damage extent. Also, independently of the damage case scenario, the residual volume and ultimately the EVR of the damage case depends upon the displacement, which varies based on the prescribed drafts and loading GMs or KGs. In a SOLAS complementary framework, the EVR would also change with the three damage stability drafts (dl, dp, ds).

Therefore, the scaling factor (λ) is the ratio of Effective Volume Ratios of the vessel in consideration divided by a constant value obtained through regressing the data set available as provided in the equation below,

$$\text{scaling factor} = \lambda = \frac{EVR_{Ship(damage-specific)}}{8.6} \quad (5\text{-}10)$$

Where,

$EVR_{Ship(damage-specific)}$	Reflects the Effective Volume Ratio of the damage in consideration accounting for the loading condition.
8.6	Represents a constant value derived based on the basis ship (ship A) used in the formulation design and the related simulation results. Further justification is provided in the foregoing.

The denominator of eq.(5-10), is derived on the basis of ship A using the residual and flooded volume of the damage depicted in Figure 21. The reason behind the selection of damage D1 of Ship A as basis for scaling is based on the fact that the damage is a characteristic critical 3-compartment equivalent damage based on SOLAS framework. Therefore, it reflects the two compartment midship damage, which was used as basis for the derivation of the current SOLAS survivability factor.

$$EVR_{shipA} = \frac{V_{residual}}{V_{flooded}} = \frac{89115.58\,m^3}{10367.6\,m^3} = 8.6 \quad (5\text{-}11)$$

The concept of the scaling factor is flexible in the way it can accommodate for adapting different basis ships having as result to translating the results relatively to the ship in consideration (with regards to volume). An application using different ships in scaling the residual properties of the data set obtained is provided in Appendix B indicating that the impact on the residual properties obtained is similar.

5.4.2. Application of scaling factor on midship collision damages

The application of the scaling factor has been systematically verified and examined with the consideration of different damage extents as they are provided in later sections and it has been proven robust at any case. Here, the scaling factor is applied on the first two cases for demonstration purposes. The values presented are un-truncated GZ properties and have been taken until the point of vanishing stability as opposed to the immersion point of openings, floodwater paths and so on. The following results present only the properties of the GZ curve, namely the scaled GZ_{max} and scaled Range.

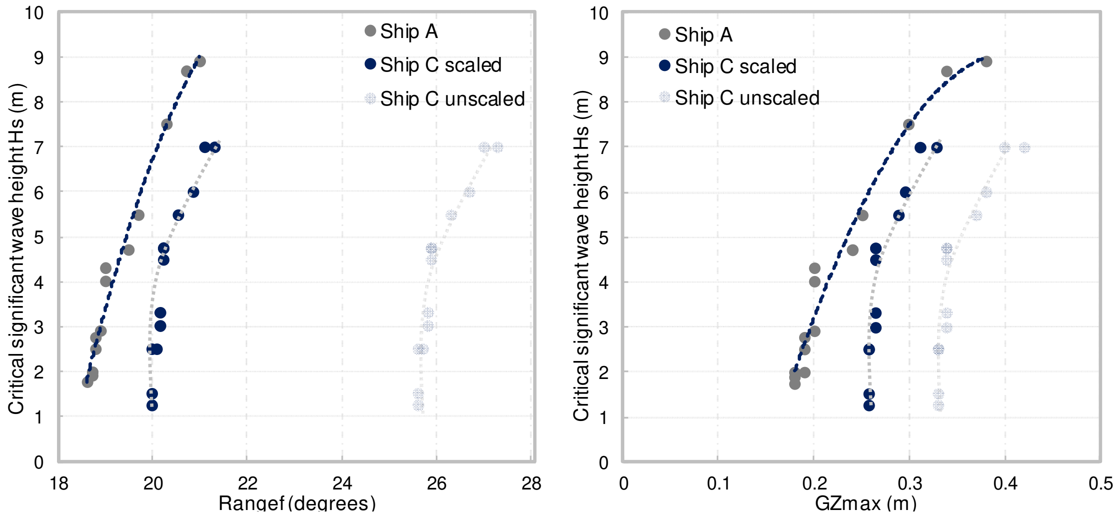


Figure 25: Scale factor application on initial results for the stability properties GZ_{max} and Range.

It would be noteworthy to appreciate that the characterisation of a very complex physical phenomenon taking place in a very intricate internal environment is captured by using only two parameters of the residual curve (GZ_{max} and Range). Being able to identify trends and dependencies in the way described in the foregoing and in the aforementioned figures, is indicative of the strong relationship between residual stability properties and ship survivability.

5.4.3. Consideration of different damage extents

Application of the derived formula in a probabilistic framework implies application to all damage cases considered in the calculation. Hence, verification that scaling works across the whole range of ships and damage cases is necessary, accounting of course for the fact that oversimplification of the phenomena being modelled will affect correlation. Moreover, the proposed formula should demonstrate robustness to changes in the parameters comprising such formulation. In this respect, application of the proposed formulation and scaling approach in the results shown above demonstrates unacceptable sensitivity, mainly due to the limitation in the number of data points obtained from the numerical simulations. It is, therefore, concluded that whilst the concept appears to be rational and consistent in its application, the final formulation needs further work. To this end, further sample ships, damage cases and subsequently data points are required to increase the robustness of the proposed formula and accuracy of the regression.

Therefore, the proposed approach has been tested not only for damage cases outside amidships, but also, for different number of compartments including 1, 2 and 4-compartment damages for all four ship sizes, scaled by using the same scaling approach described in the aforementioned section. In this sense, 3 1-comparment, 4 2-compartment, 5 3-compartment damages and 2 4-comparment damages are investigated as provided in the table below (see Table 3).

The number of the sample damages considered, as indicated in Table 3, covers a wide range of damage extents and damage volumes, which could be witnessed during a typical survivability assessment of large passenger ships. In this respect, different damage locations and size-based damages based on compartment equivalency are used for simulations and application of the concept to prove its robustness and rationale. Finally, different damages such as symmetrical or damages including the main service corridor and the centreline of the vessel have been also considered in order to cover a wide range of potential uncertainties implied by the concept formulation.

Table 3: Collision damage characteristics considered in the Hs_{crit} formula derivation

		Damage Length (m)	Zones	Location	Average Floodwater accumulation (ton)
Ship A	D1	33.38	3 (15-17)	Midship	10668
	D2	18	1(13)	Midship	1156
	D3	9	1(8)	Aft shoulder	4640
	D4	36	2(13-14)	Midship	3550
	D5	35	2(8-9)	Aft shoulder	10335
	D6	51.79	4(5-8)	Aft shoulder	12190
Ship B	D1	152	3(13-15)	Midship	10360
Ship C	D1	45	3(11-13)	Midship	12809
	D2	43	3(23-25)	Fore	9540
	D3	18.28	1(3)	Aft	2160
	D4	28	2(21-22)	Midship	7570
	D5	31.6	4(8-11)	Aft shoulder	10960
Ship D	D1	31.14	2(8-10)	Midship	1917
	D2	29	3(14-16)	Fore	1047

Numerical simulation results

The following section provides the results that have been obtained for all the damages, which have been presented in Table 3 without the application of the scaling factor.

As demonstrated in Figure 26 and Figure 27 below, the related properties of the GZ curve are scattered across the graphs. This is justified primarily by the effects of the ship size and the total residual volume on the un-truncated range and GZ_{max}. For these cases, there is small dispersion with increase of the values of the range and GZ_{max}. This signifies the sensitivity of the vessels on floodwater accumulation, which tends to be obvious for smaller cruise ships. However, the varying linear trends across the different damage cases are significantly noticeable. The floodwater presents a linear vertical trend across the same damages with the variation of the loading GM and KG. Particularly, the higher the floodwater mass relative to the size of the vessel (aka actual residual volume), the higher the observed deviation across the data.

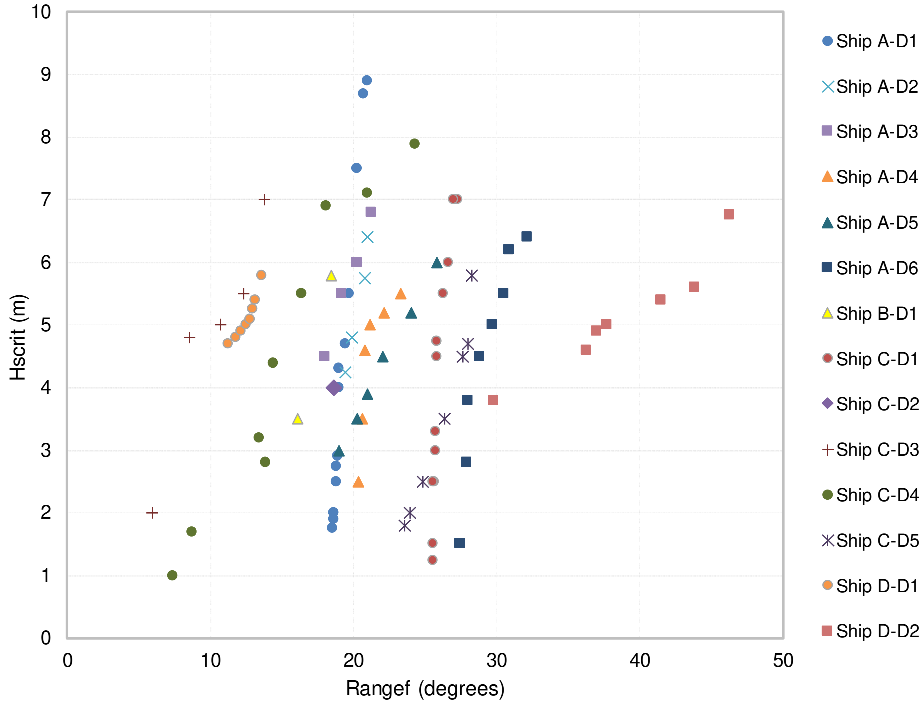


Figure 26: Relation of critical significant wave height Hs_{crit} (m) and residual range (degrees) for all damage cases considered.

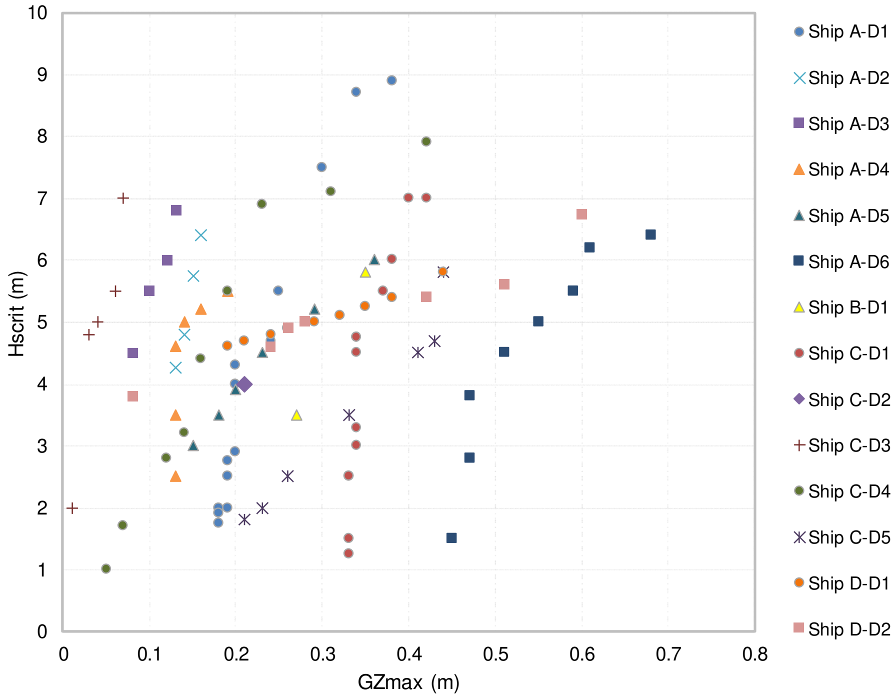


Figure 27: Relation of critical significant wave height Hs_{crit} (m) and residual GZ_{max} (metres) for all damage cases considered.

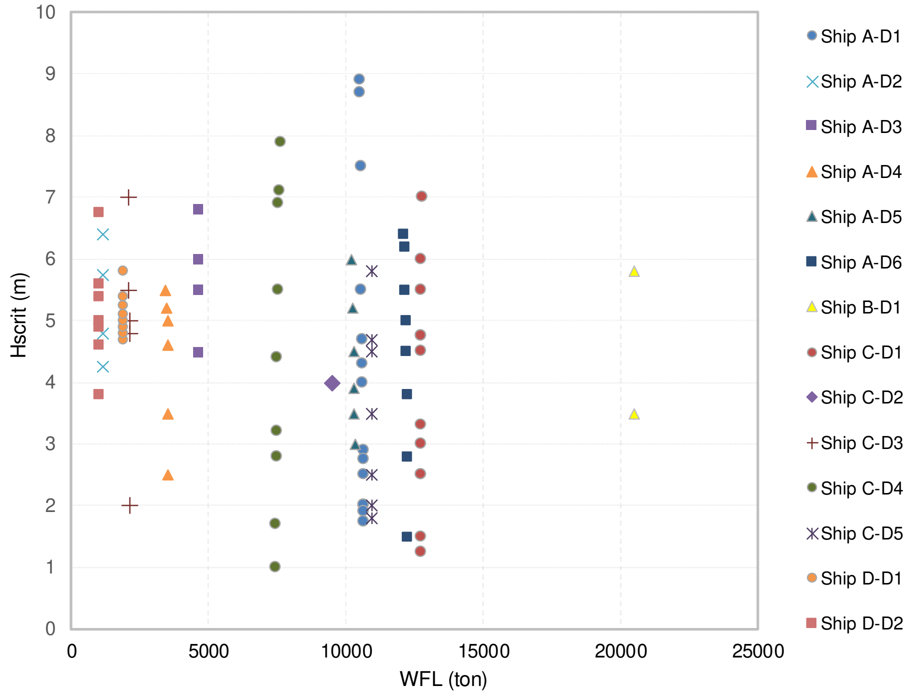


Figure 28: Relation of critical significant wave height Hs_{crit} (m) and total floodwater accumulation in damaged rooms (tons) for all damage cases considered.

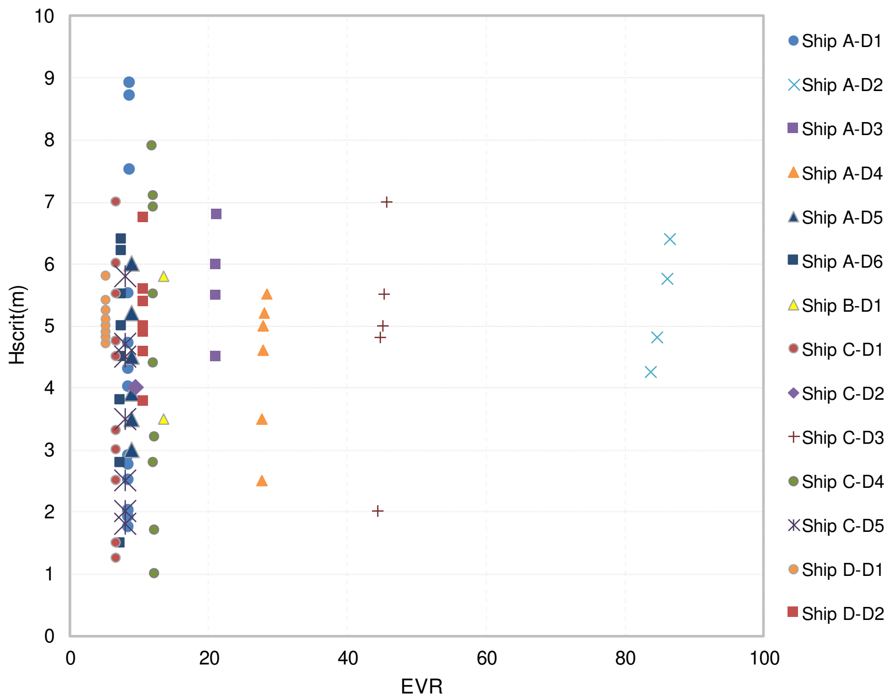


Figure 29: Relation of critical significant wave height Hs_{crit} (m) and the Effective Volume Ration for the considered damage cases.

Scaled results

The aforementioned scaling factor approach is applied on the entire data point sets, which have been obtained through simulations. The following graphs demonstrate that a better correlation is achieved for the properties of GZ curve.

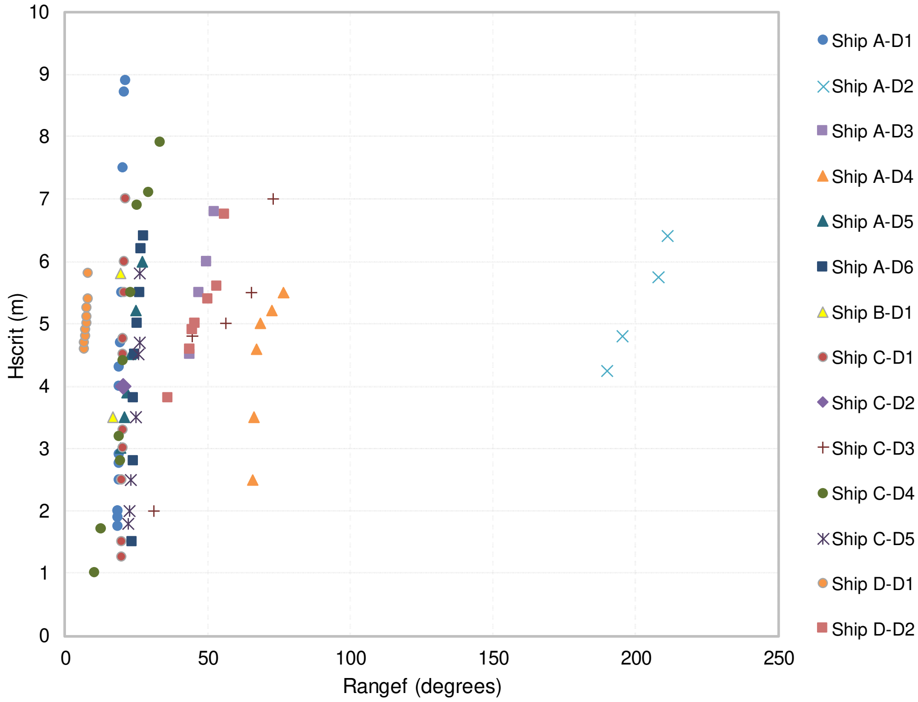


Figure 30: Relation of critical significant wave height Hs_{crit} (m) and scaled residual range (degrees) for all damage cases considered.

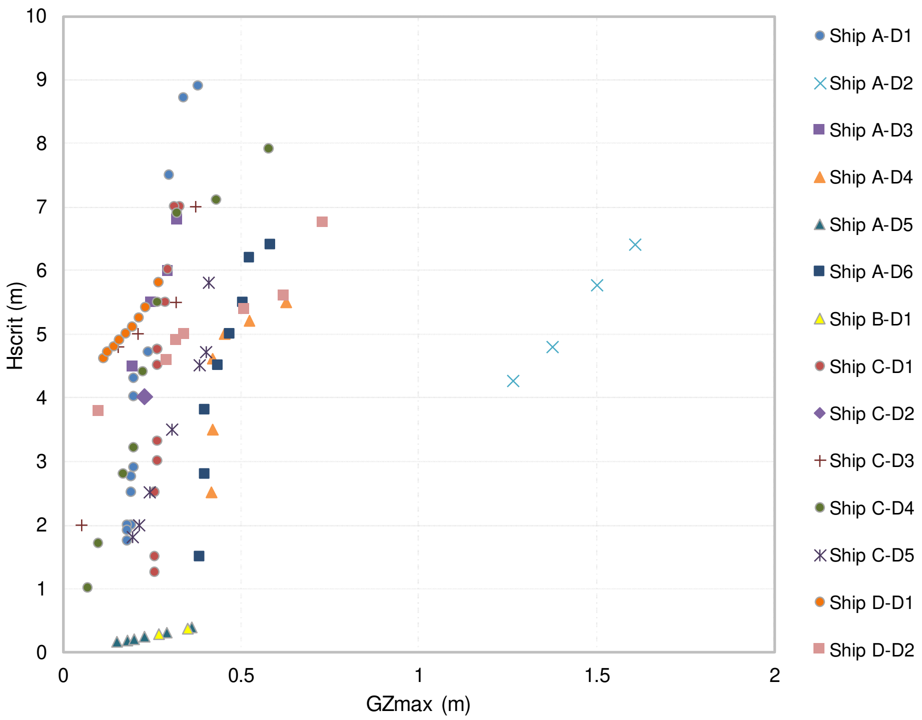


Figure 31: Relation of critical significant wave height Hs_{crit} (m) and scaled residual GZ_{max} (metres).

As it can observed from the scaled results, the one compartment damage for the large cruise ship, which entails the smallest average floodwater volume within the sample deviates entirely from the trend. This can be justified from the large residual volume of the vessel. Typically, smaller damages of the large cruise ships indicate a higher EVR as expected. Initially, this was accounted for through the implementation of conditional scaling for values smaller than a predefined threshold. However, the consideration of such boundaries from an implementation perspective in the long term, constitute high uncertainties.

Following a systematic sensitivity analysis on the magnitude of the Effective Volume Ratio for different damage extents, it was observed that the EVR can increase or decrease to such extents that the requirements (GZ_{max} and Range as explained later) move to extreme values, such cases however are unrealistic and outwith the area of interest. For example, for a vessel to have an EVR equal to 2, the floodwater mass would have to be equivalent to 50% of the residual volume, which is unrealistic. On the other hand, for a vessel to have an EVR equal to 40 the floodwater mass would be 2.5% in relation to the residual volume, which is not a problem area that would require further study.

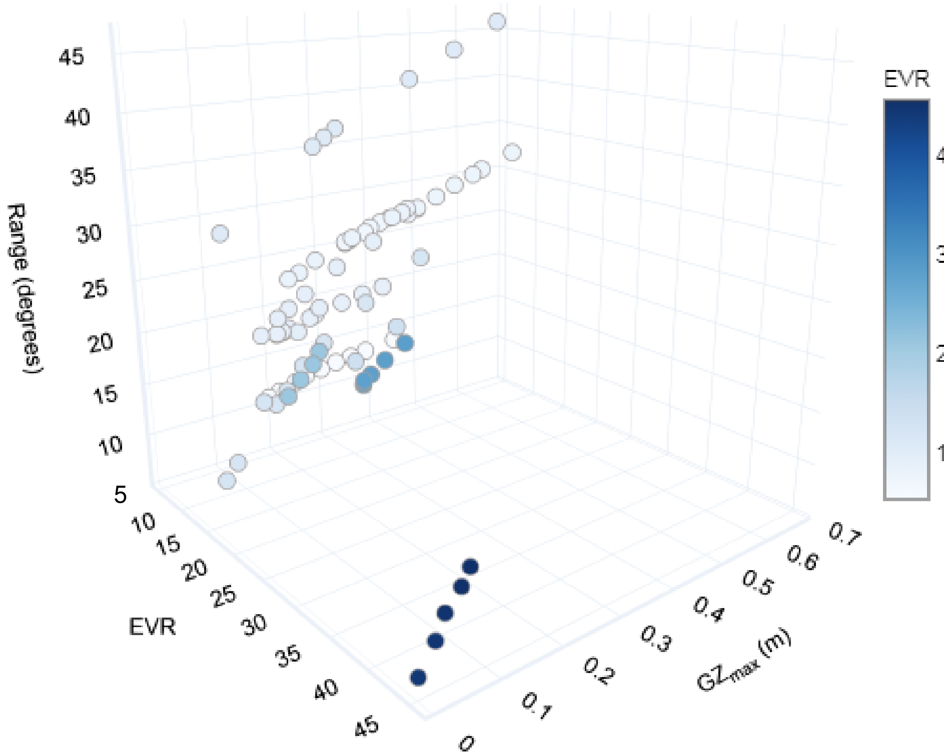


Figure 32: Effective Volume Ratio as function of GZ_{max} and Range for all damage cases.

Figure 32 presents the relationship between the Effective Volume Ratio, GZ_{max} and Range values obtained for each of the damages through simulations. Also, Figure 33 indicates the way the EVR varies with change in the floodwater volume for the three ships used in simulations, keeping constant their weathertight and displacement volumes. The results indicate that the smaller the ship size is, the more sensitive the EVR becomes towards bigger damages.

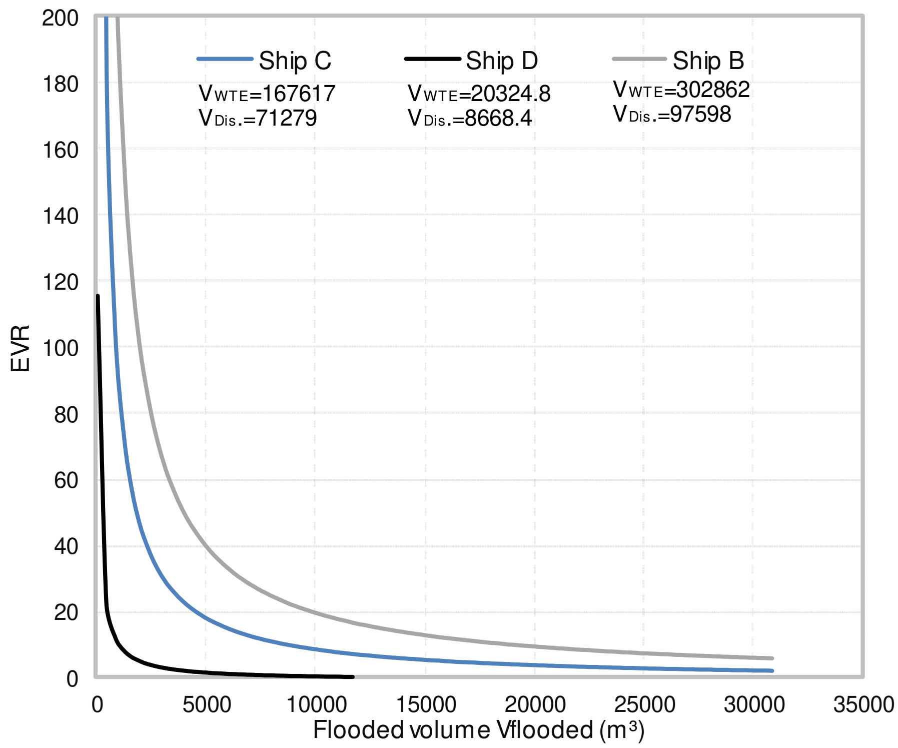


Figure 33: Variation of floodwater volume $V_{flooded}$ and EVR for three ships used in the simulations for their constant weathertight and displacement volumes respectively.

Even though truncated GZ characteristics (i.e. measured to the flooding angle) can resolve many issues in terms of the formula development, namely large intercepts, presence of unprotected and critical openings or down flooding points, achieving a reasonable level of correlation within the results is challenging. This is most likely due to the effect of ship-specific local effects, namely, we cannot capture global stability characteristics (e.g., GZ-curve properties) if local effects like openings are considered, particularly if the latter are dominant with respect to survivability. This is also in line with the results of the simulations, as they are not limited by the immersion of openings but instead account for the progression of floodwater through openings. On this basis, the calculation of survivability using the newly proposed s-factor, would employ a quasi-static approach in which progressive flooding is accounted for when openings are immersed in the final condition. This can be achieved by defining all unprotected openings as progressive flooding points in the static stability software. Ultimately, these results indicate that using hydrostatic calculations to address a very dynamic phenomenon fail to capture the complexity of the problem because of the over-simplification that is inherent in hydrostatic calculations.

Prediction of survivability utilising truncated GZφ curve values

Despite the aforementioned, consideration has also been given to the effect of using GZ properties truncated by unprotected openings in the calculation of the critical significant wave height and subsequently the vessel survivability. Figure 34 presents the differentiation between truncated and un-truncated values of the GZ_{φ} curve. According to SOLAS the GZ_{max} is taken up to the angle where the righting lever becomes negative (un-truncated), or the angle at which an opening incapable of being closed weathertight becomes submerged (truncated). Also, the range is terminated at the angle where the righting lever becomes negative, or the angle at which an opening that cannot be closed weathertight becomes submerged.

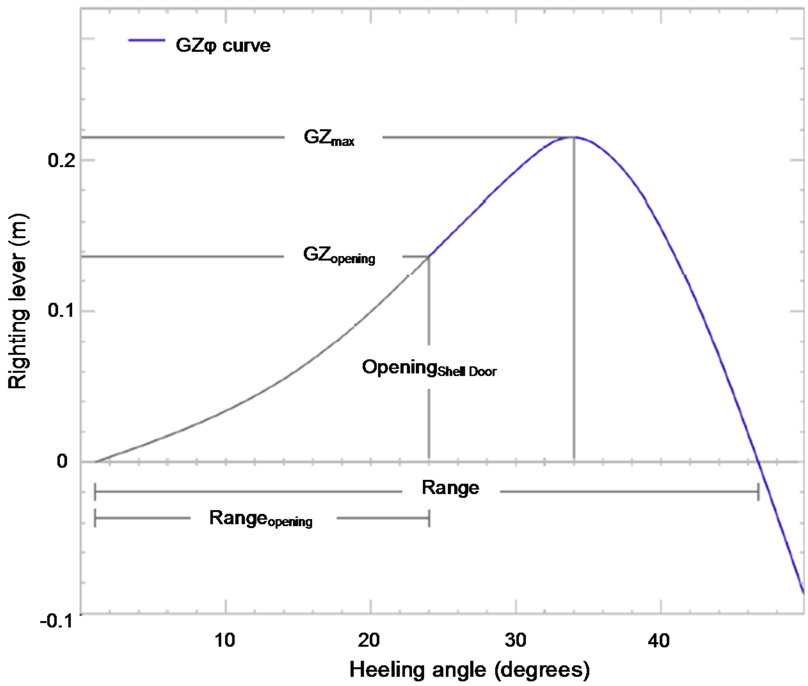


Figure 34: Interpretation of the stability curve. In the presence of an opening (shown here as " Opening shell door") the GZ curve is truncated and the Range and GZ_{max} take the values of the intersection.

In this case, both Range and GZ_{max} values have been acquired by means of static calculations at each of the simulated loading conditions and both GZ_{max} and Range have been limited to the angle at which any unprotected opening is immersed.

From the results of this process, as shown in Figure 35 , it was observed that this approach gives rise to a significant scatter in the data points, particularly with regards to GZ_{max}, in comparison to the un-truncated values obtained previously. The primary reason for this is due to the random nature of the flooding process dependent of the vessels internal geometry and location of unprotected openings, which rendered impossible the establishment of relationships between the survival state and the properties of the vessel (eq. GM, range, volume freeboard).

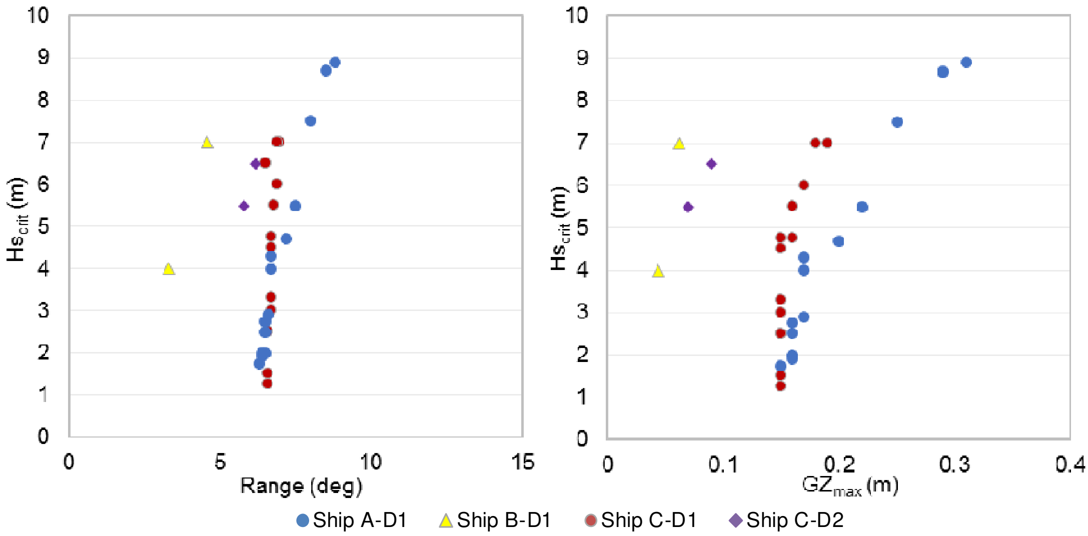


Figure 35: Relation of Range and GZ_{max} with Hs_{crit} for truncated values.

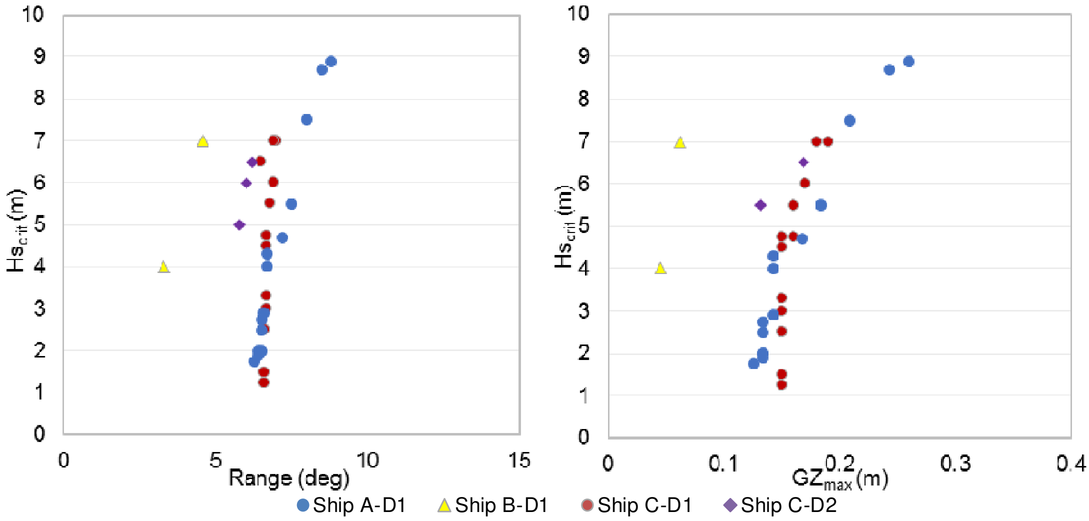


Figure 36: Relation of scaled Range and scaled GZ_{max} with Hs_{crit} for truncated values.

An attempt has however been made, as shown in the figures above, in order to appropriately scale the data but only with regards to the vessel's GZ_{max} where there was the least correlation within the data. The correlation of the Range data in this case was already reasonable and as such no further scaling was found to improve on this. The results of the scaling application are provided in Figure 36, indicating the little improvement offered in this case.

5.5.Derivation of critical significant wave height formulation

The application of the scaling factor results in a noticeable deviation of the small cruise vessel and the smallest damage cases from the trend with respect to their accumulated flooded water volume. For all the damages cases highlighted in Figure 37, the scaling factor overestimates or underestimates the residual stability properties and this is observable only for flooded water volumes less than 5000 m^3. The variation in the volume of the damaged compartments is disproportional to the change in the residual volume and that is highly relative in the case of the large cruise ships. Thus, the Effective Volume Ratios for these cases, as expected, will be higher as it is demonstrated in Figure 29 above.

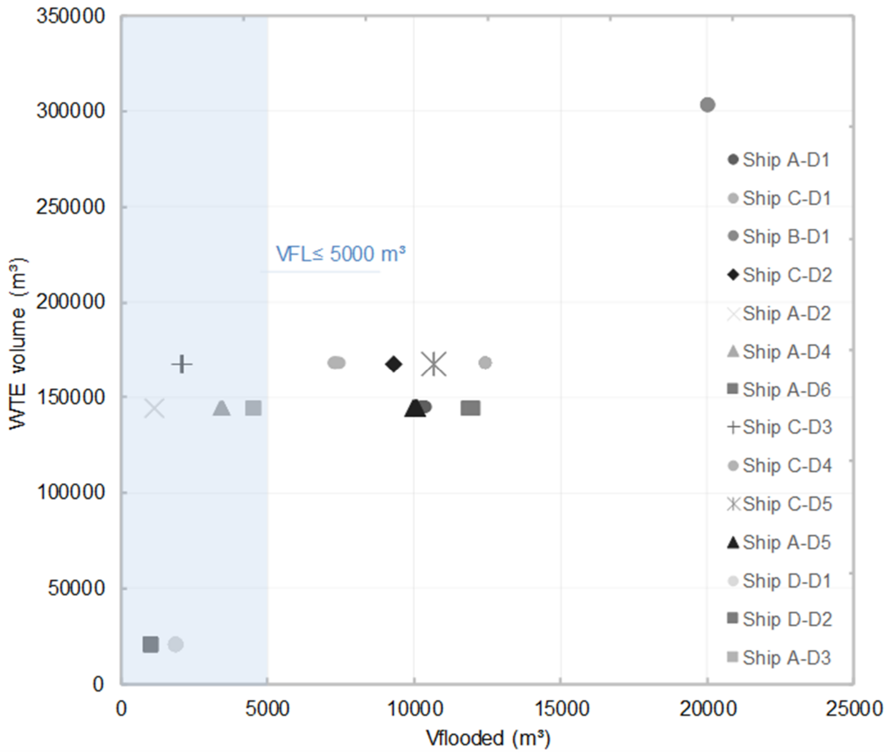


Figure 37: Graph showing the relationship between the Weather Tight Envelope volume and the average volume of flooded water in the damage compartments for all damage cases. Indication of cases for which the flooded volume is less or equal than 5,000 m^3.

Allied to this, the highlighted cases of ship A were subjected to a significant reduction in their GM, using sometimes unrealistic values, well below their limiting GM (SOLAS 2009 damage stability), in order to achieve static and dynamic capsizes. Yet, survivability will always be equal to one when using the actual loading condition limitations and thus the impact of these cases is insignificant. For this reason, these points were not considered in the final regression as explained later. The same applies to residual GMs less than 0.9 (see Figure 38). Further below, Figure 39 presents the points, which formed the basis for the establishment of the s-factor formulation considering the aforementioned observations.

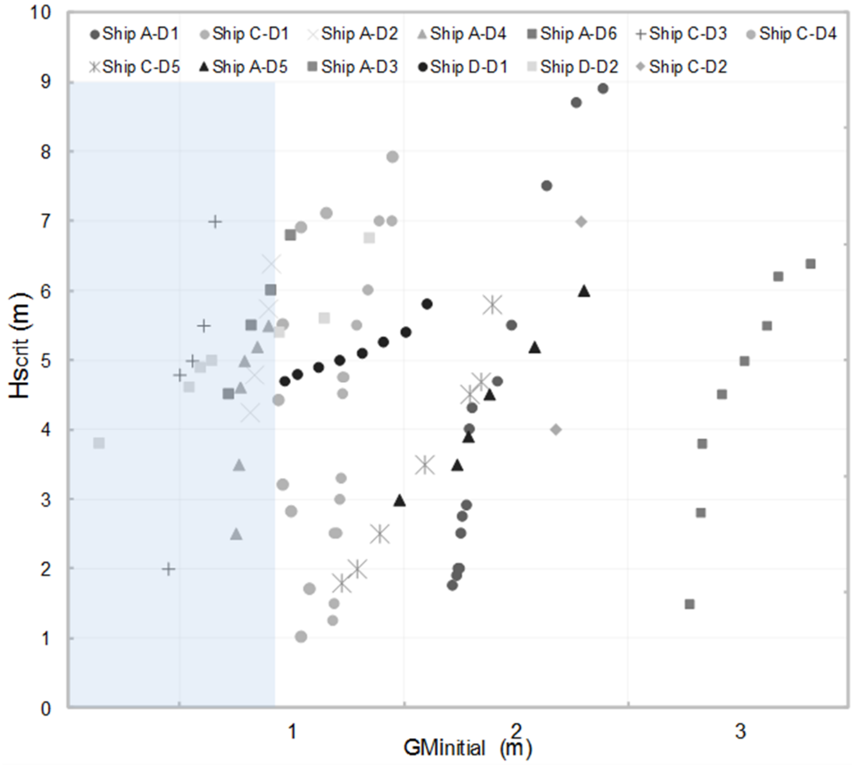


Figure 38: Depiction of the relationship between the critical significant wave height and the initial residual GM used in the simulations.

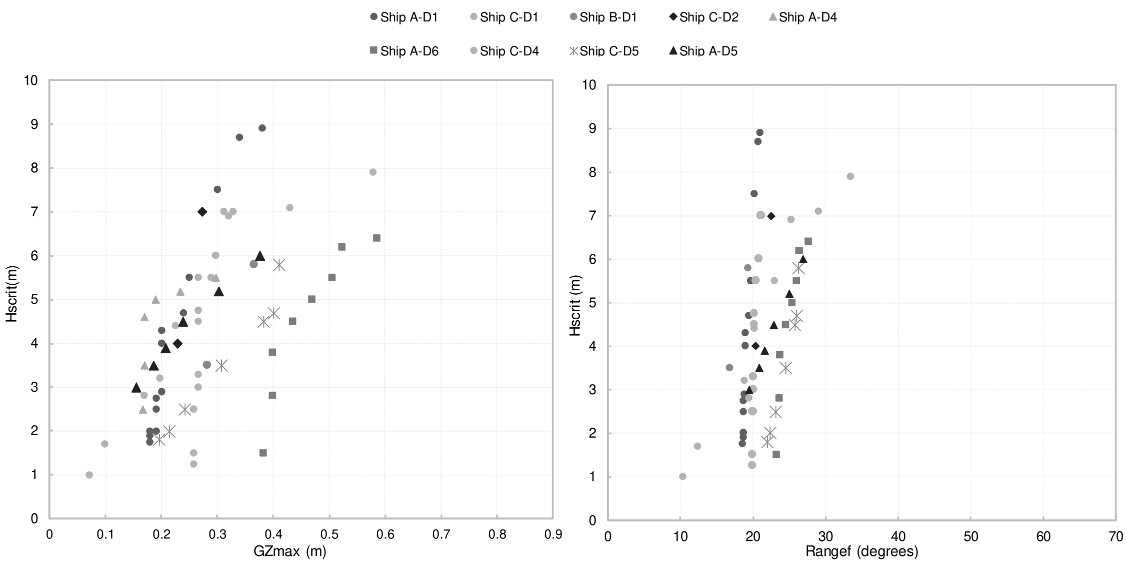


Figure 39: Scaled GZ_{max} and Range values for cases selected for regression in the derivation of the Hs critical formulation as provided in the following section.

A new formula for predicting the critical significant wave height has been developed based on the results of the flooding simulations. This has been achieved by means of a regression formula based on both GZ_{max} and Range properties and in line with the approach followed and format employed during project HARDER (Tuzcu, 2003b) but with the additional scaling factor taken into account (similarly to project GOALDS).

In an attempt to capture the physical phenomena stemming from the relationship to the sea states and in order to account for the size and residual stability properties of the vessels, a number of formulations have been investigated following statistical analysis and a response surface technique. The design of the formulation comprised main governing parameters such as the effective freeboard and/or volume, metacentric height GM, GZ properties, heel and main ship dimensions in different possible combinations.

The final formulation, proposed in the foregoing, constituted the most efficient form applicable to the data sets obtained through numerical simulations. The regression has been conducted with consideration of all data points occurring at probable significant wave heights and thus critical significant wave heights spanning up to 7 meters according to the global wave statistic distribution (see §6.3). The multiplier represents the 99^{th} percentile of higher wave of the cumulative probability based on global wave statistics.

The results for the Hs critical formulation and regression accuracies are as follows:

$$Hs_{crit} = 7 \cdot \left[\frac{MIN(\lambda \cdot Range, TRange)}{TRange} \cdot \frac{MIN(\lambda \cdot GZmax, TGZmax)}{TGZmax}\right]^{1.05} \quad (5\text{-}12)$$

Where,

TGZ_{max} =0.30 metres targeting residual GZ_{max}
$TRange$ =30 degrees targeting value for residual range
λ Scaling factor accounting for ship and damage size (see section § 5.4.1)

Table 4: Goddess of the regression fit through the data for the obtained formulation with descriptions

Correlation	Dependence of the variables	82%
Sum of Squared Errors	Sum of squares of the residuals/deviation from the actual empirical values	89.94
R-squared	Coefficient of determination/Variance	0.728
Adjusted R-square	Adjusted to number of predictors in the formula	0.72
Root Mean Square Error	Standard deviation of the residuals	1.101

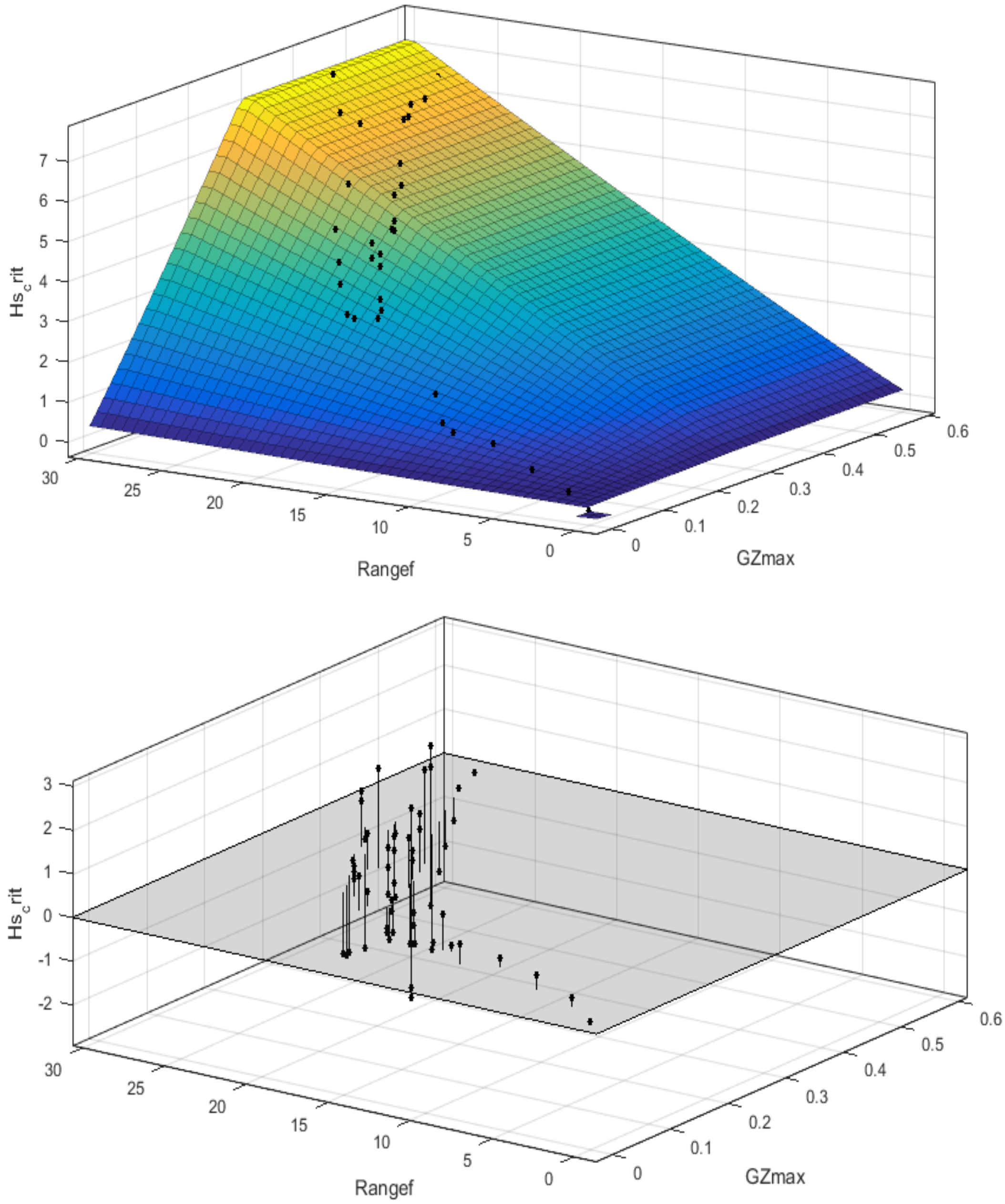


Figure 40: Regression 3-D surface and residuals of the obtained data set through numerical simulations.

The following table demonstrates how the main formula parameters vary with their accuracy (based on the sum of regression residuals) and respective impact on the Attained subdivision Indices for the four ships. A reduction in the targeting parameters leads to an increase in the sum of the residuals (i.e. the accuracy and correlation deteriorates) whilst, an increase in the accuracy can be obtained at the cost of adopting high targeting values.

Table 5: Sensitivity of new formula parameters and impact on the Attained indices on the four vessels. The table shows how the exponent (EXP) and the sum of the residuals change for different targeting values in the new formulation.

				A subdivision Index			
TRange	TGZ_{max}	EXP	Sresidual	Ship A	Ship C	Ship D	Ship B
32	0.32	0.87	88	0.9148	0.9187	0.8467	0.9178
31	0.31	0.95	88	0.913	0.9154	0.844	0.9174
30	0.3	1.05	89	0.911	0.9114	0.8418	0.9169
29	0.29	1.16	93	0.909	0.9069	0.8397	0.9164
28	0.28	1.3	99	0.9068	0.9011	0.8374	0.9157
27	0.27	1.48	110	0.9044	0.8934	0.8351	0.915
26	0.26	1.7	127	0.9019	0.8827	0.8331	0.9142
25	0.25	1.98	158	0.8993	0.8669	0.8313	0.9132
24	0.24	2.36	163	0.8966	0.8386	0.8294	0.9121
23	0.23	3	180	0.8928	0.769	0.8269	0.9103
22	0.22	4.28	196	0.8872	0.5954	0.8225	0.9069
21	0.21	7.31	224	0.8798	0.1978	0.8144	0.9013
20	0.2	9.41	339	0.8791	0.0822	0.8134	0.9
SOLAS 2009/2020		-	-	0.8213	0.8615	0.7734	0.8868

5.6.Derivation of new survivability factor formula in waves

The following section provides the new cruise ship-specific s-factor based on the methodology described in §6.3 of chapter 6. Having identified an accurate means of characterizing the critical significant wave height on the basis of the vessel residual stability properties, a formulation for calculating the s-factor can be given by the regressed CDF of wave heights (Global wave statistics) at the time of collision, as follows. Global wave statistics are selected because cruise vessels are exposed to global wave environments based on their operation.

$$s\left(H_{s_{crit}}\right) = e^{-e(1.1717-0.9042\cdot Hs_{crit})} \quad (5\text{-}13)$$

Where,

Hs_{crit} Is the critical significant wave height utilizing the global wave statistic distribution where there is 99% probability encountering wave heights smaller than 7 metres (probability of non-exceedance). Note: When Hs_{crit}=7m, $s\left(H_{s_{crit}}\right) = 1$

This limitation is based on the wave distribution of the global annual wave statistics, where, a 7 meter wave height represents the 99th percentile of waves within the

Cumulative Distribution Function. Through calculating the s-factor in this manner, the inaccuracies introduced by deriving a combined s-factor formula as found in SOLAS 2009 can be eradicated. This formula ensures that survivability equals zero when the critical significant wave height equals zero, respectively. Notably, the proposed s-factor addresses only progressive flooding (i.e. final stage of equilibrium).

The primary focus has been placed on the survivability of cruise vessels in waves and as such transient s-factor formulation does not fall under this research attempt. This has been primarily limited by the numerical simulation software in place that does not accurately account for the transient stage of flooding. In order to propose an intermediate s-factor we would require results stemming from a CFD analysis of this phenomena.

In this sense, all other current SOLAS assumptions and formulations are used namely, external moments, intermediate stage survivability formulae, cross-flooding stages, immersion of vertical escapes, escape routes, control points and so on. The form of the s-factor proposed allows taking into account the equilibrium angle in the same manner as SOLAS 2009. This, in turn, entails that the influence of external heeling moments is dealt with in the same manner outlined in SOLAS 2009 (s-moment) accounting for wind, life raft launching and passenger crowding. To accommodate for this in the current SOLAs framework, where SOLAS 2009 limits the GZ curve to the immersion of flooding points, escapes routes, etc., stability can be assessed in a quasi-static manner in order to take into account the flooding through openings in case they are immersed.

5.6.1. Comparison of the survivability factors

A direct comparison of the requirements of the current s-factor (SOLAS 2009) and the newly proposed s-factor will not be indicative as one depends on the truncated properties of the GZ curve and the latter does not. However, a direct comparison is provided in the following graphs, which would indicate that the requirements of the new s-factor appear to be comparatively more stringent. For the SOLAS 2009 s-factor the s-final value can be zero due to openings being immersed, while, with the new s-factor openings do not have any impact unless they are calculated quasi statically as explained in earlier paragraphs.

The following figures compare the application of the two s-factors (SOLAS and new) in terms of compartment equivalent damages. As it is apparent, in intermediate s-factor values (0<s<1), the new s-factor captures significantly more cases with higher concentration towards higher than 3- compartment damages. This results in fewer capsize cases and survival cases for damages larger than 4-comparments whereas SOLAS starts from 3-compartments. This reflects the effect of damages considered in the development of the new s-factor. For this specific cruise ship, the Attained Index in the case of the SOLAS s-factor is 0.73, while the new s-factor provides an A-I of 0.84.

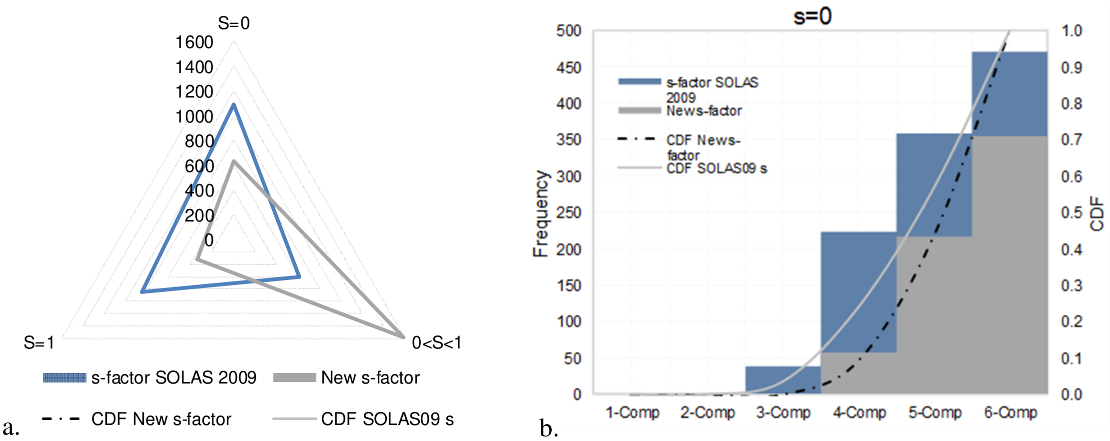


Figure 41: Comparison between SOLAS and new s-factor using respective Hs_{crit} formulations in terms of compartment equivalent damages pertinent to SOLAS. a.) Number of cases for each formula b.) Indication of histograms and cumulative distributions of cases being equal to zero.

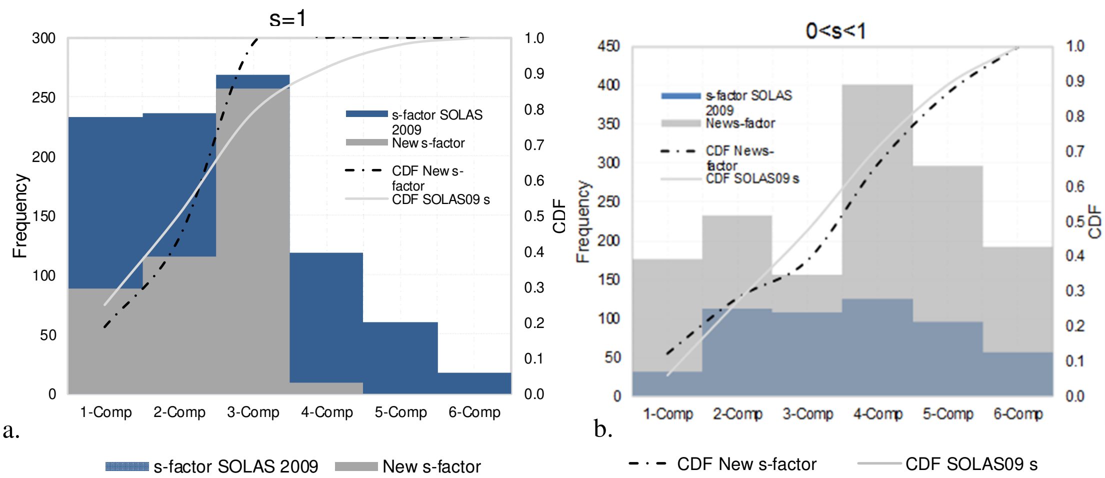


Figure 42: Indication of histograms and cumulative distributions of cases being: a.) Equal to one b.) between one and zero

5.7.Direct approach to damage survivability assessment of cruise ships

5.7.1. Background

The survivability factor in SOLAS 2009 is estimated based on the assumption that the ship capsizes within half an hour exposure (Tuzcu, 2003a). This, however, is not the case with cruise ships, hence the need to ascertain the impact of time on cruise ship survivability and to account for this by alternative means. Despite the applicability of the statutory approaches to address survivability, these fail to quantify the safety level with regards to the Time To Capsize.

The Time To Capsize (TTC), is a random variable, thus only known as a distribution determined through probabilistic methods. Moreover, survivability depends on a number of governing parameters (e.g. loading condition, sea state, damage extent) all of which are also stochastic in nature. In this respect, accounting only for the damage case scenarios implicit in SOLAS 2009 (typically over 1,000 for a typical passenger ship) and considering the 3 loading conditions, also implicit in these regulations, and some 10 sea states per damage case for estimating capsize rates, it becomes readily obvious that some form of simplification and reduction will be meritorious.

To this end, one of the most efficient ways, entails a process involving Monte Carlo sampling the distributions of pertinent random variables (damage extents, loading conditions, sea states, etc.) to generate damage scenarios and perform numerical time-domain simulations. The latter, accounts accurately for the physical phenomena of ship-floodwater-wave interactions as function of time providing robust indication on which of these scenarios would lead to ship capsize/sinking and the TTC. In this manner, any assumptions and approximations inherent in the probabilistic elements of SOLAS 2009 damage stability regulations are minimised.

5.7.2. Relation to the statistical approach

One of the fundamental assumptions of the probabilistic concept (statistical approach) as per SOLAS 2009 (IMO, 2009c) is that the ship under consideration is damaged, i.e. the hull is assumed to be breached and there is (large scale) flooding. This implies that the cause of the breach, the collision event and the circumstances leading to its occurrence are disregarded; hence the interest focuses on the conditional probability of survival. Other pertinent factors, such as size of ship, number of persons on board, life-saving appliances arrangement, and so on, are directly or indirectly accounted for by the Required Index of Subdivision R. Therefore, the probability of ship surviving collision damage is given by the Attained Index of Subdivision, A, using the expression in eq.(5-14) below (IMO, 2009c).

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \cdot p_i \cdot s_i \tag{5-14}$$

As mentioned in §3.3.1, the Attained Subdivision Index represents the conditional "averaged" probability of survival or else put simply the "weighted average s-factor" following the summation of survivable flooding scenarios as depicted from eq.(3-3).

Notwithstanding the fact that the current s-factor is a statistic based on calm water calculations and it cannot yield directly information on the Time To Capsize, the conditional probability of capsize simply becomes,

$$P_{capsize} = 1 - A = \sum_{i=1}^{I} p_i \cdot s_i \tag{5-15}$$

This means that Index A is the marginal probability for time to capsize within certain given time and specific loading condition, assuming that the time being considered is sufficiently long for capsize to have occurred in the majority of cases. This is a key observation, as this can be used to derive the flooding risk contribution, as indicated in the following. However, the assumption on time being sufficiently long is critical.

On the other hand, the survivability level obtained from time-domain numerical simulations herein denoted as "Flooding Survivability Index" uses a single significant wave height sampled from pertinent wave statistics and the random outcome (survival or capsize) is then averaged across all damages and loading conditions. The CDF of the Time To Capsize (based on the number of physical capsize cases) represents the marginal distribution of the Time To Capsize based on the averaged overall probability of capsizes during all sea states for all the generated flooding scenarios in the related loading condition. This represents the percentage of all possible damages that would lead to capsize within a given time and loading condition. Therefore, the Flooding Survivability Index (FSI) derived from numerical time-domain simulations is provided as follows:

$$FSI = 1 - CDF(probability\ of\ capsize\ when\ TTC = maximum) \qquad (5\text{-}16)$$

This represents the probability of capsizing within 30 minutes similarly to the probabilistic framework when the actual Attained subdivision Index is considered (Jasionowski, 2006).

5.7.3. Relation of non-zonal damages to the zonal approach in terms of survivability quantification through damage scenarios

The non-zonal damages are sampled based on distributions, which have been derived from work presented in (Bulian et al., 2018, Zaraphonitis et al., 2013, Bulian et al., 2016). This follows the same approach prescribed through the "zonification" technique. In the latter however, a probabilistic framework has been devised to account for bottom, side groundings and collisions. This overcomes the dichotomy present in SOLAS where survivability in case of collision is addressed in a probabilistic framework while the issue of grounding is addressed in a deterministic manner. The developed approach is compatible with the SOLAS2009 conceptual framework for collision and it can adopt modern damage distributions based on updated or actual data available following a Monte Carlo scheme. Additionally, the non-zonal approach is ideal for complex internal architecture as the ones related to large cruise liners.

One could potentially question to what degree the zonal approach used in the statistical (statutory compliance) approach deviates in terms of survivability quantification from the non-zonal approach followed in the numerical simulations using Monte Carlo. To this end, a few clarifications follow in the foregoing.

The results presented in the following sections are based on the non-zonal damage generation with the estimate of probability of survival $p(s)$ expressed as follows:

$$p(s) = \frac{N_s}{N_{dam}} \qquad (5\text{-}17)$$

Where,

N_s	Represents the number of cases resulting in survival.
N_{dam}	Represents the total number of investigated damage scenarios.

In the non-zonal approach, multiple damage breaches may lead to the same damage case with regards to the affected rooms (being damaged and exposed to open sea), as considered by the zonal model, which can be accounted for by the law of the total probability as provided in the equation below:

$$p(s) = \sum p(s|Ex_i) \cdot p(Ex_i) \tag{5-18}$$

Where,

$p(s\|Ex_i)$	is the probability of survival given the i-th damage case .
$p(Ex_i)$	is the probability of occurrence of the i-th damage case. In the limiting case the probabilities $p(E_i)$ converge to the p-factors, as used in the zonal model.

The equivalence in terms of quantification of survivability of these formulae can be demonstrated with the aid of a simple numerical example, as described in the following paragraph.

Numerical simulations over a random sample of $N = 2{,}000$ damage breaches (as used in the following results) t resulted in $N_s = 1804$ surviving runs. The individual random damages (breaches) led to three different (room) extents, Ex_1, Ex_2 and Ex_3 with corresponding probabilities (frequencies) of occurrence $p(E_{x1}) = \frac{70}{2000}, p(Ex_2) = \frac{30}{2000}$ and $p(Ex_3) = \frac{1900}{2000}$ and a survival rate in each extent of $p(s|Ex_1) = \frac{35}{70}$, $p(s|Ex_2) = \frac{19}{30}$ and $p(s|Ex_3) = \frac{1750}{1900}$ respectively. Therefore, based on this, the total probability of survival is given as follows:

$$\begin{aligned} p(s) = \sum p(s|Ex_i)p(Ex_i) \\ &= p(s|Ex_1)p(Ex_1) + p(s|Ex_2)p(Ex_2) + p(s|Ex_3)p(Ex_3) \\ &= \frac{35}{70}\cdot\frac{70}{2000} + \frac{19}{30}\cdot\frac{30}{2000} + \frac{1750}{1900}\cdot\frac{1900}{2000} = \frac{1804}{2000} = \frac{N_s}{N} \\ &= 0.902 \end{aligned} \tag{5-19}$$

The main difference between the zonal and non-zonal approaches is attributed to the utilisation of zonification and analytical formulae for the calculation of the p-factors (probabilities of flooding) for the former, while for the latter, the probabilities of flooding individual compartments or groups are derived by direct generation of breaches on the vessel without the need of analytical formulation.

5.7.4. Numerical simulations and Monte Carlo methodology applied

Survivability can be assessed with use of time-domain calculations simulations for a group of damages. The time-domain simulations allow for deriving an estimate of the expected probability of survival of a given group of damages characterised by random damage locations, damage extent and sea-states. The Time To Capsize (TTC) can be defined through an automated process using Monte Carlo sampling (see Figure 43) and dynamic flooding simulations with the time-domain numerical simulation code PROTEUS.

Two large cruise ships (Ship A and C) from the sample ships presented in §5.2.1 earlier, have been subjected to a number of Monte Carlo simulations for a single loading condition, namely the deepest subdivision draft. Following previous studies, in order to examine extreme survivability cases, the deepest subdivision draft is used in the simulations. The effects of waves on survivability are examined for collision, side and bottom groundings. These entailed a total number of 2,000 damages for each damage type. In the case of collision scenarios, time-domain simulations were also performed in calm water, in order to ascertain the impact of waves and ship dynamics on survivability. The damage distributions for the two ships using the non-zonal approach are provided in the next section.

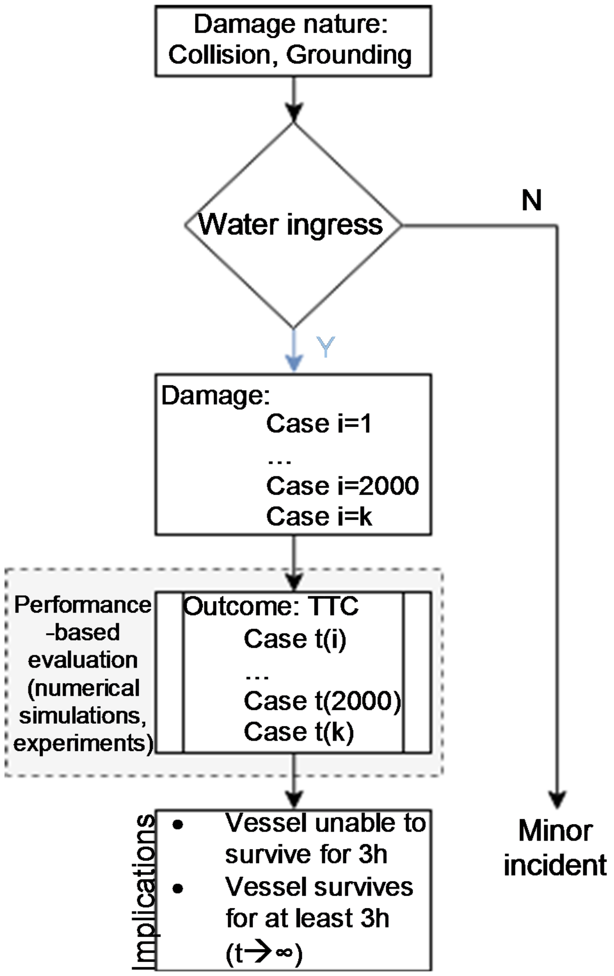


Figure 43: Sample Monte Carlo damage set-up following the Direct Approach on a cruise vessel. These can lead to minor incident (survival after accident) or implications based on the capability of the vessel to survive 3 hours (adequate for evacuation and potentially SRtP assessment).

Pictorial representation of non-zonal collision and grounding damages

The following graphs summarise the damage distributions in terms of extents for the two ships using the non-zonal approach.

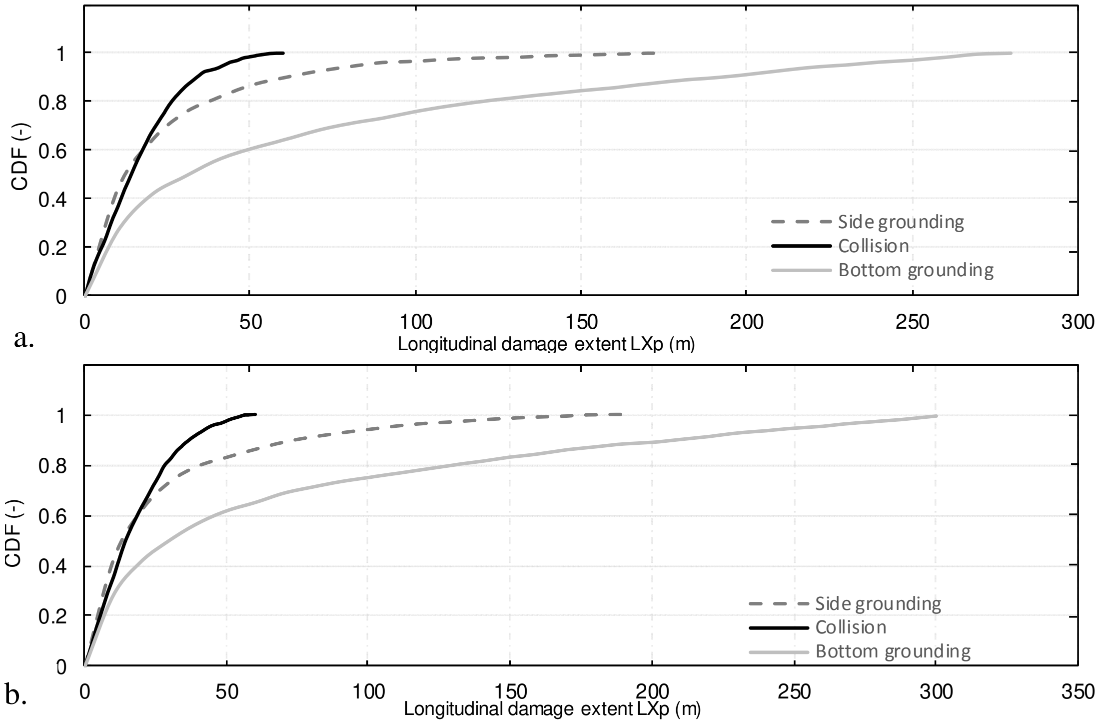


Figure 44: Longitudinal damage extent Lxp (m) for: a) ship A b) ship C

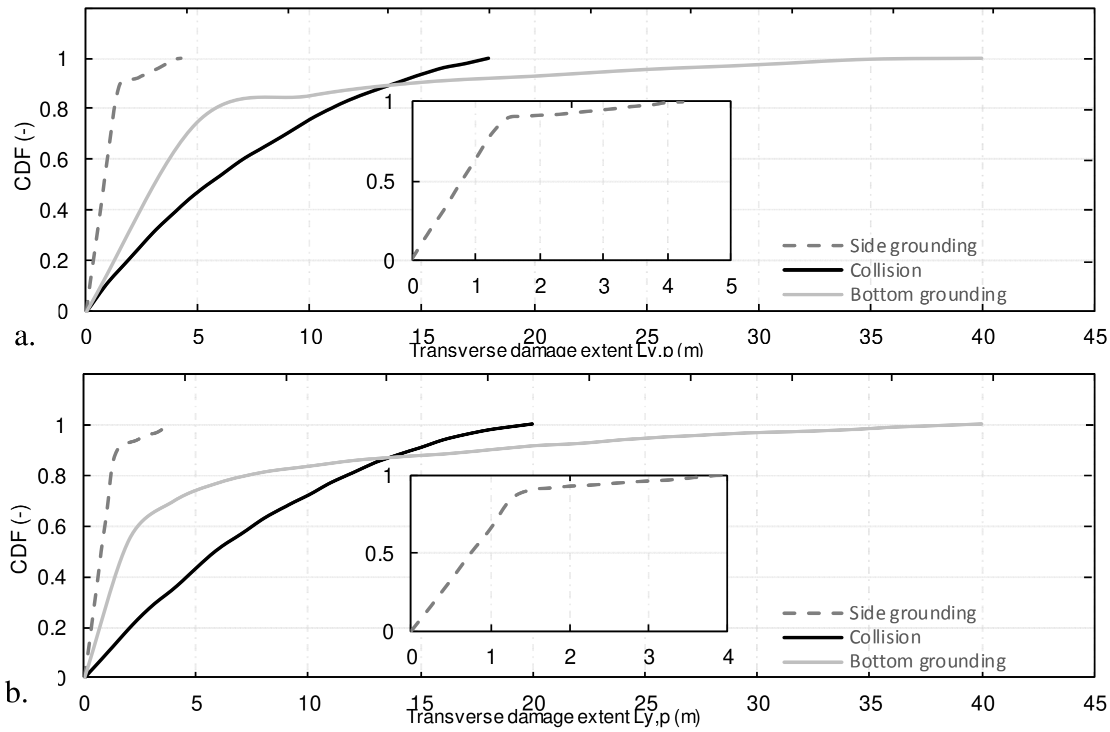


Figure 45: Transverse damage extent Lyp (m) for: a) ship A b) ship C

The following graph presents a pictorial representation of the damages for sample ship A in the case of collision (in-wave and calm water) damages.

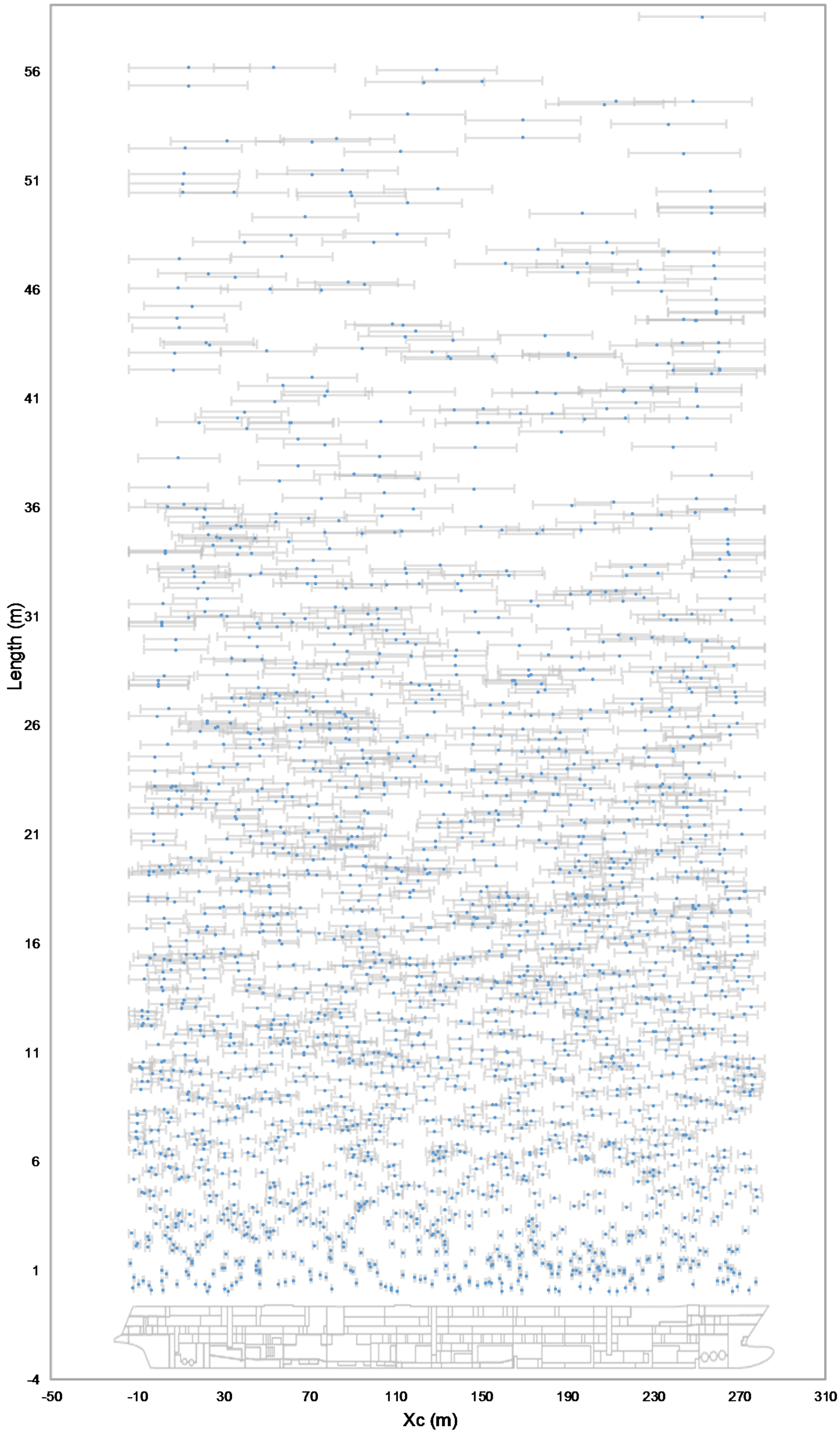


Figure 46: Collision damages (2000) for ship A distributed according to longitudinal damage extent.

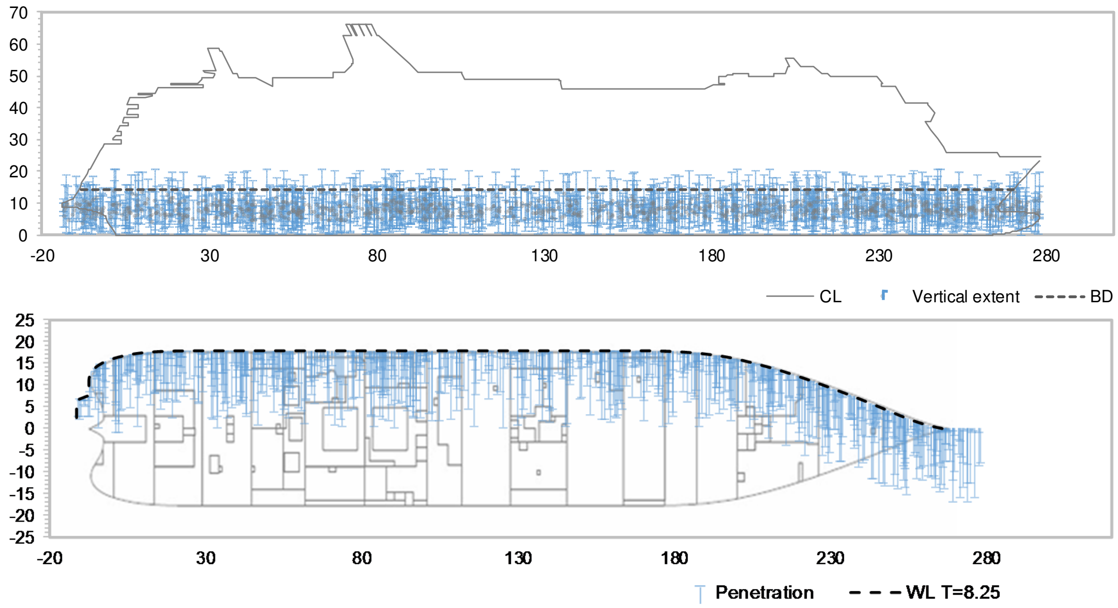


Figure 47: Representation of port side damages at profile and section at waterline for sample ship A

Simulation environment and assessment criteria

The simulations are performed with significant wave heights sampled randomly from the distribution of the global wave statistics (see §6.3) as indicated in the figure below. This comes into agreement with the statistical approach in order to form a consistent comparison basis.

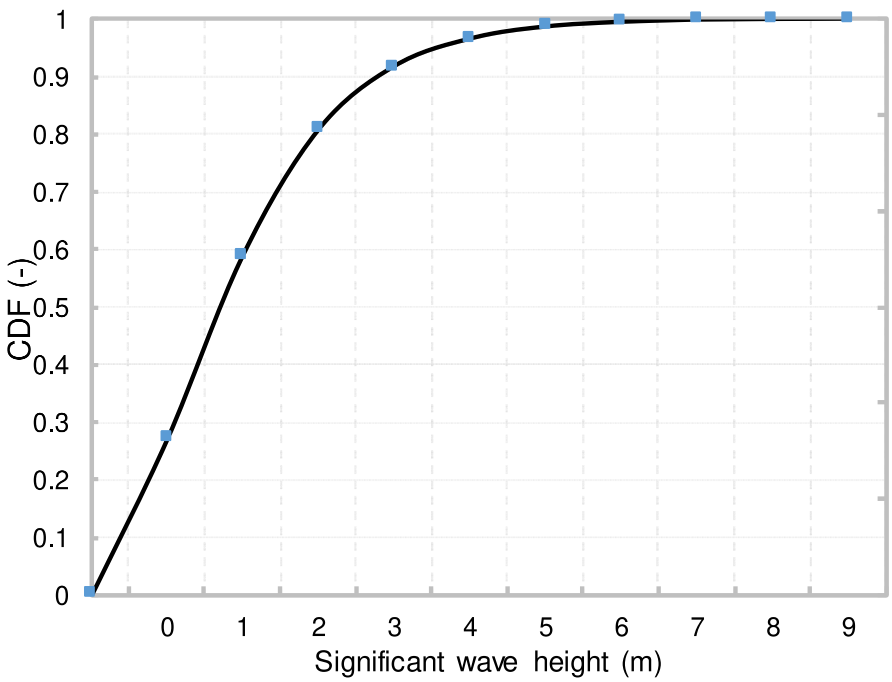


Figure 48: Cumulative distribution for global wave statistics with a 7 meter wave height ensuing 99% probability of occurrence. The derivation of the CDF is provided in chapter 6.

The total time used for each simulation run is 1,820 seconds. The simulations are initiated after 20 seconds in order to allow for any transients to settle (ramping). Even though cruise ships tend to spend a lot of time during the progressive flooding process entailing collapse of openings in adjacent rooms, 30 minutes of simulation time are adequate in terms of identifying the potential tendency of the vessel to capsize. This is achieved with the aid of a number of criteria as highlighted next.

Survivability is assessed not only on the basis of physical and actual capsizes (ship turns over, θ_{heel}>90 deg) but also on the basis of the following three criteria:

- Capsize criteria (ITTC, 2017) when the instantaneous roll angle exceeds 30 degrees or the 3-minute average heel angle exceeds 20 degrees.
- Criterion for insufficient capability of evacuation, assessing the effect of heeling angle when the angle of heel is higher or equal to 15 degrees SOLAS CH. II-1 (IMO, 2006a).
- The maximum final flooding rate of mass (tons) per hour for each damage case.

5.7.5. Numerical simulation results

The following results summarize the impact of the direct approach to survivability in collision and grounding damages. The first section demonstrates the impact in terms of the cumulative distribution of the time to capsize with indication of topology of capsizes.

Flooding Survivability Index and failing criteria

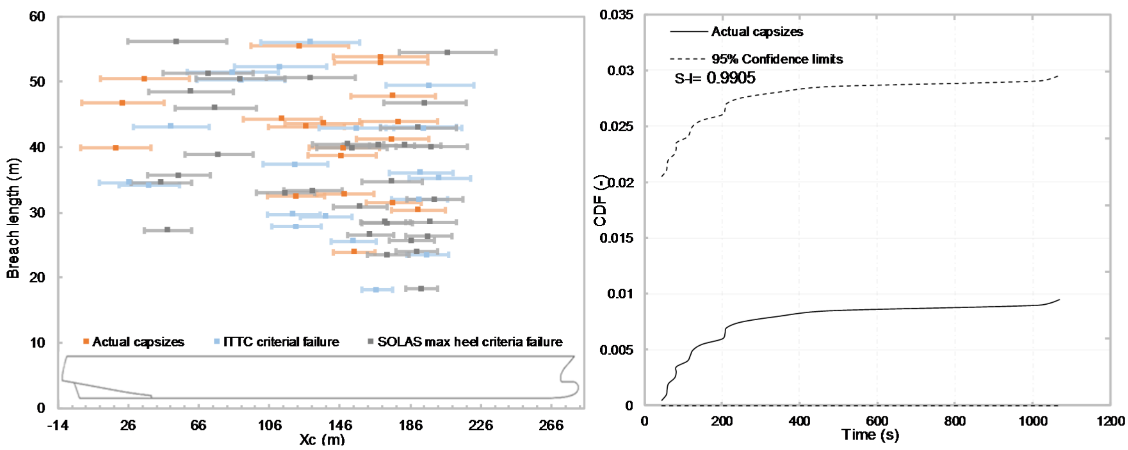


Figure 49: Longitudinal damage centre and extent for cases failed according to criteria specified and indication of the CDF of the TTC (actual capsizes) for collision damages – ship A. Estimated Flooding Survivability Index = 0.9905.

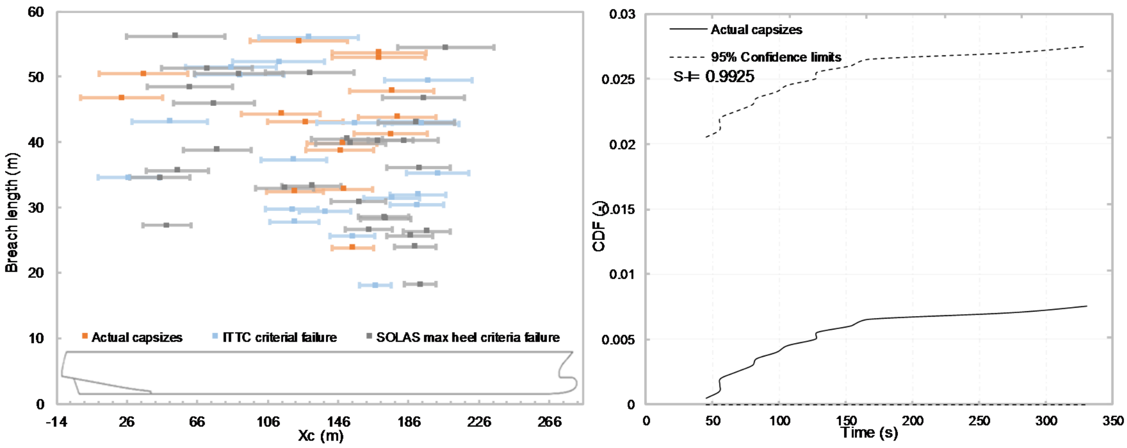


Figure 50: Longitudinal damage centre and extent for cases failed according to criteria specified and indication of the CDF of the TTC (actual capsizes) for collision damages in still water – ship A. Estimated Flooding Survivability Index = 0.9925.

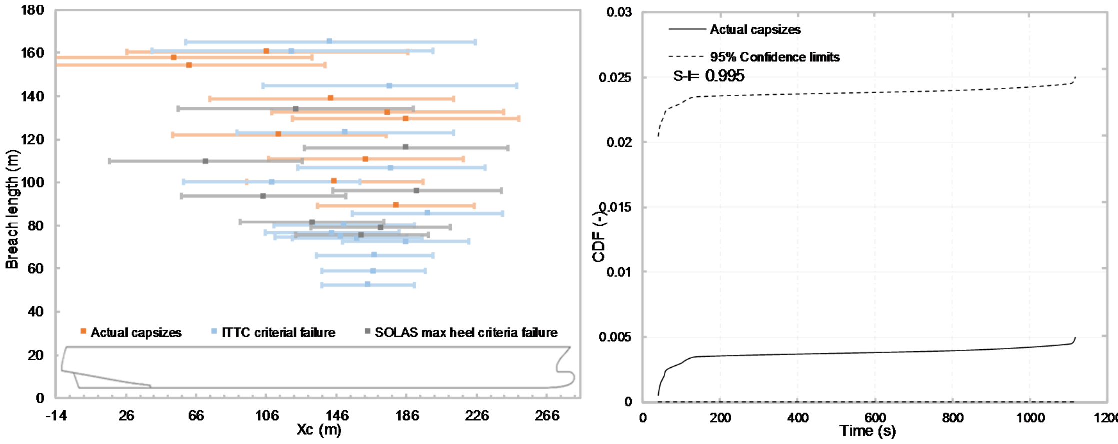


Figure 51: Longitudinal damage centre and extent for cases failed according to criteria specified and indication of the CDF of the TTC (actual capsizes) for side grounding damages – ship A. Estimated Flooding Survivability Index = 0.995.

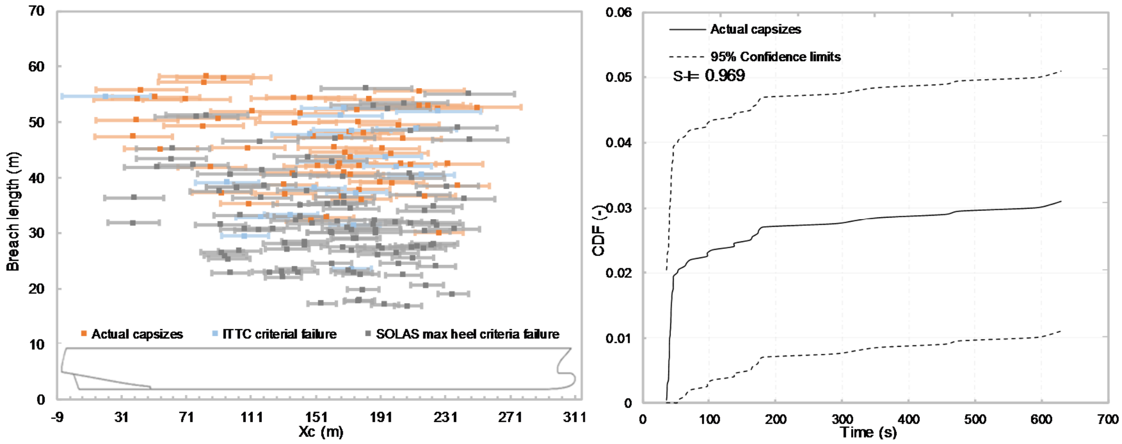


Figure 52: Longitudinal damage centre and extent for cases failed according to criteria specified and indication of the CDF of the TTC (actual capsizes) for collision damages – ship C. Estimated Flooding Survivability Index = 0.969.

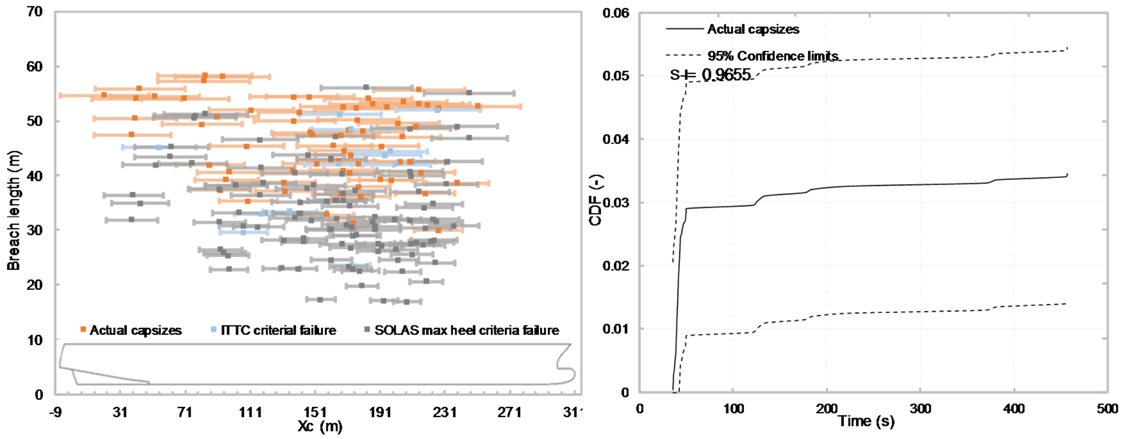


Figure 53: Longitudinal damage centre and extent for cases failed according to criteria specified and indication of the CDF of the TTC (actual capsizes) for collision damages in still water – ship C. Estimated Flooding Survivability Index = 0.965.

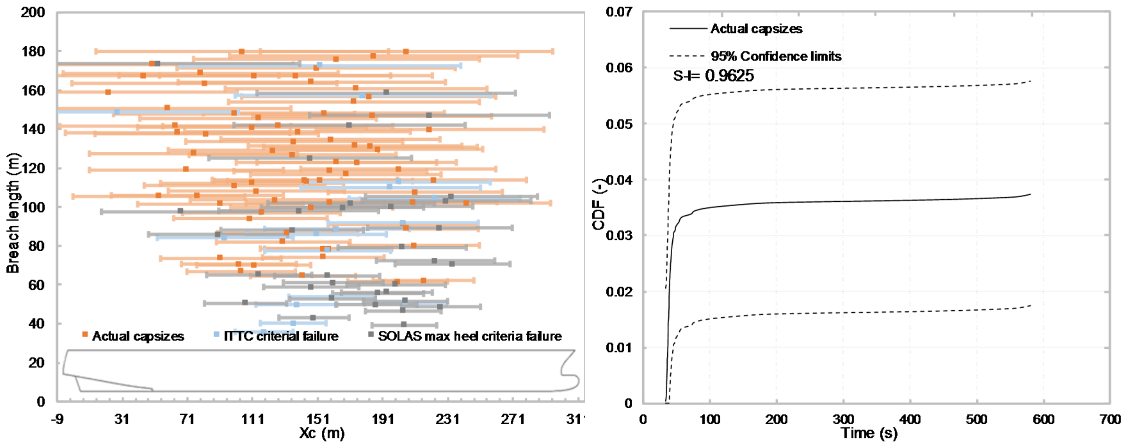


Figure 54: Longitudinal damage centre and extent for cases failed according to criteria specified and indication of the CDF of the TTC (actual capsizes) for side groundings– ship C. Estimated Flooding Survivability Index = 0.9625.

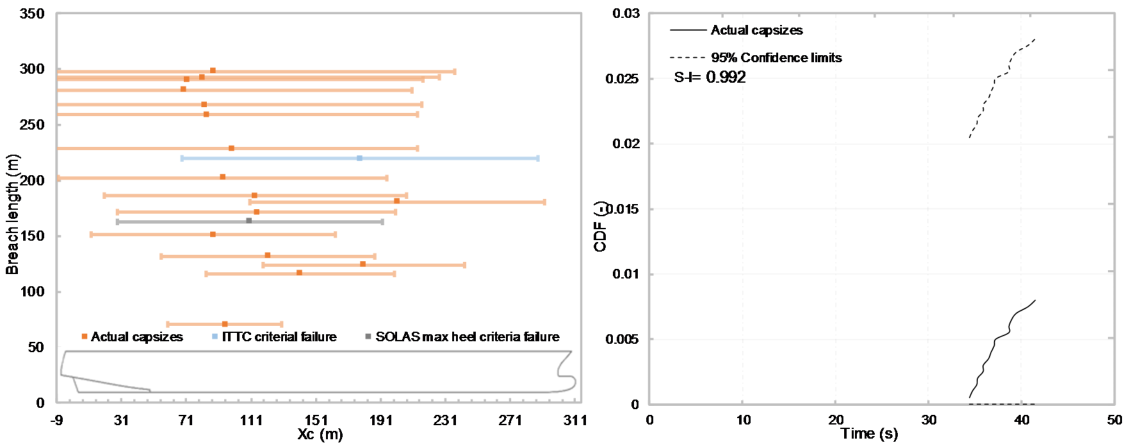


Figure 55: Longitudinal damage centre and extent for cases failed according to criteria specified and indication of the CDF of the TTC (actual capsizes) for side groundings– ship C. Estimated Flooding Survivability Index = 0.992.

The numerical simulation results are presented in Figure 56 with indications linking these to the aforementioned failure criteria for each ship in below. In particular, ship A results in 72 capsizes due to collision damages, of which 19 cases are actual capsizes (26%).

The cumulative distribution function for Time To Capsize in case of collision damages, based on actual capsizes, shows that the majority of capsizes occurred within the early stage of the simulations (under 5 minutes) with no cases beyond 18 minutes duration, as shown in Figure 49. Based on these findings, the expected probability of survival as expressed by the Survivability Index lies between 0.97 and 1 with 95% confidence (based on Dvorezky-Kiefer-Wolfowitz inequality for the estimation of confidence bands (with 5% significance level)). However, the CDF for TTC calculated for all capsizes (i.e., actual and those violating the ITTC and SOLAS maximum heel criteria) does not converge to 1, indicating that some further capsizes would be observed for longer simulation times. Nevertheless, considering the estimates based on half-an-hour runs, the average probability of surviving at least 30 minutes can be estimated to fall between 0.94 and 0.98 with 95% confidence (DKW Confidence Intervals).

The calm-water runs resulted in fewer capsizes (63 cases) when compared to collisions in waves. Specifically, three of the calm-water capsizes represent a “shift” towards more conservative failure criteria (i.e. from actual capsize to ITTC, and from ITTC to SOLAS max heel). This denotes the impact of waves on survivability assessment.

In the case of side groundings, the results indicate 2% of capsize cases (33 capsizes) of which 30% represent actual capsizes. Hence, the expected probability of survival corresponds to an equivalent Attained-Index (Flooding Survivability Index) of 98.3%. The simulations of Ship A for bottom groundings did not result in any capsizes or violations of the aforementioned survivability criteria. This is likely to be the result of insufficient duration of the simulations, given the slow up-flooding process. In fact, analysis of the final 3-minutes of the simulations reveals that 52 cases show significant rate of change of heel (over 2 deg/h), 2 show a rate of change of trim in excess of 1 deg/h and 39 indicate sinking at a rate of 2 m/h. Finally, in 62 cases the net floodwater inflow rate exceeded 1,000 t/h.

For the second ship, the results demonstrate that the probability of survival (1-A) for collisions corresponds to an FSI of 90.35%, as indicated in Figure 53. Notably, the calm-water runs resulted in fewer capsizes (181 cases) when compared to in-waves simulations (193 cases). Finally, the CDF of TTC for side groundings yields a Survivability Index of 93.7. In the case of bottom groundings, the simulations result in approximately 2% of capsize cases, of which 89% represent actual capsizes. In this case the cumulative probability distribution of Time To Capsize provides an Indication of Survivability Index as high as 99.1%.

The calm-water runs provide an invaluable insight on the impact of waves showing that a significant number of capsizes were either missed in the calm water runs or would fail only the more conservative criteria. One of the main implications of this is that the impact of waves should be explored in more detail, which could be achieved by testing individual damages in a range of wave heights, preferably with multiple repetitions per wave height. Such approach would be an extension to the methodology employed for deriving the s-factor (based on capsize band).

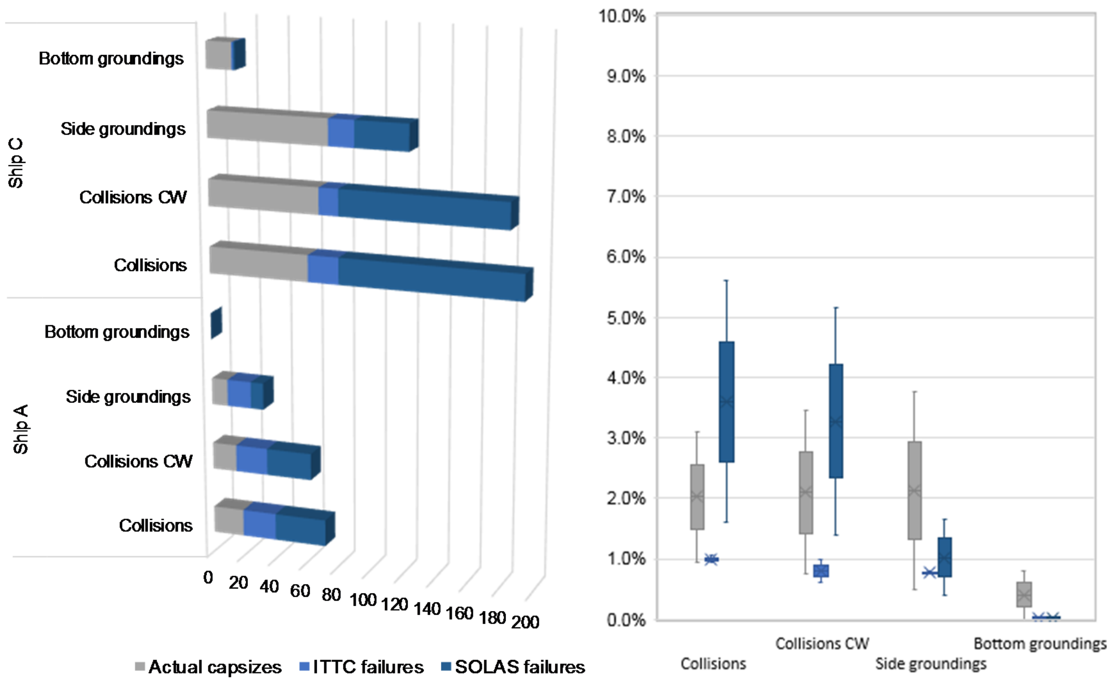
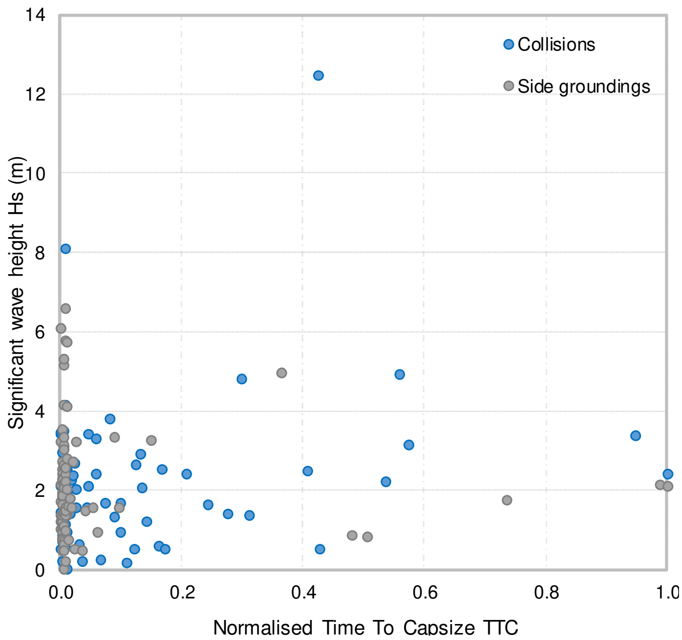


Figure 56: Damage case failure breakdown for the two cruise ships and statistical quartiles.

The difference in the number of capsizes between the two ships, even though they are of relatively similar size, it can be attributed to the difference of their respective GMs. A variation of 0.2 meters in GM can result in a significant larger number of transient capsizes as opposed to smaller GMs that result progressive flooding cases and these reflect cases that encompass rooms damaged above the watertight bulkhead deck.

Impact of sea states on survivability and on the Time To Capsize

Figure 57 indicates the normalised TTC for collision and side grounding damages for the two cruise ships. Also, Figure 58 presents the cumulative distributions of the significant wave heights and their respective Time to capsize. As demonstrated, in the case of collision damages, the majority of damages capsize between 164 and 400 seconds in 0.625m to 3.5 metres significant wave height. The majority of the side grounding capsizes fail during transient phase and this is justified merely by the extreme longitudinal and transverse extent of the damages.



Collision:		
Min	Hs=0m	TTC=46.4s
Max	Hs=12.4m	TTC=475s
Side grounding:		
Min	Hs=0m	TTC=34s
Max	Hs=6.561m	TTC=1118s

Figure 57: Indication of significant wave height with respect to normalized Time To Capsize for collisions and side groundings of the two ships

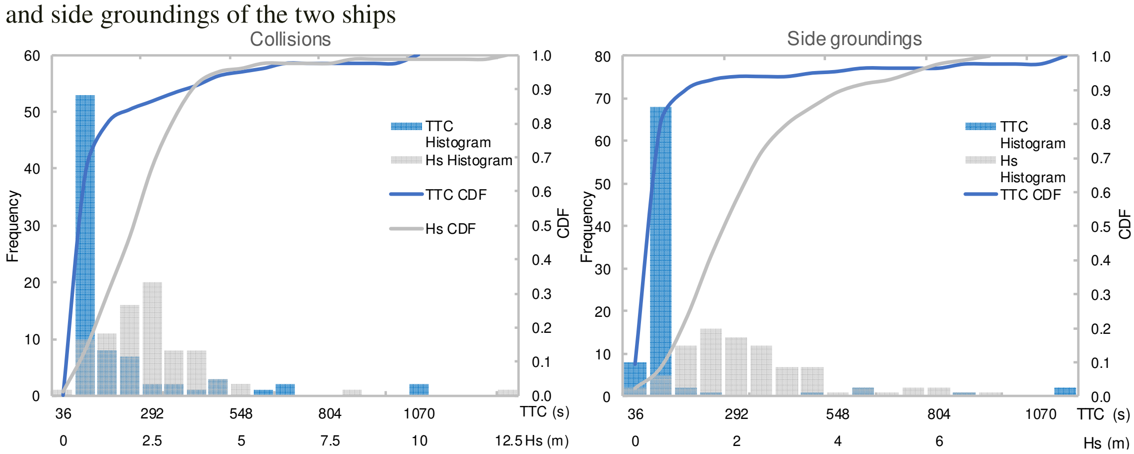


Figure 58: Cumulative distribution of significant wave height and Time to Capsize for actual capsizes occurred due to collisions and side groundings of the two ships.

5.7.6. Comparison to the statistical approach

In light of the numerical results, a comparison is conducted between the static calculations linked to the statistical approach adopted in SOLAS and numerical simulations as shown in Figure 60 and Figure 61 and respectively, linked to the Direct Method, for the two cruise vessels. The two figures demonstrate the impact on the Attained Subdivision Index using three different formulations namely, the current SOLAS s-factor, the non-zonal survivability model with the current s-factor and finally the non-zonal survivability model with the newly derived cruise ship survivability factor. In addition, the last two figures present the obtained survivability levels (namely Flooding Survivability Index) through dynamic simulations in two ways; conditionally through employing all criteria and solely actual capsizes. Initially, the results of collision damages are compared between the statistical and the direct approach as shown in Figure 59 below.

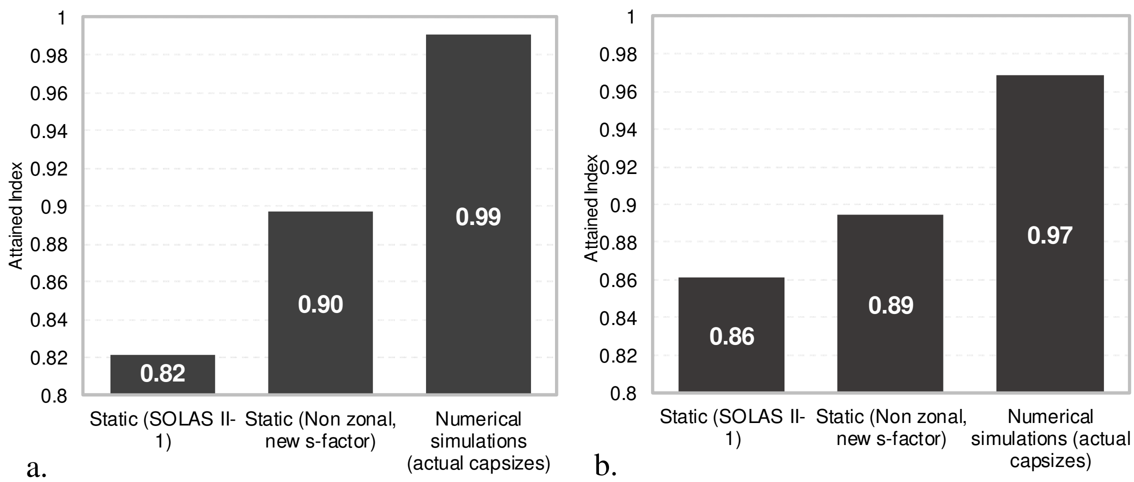


Figure 59: Comparison of survivability results in case of collision damages for: a) ship A b) ship C

On the basis of the foregoing, the newly developed survivability factor is found to underestimate survivability of cruise ships in collision damages. Cruise ships have demonstrated resistance to capsize in waves higher than 5 meters (Maximum 8m) and the prevailing s-factor does not reflect this. Numerical simulation results are consistent with the static calculations. In particular, both methods identify the same vulnerable locations along the ship. However, the numerical simulation results indicate higher survivability than the static calculations.

The discrepancies in expected survivability levels are particularly large in grounding scenarios. This is likely due to relatively short simulation durations given the slowly developing up-flooding. In general, it is understood that the time-domain simulations of flooding within complex geometries require significantly longer simulation runs. Notwithstanding this, the gap between the simulation results and static calculations has been significantly reduced, in comparison to earlier results.

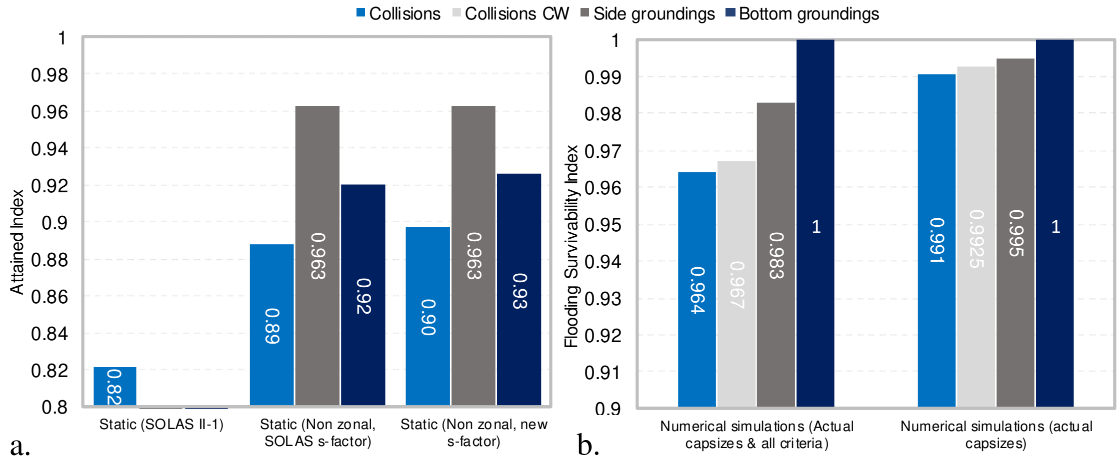


Figure 60: Comparison of survivability results for collisions, collisions in calm water, side and bottom grounding results between the : a) statistical and b) direct approach for ship A

Generally, the results represent significant steps forward in understanding flooding events, although, the differences between SOLAS Attained subdivision Index and expected survivability levels (Flooding survivability Index) based on simulations, cannot yet be fully explained and further work is needed in this direction.

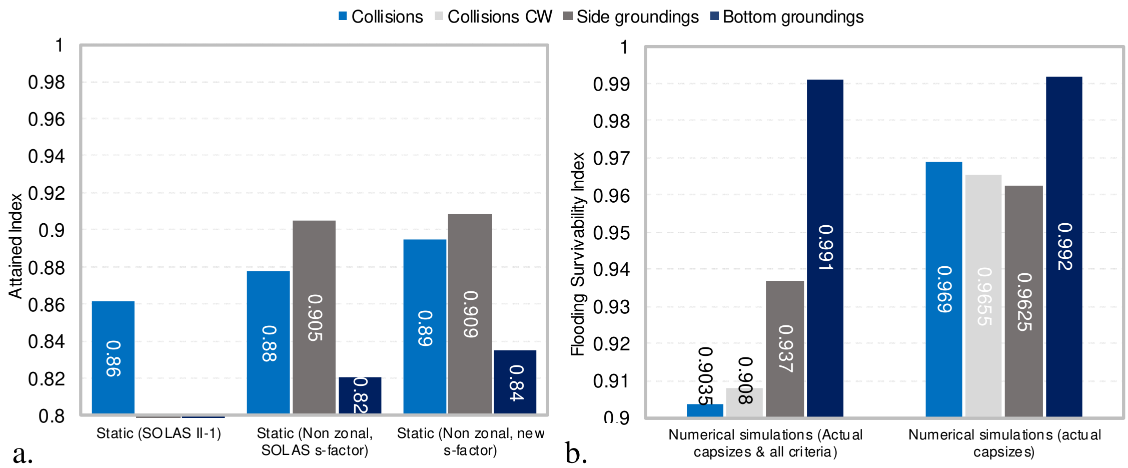


Figure 61: Comparison of survivability results for collisions, collisions in calm water, side and bottom grounding results between the : a) statistical and b) direct approach for ship C

5.8.Closing remarks

In chapter 5 survivability has been derived following the statistical and the direct approach to survivability of cruise vessels in waves and a number of conclusions can be drawn based on the aforementioned. A new survivability factor is being proposed specifically for cruise ships and a critical Hs formulation applicable to ships in service world-wide. The proposed formulation accounts accurately for the effects of the ship and damage size through a purposely derived cruise ship-specific scaling factor. Similarly to the GOALDS project (Papanikolaou, 2012) where the residual intact volume following flooding was used as a parameter within the s-factor formulation, results also indicate that ship size and amount of floodwater are linked to survivability, meaning that survivability in cruise ships is affected by scale. As such, a suitable scaling factor depending on both floodwater volume and residual volume has been derived.

The proposed formulation has been systematically tested for 2 to 4-compartment damages in in four cruise ships in operation and the results demonstrate that the concept is robust. Based on the analysis the results demonstrate that survivability does depend on sea state and a relationship that is cruise-ship specific has been derived linking Hs-critical to characteristics of the residual GZ curve, namely Range and GZ_{max}. Also, the results demonstrate differences from those based on static calculations as a result of local details not being considered properly in the latter during the flooding process, namely encountering an opening leads to s=0, irrespective of the amount of floodwater linked to such openings.

The large cruise ships considered in the sample set demonstrate resistance to capsize in a sea state for all 2-compartment damage scenarios, including extreme sea states. As a result, the limiting case of a 3-compartment damage scenario has been considered as the basis which in turn implies that cruise ships survive statically 3-compartment damages as a minimum which has been proven true. In this effort, the consideration of local openings in deciding limiting GZ properties leads to erroneous results that cannot be used to define global stability parameters for cruise ships. As a result, is has been deemed appropriate to use the un-truncated residual stability properties in the calculation of survivability. This allows the examination of the physical phenomena entailed in survivability in waves of cruise ships.

Through this work, it has been understood that the survivability level of cruise ships is considerably higher than that postulated by rules. Survivability has been derived using the direct approach and numerical simulations to assess the impact of waves. Dynamic time-domain flooding simulations provide an effective means for screening flooding scenarios, likely to lead to vessel loss. At the same time, they offer additional information to address the ensuing potential risk at a forensic level not afforded by static calculations.

The numerical simulation results indicated higher survivability than the statistical approach calculations. The discrepancies in expected survivability levels are particularly large in grounding scenarios and this is likely due to relatively short simulation durations given the slowly developing up-flooding. The outcome from this investigation could be used in its entirety to regrade the vessel to the rightful level of damage stability (Index A) based on the Guidelines for Alternatives through Class and Administration to verify the ship for the actual survivability level as demonstrated through simulations. This can be a practical alternative.

Chapter 6

Impact of Wave Statistics on Survivability

6.1.Opening remarks

The current survivability framework is based on the assumption that a damaged ship needs to survive a significant wave height of 4 meters and this will result in a survivability factor of one (Tuzcu, 2003c). Nevertheless, the current instruments used in SOLAS to gauge survivability do not refer explicitly to the critical sea states and wave height and as a result they are not adaptive in the way the requirements are stipulated for different areas of operations. Typically, the s-factor is implicitly dependent on the wave height and on the specific distribution of sea states pertaining to accident statistics. The current survivability factor is a result of the process involving the estimation of the critical significant wave height (Hs_{crit}), which represents a threshold sea state in which the ship is likely to survive given damage with certain probability for a specific time, and the calculation of pertinent sea state distributions to estimate the probability of encountering sea states below the critical significant wave height Hs_{crit}. Previous projects (HARDER, 1999-2003, GOALDS, 2009-2012) and subsequently SOLAS adapted for this purpose an approximation of the distribution of sea state encountered during collision incidents (HARDER) and later for groundings incidents (GOALDS).

The lack of consideration of localised sea state requirements in damage stability has been addressed within the Stockholm Agreement framework for RoRo ships. Generally, ships operating in sea states where the probability for exceeding a certain sea state Hs is less than four meters are subject to less stringent requirements than those in unrestricted operation. Nonetheless, SOLAS damage stability framework is inadequate as it does not provide relaxation to the stability requirements for ships that are exposed to sea states less than 4 m Hs. In this manner, one could agree that the expected probability of survival in case of a critical Hs of 2 meters is 90% even if the ship never operates in sea-states larger than 2 meters Hs.

To this end, the following chapter aims to investigate the impact of varying wave statistics on the calculation of the s-factor and ultimately the magnitude of the Attained subdivision Index. For this purpose, several alternative approaches have been taken including the use of updated accident wave statistics based on accident data ranging over the past 15 years, pertaining solely to passenger ships and especially cruise ships. Also, localised wave statistics gathered for several key trade regions including the North Atlantic, Mediterranean, Southeast Asia and the Caribbean and also statistics narrowed down to more specific areas along with the consideration of annual Global wave statistics.

In each case a new s-factor formulation has been derived based on cumulative density functions produced for each wave data set and the subsequent influence of the varying formulations on the Attained Subdivision Index has been estimated. One of the main objectives in this effort is to establish a rationale and an approach that can be adopted complementary to the current damage stability framework. Finally, the deviation from SOLAS of using actual wave statistics, rather than wave statistics pertaining to sea states at the time of the incident, is based on the argument that it is essential to estimate the risk of exposing ships to all operating sea states (thus, calculating pertinent risk), and not just those wave characteristics at which accidents have taken place in the past (historical risk).

The method can have manifold use in the design and operational phase of damage survivability assessment. With regards to the former, utilisation of actual wave statistics aids in the assessment of ships based on their actual area of operation. This implies that vessels will not be penalised based on the current subjected generic application pertaining to historical data (4 meter maximum wave height). For instance, a 2009 SOLAS ship build to operate in Adriatic Sea is subjected to a stringent wave limitation of 4 meters, while in this area, smaller wave heights are encountered (2-3 meters). Such solution enables more degrees of freedom to the designers. On the other hand, in the operational phase, the same rationale can be applied facilitating the adoption actual data for the generation of real-time survivability indicators or usage of empirical formulations to assess combined areas of operation. In this line, the aggregated survivability based on the various legs of trip can be consolidated to assess survivability. This offers an accurate means of real-time survivability assessment based on the wave environment.

6.2. The concept of survivability in waves

Accurate estimation of survivability is of paramount importance when assessing ship damage stability performance. Survivability is influenced by a multifarious range of parameters all of which are situational dependant; however, at the highest level, survivability can be viewed as an outcome involving both the post-damage restoring properties of the vessel and the prevailing sea state.

Survivability in waves, as per SOLAS 2009, refers to a distribution of wave heights, which is formed based on recorded accident sea states at the time of collision accidents. This assumption, therefore, fails to directly account for the influence of operational area on survivability and more alarmingly implies that a vessel's survivability is independent of its operational environment. Furthermore, as the accident data used in the creation of the distribution of wave heights behind the SOLAS s-factor comprised of accident data relating to all ship types, it fails to account for the influence of ship specific data.

The "s-factor" is a core component of the probabilistic damage stability framework, known commonly as SOLAS 2009 (IMO, 2006b), and is a measure of a damaged ship survivability in waves. With the assumption, as in SOLAS, that only Hs has bearing on the survivability and neglecting other environmental factors such as wave spectrum distribution, the probability of a ship surviving collision damage that has led to hull breach and flooding can be determined by application of the total probability theorem as described by (Jasionowski, 2009a):

$$s_i = \int_0^\infty f_{Hs|Coll}(H_s) \cdot F_{surv}(H_s)\, dH_s \tag{6-1}$$

Where specifically,

$f_{H_s|coll}(H_s)$ Represents the probability density distribution of sea states expected to be encountered during collision.

$F_{surv}(H_s)$ Represents the survival probability when a vessel is subjected to a given damage case and exposed to a sea state characterized by significant wave height H_s.

The development of the s-factor is based largely on the findings of the EU research project HARDER (Tuzcu, 2003b) in which model tests were conducted with a limited exposure time of 30 minutes and thus the probability of survival, as it exists in SOLAS 2009, is in fact a conditional probability (Cichowicz, 2016) provided as follows,

$$F_{surv}(H_s) \equiv F_{surv}(t = 30min|H_s) \quad (6\text{-}2)$$

This leads to the expression of eq.(5-4) as provided earlier in §5.2.

One of the key underlying assumptions in SOLAS 2009 is that, for a given damage case, there exists a critical significant wave height Hs_{crit} such that a vessel damaged in a sea state relative to this parameter will always survive for lower H_s and not always survive for higher H_s. As it has been explained in earlier sections, this theory has its roots in what is known as the capsize band (Tsakalakis, 2010), which represents the range of sea states in which the capsize probability transitions from unlikely to certain, often represented by a sigmoid curve as shown in Figure 62 below (Vassalos, 2015b).

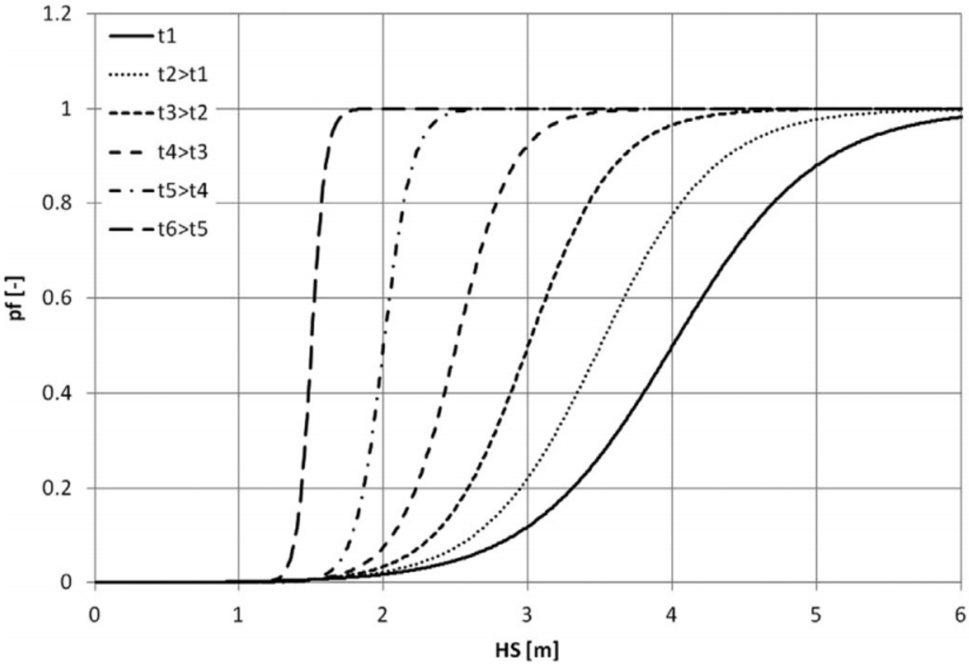


Figure 62: Example of capsize band represented by sigmoid curve and with varying observation time (Cichowicz, 2016).

The critical significant wave height H_{Scrit} is defined as the sea state at which a ship in a given loading condition and a specified damage case is exposed to the action of beam random waves for 30 minutes would have a 50% chance of survival (Tsakalakis, 2010).

Drawing on this, the survival probability for a specified loading condition and damage case when exposed to a given sea state for 30 minutes, could be approximated by a step function centred on the sea state H_{Scrit}. This is essentially the limiting case of the capsize band concept and leads to eq.(5-4).

The distribution of wave heights utilised in the formation of the SOLAS s-factor, as shown in Figure 63 , was produced during project HARDER following statistical analysis of sea states encountered during collision accidents and comprising 389 recorded incidents (Jasionowski, 2009a).

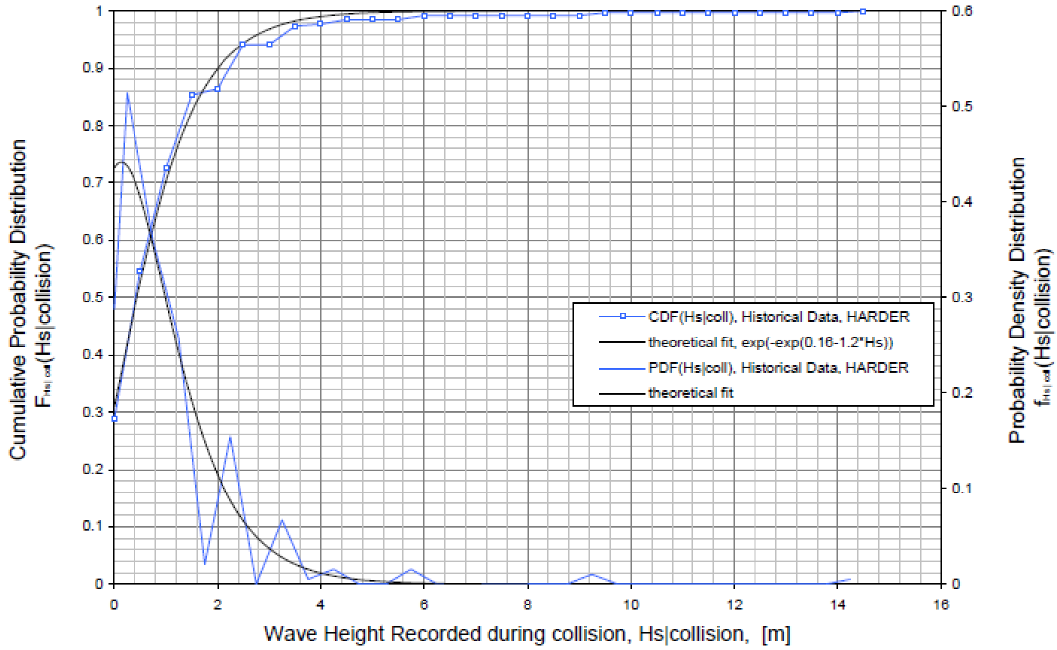


Figure 63: Accident wave statistics CDF (Jasionowski, 2009a)

Following regression of the statistical distribution of sea states with respect to Hs_{crit} the s-factor could be expressed as:

$$s_i = \Pr\{H_s \le H_{s,crit,i}\} = exp^{-\exp(0.16-1.2H_{s,crit,i})} \tag{6-3}$$

Where $H_{s,crit}$ is given from eq.(5-5).

Based on the HARDER findings in which three dimensional regression was used to correlate the mean survival sea states experienced during model testing of specific damage scenarios (worst 2-compartment damage case) to GZ_{max} and GZ Range stability parameters and where TGZ_{max} and TRange were defined as 0.12 meters and 16 degrees respectively, based on the best fit correlation (Tuzcu, 2003b) using the so-called GZ-based approach.

As explain in §3.3.6, the s-factor formula was derived by using the individual model test survival sea states multiplied by the probability of sea state occurrence and then regressing a GZ-based formula to this data, leading to the following equation:

$$s_{final} = K \cdot \left(\frac{\min(GZmax, 0.12)}{0.12} \cdot \frac{\min(range, 16)}{16}\right)^{0.25} \tag{6-4}$$

Where, K represents the heel angle at the final equilibrium based on SOLAS (IMO, 2009).

6.3.Region-specific survivability factors

As it was touched upon in the previous section, the survivability factor combines two main aspects, namely the restoring capabilities of the vessel and thus its ability to survive in waves and also the assumed distribution of sea states encountered during collision accidents.

Through using the "critical significant wave height" concept, which is a conditional parameter, survivability is measured based on both the post damage stability properties of the vessel in a given damage scenario, which define $H_{s,crit,i}$ for that scenario (i) and the distribution of sea states, which allows the s-factor to be determined as the likelihood that the survival sea state, $H_{s,crit,i}$, will not be exceeded at the time of collision (again for that specific scenario i).

During project HARDER it was asserted that there exists a certain range of sea states in which collision accidents occur and hence accident wave statistics were used in order to define the sea state distribution behind the SOLAS s-factor (Tagg and Cantekin, 2002). However, such an assumption implies that a vessel's survivability is independent of its area of operation, meaning that two identical vessels when subjected to the same damage scenario have the same probability of survival even if one is located in the North Atlantic (0m≤Hs≤9m) and the other in the Mediterranean (0m≤Hs≤5m). This, of course, cannot be the case.

In order to capture the influence of operational area on survivability it is proposed to use localised wave distributions as a basis for trade region specific s-factor formulations. To this end, four key ship trade regions have been selected for assessment including the North

Atlantic, Caribbean, Southeast Asia and the Mediterranean along with two geographically limited seas namely, Baltic and North Sea. The four former regions represent key trade regions including thousands of international cruise ship voyages, while the two latter represent domestic dense voyage regions. Figure 64 demonstrates the annual wave height contours for the regions in consideration. As expected, the North Atlantic indicates the highest recorded waves annually, whereas the Mediterranean the lowest wave heights on average (1m). One could argue that the North Atlantic does not constitute an adequate candidate since the probability of encountering a collision damage along with the probability of encountering high waves (9m) is miniscule. However, the North Atlantic is utilised in order to gauge the adaptability of the methodology and provide a rationale behind the survivability concept.

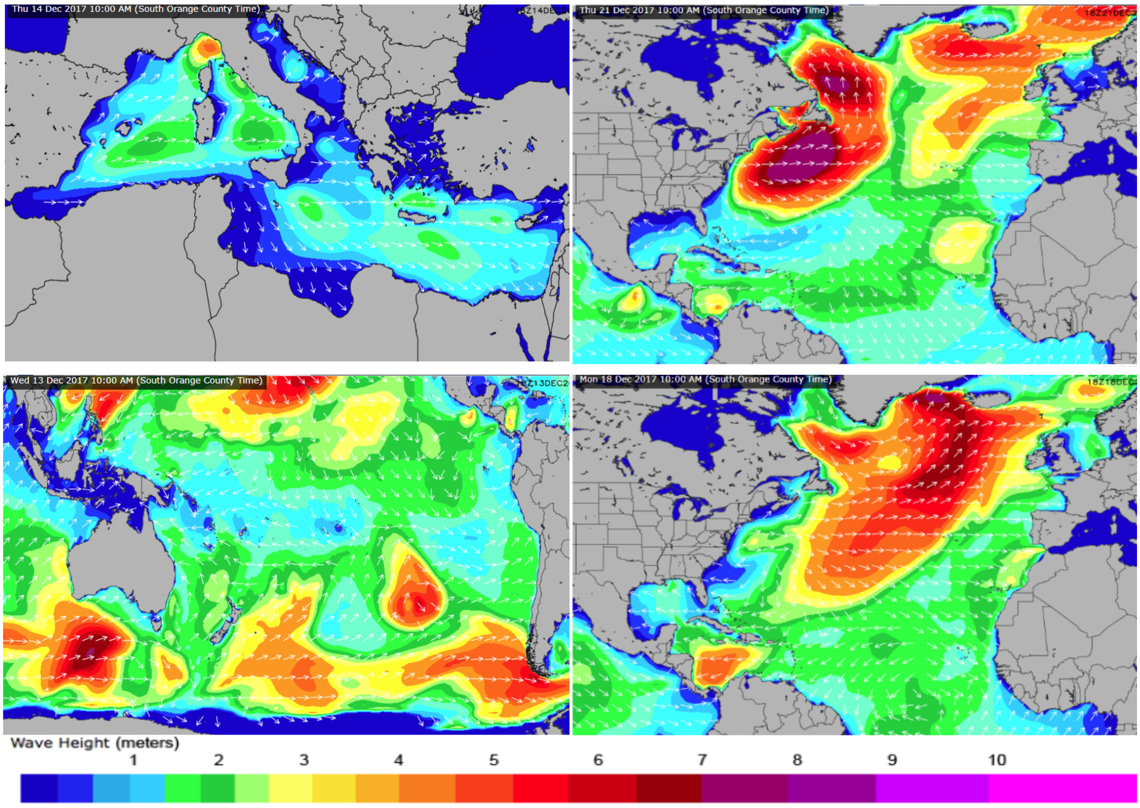


Figure 64: Wave height contour graphs across Mediterranean sea, Atlantic ocean, Caribbean and Pacific ocean with indications between the maximum and minimum wave encounters during winter season. Adopted from (Surfline, 2017).

For each sea region, annual wave statistics have been collated from wave statistic databases that provide historic data for waves encountered within 70 to 80 years of span (Dacunha, 1986) in terms of 1,000 wave averages. Even though wave distributions can change significantly over a short period of time, they do not exhibit large variations periodically or over a constant period of time. (Bitner-Gregersen et al., 2013) mentioned that there is neutral development of the mean significant wave height during periods 1985 to 2008 over the northern hemisphere oceans. Also, during the same period, there is a positive trend of the Hs at the upper hemispheres indicating as low as 0.25% increase per year at the 90th percentile and around 0.5% at the 99th percentile of the related Hs cumulative distributions (Bitner-Gregersen et al., 2013) in limited cases.

Besides, the aim of this chapter is to facilitate for a method that works complementary to the current damage stability framework and that can be subsequently adopted to a more meticulous manner for the consideration of more accurate wave statistics. The data for each trade region are derived from scatter tables indicating the wind direction, significant wave height, zero crossing period and frequency of waves. The derived seasonal and annual marginal cumulative distributions of the significant wave heights for some of the aforementioned regions are provided in Figure 65 below.

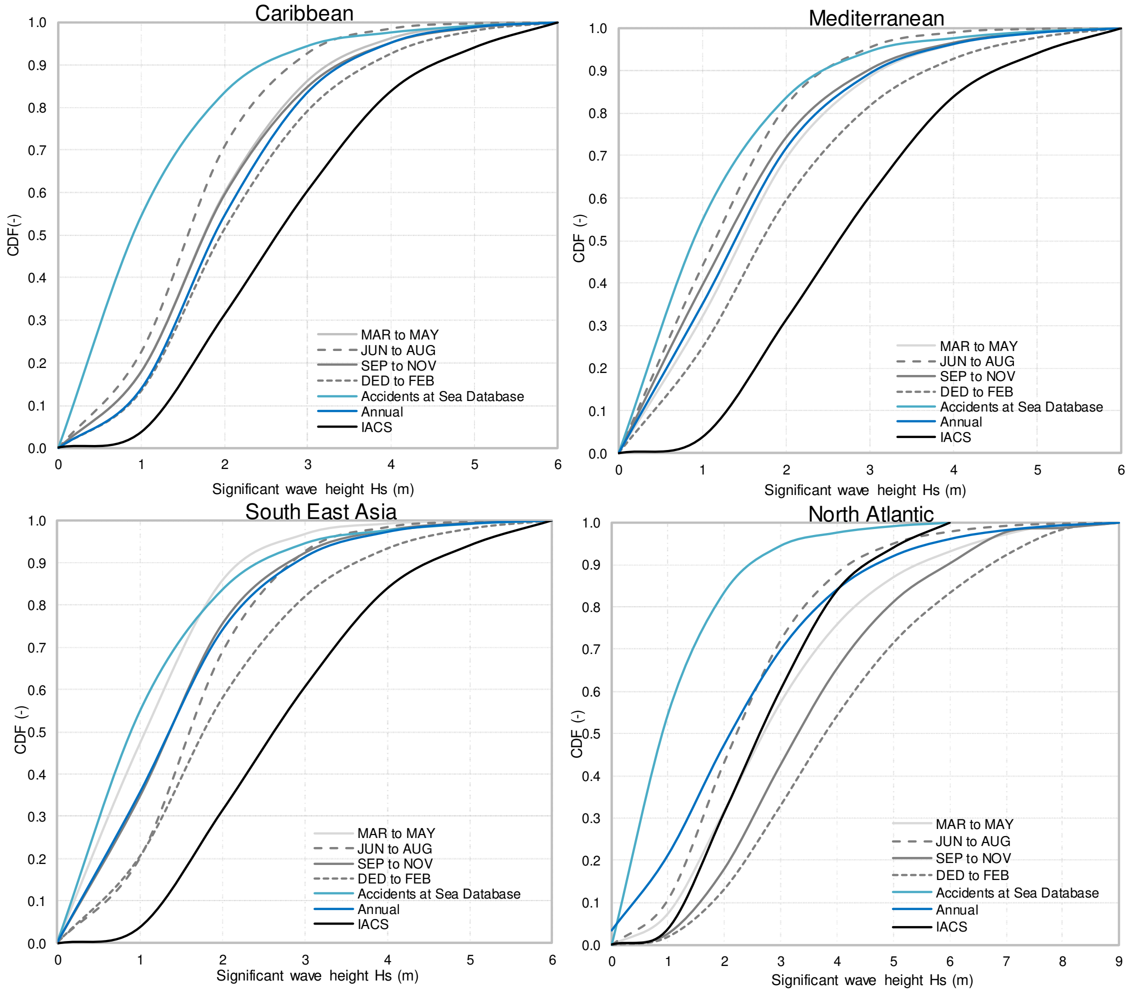


Figure 65: Marginal cumulative distributions of four key trade regions for their annual and seasonal wave

statistics along with the wave statistics from IACS. The accident at sea database CDF is explained later.

For the sake of comparison, annual Global wave statistics and the wave statistics from (IACS, 2000) worldwide distribution have been utilised. As shown in Figure 65 and as expected the probability of encountering higher waves increases during the winter season and this is more transparent in the case of the Mediterranean and Caribbean since these regions experience milder wave environments. The annual CDF overlays the winter season CDFs indicating an average trend across the regions, while, the IACS wave statistics are proven more stringent in terms of wave heights. Figure 66 to Figure 70 below represent the joint probability of the significant wave heights (Hs) and zero crossing periods (Tz). Particularly, the Caribbean, Mediterranean and SEA represent higher joint probabilities (maximum 15%) at wave height between 5 and 7 meters whereas, the Global and North Atlantic smaller joint probabilities in higher wave heights (7-9 meters).

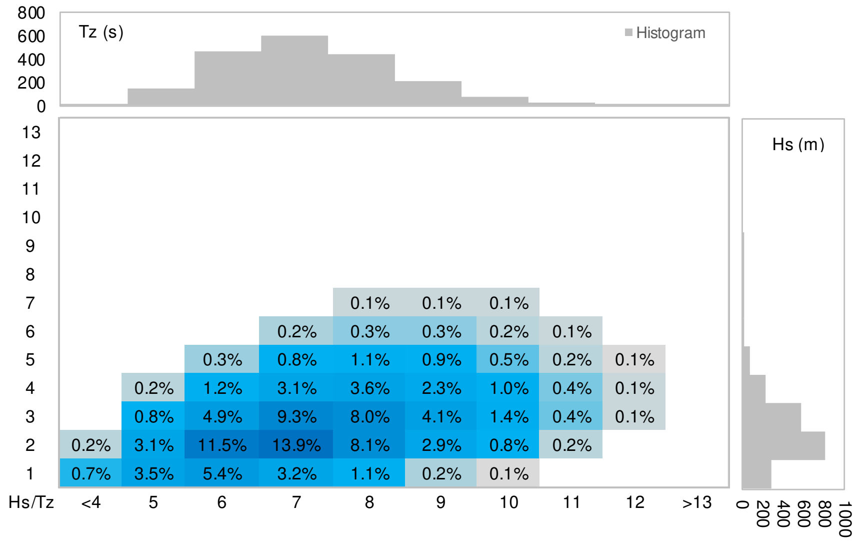


Figure 66: Joint probabilities and marginal histograms of significant wave heights (Hs) and zero crossing periods (Tz) at wider Caribbean sea region pertaining to all directional wind (Annual).

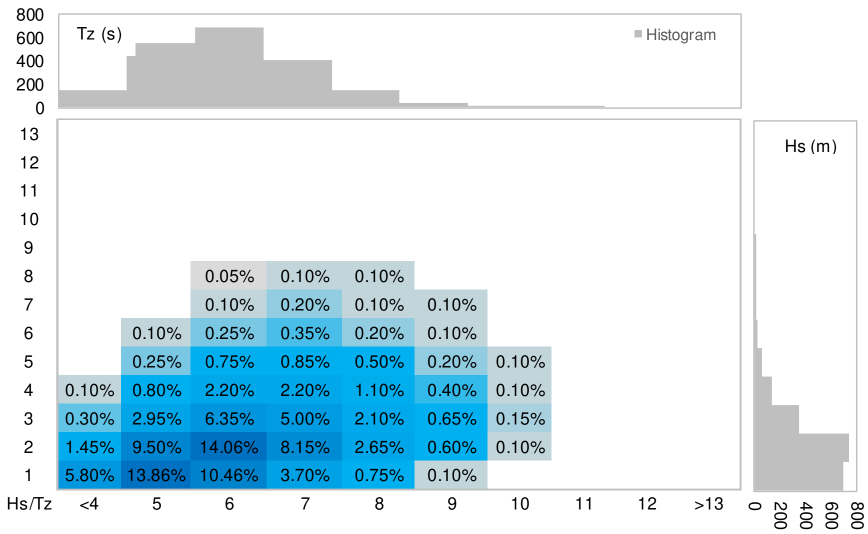


Figure 67: Joint probabilities and marginal histograms of significant wave heights (Hs) and zero crossing periods (Tz) at wider Mediterranean sea region pertaining to all directional wind (Annual).

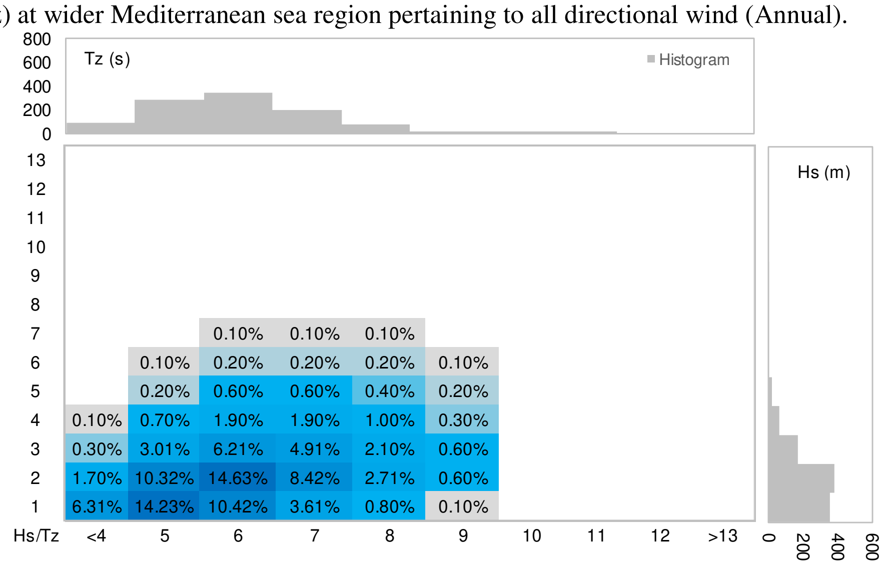


Figure 68: Joint probabilities and marginal histograms of significant wave heights (Hs) and zero crossing periods (Tz) at wider South East Asia sea region pertaining to all directional wind (Annual).

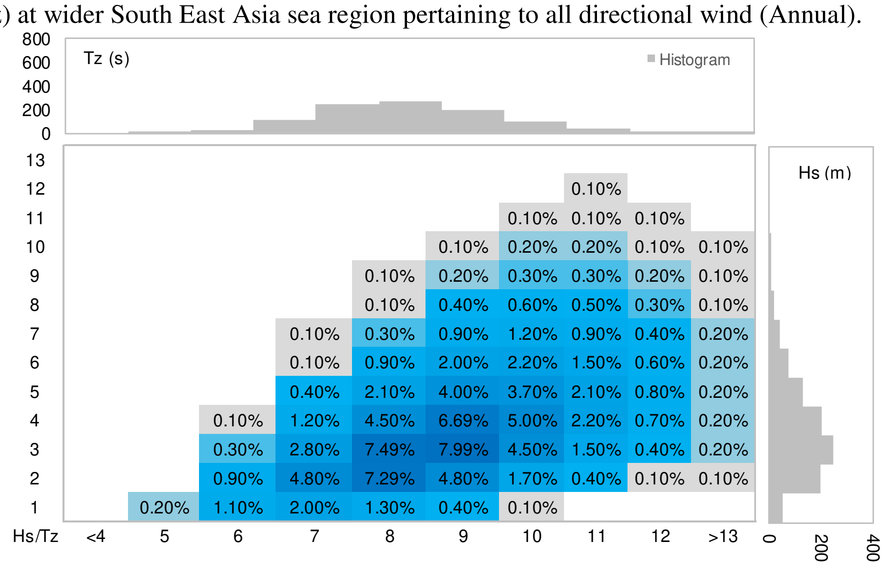


Figure 69: Joint probabilities and marginal histograms of significant wave heights (Hs) and zero crossing periods (Tz) at wider North Atlantic sea region pertaining to all directional wind (Annual).

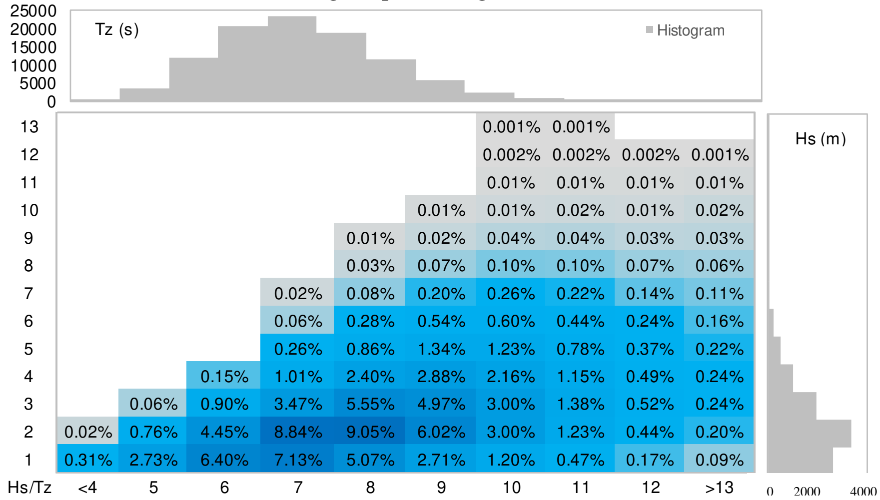


Figure 70: Joint probabilities and marginal histograms of significant wave heights (Hs) and zero crossing periods (Tz) for Global wave statistics pertaining to all directional wind (Annual).

The corresponding cumulative distribution function (CDF) of significant wave heights, $CDF(H_S)$ has been fitted to the data using the exponential regression form provided in eq. (6-5) below. The following equation is in line with that obtained in HARDER and it represents the best means of regressing the data (100% correlation) at hand of the various regions among a number of investigated formulations. The limiting significant wave height in each case was defined as that relating to the 99th percentile for each area of operation.

$$CDF(H_S) = \exp(-exp(\alpha - \beta \cdot H_s)) \qquad (6\text{-}5)$$

Where, α and β are regression coefficients based on trade region. The results of this process are summarised in Table 6 and Figure 71 below. As demonstrated the North Atlantic represents the more stringent transition of wave encountering probabilities while, the South East Asia is more lenient as it represents lowest wave heights.

Table 6: Trade region specific regression coefficients

Trade Region	Regression Coefficients
Caribbean	α=1.888, β=1.2035
Mediterranean	α=1.178, β =1.1320
Southeast Asia	α=1.262, β =1.2280
Global Annual	α=1.1717, β =0.9042

North Atlantic	α=1.9179, β =0.7383
Baltic Sea	α=1.3245, β =1.2577
North Sea	α=1.1407, β =0.8426
English Channel & Gulf of Biscay	α=1.0443, β =0.8416
HARDER	α=1.1407, β =0.8426

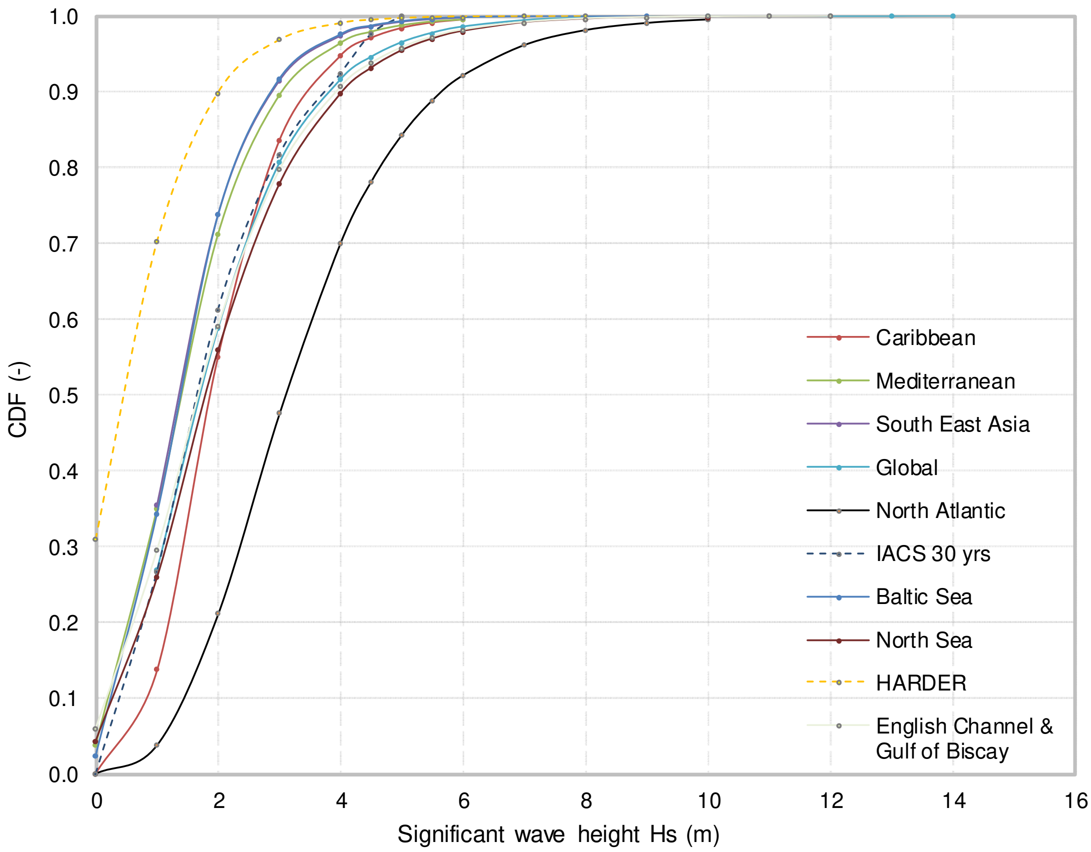


Figure 71: Fitted Cumulative Distribution Function of significant wave height for all sea regions.

The waves from HARDER relate to those encountered during the time of collision accidents. It is shown that the HARDER CDF overlays the rest of the operational area CDFs. This is primarily due to the fact that the majority of incidents occur generally in sheltered terminal areas with low wave height whereas the seasonal wave data is recorded at open sea where larger wave heights are to be expected. As a result, it can be expected that the survivability level estimated using only wave data will be less than that calculated utilising accident wave data as greater weighting will be given to higher wave heights. It is important to be emphasised that HARDER data are based on collision accidents and therefore a direct comparison with wave statistics would be only indicative.

At the first instance, and in line with previous work, survivability within each trade region can then calculated using the following formulation:

$$s_i = \Pr\{H_s \leq H_{s,crit,i}\} = exp^{-\exp(\alpha - \beta \cdot H_{scrit})} \quad (6\text{-}6)$$

Where, α and β represent the trade region-specific regression coefficients as obtained earlier. Further details will follow on the derivation of the survivability formulae.

6.3.1. Estimation of the critical significant wave height, Hs_{crit}

During project HARDER the regression formula for estimating $H_{s,crit}$ was based on both GZ_{max} and Range parameters and it was limited to a significant wave height of Hs=4m and for this reason it cannot be applied, in its current form, to the trade regions where the probable significant wave height exceeds this value, i.e. the North Atlantic where Hs=9m has been recorded. Instead, a formula in the same manner has been produced for each trade region through three dimensional regression of the surface produced from the HARDER model test results, which links Range and GZ_{max} to the survival sea state, as shown in Figure 72 below. In each case, the regression has been limited to the Hs, which constitutes the 99th percentile significant wave height within each trade region. The regression functions produced are shown in Table 7 below along with the formula for predicting Hs_{crit} as per (Tuzcu and Tagg, 2002) as shown in §5.2.

The critical significant wave height Hs_{crit} is in this case limited to 4m based on the CDF of wave heights at the time of collisions derived during project HARDER where all accidents occurred in sea states with HS≤4m. With an established means of ascertaining Hs_{crit}, the survival probability could be estimated as the probability of $Hs \leq Hs_{crit}$ at the time of accident. Based on the accident wave statistics CDF, the survival probability for a given damage case d_{ci} could be expressed as per eq.(6-7) .

$$s_{i,SOLAS} = \Pr\{H_s \leq H_{s,crit,i}\} = CDF(H_{s,crit,i}) = exp^{-\exp(0.16 - 1.2 H_{s,crit,i})} \quad (6\text{-}7)$$

Survival in seaways can be estimated by establishing both a GZ_{max} and a Range criterion as presented in eq (6-8) below.

$$Hs_{crit} = MIN\begin{cases}0.0153\ Range^{1.9012} \\ 108.42\ GZmax^{1.544}\end{cases} \tag{6-8}$$

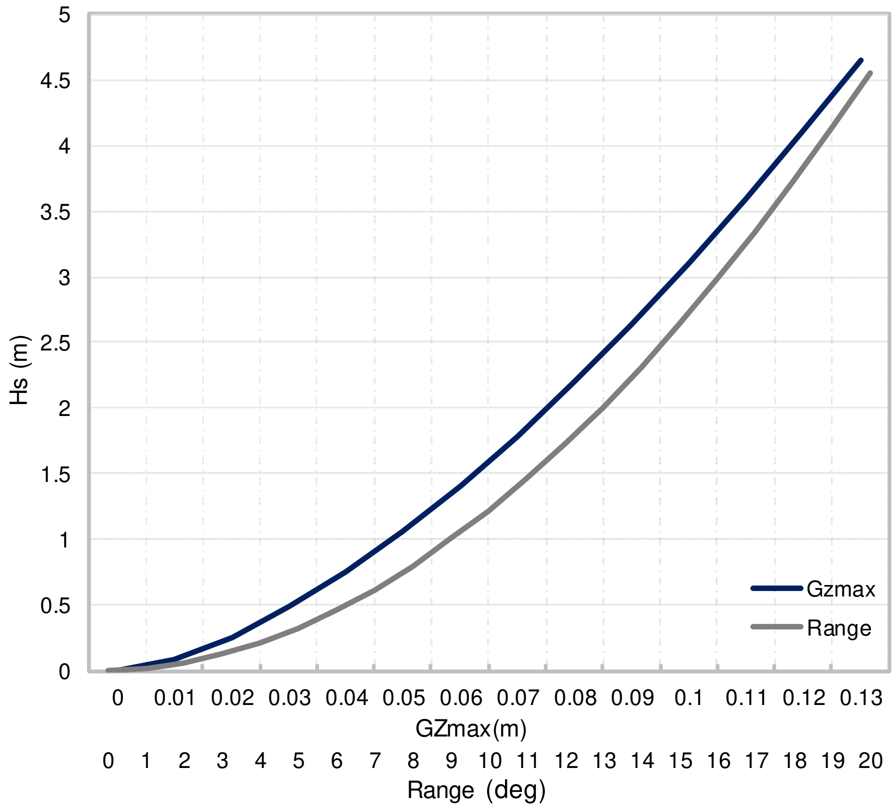


Figure 72: Established Range and GZ_{max} criterion through project HARDER

In order to establish an accurate means of estimating $Hs_{,crit}$ for each specific operational area, an approach, namely the GZ-based method, was followed in line with project HARDER. The regression formula for estimating $H_{s,crit}$ is based on both GZ_{max} and Range parameters and is limited to Hs=4m and for this reason this formula cannot be applied to operational areas where the probable significant wave height exceeds the value of 4 metres. Instead, using the same approach as in project HAREDER, a formula has been produced for each area through three-dimensional regression of the HARDER model test results linking Range and GZ_{max} to the survival sea state as shown in the following figure.

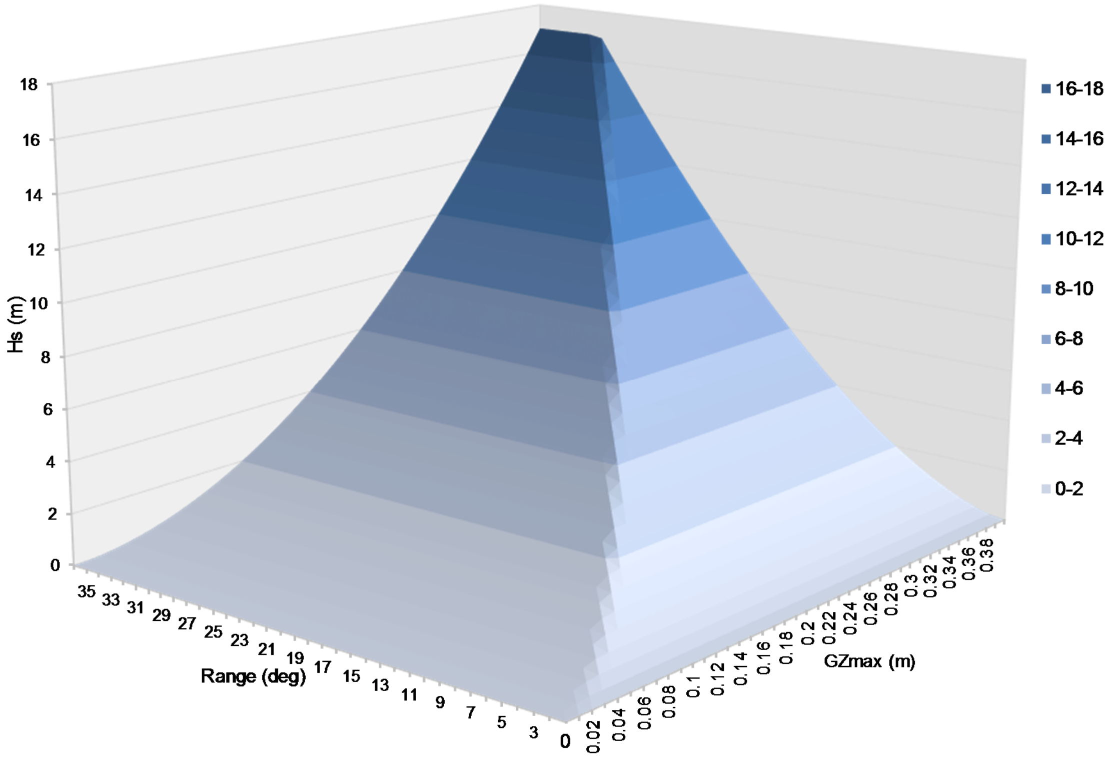


Figure 73: GZ-based significant wave height Hs(m)

Notably, the pertaining GZ_{max} and Range values, as mentioned in chapter 3, have been derived on the basis of RoRo/passenger ships. Therefore, the derivation of specific region critical wave height factors would be incompatible with cruise ships and further considerations utilising the datasets obtained in chapter 5 should be made. It should also be noted that the prediction of the critical significant wave height, for a given damage case, is independent of trade region, however, regional specific $H_{s,crit,i}$ formulations have been derived in order to facilitate the creation of GZ-based trade region specific s-factor formulations. The results of this process are summarised below along with the regression accuracies in Table 7 and Table 8 in the next page. In addition, the effects of narrower trade areas have been investigated by splitting the region of Mediterranean into west and east regions based on respective wave statistics. As it can be observed in the tables below following regression, for areas with higher wave heights, the targeting values increase accordingly.

Table 7: Summary of region specific Hs_{crit} formulations

Sea region	Maximum significant wave height (m)	Hs_{crit} formula
Caribbean	6	$Hs_{crit} = 6 \times \left(\frac{GZmax}{0.19} \times \frac{Range}{25}\right)$
Mediterranean	5	$Hs_{crit} = 5 \times \left(\frac{GZmax}{0.16} \times \frac{Range}{23}\right)$
South East Asia	5	$Hs_{crit} = 5 \times \left(\frac{GZmax}{0.16} \times \frac{Range}{23}\right)$
Global statistics	6	$Hs_{crit} = 6 \times \left(\frac{GZmax}{0.19} \times \frac{Range}{25}\right)$
North Atlantic	9	$Hs_{crit} = 9 \times \left(\frac{GZmax}{0.21} \times \frac{Range}{38}\right)$
Baltic Sea	4	$Hs_{crit} = 4 \times \left(\frac{GZmax}{0.13} \times \frac{Range}{21.3}\right)$
North sea	6	$Hs_{crit} = 6 \times \left(\frac{GZmax}{0.17} \times \frac{Range}{26.37}\right)$
English Channel and Gulf of Biscay	6	$Hs_{crit} = 6 \times \left(\frac{GZmax}{0.17} \times \frac{Range}{26.37}\right)$
West Mediterranean	5	$Hs_{crit} = 5 \times \left(\frac{GZmax}{0.15} \times \frac{Range}{24}\right)$
East Mediterranean	4	$Hs_{crit} = 4 \times \left(\frac{GZmax}{0.13} \times \frac{Range}{21.3}\right)$

Table 8: Summary of regression accuracy for each sea region

Region	Highest overestimate	Lowest underestimate	Mean error	Sum of Squares
Caribbean	0.85	-1.03	0.1289	7.092
Mediterranean	1.06	-1.18	0.10398	13.337
South East Asia	1.18	-0.955	-0.146	11.849
Global statistics	1.06	-1.18	0.10398	13.337
North Atlantic	1.23	-1.553	0.0762	21.442
Baltic Sea	0.704	-0.813	0.0414	26.192
North Sea	1.0569	-1.269	0.0536	93
English Channel & Gulf	1.0571	-1.268	0.0536	93
West Mediterranean sea	0.8775	-1.003	0.0524	52.848
East Mediterranean sea	0.7046	-0.813	0.0414	26.192

6.3.2. GZ-based combined survivability formulations

Alternative to the survivability formulations obtained through the actual wave statistic distributions in the previous section, combined s-factor formulations for each trade region have also been derived. Assuming that the true survivability can be estimated using eq.(6-5), a 3D surface relating survivability to both GZ_{max} and Range has been produced on a finely discretized grid of combinations $(GZ_{max}, Range)$ as shown in Figure 74 for the case of global wave statistics for the purposes of demonstration.

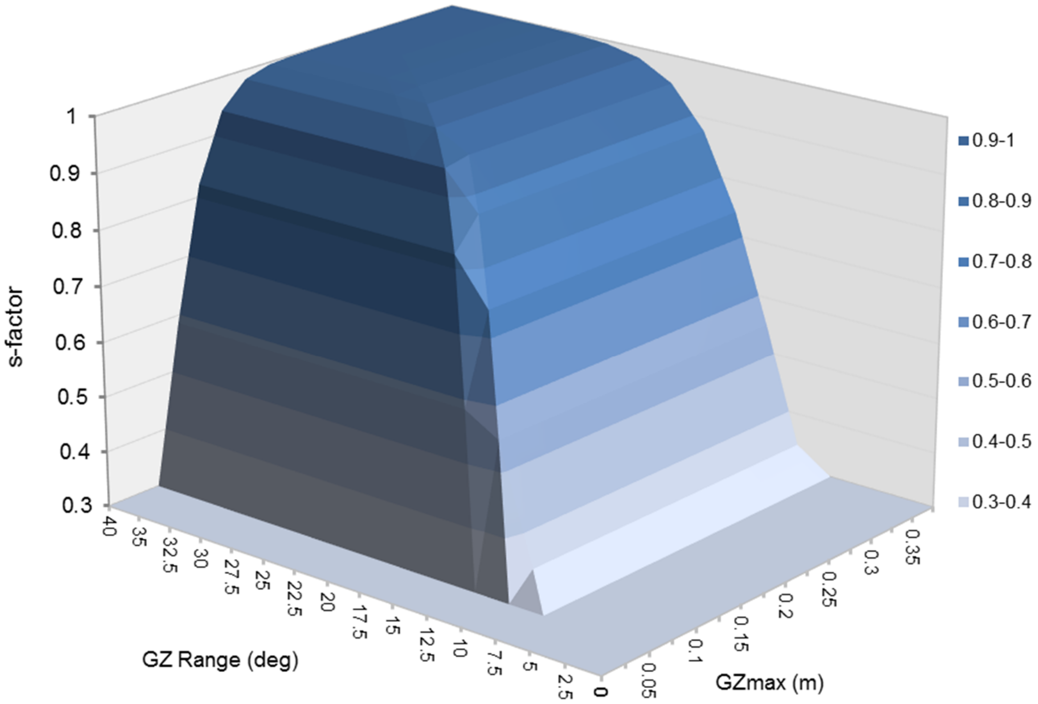


Figure 74: GZ-Based survivability factor for global wave statistics used for demonstration

GZ-based s-factor formulations have then been created for each trade region through performing three dimensional regressions to the region specific surfaces linking survivability to residual stability parameters in the following format

$$s = \left(\frac{H_{s,crit}}{H_{s,lim}}\right)^x = \left(\frac{\min(GZmax, TGZmax)}{TGZmax} \cdot \frac{\min(Range, TRange}{TRange}\right)^x \tag{6-9}$$

Where $H_{s,lim}$ is the region specific 99th percentile Hs, $TGZmax$ and $TRange$ are the region-specific limiting stability parameters and x is an exponent based on the best fit correlation. The results of this process are provided below and they show of a very good correlation to the data through non-linear regression.

Table 9: Region specific s-factor formulations

Sea region	survivability formula
Caribbean	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.19} \cdot \frac{\min(\text{Range}, \text{TRange})}{25}\right)^{0.7}$
Mediterranean	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.16} \cdot \frac{\min(\text{Range}, \text{TRange})}{23}\right)^{0.6}$
South East Asia	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.16} \cdot \frac{\min(\text{Range}, \text{TRange})}{23}\right)^{0.6}$
Global statistics	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.19} \cdot \frac{\min(\text{Range}, \text{TRange})}{25}\right)^{0.6}$
North Atlantic	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.21} \cdot \frac{\min(\text{Range}, \text{TRange})}{38}\right)^{0.9}$
Baltic Sea	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.13} \cdot \frac{\min(\text{Range}, \text{TRange})}{21.3}\right)^{1.13}$
North sea	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.17} \cdot \frac{\min(\text{Range}, \text{TRange})}{26.37}\right)^{0.68}$
English Channel and Gulf of Biscay	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.17} \cdot \frac{\min(\text{Range}, \text{TRange})}{26.37}\right)^{0.685}$
West Mediterranean	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.15} \cdot \frac{\min(\text{Range}, \text{TRange})}{24}\right)^{0.79}$
East Mediterranean	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.13} \cdot \frac{\min(\text{Range}, \text{TRange})}{21.3}\right)^{1.13}$

6.4.Areas with wave heights less than 4 metres

In order to produce formulations to account for wave heights less than 4 meters, a parametric approach is sought. In the absence of complete and detailed wave statistics for these areas it was necessary to develop Cumulative Distribution Functions that reflect appropriately wave heights. Usually these reflect operational routes with close proximity to ports and estuaries. Such method can potentially aid in the development of a unified method for assessing the impact of wave heights for comparative purposes in the absence of wave statistical data.

An important assumption made is that the presented wave heights represent the 90^{th} percentile probability of their respective wave cumulative distributions. Thus, for each area there is 10 percent probability of exceeding the indicated wave height.

$$P(H_s > H_{s,MAX}) \geq 0.1 \quad (6\text{-}10)$$

Following the rationale presented in the aforementioned sections, a regression formula has been derived and presented below.

$$CDF(H_s) = 1 - \exp(-\beta \cdot (H_s)) \quad (6\text{-}11)$$

A regression coefficient beta can be derived from each wave height, being considered with the 90% probability, as follows:

$$\beta = \frac{Ln(1-0.9)}{Hs} \quad (6\text{-}12)$$

Having established all beta coefficients for all the wave heights spanning from 1m to 4.9 metres, cumulative distributions can be obtained as demonstrated in Figure 75 below. Following the same procedure as mentioned in previous sections a three-dimensional regression of the surface produced from the HARDER model test results is carried out with the view of linking Range and GZ_{max} to the survival sea state. The regression for each area is limited to the maximum wave height constituting the 90th percentile of their respective wave distributions. The ensuing results and associated estimate errors are provided in Table 10 below.

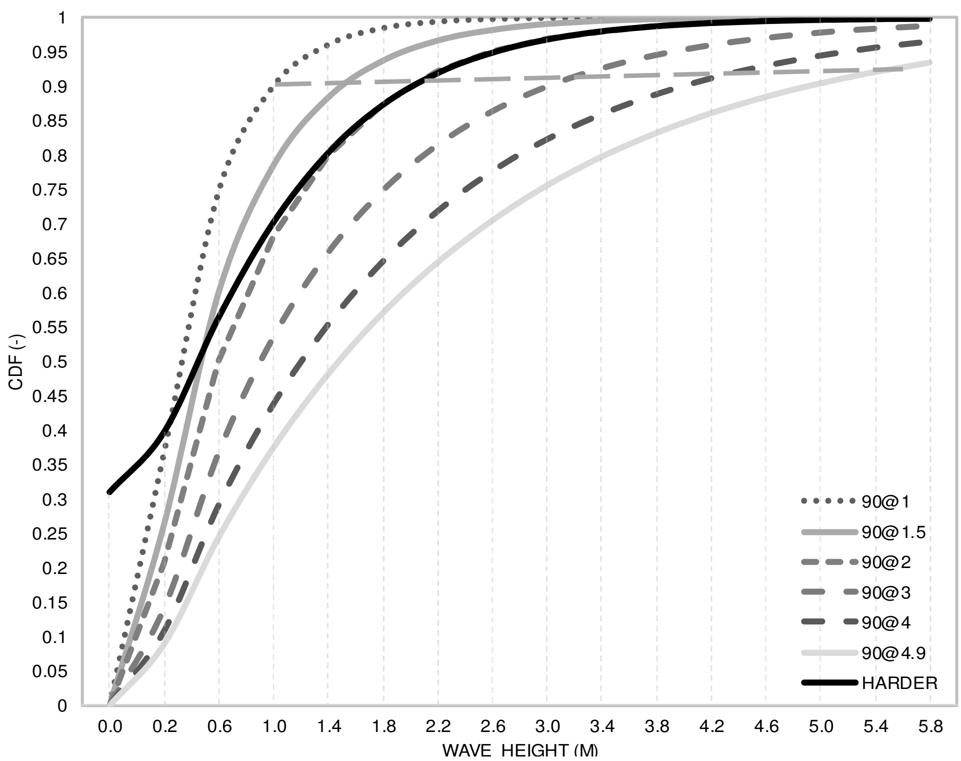


Figure 75: Parametric CDFs

The equation of the critical wave height takes the same form as eq. (6-9) above,

$$Hs_{crit}(GZmax, Range) = Hs(P(Hs) = 0.9) \cdot \left(\frac{GZmax}{TGZmax} \cdot \frac{Range}{TRange}\right) \quad (6\text{-}13)$$

Table 10: Regression coefficients and targeting values

Wave (m)	beta	TGZmax (m)	TRange (deg)	Lowest Underestimate	Highest overestimate	Mean error
1	-2.302	0.0529	10.219	-0.161	0.178	0.0153
1.1	-2.09	0.055	10.62	-0.15	0.2009	0.0247
1.2	-1.918	0.0574	11.092	-0.15	0.2193	0.0326
1.3	-1.77	0.0653	12	-0.251	0.2199	0.0035
1.4	-1.64	0.0672	12.195	-0.229	0.2477	0.0161
1.5	-1.53	0.07	12.983	-0.337	0.251	0.0047
..	..	..	-	-	-	-
3	-0.76	0.1099	18.285	-0.617	0.4344	0.0088
3.1	-0.74	0.11	18.893	-0.619	0.53	0.0252
3.2	-0.71	0.1123	19	-0.608	0.5604	0.0331
3.3	-0.69	0.1155	19.2	-0.624	0.5845	0.0314
3.4	-0.67	0.1196	19.749	-0.69	0.5865	0.0127
3.5	-0.65	0.12	20	-0.78	0.6064	0.0274
3.6	-0.63	0.121	20.063	-0.696	0.62382	0.0428
3.7	-0.62	0.1236	20.552	-0.784	0.6052	0.0265
3.8	-0.60	0.1263	21	-0.752	0.6503	0.026
3.9	-0.59	0.1296	21	-0.752	0.6884	0.0298
4	-0.5	0.13	21.3	-0.813	0.7046	0.0414

6.5. Passenger ship-specific survivability factor and accident database

The current SOLAS 2009 s-factor formulation utilises wave statistics based on the average significant wave height encountered during recorded accidents for all vessels and, as such, fails to distinguish between ship types and operational patterns. As an alternative, a new method is proposed in which ship-specific accident data is utilised. In the following an example of this process is provided in which a new accident database namely Accidents at Sea Database (ASD) is derived comprising of passenger vessel data only and using actual weather data in order to fill information gaps. This can form a rational methodology for implementation on different ship types with different levels of focus.

The database (ASD) was formed by collecting accident data from a number of reliable sources (Luhmann et al., 2018b, Luhmann et al., 2018a) such as to collate a comprehensive account of all accidents occurring at sea over a period spanning from 2005 – 2013. A representation of the vessels involved in the accident database is provided in Figure 76 with regards to their overall length and GT. The information included within the database comprise the exact accident location, time, and description of the accident, name of the vessel and IMO number.

However, the information was incomplete and as such the environmental conditions at the time of the accidents were inadequate. In order to fill this information gap, accident time and date information was used to identify the significant wave height and average periods experienced during each recorded accident. For this purpose, a number of wave databases found online were utilised and the significant wave height at the exact time of the accident was obtained. The online data comprises wave height measurements for all days at increments of three hours taken over a 10-year period for each of the locations the accidents occurred. Knowing the date, time and location of each accident, the significant wave height could be found in each case. In cases where the time of the accident did not coincide with the time of a wave height reading, the value was estimated as the average between the two closest time points. The statistical analysis for each incident led to the derivation of the significant wave height and zero crossing period for each of the cases, respectively. As shown in Table 11, the resulted database comprises a total of 129 accidents with 51 groundings and 78 collisions covering the period from 2005 to 2013. Among them, the database included 21 collisions and 18 groundings for cruise ships in particular. The basic data for accidents listed, are provided in Appendix C.

As is apparent from Figure 65 the Accidents at Sea Database CDF curve overlays all the seasonal curves for each of the four main trade regions demonstrating that the use of wave data at the time of the accident assigns higher probability to the lower range of wave heights. This is primarily due to the fact that the majority of incidents occur generally in sheltered areas with low wave height, whereas the seasonal wave data is recorded at open sea where larger wave heights are to be expected. As a result, it can be expected that the survivability level estimated using only wave data will be less than that calculated utilising accident wave data as greater weighting will be given to higher wave heights.

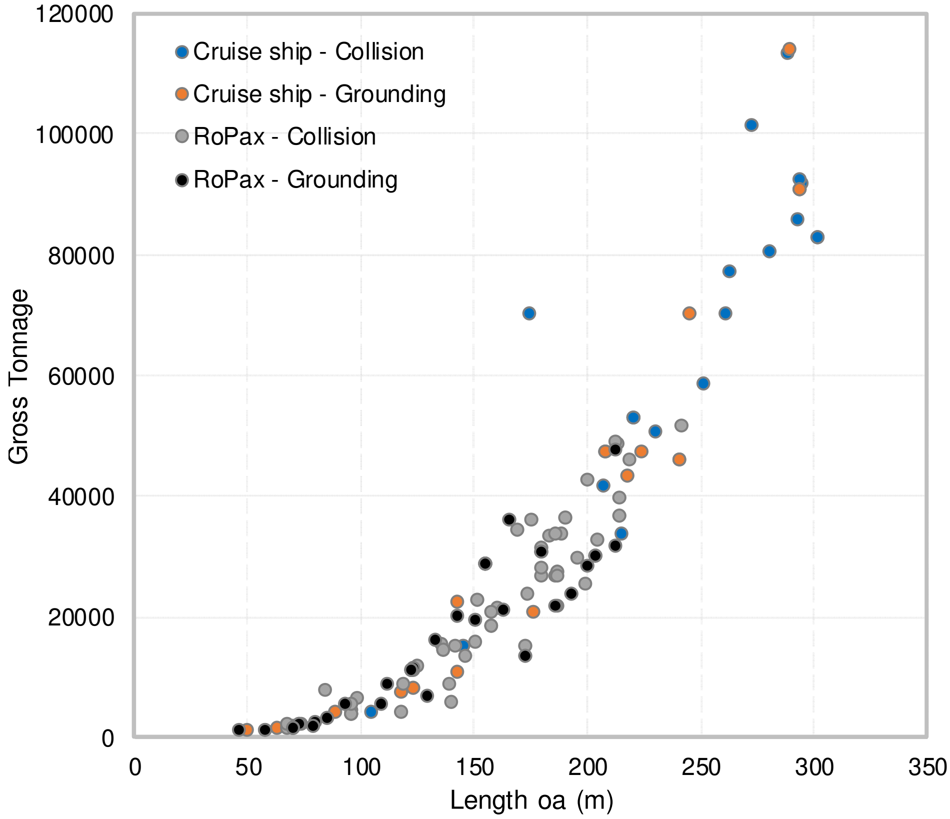


Figure 76: Representation of the passenger ships (IACS ships built≥1982) involved in collisions and grounding accidents between years 2005 and 2013 as incorporated in the Accident at Sea Database

Table 11: Accidents at Sea Database breakdown

	All Passenger ships	Cruise ships
	Total	Total
Collision	78	21
Grounding	51	18
Total	129	39

Indicatively, the statistical average significant wave height identified using the database for both collision and grounding accidents was 1.49m with the maximum and minimum significant wave height identified as 5.43 (1% probability to encounter higher than 4.5m) m and 0.01 m, respectively. Finally, the Zero Crossing periods at the time of the accident were used to provide some indication of the wave nature providing an average value of 5.25 seconds. Figure 77 provides the CDFs and histograms for both collisions and grounding damages with differentiation between cruise ships and RoPax. Having collated all results a minor variation was observed in the wave heights encountered between the two different damages and therefore it was deemed appropriate to consider the two types in a unified way in the regression.

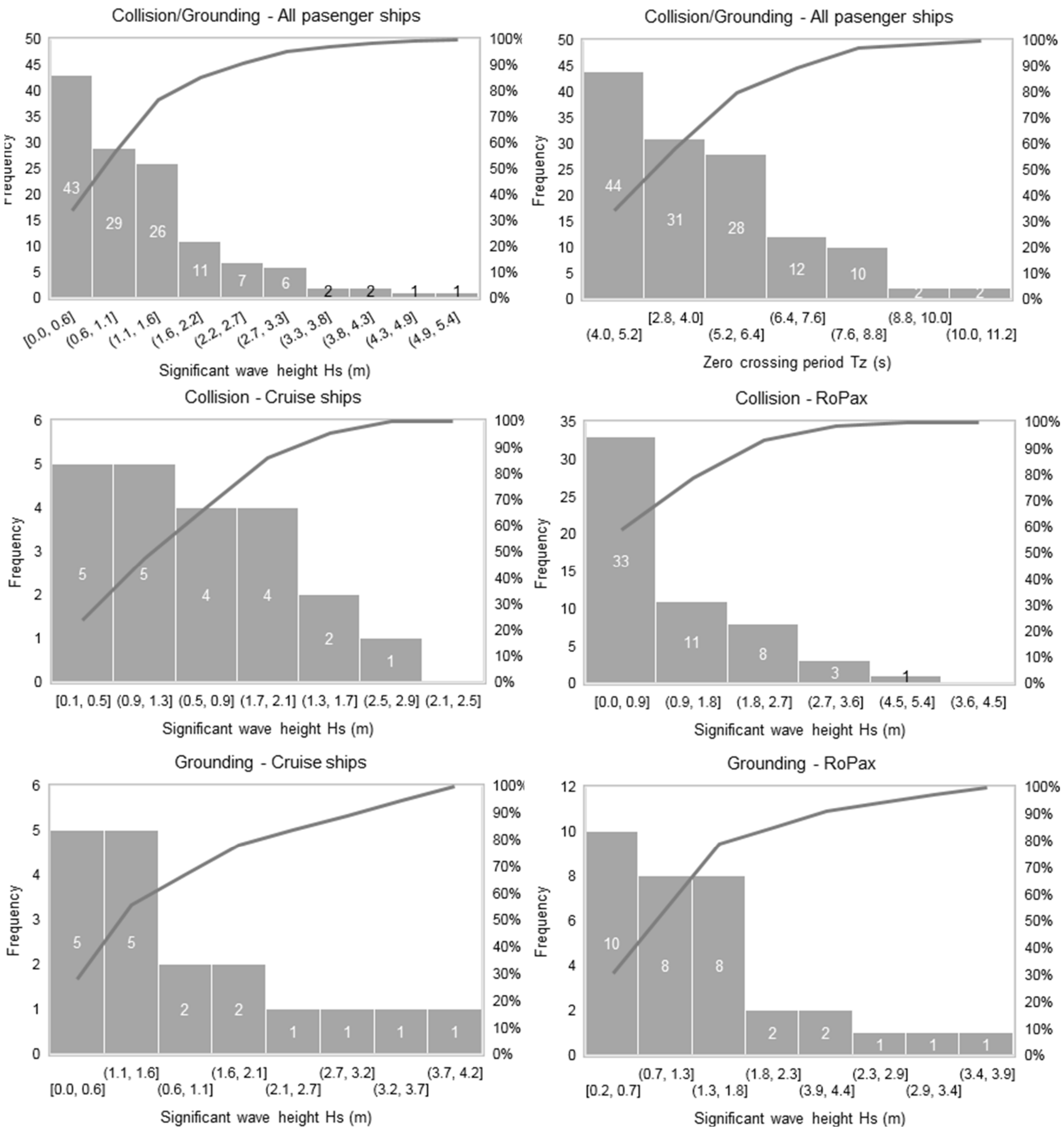


Figure 77: Histograms and cumulative distributions (CDF) for passenger ships included in the ASD with differentiation between RoPax, Cruise ships for collision and grounding damages respectively.

Employing the same approach, as highlighted in the previous section, a curve has been fitted to the data of a functional form, as outlined in eq.(6-5), producing the formula shown in eq. (6-14) and the CDF as presented in Figure 78 below. The curve obtained in project HARDER has also been plotted in Figure 78 showing that the new CDF based on passenger ship data provides slightly lower probabilities of encountering waves smaller than 3.8 meters.

$$CDF(H_s) = e^{-e^{(0.6887-1.1958\times H_s)}} \quad (6\text{-}14)$$

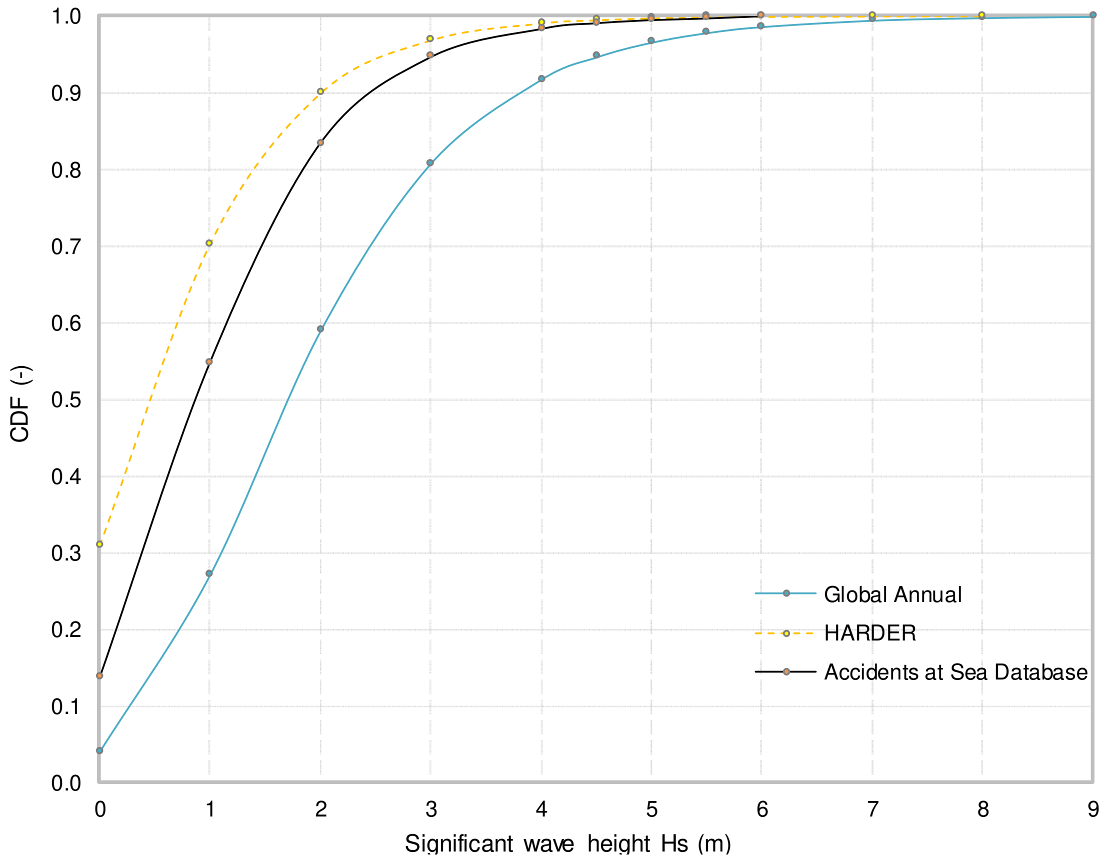


Figure 78: Fit of accident based distribution of wave heights and comparison to the HARDER and Global annual wave height distributions.

Based on the wave heights CDF, the survivability according to the updated accident database can be expressed as depicted in the equation below.

$$s_i = \Pr\{H_s \leq H_{s,crit,i}\} = e^{-e^{(0.6887-1.1958\cdot H_s)}} \quad (6\text{-}15)$$

As previously, a formula for predicting the critical significant wave height can be derived through regression, this time limited to Hs=4.5m, that being the significant wave height which constitutes the 99th percentile within the distribution of the new wave statistics. The resultant expression for $H_{s,crit,i}$ is as follows:

$$H_{scrit} = 4.5 \cdot \left(\frac{\min(GZmax, TGZmax)}{0.16m} \cdot \frac{\min(Range, TRange)}{20deg} \right) \quad (6\text{-}16)$$

With the following regression accuracy shown in the table below.

Table 12: Goodness of fit for ASD data

Sum of squares	7.092
Mean error	0.1289 m
Highest overestimate	0.85 m
Lowest underestimate	1.03 m

A combined formulation for predicting the survival probability can then be found through regression conducted according to the previously outlined methodology, producing the following s-factor formula:

$$s = \left(\frac{\min(GZmax, TGZmax)}{0.16m} \cdot \frac{\min(Range, TRange)}{20deg} \right)^{0.4} \quad (6\text{-}17)$$

In comparison to the HARDER targeting values that of GZ_{max} of 0.12 meters and Range of 16 degrees respectively, here an increase is observed justified by the larger wave height during the regression process. Based on previous studies (Jasionowski, 2009b) it was demonstrated that raising the range to 20 degrees can increase substantially the accuracy of the survivability factor. Given the consideration of the formulation of higher wave heights and the fact that only passenger ships are considered, the conceptual gap reduces significantly.

6.6. Cruise ship trade region-specific critical wave height formulation

Having identified the relationship between the survival wave heights and residual stability properties of the GZ curve of cruise ships in chapter 5, the same approach applied earlier is applied with the view to deriving cruise ship region-specific critical wave formulations. Figure 79 below indicates the correlation of the achieved targeting values derived using RoRo/passenger data (HARDER) and cruise ship data (Chapter 5). As it is obvious, the cruise related targeting values are more conservative, while the correlation with cruise ship targeting Range exhibits higher correlation to the HARDER targeting Range. Table 13 shows the results of the regression analysis for all the trade regions.

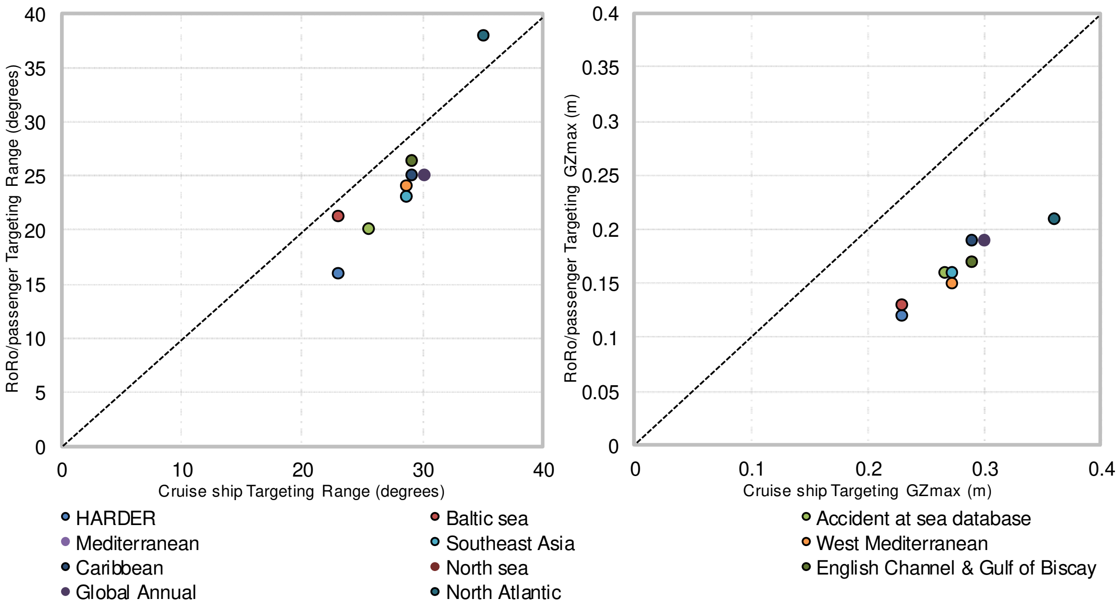


Figure 79: Correlation of Targeting values (Range and GZ_{max}) utilizing different data sets for derivation of critical significant wave height formulations.

Table 13: Cruise ship region-specific targeting values, formulation parameters and fit goodness

	Max Wave height (m)	Lower Underestimate	Highest Overestimate	Mean	Sum of squares	TRange (degrees)	TGZmax (m)	Exponent eq. (6-9)
Baltic sea	4	-0.745	-0.161	-0.16	10.2	22.9	0.23	0.86
East Mediterranean	4	-0.745	-0.161	-0.16	10.2	22.9	0.23	0.86
ASD	4.5	-0.835	0.4952	-0.1309	14.32	25.4	0.267	0.846
Mediterranean	5	-0.92	0.64	-0.15	18.85	28.6	0.272	0.9
Southeast Asia	5	-0.92	0.64	-0.15	18.85	28.6	0.272	0.9

West Mediterranea n	5	-0.92	0.64	-0.15	18.85	28.6	0.272	0.9
Caribbean	6	-1.13	1.32	-0.16	41.7	29	0.29	1.077
North sea	6	-1.13	1.32	-0.16	41.7	29	0.29	1.077
English Channel & G of Biscay	6	-1.13	1.32	-0.16	41.7	29	0.29	1.077
Global annual	7	-1	2.32	0.018	58.32	30	0.3	1.05
North Atlantic	9	-1.65	1.1	-0.55	153	35	0.36	1.31

6.7.Impact assessment on the Attained subdivision Index

Figure 80 demonstrates the applicability of the localised wave formulations on the Attained Subdivision Index for four vessels. This provides the conditional probability of the ship surviving collision damage and as such is a measure of the ship safety level in this respect. Initially, three sample cruise vessels are used (ship A, B and C as provided in chapter 5) and one containership. A comparison is conducted between the derived formulation stemming from RoRo (HARDER) and Cruise ship data (Chapter 5) respectively, while the containership is assessed in order to investigate the robustness of the concept on other than passenger type vessels.

A decrease is marked in the Attained Index of each case when compared to SOLAS 2009. In the case in which North Atlantic wave statistics were used, the Attained Index decreased significantly (maximum decrease of 48%). This highlights the stringency and impact of very high waves on vessels. Similarly, the use of Caribbean wave statistics yielded a reduction of 9%, whilst, the Accidents at Sea Database statistics almost a 12% on average decline. The Attained index obtained for the Accidents at Sea Database is 6% higher than the global annual statistics, which implies that the significant wave heights experienced during accidents are in fact less severe than the global statistical average.

In summary, the results show that the wave statistics utilised in the determination of the survival probability hold a large influence over the magnitude of the final Attained indices. More significantly, A-Indices linked to specific operational areas could be derived to reflect survivability of the vessel linked to the operating environment.

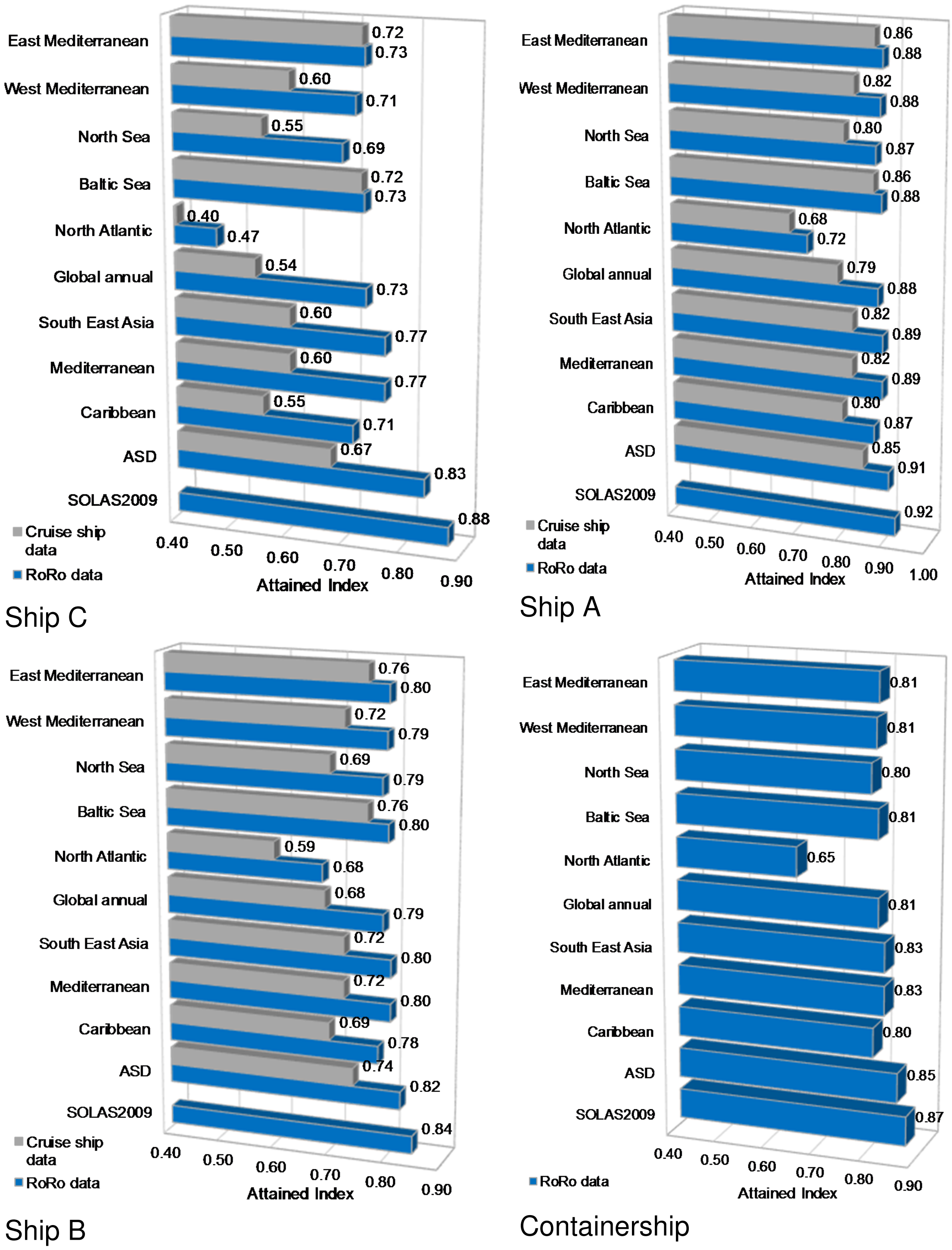


Figure 80: Impact of the localized survivability factors on the Attained subdivision Index for three large cruise ships and one containership. The graphs provide comparison between the critical wave height formulations obtained regressing the RoRo data and the cruise ship data.

6.8.Expected critical sea-state

In addition to the normalised s-factor, which is explained in previous sections, an alternative way of predicting the critical significant wave height to be encountered is sought. Even though the probabilistic framework as outlined in SOLAS (IMO, 2009c) does not explicitly refer to the critical wave height, it has been demonstrated that the assessment of the critical significant wave height Hs_{crit} is an important step in deriving s-factor formulations. In fact, results of damage stability calculations can be used to calculate the critical Hs for all damage cases contributing to A-Index. Therefore, in line with the way the Attained Index represents the weighted average of s-factors, one can calculate the average (i.e. expected) Hs_{crit} as described in (Cichowicz et al., 2018a, Cichowicz et al., 2018b). Figure 81 below demonstrates the application of the concept on 5 medium size RoRo ships.

$$\overline{Hs_{crit}} = E[Hs_{crit}] = \sum_{i,j} w_j p_i Hs_{crit} \qquad (6\text{-}18)$$

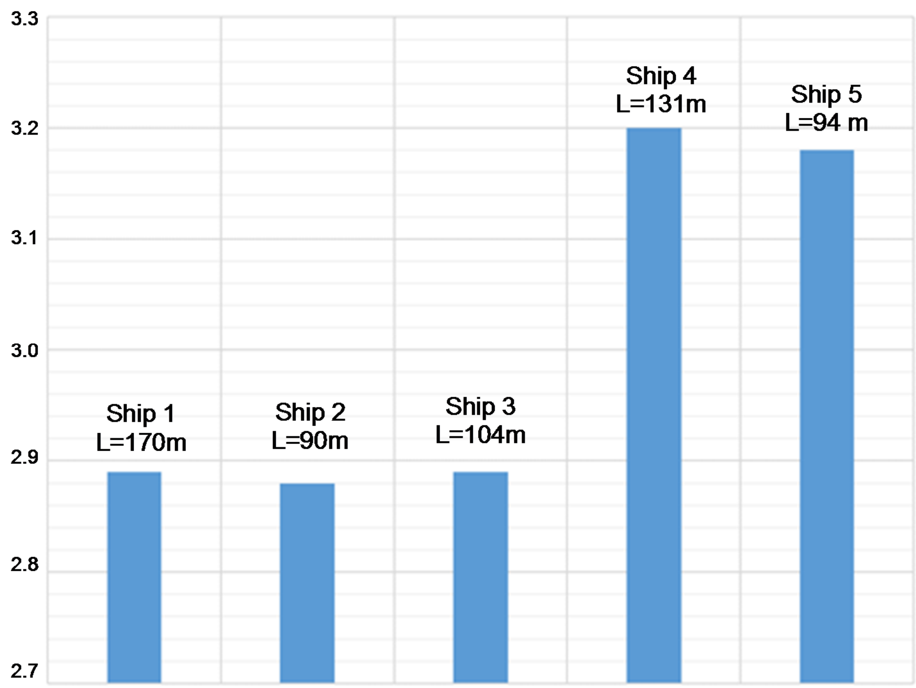


Figure 81: Expected Hs_{crit} application for five selected ships

The $\overline{Hs_{crit}}$ can be used to calculate the probability of not exceeding a specific limiting wave height for the particular area of operation, i.e. $P(Hs_{max} \leq \overline{Hs_{crit}})$. This probability could be potentially used to assess safety level for the operation with limiting wave heights by, for instance, comparing it to the Required Index of subdivision.

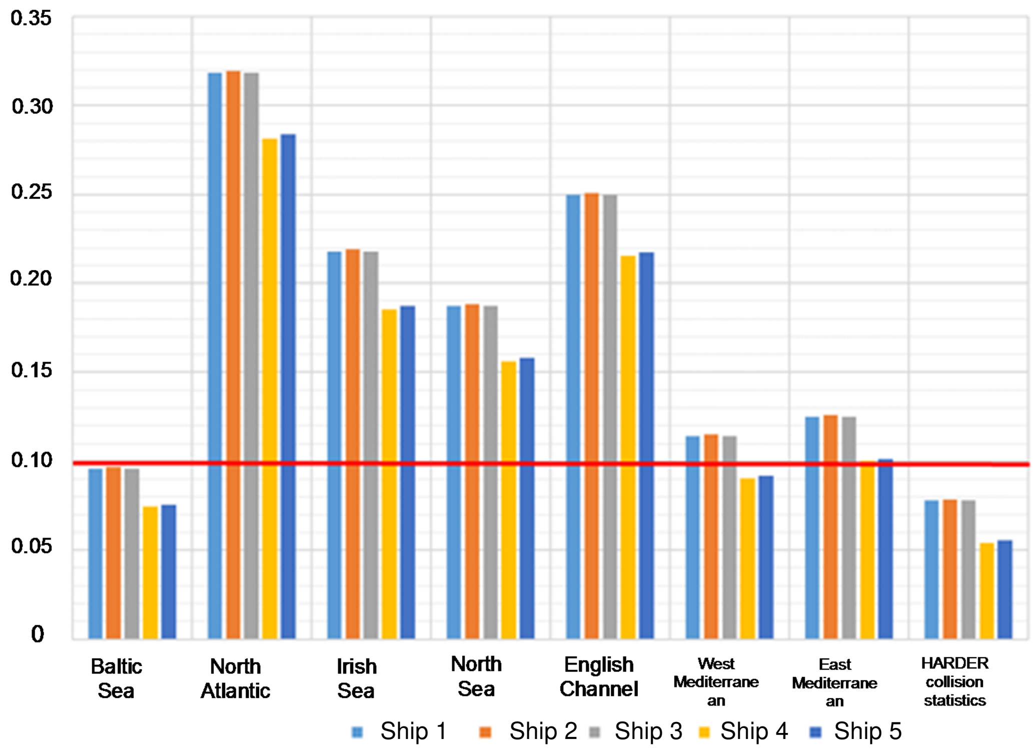


Figure 82 : Probability that the sea state in specific areas of operation will exceed the expected Hs_{crit}

The graph presented in Figure 82 above, provides an attempt to demonstrate the concept of the average critical sea state. The red horizontal line is to represent the 10% probability of exceeding the limiting operational wave height (in the same manner Stockholm Agreement imposes wave height limitations (Vassalos & Papanikolaou, 2002b)). The adoption of the average critical wave height will result in a probability exceeding the critical wave height smaller than 10 per cent. For example, Baltic Sea for ships 1, 2, 3 and 5, West Mediterranean for ships 4 and 5 and finally, east Mediterranean for ship 4.

6.9.Closing remarks

Based on the findings of chapter 6, it can be drawn that it is possible to derive trade region specific s-factor formulations using localised wave statistics and, in turn, assess their impact on survivability and subsequently the safety level of passenger ships as demonstrated in the foregoing. Also, the current SOLAS s-factor, by failing to account for area of operation, appears to overestimate survivability through lack of consideration of the probability of wave heights being less than the critical wave height (this being 4 metres). As it has been shown, weather data records can be used in order to fill information gaps for incidents in which the sea state at the exact time of accident was previously unknown. In addition, as it has been demonstrated, passenger ship-specific accident data can be employed with the view to derive ship type-specific s-factor formulation that better accounts for this ship type and also caters for passenger ship trade routes, in particular. Using an updated ship specific accident database, the distribution of wave heights used in the formation of the SOLAS s-factor has been shown not to provide coverage of all wave heights experienced. As a result of the above, SOLAS overestimates the survivability in comparison to the updated database and a more accurate estimation of ship survivability can be made through utilising localised wave statistics. The derived concept has been demonstrated to be robust by implementing it to four vessels.

Chapter 7

Consideration of Actual Operational Profiles in Damage Survivability Assessment

7.1.Opening remarks

The probabilistic damage stability concept currently in place, as outlined within SOLAS 2009 for passenger ships, calculates the Attained Subdivision Index based on three loading conditions, which combine to form a theoretical draft range for a given vessel. To each of these loading conditions a weighting factor is then applied to account for the probability that a vessel will be operating at or near any of these drafts at the time of collision, should one occur. At present, the weighting factors are applied regardless of the ship size with the same weightings to be applied in the case of cargo vessels and passenger vessels despite the fact that these ship types are known to have very different tendencies when it comes to the nature of their operation. In this sense, someone could question the suitability of these weightings with regards to what degree, in reality, they reflect the operational profile of the vessels covered by the standard. With this in mind, the following chapter aims to investigate the suitability and accuracy of the currently assumed draft weighting factors with regards to cruise vessels. This study is conducted using operational loading condition data sourced from 18 ships and spanning up to a period of two years in some cases. On the basis of this data, draft probability distributions are derived and new weighting factors are formed specifically pertaining to cruise ships and the nature of their operation. Also, an assessment is conducted looking into the impact of the newly derived weighting factors on the magnitude of the Attained Subdivision Index and recommendations are made on how best to implement them in a design and operational stage.

7.2. Introduction to the problem and background

The current IMO instrument for assessing the damage stability performance of passenger vessels and dry cargo ships is applied widely in the industry, as stipulated by SOLAS Chapter II-1, Res. MSC.216(82) (IMO, 2006). This led to the end of the age of the, ameliorated now, deterministic requirements for the subdivision of passenger vessels on the basis of what was widely perceived as anachronistic means of assessing damage stability. This included characteristics such as the floodable length and margin line criteria that existed in the regulations for over half a century and finally started to show their pitfalls and limitations in their implementation. Alternately, the probabilistic damage stability assessment framework was gradually favoured, a new approach. In fact, this had already began before with the methodology and rules providing mandatory requirements for dry cargo ships as highlighted in Chapter II-1, part B-1 from 1992 along with the seldom used though highly innovative alternative regulations for passenger ships, Res. A.265 (VIII) from 1973 (IMO, 2010). On the other hand, SOLAS 2009 had the effect of harmonising damage stability assessment under one common and rational methodology (Tagg and Tuzcu, 2002). However, a fully probabilistic approach has never been sought and there remains a requirement to supplement the criteria with a number of prescriptive rules.

One of these, concerns the assumptions made regarding the assumed draft range and respective weighting factors as defined within SOLAS 2009 (IMO, 2009c). The underlying concept behind the probabilistic approach to damage stability is simple, and one that is based upon the probability of a vessel surviving collision damage in waves. This probability is then used as an objective measure of ship safety in the damaged condition and is represented within the rules by the Attained Subdivision Index, A. This index is formed on the basis of three partial indices calculated with respect to three drafts assumed to be representative of the operational draft range of the vessel. To each of these indices, a weighting factor is then applied which does not vary with regards to ship type and which is intended to account for the likelihood that the vessel will be operating near or at any of these drafts at the time of collision. In this respect, the weighting factors can be viewed as a representation of the vessel operational profile and it is this deduction in combination with a number of other observations that present cause for concern.

To begin with, the means by which the current weighting factors were determined remains somewhat obscure as there is little that can be found in literature on their derivation. As a result, the current weighting factors appear, at least on the surface, to be completely unsubstantiated. This, in turn, calls into question the accuracy of these weighting factors with respect to how representative they are of the operational profiles of the vessels covered by the standard. Even if the above is disregarded, the harmonised approach currently in place would appear to be a gross over simplification. The current regulation assumes in essence that RoPax, dry cargo and cruise vessels are operated according to the same operational profile despite the fact that these ship types are known to have very different tendencies when it comes to the nature of their operation. In order to substantiate such an assertion, one must first be able to show that there is adequate correlation between the loading behaviours of each of these ship types, which intuitively speaking is unlikely to be the case. In this respect, even if it was found that these values are accurate for any one of the vessel types covered by the standard, confirmation of that fact would subsequently indicate that they were inaccurate for the others.

In fact, a number of studies have been conducted in which certain aspects of the current SOLAS 2009 regulation have been challenged with a view to improving the prescribed assumptions. This includes such studies as the joint research project eSAFE where proposals were made regarding more accurate calculation of cruise ship survivability (Luhmann et al., 2018a, Luhmann et al., 2018b) from which the findings are provided in this chapter. In addition the assumed sea state distribution behind the SOLAS s-factor has also been challenged with a view to better accounting for the impact of operational environment on ship survivability, which has been presented earlier. Building on this, it is important that where circumstances permit us to reduce uncertainty or to replace any of these simplifying assumptions with more accurate information, not only should we do so, but such efforts should be actively encouraged. The SOLAS probabilistic framework does not support best-practice design, meaning that potential solutions for enhancing cruise ship survivability will not be adequately rated and subsequently dismissed (Vassalos et al., 2005, Vassalos, 2014).

Due to the unrelenting increase in demand and reflecting the changing travel patterns of consumers, the world’s most competitive cruise line groups are planning to expand the segment by increasing number of newbuild ships aiming towards higher passenger ship capacity. In this respect, safety levels should be commensurate with the exponential increase in number of passengers on board. This fuels the incentive towards the adoption and development of accurate means of stability calculation. Availability of operational data and stability information thrives through the use of on board stability programs and thus utilisation of such data should be encouraged in the future.

It is with this in mind that the following sections investigate to what degree the currently assumed draft weightings reflect the true operational profile of cruise vessels, which is a particular class of vessel for which the suitability of SOLAS 2009 has already previously come under question (Vassalos, 2015b). This is achieved through analysis of operational loading condition data sourced from a total of 18 cruise vessels and over a time frame spanning in some cases up to two years. Drawing on this analysis, a further study is conducted in which weighting factors more representative of the manner in which cruise vessels are operated are derived and their impact on the magnitude of the Attained Index is measured. This is conducted with a view to satisfying two objectives. Firstly, an attempt is made in order to provide a more appropriate means of assessing cruise vessel survivability within the design stage and with the understanding that uncertainty at this stage calls for certain assumptions to be made. Secondly, proposals are made in order to provide a simplified assessment for vessels that are already in operation and where sufficient data is available in which to constrain the assessment allowing for a more straightforward approach to be taken.

The solutions sought in the chapter address operational and designed vessels. This, in turn, can cater for design and operational issues, but first an important differentiation shall be made between the two. A design issue arises when there is uneven weight distribution that causes large angles of heel or there is uneven trim caused by the subdivision design (including large undistributed spaces at upper decks) and tank arrangements, which can be reflected entirely throughout the considered design loading conditions. On the other hand, operational issues can be related to insufficient crew training and wrong crew actions, erroneous loading, inadequate ballasting and false manoeuvring during operation which are again represented through operational loading conditions and can impose significant impact on survivability. One example in this directions relates to the capsize event of MV Sewol, which it was caused by excessive loading of the vessel and a faulty manoeuvre action considered by the crew at the time of operation.

The survivability of a vessel following collision damage that has led to hull breach and subsequent flooding is dependent on a number of factors, none more so than the loading condition of the vessel. The manner in which a vessel is loaded effects greatly its ability to withstand the effects of flooding, with draft and trim influencing important parameters such as freeboard and reserve buoyancy, and the centre of gravity affecting the vessel restoration properties. As touched upon within the introduction of the chapter, SOLAS 2009 assumes a draft range based on three values defining the lower and upper limits of an assumed draft range along with consideration of an intermediate condition, each of which are defined as follows:

- Light service draft - dl: Service draft corresponding to the lightest anticipated loading and associated tankage, including ballast as required for adequate stability and immersion. In the case of passenger ships, dl also includes a full complement of passengers and crew on board.
- Deepest subdivision draft – ds: corresponds to the Summer Load Line draft of the ship.
- Partial subdivision draft – dp: this is estimated by the service draft with the addition of 60% of the difference between the light service draft and the deepest subdivision draft.

$$dp = dl + 0.6 \cdot (ds - dl) \tag{7-1}$$

A partial Attained Index is then calculated at each of these draft values and the Attained Index is found as the weighted sum of these indices according to the formula below:

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \cdot p_i \cdot s_i \tag{7-2}$$

Where,

j The loading condition under consideration.

J The total number of loading conditions considered in the calculation of A, usually three drafts covering the operational draft range of the vessel.

w_j A weighting factor applied to each initial draft.

i Represents each compartment or group of compartments under consideration for loading condition j.

I The total number of all feasible damage scenarios involving flooding of individual compartments or groups of adjacent compartments.

p_i The probability that, for loading condition j, only the compartment or group of compartments under consideration are flooded, disregarding any horizontal subdivision.

s_i Accounts for the conditional probability of survival following flooding of the compartment or group of compartments under consideration for loading condition j weighted by the probability that the space above a horizontal subdivision may not be flooded.

Digging deeper in the underlying functions, probability A can be interpreted as the probability of surviving a flooding event stemming from any breach that leads to flooding in any zone i. Equation (7-3) shows probability A where v_k is a reduction factor or else depicts the probability of flooding being extended up to horizontal subdivision k for varying draft T and flooding extending up to horizontal subdivision h_k (Jasionowski, 2009b) .

$$A = \sum_i p_i \cdot \left(\sum_{j=1}^{3} \sum_{k=1}^{n_{Hk}} w_j \cdot (v_k - v_{k-1}) \cdot s_{i,j,k} \right) \tag{7-3}$$

Eq.(7-3) from above can be rearranged in the form of eq.(7-4) below.

$$A = \sum_i p_i \cdot \left(\sum_{j=1}^{3} w_j \cdot s_{i,j} \right) \tag{7-4}$$

However, probability p_i is independent from drafts and therefore it can be altered into eq.(7-5).

$$A = \sum_{j=1}^{3} w_j \cdot \sum_i p_i \cdot s_{i,j} \tag{7-5}$$

The notion of the conditional probability $A|T$ is adopted by assigning probability A to every draft available for each vessel having the following equation.

$$A|T_j = \sum_i p_i \cdot s_{i,j} \tag{7-6}$$

Integrating eq.(7-5) into eq.(7-6) we have the following equation for probability A.

$$A = \sum_{j=1}^{3} w_j \cdot A|T_j \tag{7-7}$$

Finally, allocating the three damage stability loading conditions into eq.(7-7) we have the well-used prevalent formula provided below in eq.(7-12). The weighting factors represent the time t spent in each loading condition T as provided in the following equations.

$$w_{dl} = P(t|T_{dl}) = 0.2 \tag{7-8}$$

$$w_{dp} = P(t|T_{dp}) = 0.4 \tag{7-9}$$

$$w_{ds} = P(t|T_{ds}) = 0.4 \tag{7-10}$$

$$\sum_{j=1}^{3} w_j = w_{dl} + w_{dp} + w_{ds} = 1 \tag{7-11}$$

$$A = 0.2 \cdot A_{dl} + 0.4 \cdot A_{dp} + 0.4 \cdot A_{ds} \tag{7-12}$$

The mandated level of safety is dictated by the Required Subdivision Index, R, which is determined predominantly by the passenger and lifeboat capacity of the vessel and to a lesser extent by the subdivision length. So as long as a vessel possesses an Attained Index greater than or equal to the Required Index it is deemed safe from a regulatory perspective.

The partial Attained Index values are also used in order to form the vessel's limiting GM envelope, Figure 83. GM limits are determined as those required such to satisfy the following conditions at each calculation draft:

- A_{ds}, A_{dp} and A_{dl} ≥0.9R in the case of passenger vessels
- A_{ds}, A_{dp} and A_{dl}≥0.5R in the case of dry cargo ships

These conditions have been set in order to ensure a certain level of safety is maintained across the entire draft range. However, the question remains as to why this was not set as A≥R. Currently, the Attained Index for a given loading condition can fall short of the requirements by 10% in the case of passenger vessels and more shockingly by 50% in the case of dry cargo vessels, so long as the deficit in Attained Index is made up for by another loading condition. If we consider this with regards to the GM limit curve, it enables the limits to be manipulated in such a manner as to apply a more stringent limit on a draft at which the vessel will rarely operate or that is limited by intact stability requirements such as the lower draft often is, and then allows a relaxation on the GM limitation around the design draft where the vessel is likely to be more vulnerable to damage and where GM margins are tighter.

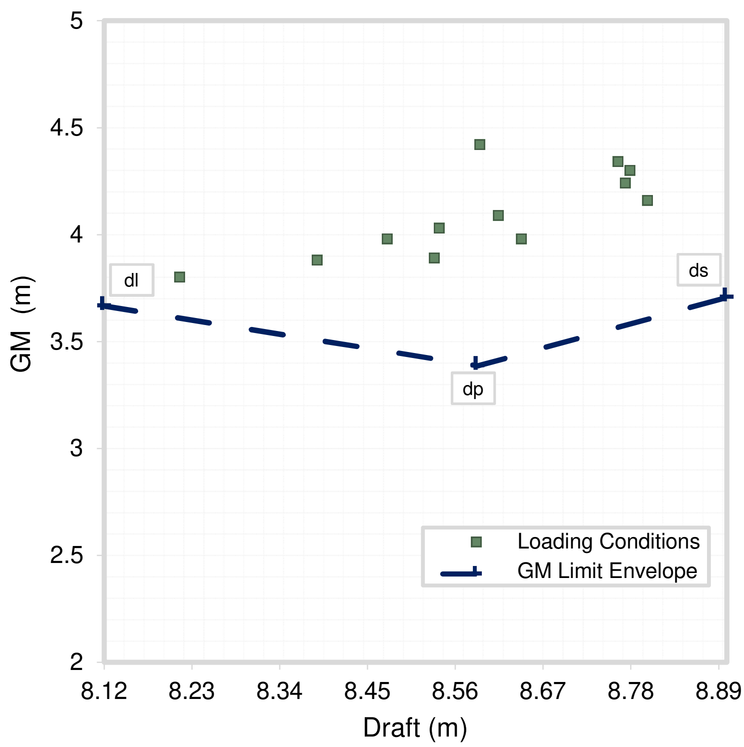


Figure 83: Limiting GM curve, three loading conditions (typical example for cruise ship).

7.3. Weighting factor derivation methodology

In the development of new draft weighting factors that are more reflective of the manner in which cruise vessels are operated, loading condition data from a total of 18 cruise vessels has been sourced. This data contains in some cases up to two years of operational loading information from a range of cruise vessels that provide ample coverage of the fleet demographic both with regards to size and age. The data have been derived through employing the on-board loading computer software and colleting noon reports in some cases. Then, the data were shaped in the required form comprising the operational drafts, GMs, tank loadings and trims following the development of specific scripts. Figure 84 presents the sample ships relatively to the fleet. The number of sample used in the analysis is representative of the fleet currently in operation in terms of year build, as they cater for different regulation standards, number of people on board and size, while they are restricted based on the availability of data from the operators. Further sample ship particulars are not provided for confidentiality reasons. The information obtained has been processed accordingly in order to yield draft probability distributions, both ship-specific and in a generalised format with consideration of all vessel data. The distribution of all the drafts if shown in Figure 85.

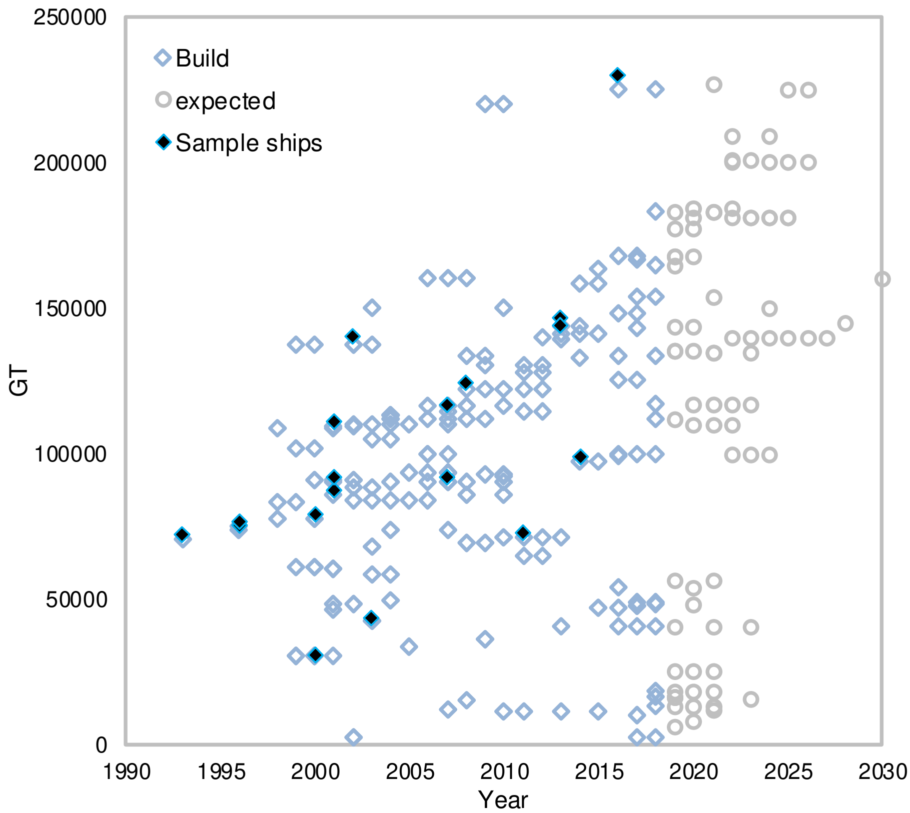


Figure 84: Sample ships relative to world fleet (size and age)

Due to the large variance in size between the vessels contained within the test group, it was imperative to process the data in a uniform way though normalising the draft distributions. Two sets of results are obtained; in the first, the data are normalised with respect to the actual operational draft range of the vessels, whilst in the second, with regards to the SOLAS 2009 assumed draft range. Generally, normalisation scales all numeric variables in the range (0, 1). The lightest draft (dl) will reflect the zero value whilst unity the highest draft (ds) of the non-dimensional data set, respectively. A linear scaling to unit range approach was performed from the family of linear transformation techniques for data normalisations applicable to unbiased data sets pertaining to small noise tendencies (Jayalakshmi and Santhakumaran, 2011). The generalised formula for the max-min normalisation is indicated below.

$$\widehat{x_i} = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \tag{7-13}$$

Where, x_i is taken as the mean value $(\overline{x_i})$ between the respective aft and fore draft of each vessel. This was essential as the sample data varied largely with regards to operational trim.

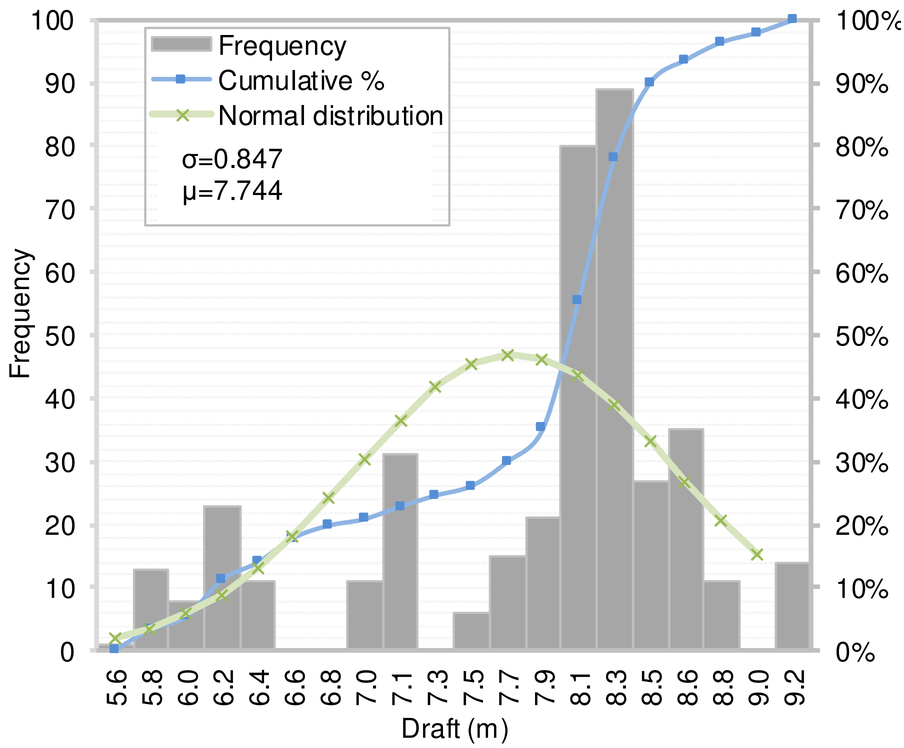


Figure 85: Statistical presentation of mean drafts under consideration covering all sample ships.

Translating eq.(7-13) with respect to drafts yields the following:

$$T_{ND} = \frac{\overline{T_i} - \min(\overline{T_\iota})}{\max(\overline{T_\iota}) - \min(\overline{T_\iota})} \tag{7-14}$$

Where, $\max(\overline{T_\iota}), \min(\overline{T_\iota})$ represent the maximum and minimum operational drafts and $\overline{T_i}$ the mean draft and T_{ND} the non-dimensional draft value.

The frequencies of the normalised draft ranges are apportioned within the specific value of the normalisation range spanning from 0 to 1. Consequently, the sum of all frequencies coincides with the total number of drafts for each case. An inverse normalisation is considered to identify the actual values of the drafts that reflect each increment within the range (0, 1). This provides a clear picture of the draft distribution of the vessels by also determining the lightest and deepest subdivision drafts. The drafts are utilised for the derivation of the partial Attained subdivision Indices for the different types of draft probability distributions that are investigated. The following formulation is obtained by the inverse of eq.(7-14):

$$\overline{T_\iota} = T_{ND} \cdot (\max(\overline{T_\iota}) - \min(\overline{T_\iota})) + \min(\overline{T_\iota}) \tag{7-15}$$

7.4. Operational distributions of drafts

7.4.1. Ships in operation

The operational loading condition data from a range of cruise vessels has been utilised in order to generate a number of different draft probability distributions. In the first case, the data from each vessel has been non-dimensionalised with respect to their operational draft range. Through doing so, it is possible to assess the manner in which cruise vessel behave in operation as opposed to the manner in which SOLAS 2009 assumes. The distribution yielded in this case is presented in Figure 86 below. Here we see that cruise vessels have a tendency to operate towards the upper region of their draft range with limited time having been spent towards the lower end. It should also be noted that, in the majority of cases, the vessels operational draft range was found to be much narrower than that assumed within SOLAS 2009. As such, it is important to consider that the distribution shown below corresponds to minimal variance in draft and is over a draft range that is relatively speaking towards the upper portion of the assumed SOLAS 2009 draft range.

In light of the above, it has been found that as a simplified means of assessing/monitoring survivability once a vessel has entered operation, a one draft approach to calculating the Attained Index could be taken. In such a case, the Attained subdivision Index would be calculated using the highest recorded draft value within the vessels loading condition history, weighed with a factor of 1 and using actual trim, fluid GM and respective KG values, as shown in the following:

$$A = w \cdot A(T_{dS}) \quad (7\text{-}16)$$

$$A = 1 \cdot A_{DS} \quad (7\text{-}17)$$

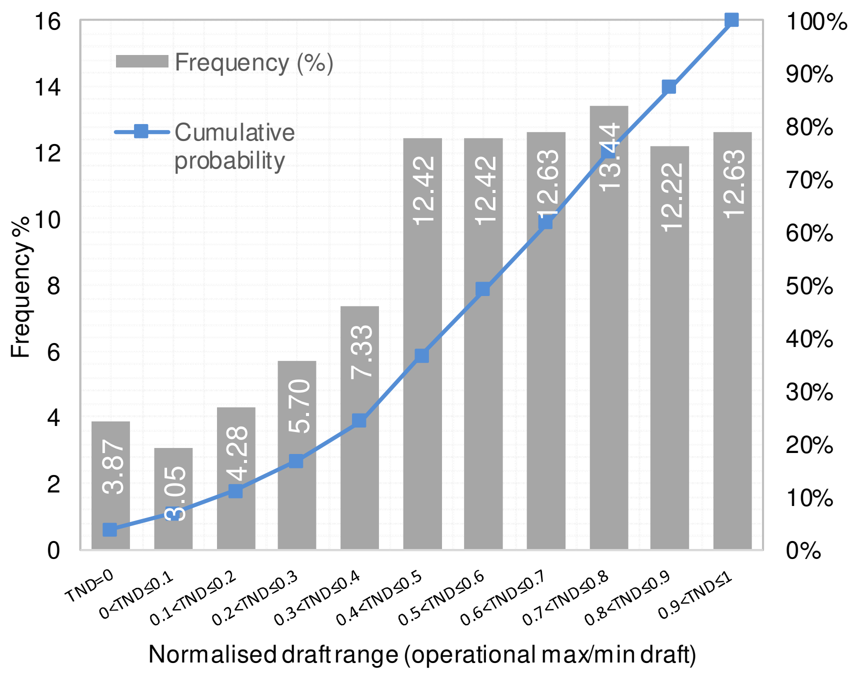


Figure 86: Draft distribution non-dimensionalised by operational draft range and based on all sample vessel data.

Such a simplified approach is made possible due to two reasons; firstly, the availability of information within the operational phase, which would otherwise be an unknown within the design stage, enables the problem to be substantially constrained. During the design stage the actual operational profile of the vessel is unknown, and so, certain conservative estimations of the lower and upper bounds of the draft range have to be made in order to account for this uncertainty. When the vessel enters operation, this is no longer the case and the true lower and upper bounds of the draft range are known. Secondly, as cruise vessels operate within a minimal draft range, the magnitude of the Attained Index calculated has little sensitivity with regards to the number of drafts considered within its calculation. This, in turn, allows for only one draft to be considered whilst producing accurate results. This last point is further substantiated within the next section where sensitivity analysis is performed. By the time at which a vessel has entered operation, design risk is more or less fixed and as such Attained Index calculation of this kind is unlikely to impact design. However, it could foreseeably be used as a simple monitoring tool, in line with such proposals as outlined in (Vassalos et al, 2018) for measuring operational risk and allowing risk information to be used in order to guide decision making and enhance safe operation.

7.4.2. Ships within the Design Stage

Unlike vessels that are in operation, those within the design stage suffer from a lack of operational data which produces a greater amount of uncertainty and calls for assumptions to be made. However, certain steps can be taken in order to ensure that the draft weighting factors are more representative of cruise vessel operation in general. With this in mind, an additional draft distribution has been generated, this time having non-dimensionalised the draft data of each vessel with regards to their respective SOLAS 2009 assumed draft ranges. The resultant distribution, shown in Figure 87, illustrates more predominantly the tendency of cruise vessels to operate towards the upper portion of their draft range. Though there are however incidents, albeit infrequently, where the lower end of the draft range is also utilised.

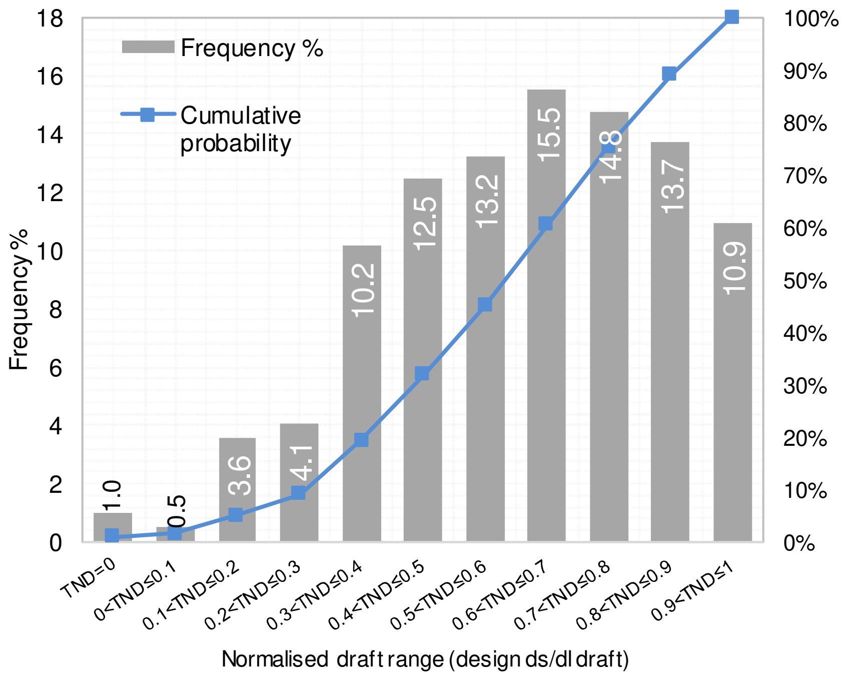


Figure 87: Draft distribution – operational profile for all ships with regards to SOLAS drafts (global statistics)

When deciding upon which draft values and associated weighting factors would be most suitable for the calculation of the Attained Index it was recognised that both the upper and lower ends of the draft range would need to be catered for. This is despite the fact that, in theory, a one draft approach similar to that proposed for vessels in operation would suffice with regards to accurate calculation of the Attained Index. However, in contrast with the operational phase where the primary interest would be safety monitoring within the vessels permissible operational limits, during the design stage not only must the safety level be calculated but also the operational limitations defined. Furthermore, these limitations need to cover all foreseeable eventualities in order to account for uncertainty and as such must consider a wider, more versatile draft range than that found during operation. For this reason it is proposed that during the design stage a two draft approach is utilised corresponding to the non-dimensional drafts 0.15 and 0.65 based upon the SOLAS 2009 assumed draft range. Both drafts 0.15 and 0.65 have been selected due to the nature of the draft distribution which shows approximate uniform probability for non-dimensional draft range 0.1–0.3 and near uniform probability from 0.3-1 with the calculation drafts taken at the centroid of these ranges. The weighting of these drafts is identified by summing the individual frequencies within each draft discretisation within these ranges, resulting in weighting factors of 0.1 and 0.9 respectively as depicted in Figure 88 below.

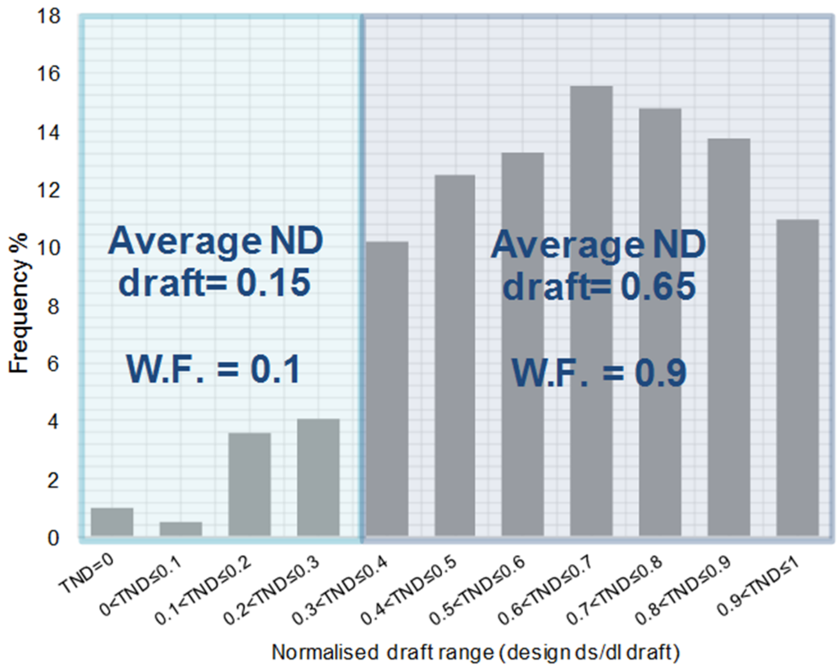


Figure 88: Draft distribution based on SOLAS 2009 draft range and two draft approach.

Thus, the Attained Subdivision Index, eq.(7-6) and eq.(7-12) can be translated to the following,

$$A = \sum_{j=1}^{2} w_j \cdot A(T_j) \tag{7-18}$$

$$A = 0.1 \cdot A_{0.15} + 0.9 \cdot A_{0.65} \tag{7-19}$$

Where, $A_{0.15}$ and $A_{0.65}$ are the partial Attained Indices for the two normalised drafts. The calculation of the two draft values to be considered is achieved through re-dimensionalising the draft values 0.15 and 0.65 as shown:

$$T_{Act} = (T_{ND} \cdot (d_s - d_l) + d_l) \tag{7-20}$$

Where,

T_{ND} Represents the non-dimensional draft values taken from the draft distribution, defined as 0.15 and 0.65, respectively.

d_s Is the deepest subdivision draft as defined in SOLAS 2009

d_l Is the lightest service draft as defined in SOLAS 2009.

It is then proposed to base GM limit curve upon these two draft values with the requirement to satisfy the condition A≥R in order to prevent areas of vulnerability within the draft range. For draft values spanning below non-dimensional draft 0.15 it is recommended that the GM limit continue uniformly. For non-dimensional drafts above 0.65 it is recommended that the GM limit be projected at the same slope formed between the two calculation drafts as shown in Figure 89.

In the case of newbuilding vessels, for the purpose of assessing the impact of trim, it is deemed appropriate to conduct a trim sensitivity analysis. In this respect, the trim is assessed according to ±0.25%Ls and ±0.5%Ls along with level trim. The final Attained subdivision Index should be taken as the lowest Attained index obtained in either case.

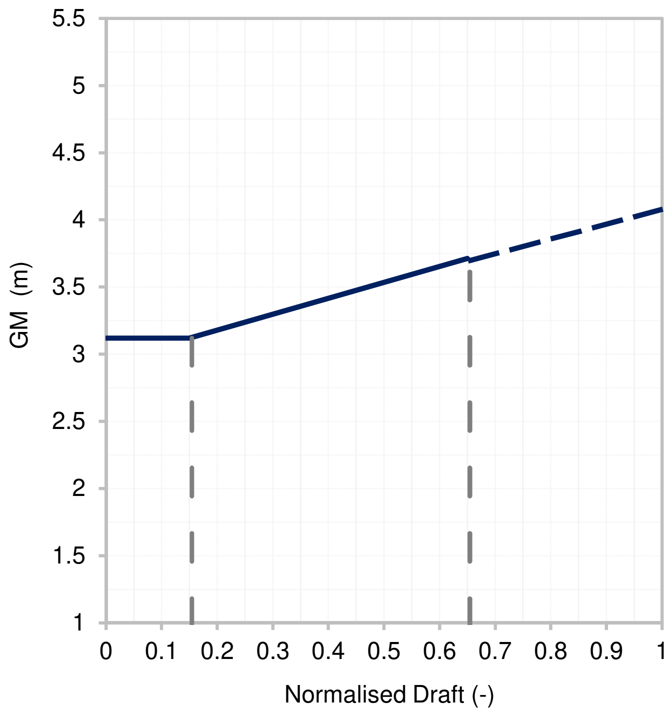


Figure 89: Ship-specific draft distribution

Looking into Figure 90, which depicts the distribution of actual trims from the range of the considered sample cruise ships, it can be noticed that the trim by bow is dominant since vessels operate 65% of their time with a positive trim by bow. In addition, according to SOLAS Req7.2 Ch II-1(IMO, 2009a), damage stability assessment shall be conducted utilising a level trim for the partial and deepest drafts, while an actual service trim for the lightest condition if it spans within ±0.5% of the subdivision length. In the case of the later, beyond the range of ±0.5%, an additional damage stability assessment is required. This entails variations in the GM limiting curve to meet the required index accordingly when developing the limiting envelop. As it is apparent from figure 8**,** the maximum and minimum operational trims are well below the suggested variation from SOLAS, with their values being -0.27%Ls and +0.38%Ls respectively. Yet, the operational maximum and minimum trims are 0.87 and -0.79 respectively based on the actual on-board collected data. The proposed interval of 0.5% of the length exceeds the operational maximum average by almost 60%. This indicates that there is considerable agreement with the aforementioned assumption. However, as it has been highlighted in previous sections, the vessels mainly operate at their subdivision draft Ds which, in turn, suggests that a level trim would not cater for an accurate damage stability assessment. As a result, in the case of operational vessels, it is recommended utilisation of the service trim for the most recurrent loading condition.

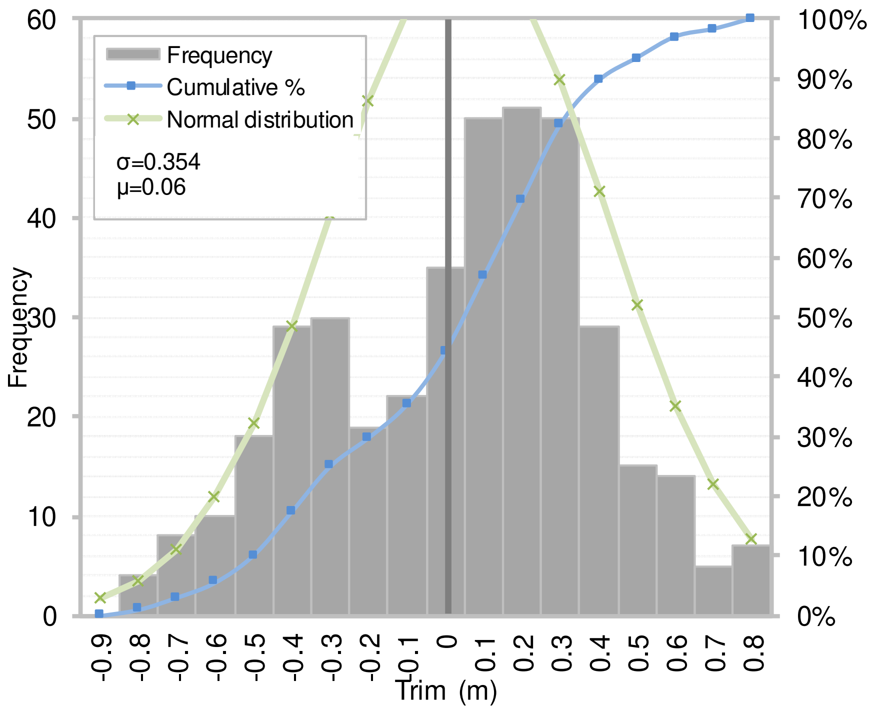


Figure 90: Histogram of trims and cumulative distribution function for all sample vessels

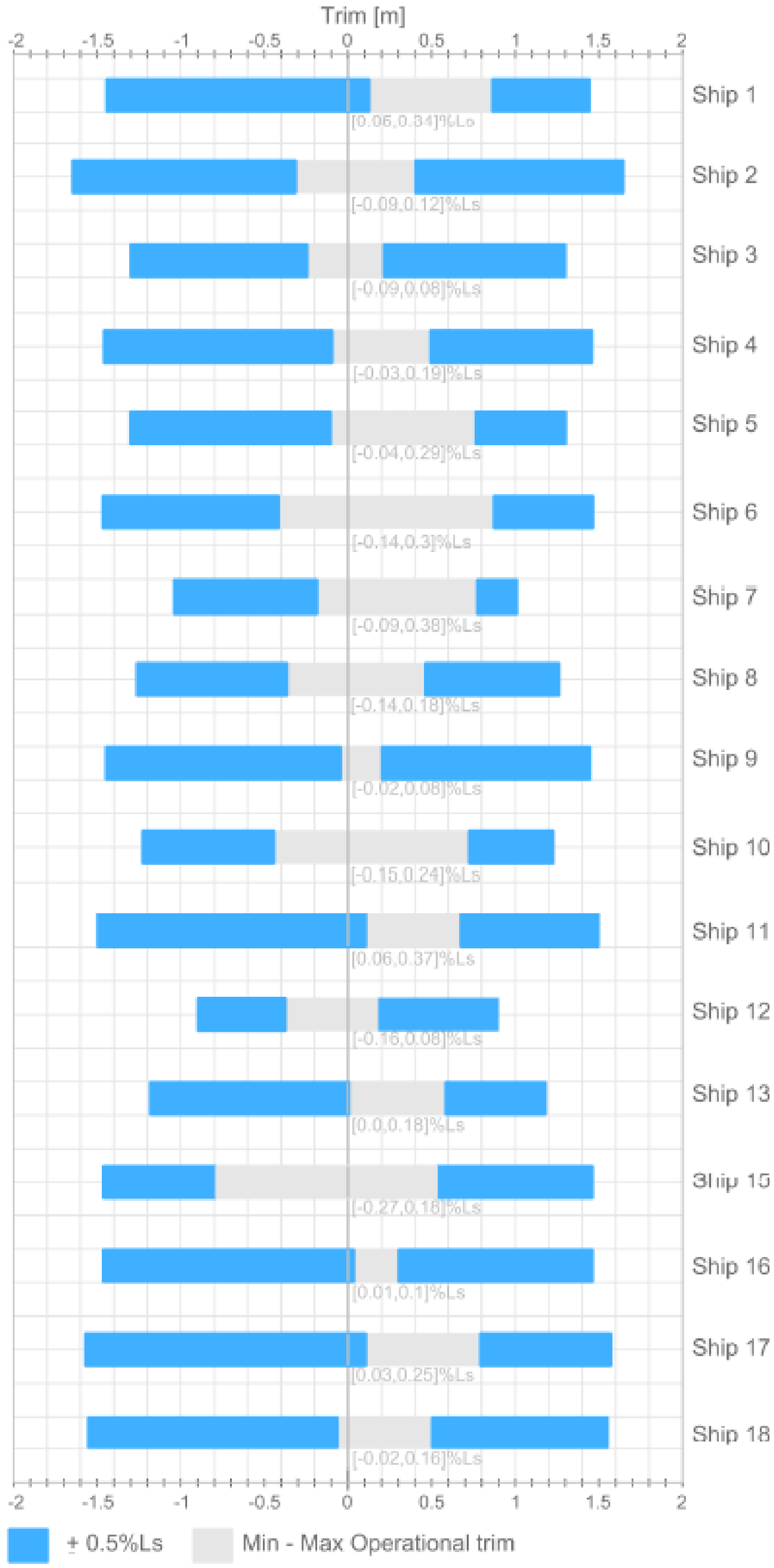


Figure 91: Minimum and Maximum operational trims and ±0.5%Ls trim for all sample ships

7.4.3. Ship-specific operational distributions

The third manner in which the data has been utilised is to generate ship-specific draft and trim distributions. In this case, ship-specific loading condition information was utilised in order to generate draft probability distributions for each vessel, an example of which is shown in Figure 7 along with their trim distributions and associated frequencies. The reason for this was primarily to gauge the correlation between the trends witnessed for each vessel and in order to perform a sensitivity analysis on the Attained subdivision Index with regards to using the ship-specific draft distributions and the more generalised approach previously outlined in earlier sections. In addition to this, the actual operational distributions with regards to trims and drafts can be utilised in the same manner the wave heights are sampled when performing Monte Carlo simulations and eventually, the equivalent method of assessing damage survivability and ultimately the Attained subdivision Index utilising the direct approach. As a result, the designs are assessed in an effective manner based on factual values. Figure 92 indicates the operational cumulative distributions for a large cruise ship, highlighting the normalised range produced when employing the aforementioned inverse normalisation technique. This will constitute an accurate means of considering actual operational profiles especially within the design and operational life-cycle of a vessel taking into consideration their operational tendencies.

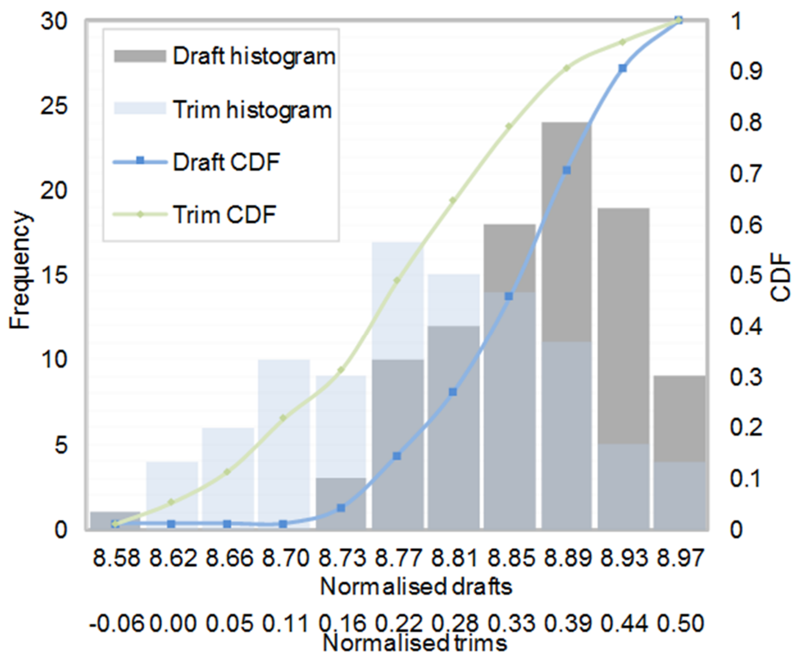


Figure 92: Sample ship-specific draft distributions for drafts and trims for a large cruise ship.

7.5.Draft and trim distribution sensitivity analysis

Following on from the previous section, the various draft probability distributions derived have been assessed in order to identify the sensitivity of the Attained Index with regards to the distribution employed within its calculation. Focus in this case has been placed upon those distributions generated with respect to the vessels actual operational draft range and with a view to assessing the impact on Attained Index with consideration of the following:

- All draft increments within the draft distribution (T_{ND}=0.1, 0.2, 0.3…1) weighted according to the combined draft distribution of all basis ships as shown in Figure 86.
- The two-draft Attained Index calculation Approach as elaborated earlier for vessels during the design stage, T_{ND} = 0.1 and 0.65, weighted by factors 0.1 and 0.9 respectively (see eq.(7-13)).
- All draft increments within the draft distribution (T_{ND} =0.1, 0.2, 0.3…1) weighted according to ship specific draft probability distributions, i.e. consideration of ship specific operational data only in the derivation of the draft distribution but applied to one vessel only as opposed to each individual vessel.
- The one-draft approach suggested earlier for vessels during operation, specifically using only the highest recorded operational draft and associated GM and trim values for the specific sample vessel assessed.
- The current SOLAS 2009 draft weighting values.

For each of the above conditions the Attained Index of one of the vessels from which the operational data was sourced has been calculated. Where ship specific draft distributions have been considered, these have each been applied to the same vessel but with consideration of their unique weighting factors. The results of this process are highlighted below in Figure 93. Observation of the results demonstrates firstly that there is little sensitivity in the magnitude of the Attained subdivision Index with regards to using the generalised draft probability distribution over the ship-specific variant. In addition, there is also little sensitivity with regards to the number of drafts considered within the calculation of the Attained Index, having shown less than 1% variance in either case. Translating the Attained Index to the marginal risk (as explained in §5.7.2) for the case demonstrated in figure 93 and for 5020 People On Board, it can be observed that the risk is relatively insensitive for the different developed solutions, differing almost 3 to 4% from SOLAS 2009, while, the 1-draft solution is proven more sensitive to variations.

The primary reason for the observed lack of sensitivity is due to the fact that cruise vessels operate within a very narrow draft range and as such the change in condition of the vessel across its draft range is minimal. There, is however, a considerable difference between the results found using the newly derived weighing factors and those currently in place within SOLAS 2009. This is highlighted further in Figure 92 where the sensitivity of the Attained Subdivision Index in relation to the number of calculation drafts considered and the type of draft probability distribution is highlighted, with "Global Statistics" relating to distributions/weightings derived based on data sourced from all vessels and "Ship-specific statistics" relating to individual vessel distributions/weightings. In addition, a range of +/-1% of the Attained Index calculated with consideration of all draft intervals has been included in order to provide an indication of the magnitude of variation between the various approaches.

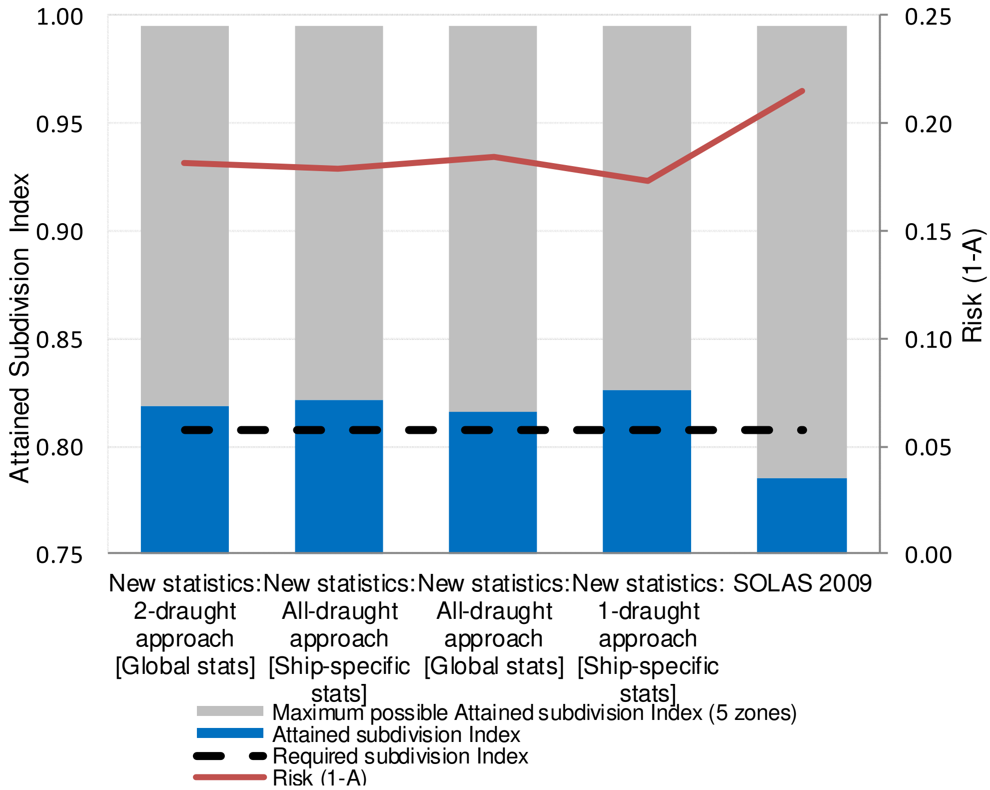


Figure 93: Comparison of impact assessment on Attained subdivision Index for a typical cruise ship complying with SOLAS0 90' and indication of risk.

The reason for the disparity in the Attained subdivision Index value calculated according to SOLAS 2009 in contrast with those calculated using the newly derived weighting factors stems from several reasons. Firstly, the weighting factors used within SOLAS 2009 overestimate the time cruise vessels operate within the lower to mid draft range. Secondly, the draft range assumed within SOLAS 2009 is too wide and in fact cruise vessels operate within a much narrower range. Furthermore, it was observed that in the majority of cases the sample vessels were operating with a considerable GM margin, which gives rise to a large discrepancy between the design and operational risk. Regarding the latter, it should be noted that the SOLAS 2009 Attained Index has been calculated using the exiting GM limit curves which have been formed on the basis of the requirements of SOLAS 90'. For this reason it can be observed that the vessel falls short of the Required Index in Figure 93.

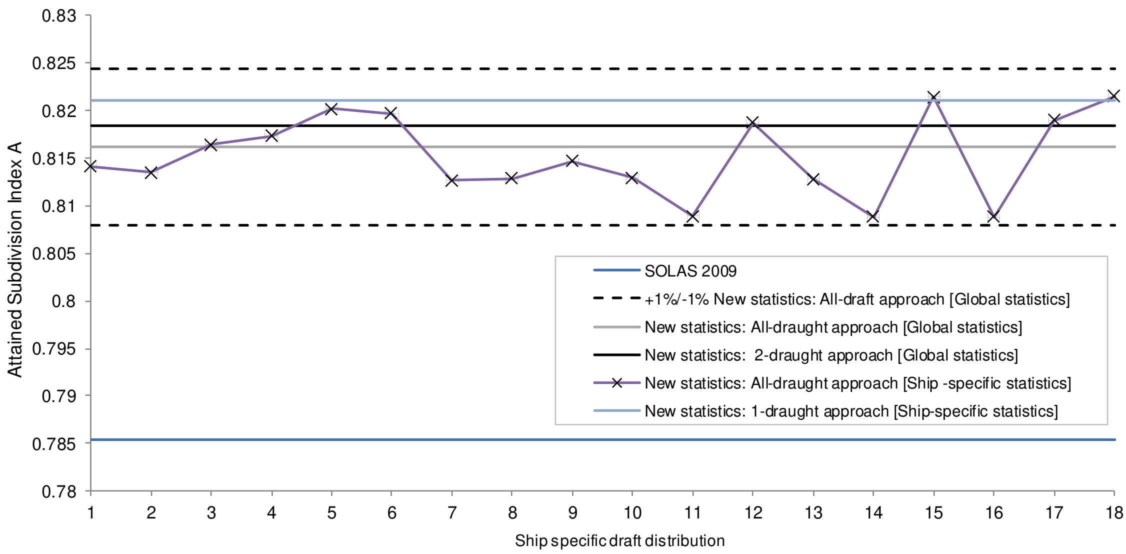


Figure 94: Draft sensitivity analysis on Attained subdivision Index including 18 sample ships.

As real loading conditions were used to perform this assessment, which is not possible in the design stage due to the unavailability of operational data, the effect of trim variation on the magnitude of the Attained Index was also considered. As the most efficient approach to calculating the Attained Index was found to be with consideration of only one draft that being the highest draft in the draft range, this sensitivity analysis was calculated for using this draft only.

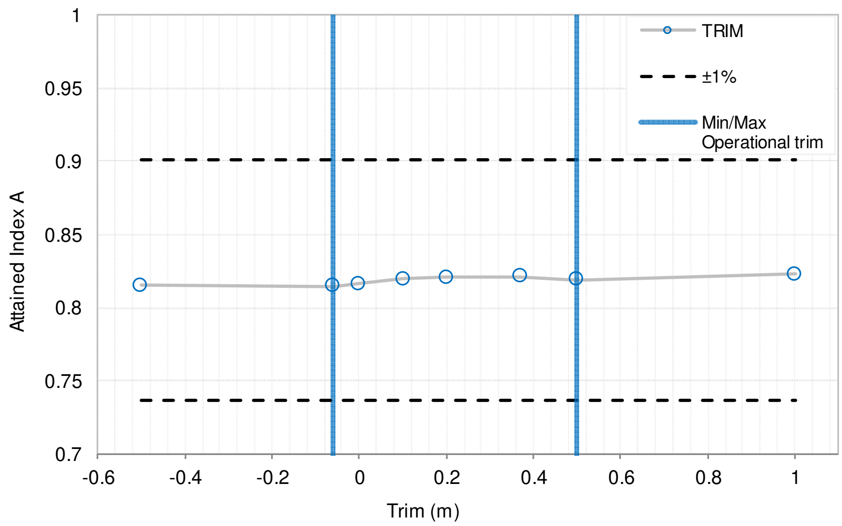


Figure 95: Trim sensitivity analysis on one sample vessel

Observation of Figure 95 shows Attained Index to be insensitive to variations in trim in the case of the sample vessel considered. However, this process could be repeated for a given vessel during the design stage at expected trim values in order to investigate ship specific sensitivity. The lowest recorded Attained Index values during this process could then be taken as the final Attained subdivision Index value for the vessel.

7.6.Continuous stability monitoring for ships in operation

The availability of operational loading condition data opens the doors to continuous stability monitoring, which can be proven to be potentially beneficial. Particularly, it can enable identification of high risk practices that lead to reduction of stability and establishment of techniques appropriate for maximisation of the GM margin. Additionally, continuous monitoring would enable monitoring of GM margin erosion and facilitate life-cycle stability management (GM). This in turn, can significantly contribute in the quantification of life-cycle risk (Vassalos et al., 2018).

Operation is the longest of the three different phases in the life-cycle of the ship, during which changes have a direct and significant impact on the risk. Risk must, therefore, be monitored and studied in order to ensure that changes in design / operation are well accounted and reflected in the risk management. This sounds straightforward in so far as changes take place in tangible, hence measurable, ship and environmental parameters, e.g., draft levels, loading condition, fluid tank levels, even watertight door status as well as prevailing wind and wave conditions. However, there are many other important parameters and conditions, such as changing the ship master, improving navigational equipment, etc., which have a significant and unquestionable impact on ship safety. Amazingly, however, the impact of most of these changes on safety can not currently be measured and therefore monitored, since we have not yet developed a way to assign risk credit / value to these changes.. Notwithstanding this, monitoring what can be measured and is known to be KPI for safety is a step in the right direction. The saying that if "we can measure it we can improve it" applies equally well here.

With this in mind, an attempt to monitor the operational profile of two vessels is provided below. Figure 96 and Figure 97 below demonstrate the operational profile of two relatively large cruise ships currently operating. In the first case, observation of the results shows that the vessel in its worst operational condition still has a minimum of 0.21m GM in excess of the requirement. Therefore, it stands to reason that an Attained subdivision Index based on the GM limiting curve would underestimate the safety level of the vessel under consideration. While the requirement for a GM limit cannot be disputed, the use of A=R as the limiting curve criteria can be challenged.

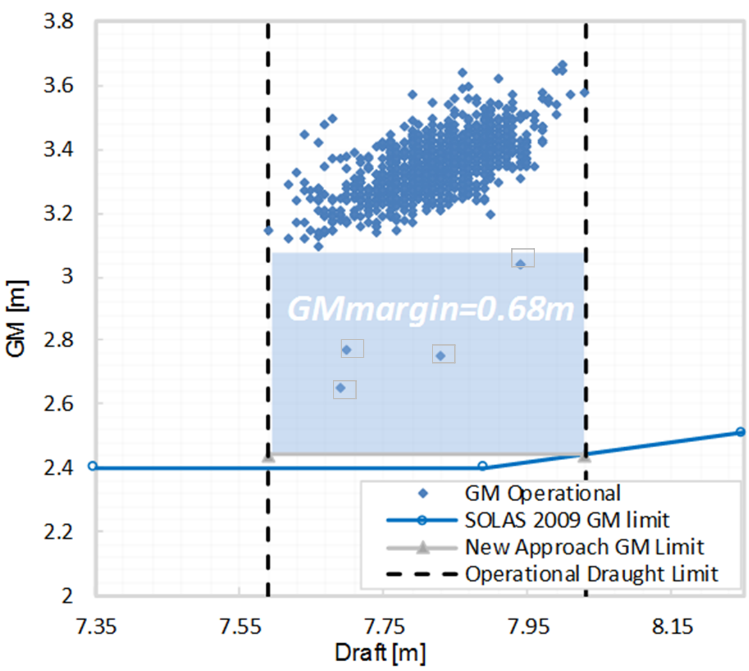


Figure 96: Limiting GM curves using new and old approach with illustration of operational loading conditions accumulated over two years for a typical large cruise ship.

In theory, a new GM limit based on the actual operational profile of the vessel could be used in order to provide a more accurate and, as it turned out as shown in Figure 96, a larger Attained subdivision Index value. This being said, a GM value of 2.6 metres would produce a higher Attained Index and redefine the GM limit as 2.6 metres across the draft range of the vessel whilst the vessel is not penalised with regards to its operation. In the second case, the cruise ship is over-penalised having an average GM margin of 1.32 metres resulting to lower survivability and therefore, as expected, an underestimated level of safety. Further to the information above, Figure 98 below highlights the relationship between the non-dimensional draft data for all vessels against their respective GM margin. This shows that in some cases there is a large gap between the GM limit and the operational GM but also highlights that some vessels operate very closely to their GM limit. In consideration of the foregoing, continuous stability monitoring can be advantageous as it can give prominence to unfavourable trends and provide guidance to cost-effective actions that can enhance stability and hence safety.

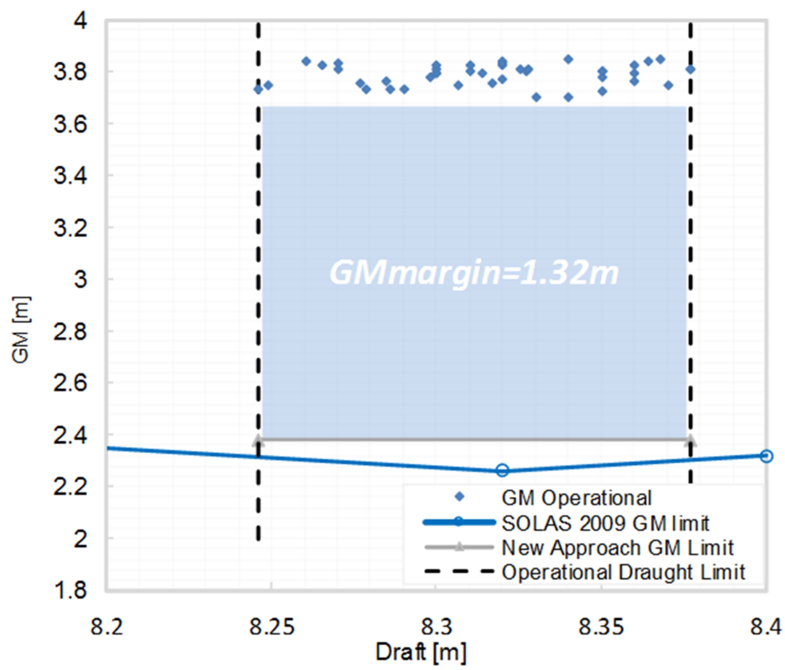


Figure 97: Limiting GM curves using new and old approach with illustration of operational loading conditions of a typical cruise ship.

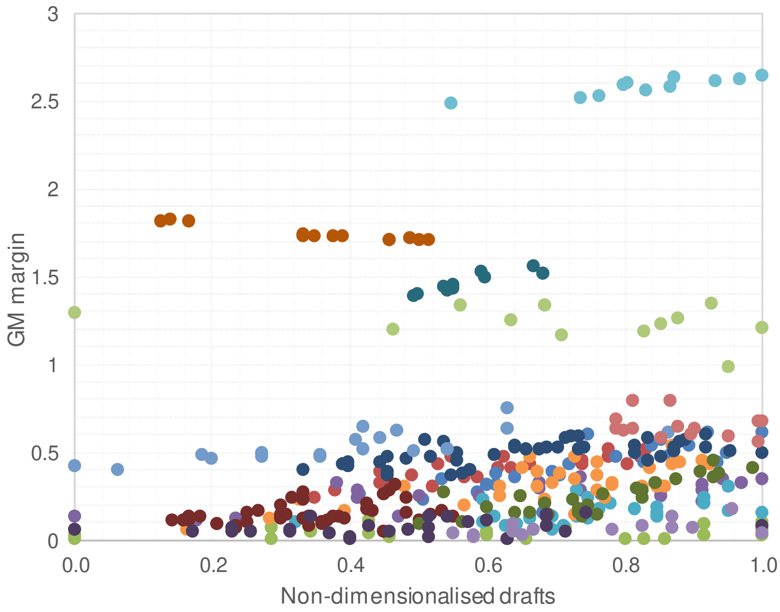


Figure 98: GM margin [m] versus non-dimensionalised draft overview of sample cruise ships. A total of 18 large passenger ships are depicted.

7.7. Closing remarks

On the basis of the foregoing section and the analysis presented in the chapter, a series of concluding remarks can be drawn. Initially, the weighing factors used within the SOLAS 2009 framework appear not to reflect the nature of operation of cruise vessels and subsequently underestimate the Attained subdivision Index (safety level). In line with this, the theoretical draft range of each considered sample vessel has shown to be overestimated as the sample vessels never operate at their light service condition. Alternatively, the use of real loading condition , including draft and trim, data can be employed to generate weighting factors based upon draft and trim probability distributions that represent the true operational profile of the vessels. This in turn will allow for more accurate damage stability assessment pertaining to operational and newbuilding vessels. In the case of existing ships, a one-draft approach to calculating the Attained subdivision Index has been identified, which will simplify calculations significantly whilst resulting in higher Attained Index that better reflects cruise ship operation. Eventually, this will allow for continuous stability monitoring and management of the vessels currently in operation. For the assessment of cruise vessels during the design stage, a solution is recommended that offers necessary flexibility during the design stage for newbuilding vessels. This is to apply a two-draft approach with appropriate weighting factors formed on the basis of cruise vessel specific loading condition data and which is ultimately more reflective of the operational profile of cruise vessels. Whilst real loading conditions were used throughout the assessment, a sensitivity analysis was conducted on trim for the test case vessel showing the Attained Index to be insensitive to trim. While this may be case specific it is recommended that this process be repeated on a case by case basis. When the Attained Index is found to be insensitive to trim, level trim conditions at the design draft can be assessed for the calculation of Attained index. Notwithstanding the above, the availability of on-board data can be turned into a substantial tool for survivability assessment not only in the case of the conventional assessment approaches, but also, it can aid into an accurate implementation of the direct approach, by assessing damages via sampling operational drafts and trims.

Chapter 8

Impact Assessment of Permeability on damage Survivability

8.1. Opening remarks

In the previous chapter, the impact of the utilisation of actual operational data on safety is gauged through assessing survivability from a static and dynamic stability perspective. Another dominant element, which has not yet raised significant research awareness, is the impact of permeability on ship survivability. Despite the historical attempts of the industry, as they have been highlighted in the literature review, to address this impact, focus has been placed on local detail rather than on the global perspective. As a result, the crux of the matter has not yet been subjected to adequate scrutiny. The current damage stability regulatory framework for passenger ships (SOLAS) suggests values that represent different types of compartments namely, accommodation, machinery spaces and stores.

Even though their values are fit for different purposes, their magnitude remains ambiguous since it is unclear to what degree they represent actual permeable space. Permeability is inherently interrelated to numerous stability parameters that, in turn, influence the events following damage and flooding. Several ensuing implications on damage stability can emerge whilst, the impact on survivability can be proven to be manifold. The following chapter aims to delve in this direction by assessing the impact of permeability on damage ship survivability for a number of cruise ships. Building on this, the chapter attempts to accentuate the need for the utilisation of real data through the assessment of stability and it provides the requisite evidence to substantiate the argument.

8.2. Introduction

The prevailing damage stability probabilistic framework has been widely used in the maritime industry over the past decades. The instruments and tools that aid in the assessment of damage stability account for the manner in which the volume of a room is represented through permeability. Permeability is a property that is used in multifarious disciplines and industries from the science of electromagnetism to the science of earth, soil and chemistry. Terminologies such as vacuum permeability and vascular permeability are daily used to describe essential properties or their rate of change in different fields respectively. Nevertheless, in the naval architecture lexicon, permeability (μ) is merely regarded as the fraction of floodable volume of a room to that of its overall volume or put simply, the percentage of the free space of a room (IMO, 2009). A simplified equation to represent permeability can be depicted in eq.(8-1) below.

$$\mu = \frac{Floodable\ volume}{Total\ volume} = \frac{V_{floodable}}{V_{total}} \tag{8-1}$$

Touching upon the argument presenting in chapter 7, in the same manner another significant example of the assumptions within the probabilistic framework concerns the adopted values for permeability as outlined within SOLAS 2009. The underlying concept behind the values is simplistic and yet one that needs to be addressed thoroughly. The current damage stability framework for passenger ships namely SOLAS (IMO, 2009c) specifies values for three different compartment types, namely accommodation or voids, machinery and stores with designated values of 0.95, 0.85 and 0.6 respectively. The aforementioned values account for the manner in which the volume and items are distributed across each different type of space and also from the nature of the items themselves. The values are applicable to all passenger ships carrying more than 12 passengers on international voyages as outlined within SOLAS. Based on the vast number of passenger ships encountered currently in operation, one could comprehend that the applied values constitute a serious assessment component in the case of damage stability (Vassalos et al., 2019). In this respect, permeability can be viewed as a representation of the ship's precarious safety component and it is this deduction in combination with a number of other observations that cause a number of concerns as outlined in the foregoing paragraphs.

First and foremost, the means by which the current permeability values were established is not known as there is very little related literature, given what is presented in the critical review chapter to support this statement. As a result, the current values appear to be entirely unsubstantiated. Consequently, this questions the accuracy of permeability values with respect to how representative they are of the permeable spaces of the ships covered by the standards in place. This, in turn, presents an approach which is applicable to every ship type and appears to be over simplified as it fails to distinguish any variations in internal volume distribution between different ship types.

The current regulation assumes in essence that RoPax, dry cargo, tankers and cruise vessels are assessed using the same permeability values in the main four space types despite the fact that these ship types are known to have very different tendencies when it comes to their design and arrangement. This is based on the values recommended in SOLAS and MARPOL (IMO, 2009c, IMO, 2004) but this cannot be true. Large passenger ships are known to have very complex internal arrangements with accommodation spaces and galleys, filled with furniture and appliances, whereas dry cargo ships have simplified accommodation spaces and over-packed machinery spaces. This can be elaborated by proving that there is enough correlation between ships of the same type but again this would be rather challenging. In this respect, even if it were found that these values are accurate for any one of the vessel types covered by the standard, confirmation of that fact would subsequently indicate that they were inaccurate for the others.

Another significant fact relates to the values of permeability, which were introduced initially in 1912 as part of the first committee on safety of construction (CSC, 1913) and they have been widely used since then. They are retrospectively applied over the past decades through the treaty series of (UKG, 1929), (UKG, 1948), (UKG, 1960) and (IMCO, 1973) respectively, leading to the current framework (IMO, 2009c). The ameliorating norms have no provisions for utilisation of actual data but instead support the utilisation of the first adopted arbitrary values. With this in mind, one could argue that even though the regulation standards have not changed, ship technology, design and equipment has changed and advanced significantly over the years. Smaller boilers, compact cable and pipe units, reduced size of gearboxes and pumps, alternative fuel tanks, innovative electric propulsion units, scrubbers and modern packed furniture with trivial volumes are a few examples of the technological advances that have gained momentum over the years. In this respect, the aforementioned prove that the existing values will tend to disregard the way technology changes and its ensuing impact on damage stability assessment, unless actual/real values are utilised and new provisions in the regulations are sought.

Even though cutting edge technology is available, it is not utilised due to the cost excessive nature and the long post-processing such applications would necessitate. One relevant example is the measurement of spaces using 3D laser scanning for the implementation of ballast water treatment systems on board ships. In the wake of this, the scope of the problem can be narrowed down to the assessment of varying permeability for different spaces and their subsequent impact on survivability. As it has been highlighted in the literature review, very little effort has been exerted on identifying the impact on survivability over the years, despite the opportunity presented in several research projects over the past years.

The following sections provide an impact assessment of permeability in two ways; firstly a series of sample ships, which are used in previous chapters, are assessed through using a damage stability assessment software. This will provide an indication of the Attained subdivision Index (statistical approach) as a statutory compliance measurement that will aid as an indicative measure for conducting comparisons. Based on this, an attempt to parameterise the results will be performed with a view of utilisation of the formulations in time-effective computational way. In a second manner, two ships are subjected to numerical time-domain simulations for a group of damages via Monte Carlo assessment and individual damages respectively. As a result, permeability will be assessed dynamically (direct approach) from a local and global perspective. The chapter aims to accentuate the need for the utilisation of actual data during the life-cycle damage stability assessment of vessels. In pursuit of this, permeability will be subjected to multiple variations, but first, there is number of aspects which need to be addressed, as outlined next.

8.3.Assumptions that affect permeability in damage stability assessment

The values of permeability are assigned in the form of room purposes within the early phases of the design, following the completion of the design arrangements where the decisions are made. These in turn, are connected to a number of assumptions that have bearing on the manner in which permeability serves the reflected volumes and the way in which they are considered within the damage stability assessment process.

To begin with, one of the main properties concerns the level of uniformity and density of the volume in any room under consideration. Typically a volume can have either homogeneous or heterogeneous properties (Kantzas et al., 2016).The former signifies that the components of a space have the same proportions throughout the space and these will follow the same pattern if segregated into any way. In this respect, the permeability of a room has one value and it can sustain it uniformly across the entire space without being subjected to any deviations. This, however, is an inadequate way of representing a space but it can be proven time-efficient. A change in the level of the water inside a flooded compartment will influence the value of the remaining permeability but not the associated properties pertaining to the room and its components. In turn, these can influence the way the water progresses to adjacent spaces through the leakage area and time (Ruponen, 2017). A number of studies (Illario, 2014, Vassalos et al., 2016a) as have been described in the critical review for innovative applications, have proved the applicability and impact of homogeneous permeability in damage stability assessment through the standard assessment instruments.

On the other hand, a heterogeneous space entails that the comprising components are not uniformly distributed across the entire space and they might be imposed to localised regions with distinct properties. In this case, the volume can be viewed simply as a cubicle including smaller cubicles with different permeability than the surrounding room. This means that the distribution of floodwater in a room will differ since the centre of gravity of the overall floodwater mass will be uneven. In reality, a heterogeneous space is a realistic representation of any room for any real ship with a cost of computational modelling time. The impact of heterogeneous spaces on the damaged ship motions has been proven to be dominant as presented in the literature review section. In fact, a heterogeneous permeability can cause excessive heeling because of uneven floodwater distribution and large angles of roll especially when the occupied space is above the water tight bulkhead. Related literature (Santos and Soares, 2009), demonstrates the applicability of a space breaking down permeability into smaller groups for a small room in a machinery space.

Another important element in this direction is the classification of items and their respective permeability. However, this is entirely dependent on the achieved modelling detail of the rooms in consideration. Usually, the designs are kept to a simplistic degree with as much features as necessary to perform damage stability assessments and as a result a great deal of detail is neglected. Conversely, in the case of time domain numerical simulations, which tend to capture better the detail, the assignment of accurate permeability for each of the items can be proven beneficial. Every item can be attributed with different permeability and potentially can affect the manner in which permeability changes with regards to the floodwater accumulation and the increase of the water level. Different properties such as friction and geometric coefficients, different items and materials will have strong bearing on the way the properties of overall room permeability are accounted for. This, in turn, can affect sloshing, compressibility and the free surface effects altogether.

In the current instruments of damage stability assessment, the designer has the capacity of selecting across a range of designated purposes fit for specific rooms in the arrangement that are associated with various permeability values accordingly. In turn, these fall under one of the primary permeability groups as mentioned in previous sections. One example relates to the store spaces where hospital, laundry, machinery, luggage and kitchen supply stores are under the same primary permeability group and assigned a value of 0.6. One could understand that even though spaces relate to stores, they enclose various materials with different properties and as a result they do not capture the actual permeable space in an effective manner.

The following section delves deeper into the undertaken methodology and the reasoning behind it. A number of assumptions are considered and will be provided for each case respectively.

8.4.Impact assessment of permeability on survivability

Having identified the main assumptions and concept of permeability behind the assessment of damage stability, an insight follows into the methodology undertaken to assess a number of large passenger ships with a view of gauging the impact of permeability.

8.4.1. Overview of applied methodology

In the absence of actual/real and accurate permeability values for the ship designs in consideration, a number of permeability variations is deemed appropriate. In this respect, any potential variations of the floodable volume of the rooms into consideration are accounted for throughout the damage stability assessment. In this direction, six sample cruise ships of medium and large size are subjected to an extensive sensitivity analysis through varying permeability regarding the primary groups stipulated in SOLAS, namely machinery, stores and accommodation. Specifically, permeability is varied with a range from 0.95 to 0.45 in some cases for each group respectively. Taking this into account, one can question the extent of the possible and applicable variation. In the case of modern cruise liners and passenger vessels in general, even though the accommodation spaces can vary in terms of volume and range in appliance and design options, the engine room and machinery spaces tend to become over-simplified. The pace of new technology developments and innovations in the field has introduced non-intrusive solutions to minimise the volume of the equipment pertaining to each space. In this respect, even though a value of 0.95 correlates to almost an empty space, it might fit the purpose of the sensitivity analysis since there in no availability of actual data for such spaces to prove otherwise. In the same manner, a value as low as 0.45 or 0.5 can reflect the space of a relatively full store room. The capacity of the stores can be disputed since the spaces are fully utilised. Conversely, the rooms can be relatively empty at the time of damage or in the wake of flooding. This, however, depends on the operation scheme since different ships might be loaded and operated in different way as they were initially designed.

For the sake of the sensitivity analysis, each compartment type is subjected to categorisation based on their general utilisation. More specifically, the accommodation group comprises passenger cabins, dining rooms, galleys, crew cabins, restaurants and theatres. In the same manner, the group of stores includes spaces such as engine, linen, luggage, hotel, carpenter, chemical and provision stores, whereas, the machinery space group encompasses the main engine room, thruster, auxiliary and gear rooms. Nevertheless, the above is depended upon the subjected level of modelling detail assigned by the designers during the design phase. One could argue on what determines which group a given compartment should belong to. For instance, machinery spaces such as pump rooms and store spaces such as the Bosun stores are assigned the same value of permeability, that of 0.95.

As demonstrated in Figure 99 a number of cruise ships have undergone a sensitivity analysis. The ships represent a reflective sample of the current fleet as they range in size and capacity. Indicatively, the vessels vary from 60 to 320 meters in length and the total volume for each group takes the min and max values of 850 and 40,900m^3 for machinery, 1,000 and 65,000m^3 for accommodation and 300 to 13,000m^3 for store spaces respectively.

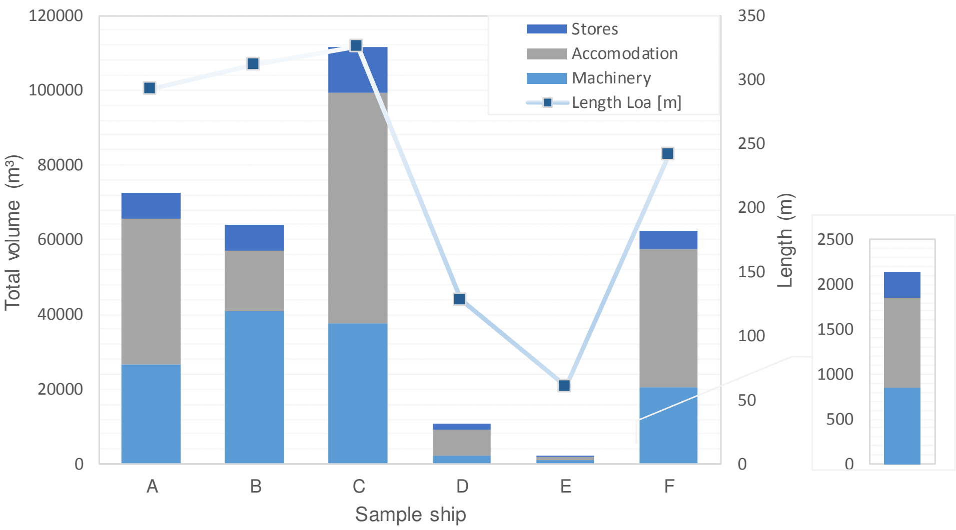


Figure 99: Floodable volume distribution for machinery, accommodation and store spaces for which permeability has been varied. Sample ships A, B and C have been described in chapter 5.

The decisions made during the design phase shape safety over the whole life cycle. In this respect, use of advanced tools and exploiting knowledge in all forms at the design stage is most effective and, hence, highly desirable. This may be done incrementally, with simpler tools at the initial stages, then progressively introducing more advanced tools as design matures. In this respect, the sensitivity may be addressed in two levels namely, (Vassalos et al., 2018) static vulnerability assessment and dynamic vulnerability assessment as addressed in the following sections. The term vulnerability in the two aforementioned levels pertains to the degree of capturing and identifying design sensitivities (i.e. vulnerabilities) through performing either static or dynamic assessments. Building on this, the cruise ships are assessed in two ways. At the first instance the impact of permeability is investigated though employing a static calculation tool. This will allow for the estimation of survivability via the means of statutory compliance. In a second manner, a dynamic numerical simulation tool is used to assess survivability. Thus, local and global details pertaining to the design are evaluated, accounting for the effect of dynamics.

8.4.2. Static vulnerability assessment

The first step towards the comparative study constitutes the implementation of simple static calculations using the total Attained Subdivision Index (IMO, 2009) and varying permeability across the different three permeability groups. Here, an industry standard damage stability software is utilised to undertake probabilistic damage stability calculations, leading to assessing subdivision Index A for rule compliance. This entails generating damage scenarios from flooding (presently only collision) events deriving from SOLAS-related accident statistics (IMO, 2009c). The calculations are performed through developing and coding a macro within the static calculation software NAPA version 2016.1-1x64 that facilitates the automatic alteration of permeability values and also identifies and categorises rooms and compartments based on their purpose.

The following graphs, as summarised in Figure 100, demonstrate the results obtained for all the sample ships in consideration. From the figures, it is obvious that the change in the total Attained Index follows a linear trend across the varied permeability in each case and the impact on each vessel is consistent, which is the result of their available respective floodable volume.

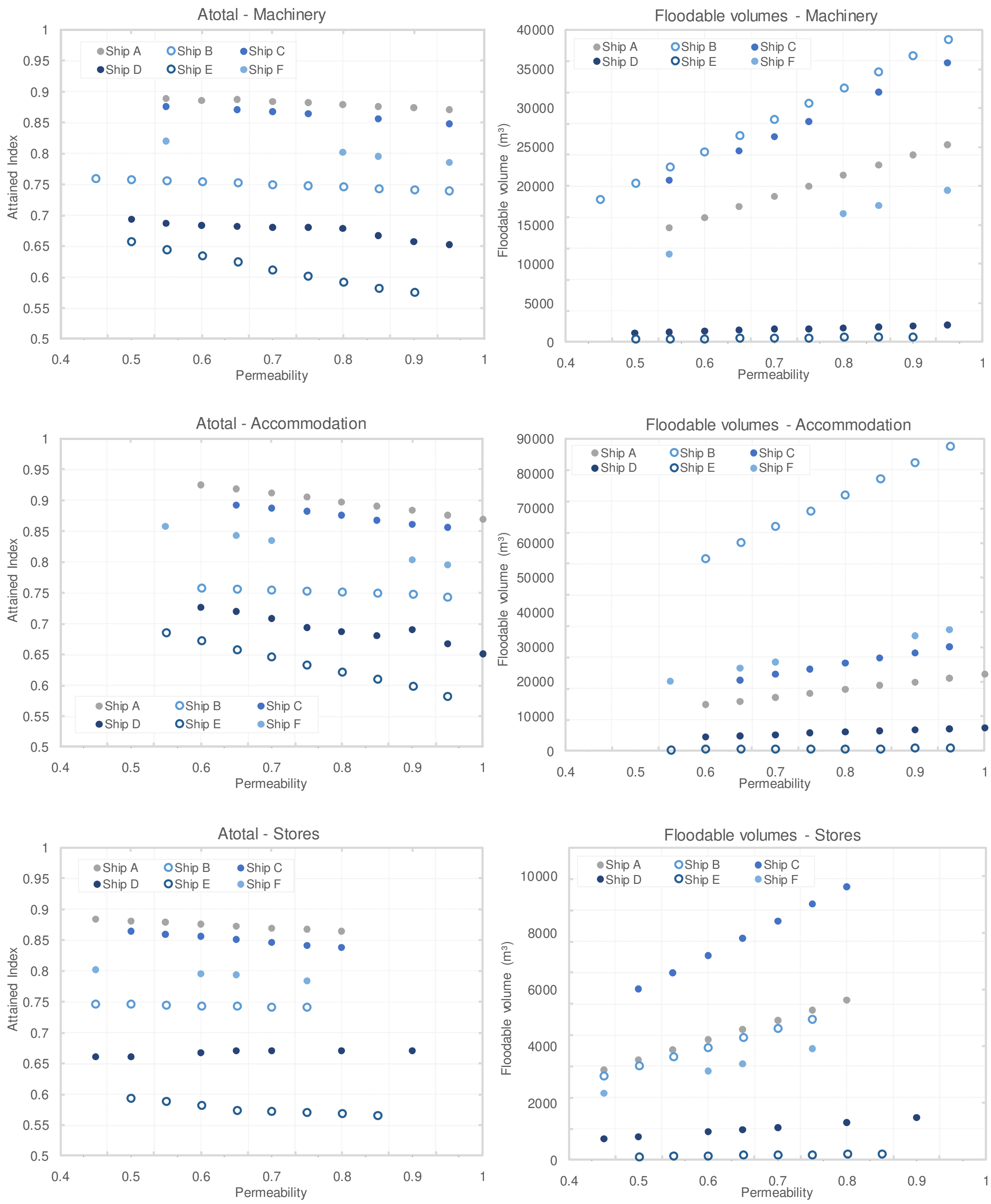


Figure 100: Summary graphs indicating the impact of varying permeability on the total Attained subdivision Index along with the variation of the floodable volumes.

In particular, for machinery, the two smaller ships (E and D) exhibit a lower Attained Index, below 0.69, representing their small machinery spaces with volume 425 to 2,000 m^3 as opposed to the large ships with volume higher than 15,000 m^3 and an Attained Index as high as 0.89.The accommodations present a steeper decremented tendency towards higher permeability showing more sensitiveness. This is due to the location of the accommodation spaces, as for example the large ship C encloses an accommodation volume of 20,500 m^3 as compared to the smaller ship D with volume of 4,000 m^3. Despite the dominant role of the floodable volume in this sensitivity, the location of the spaces is significant and this accentuates the need for potential dynamic simulations to identify further local and global sensitivities pertaining to the vessel. In the case of store spaces, the impact is reflective of the floodable volumes. The largest of the ships (A and C) achieve an Attained Index of 0.83 to 0.88 for volumes of 5,600 to 9,600 respectively, while, the smallest ship (E) leads to an Attained Index as low as 0.6. The complete impact on the three damage stability loading conditions (dl, dp, ds) that form the Attained Index is provided in AppendixD for further reference.

The following graphs indicate the impact via the slope of the change in the total Attained Index as a function of the change in permeability as a percentage. The origin of the graph depicts the default value as stipulated by SOLAS.

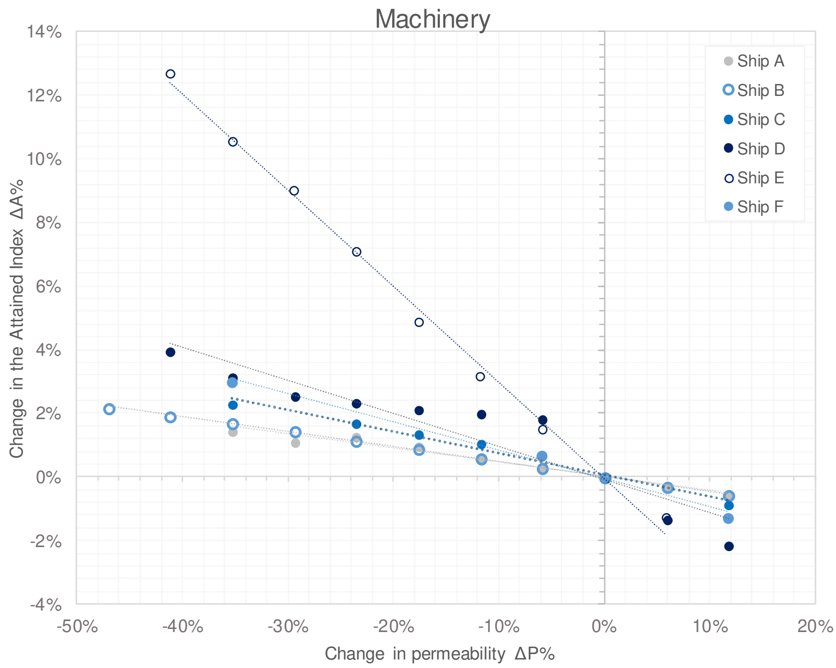


Figure 101: Change in the total Attained Index versus change in permeability in machinery spaces. The origin represents the default value 0.85 as per SOLAS.

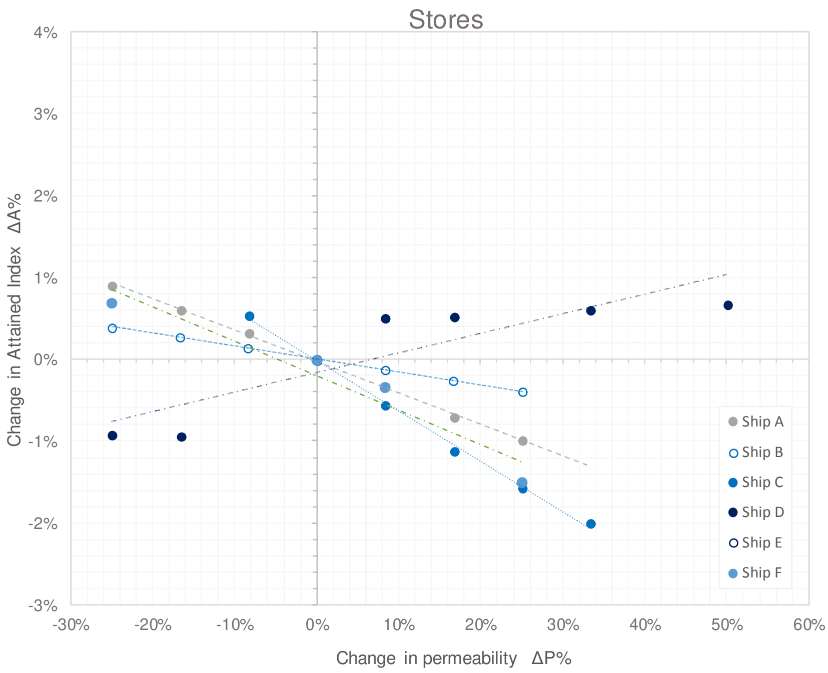


Figure 102: Change in the total Attained Index versus change in permeability as percentage in store spaces. The origin represents the default value 0.6 as per SOLAS.

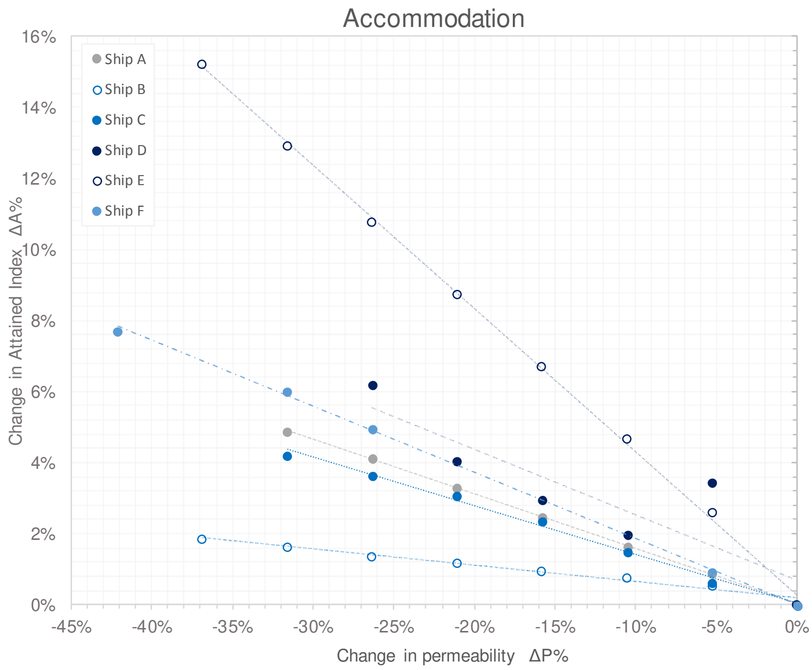


Figure 103: Change in the total Attained Index versus the change in permeability as percentage in accommodation spaces. The origin represents the default value 0.95 as per SOLAS.

In Figure 101, the smallest ship E exhibits the highest change across the sample ships in the case of machinery spaces with a slope of 0.3. This means that for 10% change in permeability there is 3% change in the Attained Index, which in turn can be proven significant for the case of smaller ships. Generally, all the machinery spaces are located within the watertight envelope while the accommodation spaces are scattered. Saying this, the impact on Attained Index from machinery ranges between 1.5 and 4% but in the case of accommodation this can be 2% to 8%.

Figure 103 demonstrates that the impact of the store spaces is small compared to that observed in the case of accommodation (Figure 102) and machinery spaces. For instance, as shown in Figure 103, ship E displays 10% change/increase in the Attained Index with a 20% decrease in permeability. Also, ship A displays 5% change in the Attained Index with 25% reduction of its initial permeability. The latter can be subsequently translated into a decrease of the potential loss of life of the order of 5%. In the light of the above, the impact on the safety level can be detrimental given especially the case of smaller cruise ships. A noticeable trend that deviates from the other ships is observed in the case of ship D when varying permeability in the store spaces. The justification behind this lies in the asymmetrical location of the store spaces on the starboard side that leads to potential excessive heel when flooded.

The size of the vessel and the available floodable volume are identified as the main influential contributors to the impact of permeability. Having said this, the results are formulated for the three main damage stability loading conditions. The slope-intercept or steepness of the linear regression is denoted with m and it represents the fraction of the change of the Attained subdivision Index and the permeability $\left(\frac{\Delta A}{\Delta \mu}\right)$ whilist b is the y-intercept. Following linear regression fitting through the data, the resultant slopes are provided in the following table. The intercept always crosses the origin and therefore has been omitted from the given equation.

$$f(x) = m \cdot x + b \qquad (8\text{-}2)$$

Table 14: Slope of change of the Attained Index for permeability change in machinery

	Atotal	Adl	Adp	Ads
Ship A	-0.044	-0.079	-0.044	-0.025
Ship B	-0.047	-0.052	-0.045	-0.046
Ship C	-0.069	-0.042	-0.063	-0.088
Ship D	-0.104	-0.039	-0.092	-0.150
Ship E	-0.302	-0.471	-0.394	-0.141
Ship F	-0.089	-0.074	-0.058	-0.129

Table 15: Slope of change of the Attained Index for permeability change in store spaces

	Atotal	Adl	Adp	Ads
Ship A	-0.038	-0.034	-0.045	-0.032
Ship B	-0.016	-0.022	-0.021	-0.008
Ship C	-0.062	-0.043	-0.043	-0.043
Ship D	0.024	0.001	0.037	-0.023
Ship E	-0.081	0.039	0.060	-0.119
Ship F	-0.042	-0.034	-0.036	-0.053

Table 16: Slope of change of the Attained Index for permeability change in accommodation spaces

	Atotal	Adl	Adp	Ads
Ship A	-0.1547	-0.1662	-0.165	-0.1369
Ship B	-0.0457	-0.0057	-0.0434	-0.0646
Ship C	-0.1371	-0.0931	-0.0931	-0.0931
Ship D	-0.1836	-0.2656	-0.2624	-0.2256
Ship E	-0.4033	-0.4953	-0.5275	-0.2626
Ship F	-0.1862	-0.212	-0.1842	-0.1749

Observing the slopes of change from the tables above a trend across the three loading conditions is noticeable. The impact on survivability generally decreases towards the deepest subdivision drafts. Having gauged the impact on survivability, it is deemed appropriate to establish trends and patterns of the rate of change of the Attained Index among the sample ship range by utilising parameters that constitute an indication of their size and extent of the exposed volume for each of the different permeability groups being examined. To this end, the data are represented in a meaningful manner with respect to the overall length and the volume of displacement for each of the vessels. In the wake of this, a non-linear regression following a power model as shown in eq.(8-2) is performed to identify the best fit through the data. As shown in eq. (8-3), the rate of the Attained Index change increases as a power function of the overall length (L_{OA}) with a scaling exponent b and an additional adjustable regression parameter c.

$$f(x) = a \cdot x^b + c \tag{8-3}$$

$$\frac{\Delta A}{\Delta \mu}(L_{OA}) = a \cdot L_{OA}^b + c \tag{8-4}$$

$$\frac{\Delta A}{\Delta \mu}(V_{displacement}) = a \cdot V_{displacement}^b + c \tag{8-5}$$

The projected regression with fitted curves for the total Attained Index are provided in the following figures while similar information reflecting the three damage stability loading conditions is provided in the Appendix.

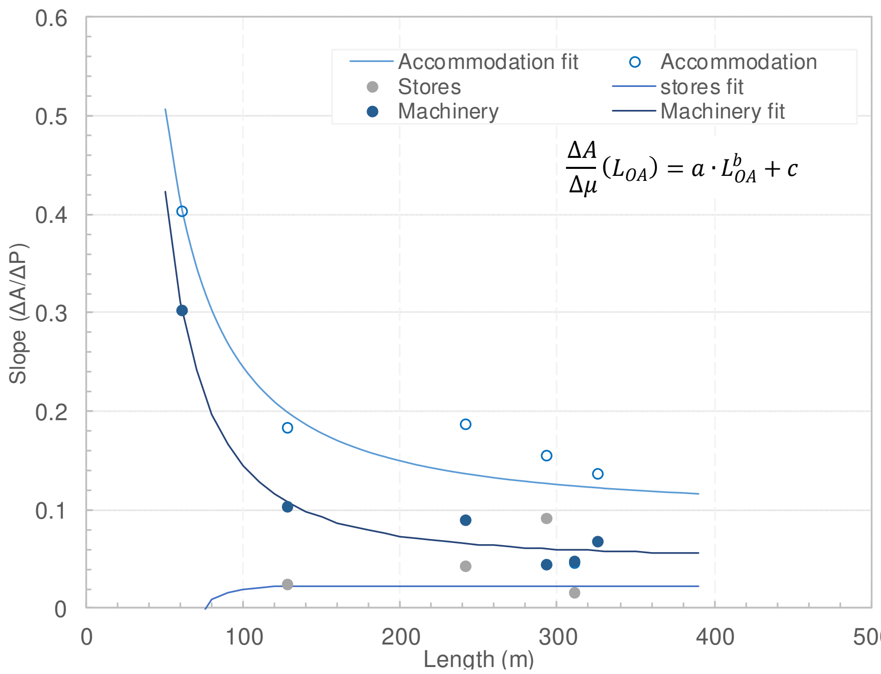


Figure 104: Regression fit for slope $\left(\frac{\Delta A}{\Delta \mu}\right)$ against overall length (m)

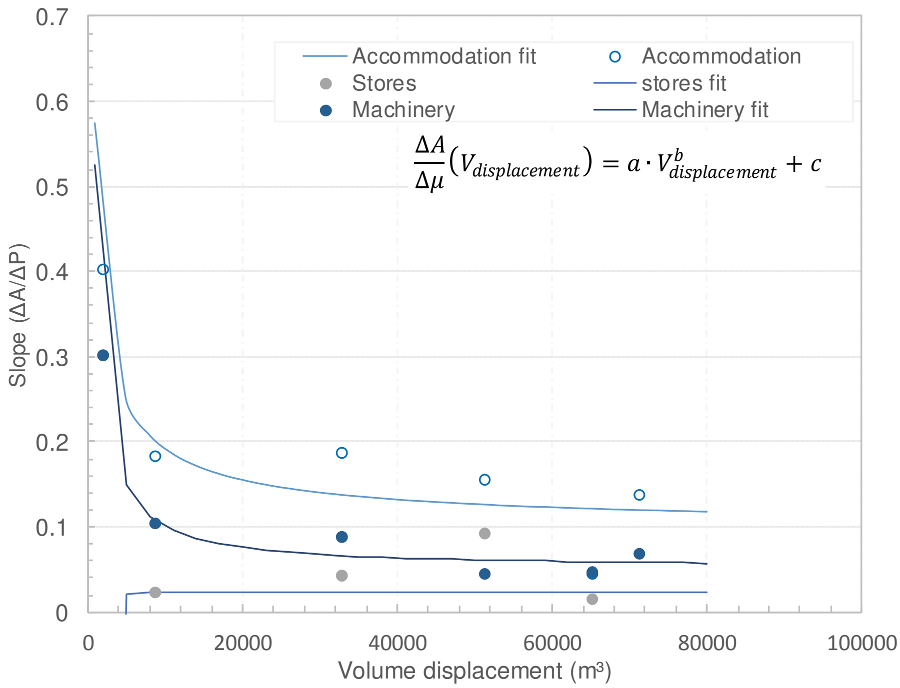


Figure 105: Regression fit for the slope $\left(\frac{\Delta A}{\Delta \mu}\right)$ against volume displacement (m^3)

Table 17: Regression fit accuracies and parameters for Length function

	Machinery	Stores	Accommodation
a	839	-1.5E+12	132.6
b	-1.972	-7.372	-1.477
c	0.04924	0.02257	0.09674
SSE	0.001081	0.01237	0.009846
R-sqr	0.9771	0.4176	0.8599
RMSE	0.01898	0.06421	0.05729

Table 18: Regression fit accuracies and parameters for volume displacement function

	Machinery	Stores	Accommodation
a	413.8	-5E+12	56.5
b	-0.9804	-4.169	-0.6905
c	0.05097	0.02252	0.09508
SSE	0.001066	0.01237	0.009564
R-sqr	0.9775	0.4177	0.8639
RMSE	0.01885	0.06421	0.05646

Through reverse engineering on the aforementioned formulae, a complete picture can be provided on the relative impact on the Attained subdivision Index. Even though the sample ships considered constitute a representative sample of the fleet and ships currently in operation, there is a relative large span of length not being taken, into account, namely between 150 and 250 metres length.

Other research (Ravn, 2003) attempted to oversimplify the calculation of the Attained Subdivision Index through using data mining techniques and achieving optimisation of the main subdivision parameters of Ro-Ro ships coming closer to a computational-efficient method. However, the related approach included ±15% deviation error from the actual results. This is mainly due to the fact that not only the Attained Index is associated with multifarious number of parameters but also, the concept of damage stability and subdivision itself, in general. An example is the loading condition including draft and trim, the number of the bullheads or the probability of encountering a specific damage extent within the probabilistic damage stability framework. The combination of the aforementioned entails a substantial number of statistical deficiencies which would deem impossible the establishment of an accurate means of calculating the Attained Index by employing only two or fewer parameters thought regression of the data at hand.

In order to achieve an accurate parametric formula that accounts for different ship lengths and the enclosed space volumes it would require identification and establishment of dependencies between the different parameters that form requisite data for estimating the Attained Index.

8.4.3. Dynamic vulnerability assessment

In a second manner, dynamic vulnerability assessment is conducted on a number of cases through assessing survivability in two ways. For more in-depth information on the mechanics of the flooding process, numerical time-domain flooding simulations need to be performed for the sake of sensitivity analysis.

The concept of the capsize band (see §3.4) has been introduced in chapter 3, but is brought up here for a different analysis scope. In project GOALDS (Vassalos, 2009b) the Hs_{crit} changed definition to that of the highest sea state at which no capsizes are observed within half-hour runs. A number of refinements were followed (Tsakalakis, 2012) in the derived formulation to more accurately capture the unsafe and safe region envelop in the case of passenger ships. (Tsakalakis et al., 2010a) parametrically defined the sigmoid function employing the Boltzmann's sigmoid form which in turn allows for direct regression of measured rates without performing numerical differentiation.

$$y(x) = \frac{A_2 + (A_1 - A_2)}{1 + e^{\frac{x - x_0}{dx}}} \tag{1}$$

Where, A_1 and A_2 represent the asymptotic limits, x_0 the ordinate of centre of symmetry and d_x the time constant.

At the first instance, two SOLAS damage cases are examined from one large and one relatively small cruise ship, as observed in Figure 106 and Figure 107 respectively. The ships are simulated in their deepest draft loading conditions and they are retained constant during the process. The damages are selected from chapter 5 and are subjected to three permeability variations namely 0.75, 0.95 and 0.65 from their default value of 0.85. In order to capture adequate impact from the analysis, it was deemed appropriate to vary spaces with large volumes. Based on research findings (Atzampos et al., 2018a), cruise ships tend to exhibit vulnerabilities in their fore and aft shoulder with main contribution from the main engine room or other adjacent machinery spaces leading to up flooding and eventual large angle heel. This being said, the machinery spaces are identified as an ideal candidate that would fit such purpose.

Figure 108 and Figure 109 demonstrate the results of the numerical simulations for the two damage cases. The vertical axis represents the probability of capsize and is derived as the fraction of number of capsizes over the number of survival cases. This is produced for each wave height for 10 runs per wave height but different wave realisations. In the first case, the large ship demonstrates significant variation among the different permeability alterations. The critical significant wave height for the default permeability is equal to 1.8 meters. A 10% increase in permeability results in a 50% decrease in the critical wave height to that of 0.6 meters. On the other hand, a decrease in permeability to 0.75 and 0.65 yields an increase to 4.6 and 5.2 metres critical wave heights respectively. In the case of the small cruise ship, minor differences are observed as the sigmoid curves, leading to overlap in some cases. Specifically, the critical significant wave height is equal to 5.2 meters for the default permeability values. Decreasing 10% and 20% permeability can lead to an increase to 5.4 and 5.46 metres critical wave height, respectively. This implies that smaller ships are more insensitive to permeability variation as opposed to large cruise ships. However, this entails a damage-specific approach and even though it is robust, it does not allow for an overall dynamic survivability assessment providing a comparative metric and therefore another analysis is sought.

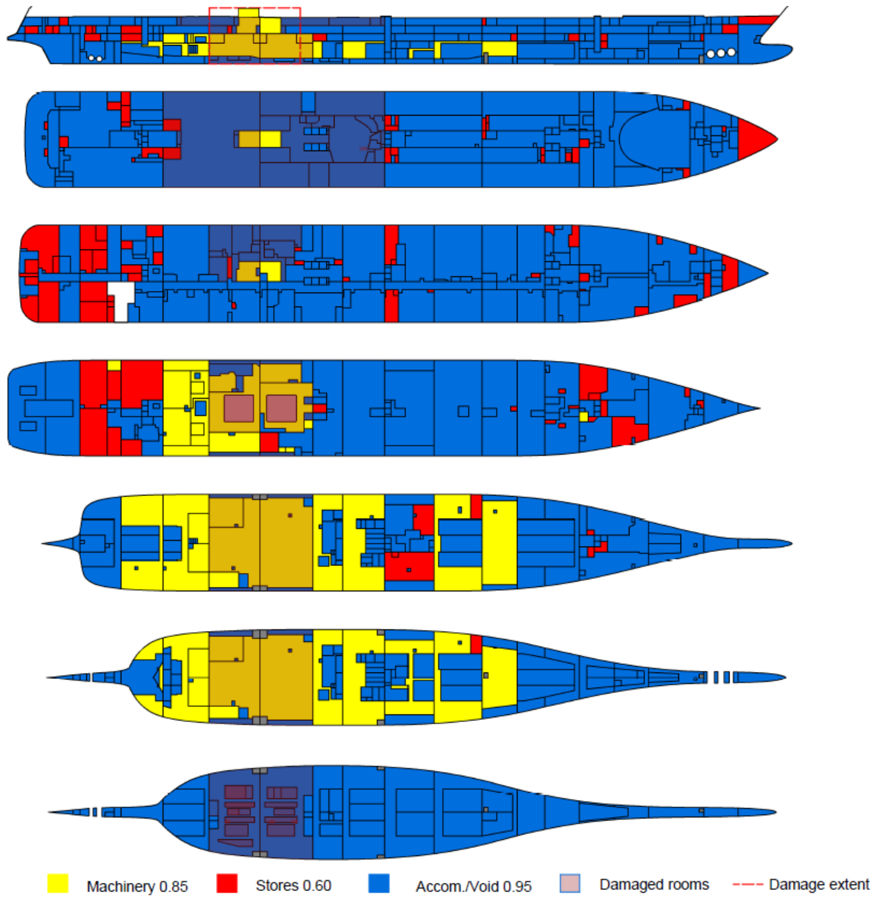


Figure 106: 2 - compartment damage from sample ship A as identified and selected in chapter 5. Indication of different permeability groups along the ship.

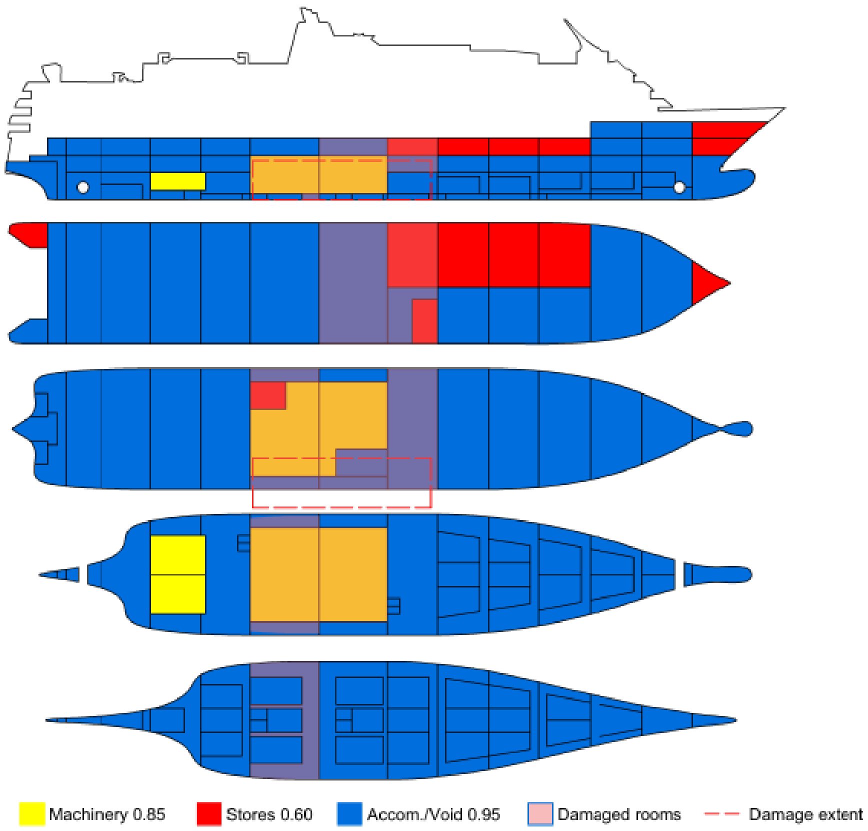


Figure 107: 3 - compartment damage for sample ship D as identified and selected in chapter 5. Indication of different permeability groups along the vessel.

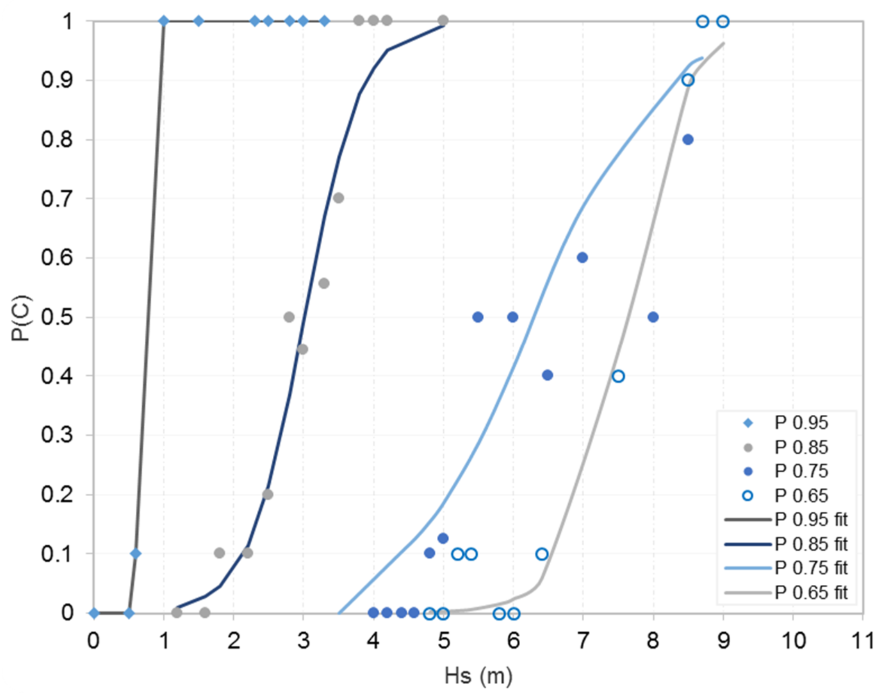


Figure 108: Sample ship A - Capsize rate for varied permeability in the machinery rooms for fixed damage and loading condition (damage demonstrated in Figure 106)

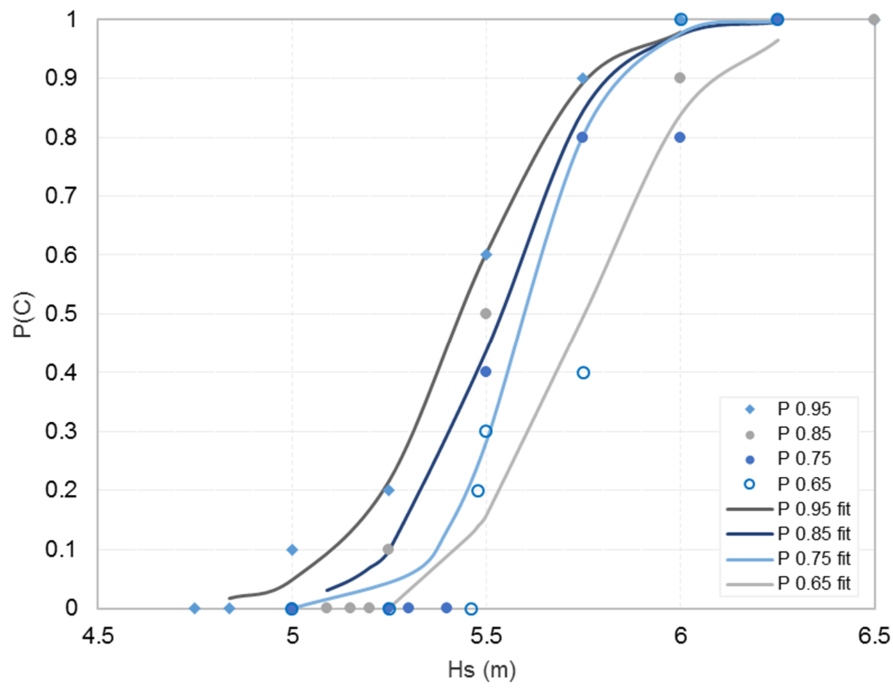


Figure 109: Sample ship D – Capsize rates for varied permeability in the machinery rooms for a fixed damage and loading condition (damage shown in Figure 107).

Following the identification of the critical significant wave heights via the derivation of the capsize rate concept for the two cases described above, an alternative assessment of survivability is sought in order to account for the global characteristics of the vessel rather than their local details. This in turn, will allow for identification of the overall impact of varying permeability for individual or combination of permeability groups on the damage stability performance of the vessel in waves. The direct approach, which has been described in previous chapters, has been implemented for the case of one cruise ship, investigating a group of MC damages with the view of assessing survivability using the Time to Capsize (TTC). In this case, the permeability group under consideration is the machinery spaces including rooms that occupy a large area on DB and TWD decks. The general arrangement of the vessel under consideration is provided in Figure 111 below. Even though, a reduction in permeability in lower spaces can result in an increase in the Attained subdivision Index, this might have counteractive effects for spaces being in the upper decks. This is merely stemming from the impact of the vertical centre of gravity of the rooms being flooded, which is relatively deteriorated for large asymmetrical spaces. The cumulative distribution of the TTC provides information for the cases that have actually capsized (physical capsize). However, the impact of varying permeability can be assessed for the cases that involve only rooms with altered permeability. To this end, the time to capsize (TTC) for these capsize cases has been accumulated, in the same manner as before, in order to provide an identical comparative measure.

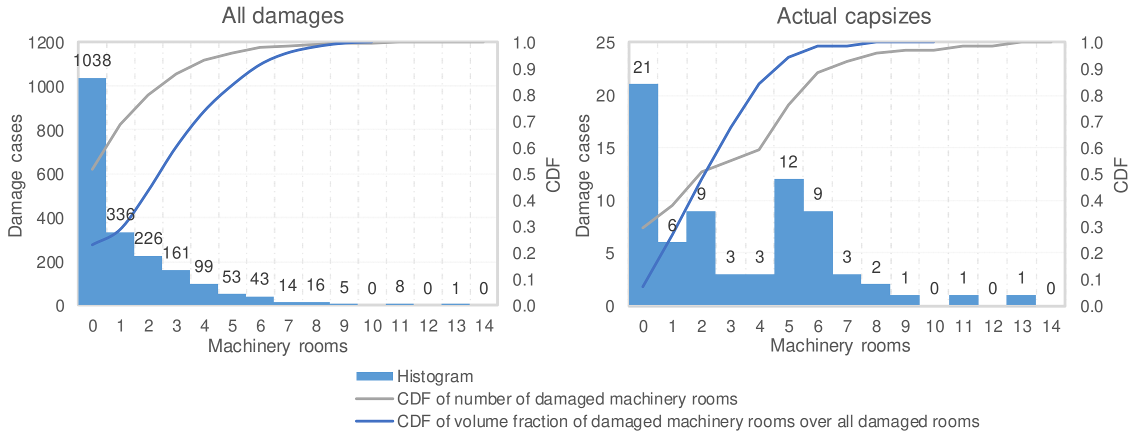


Figure 110: Histogram and cumulative distribution of machinery spaces and volumes across generated damages and actual capsizes for the case of 0.95 permeability where the largest number of capsizes occurs.

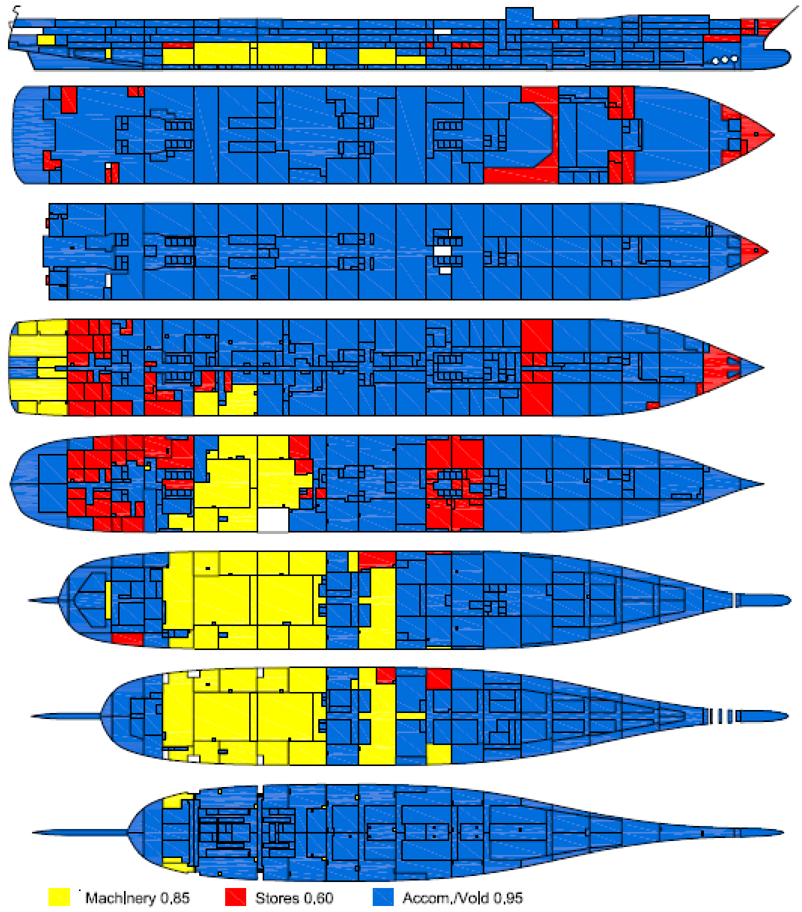


Figure 111: Indication of different permeability groups for large sample ship C.

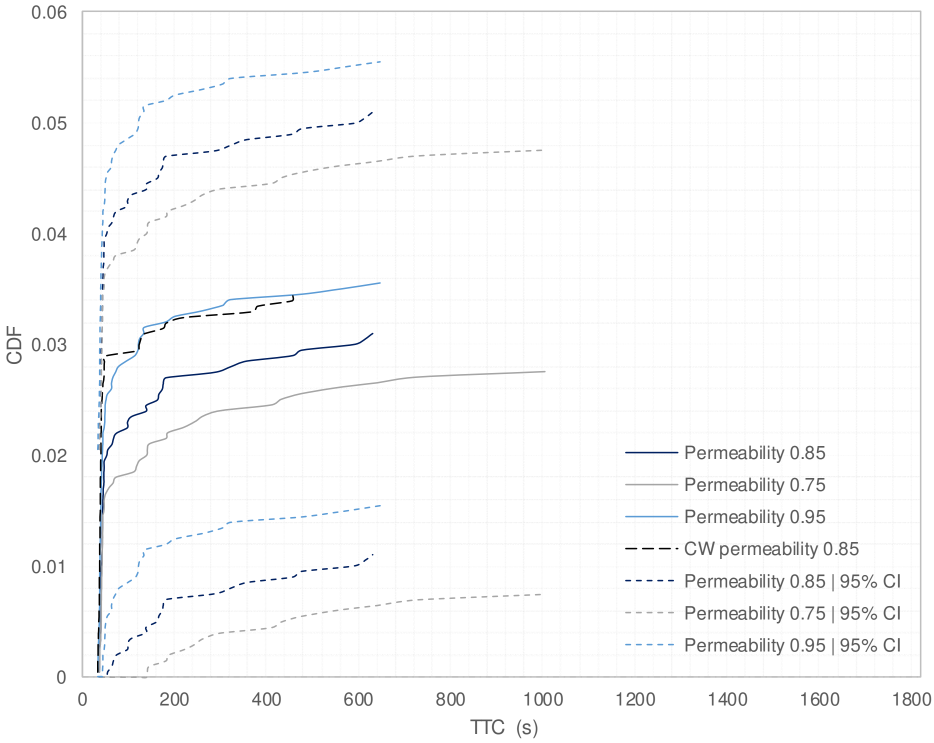


Figure 112: Cumulative distribution function of the Time to Capsize (TTC) for different permeability variations in machinery spaces including Calm Water numerical simulation results.

The simulations are performed for three permeability variations (0.75, 0.85 and 0.95) including calm water runs for the default permeability values of the vessel (IMO, 2009c) and waves sampled up to 7 meters as described in earlier chapters. The same wave realisations are utilised for each damage in order to form a comparative ground and rationale. Figure 110 indicates the total number of machinery rooms included across 2,000 MC sampled damages. As it can be observed, a large number of damage cases which have actually capsized include machinery spaces out of which 60% include 2 or more machinery rooms. Therefore, a variation in machinery space permeability can potentially bring significant impact on the safety level of the vessel. Figure 112 comprises the overall impact indicating the cumulative distribution of the time to capsize for the different cases. The curves complete at values other than 1 since the cumulative distribution represents the fraction of the number of capsizes to the total number of simulation runs. According to Figure 112, the impact on the overall capsizal time is substantial. The reference CDF that of 0.85 permeability, completes at 629 seconds. In contrast, in the case of 0.75 permeability, the CDF curve completes at 1005.5 simulation time seconds whereas, for a 0.95 permeability at 646 seconds. The inflation or deflation in the values of CDF demonstrate the increase or decrease respectively in the number of capsize cases. This is elaborated further later, providing a few damage case examples. A reduction in permeability resulted in a decrease in the number of transient capsizes whilst, some cases transitioned from transient to progressive flooding. The opposite is true when increasing permeability. When comparing to the calm water runs, the impact of waves is apparent as it tends to have the same effect as increasing permeability to 0.95. As a result of the above, the results can be translated into an equivalent Survivability Index with values of 0.965, 0.97, 0.972 and 0.964 for calm water (permeability of 0.85) and in-waves with permeability of 0.85, 0.75 and 0.95, respectively. Even though the variation appears to be relatively small, the impact on the number of capsize cases appears to have a significant effect.

Looking into the number and location of capsize cases, as shown in Table 19 below, we can draw some important conclusions. In more detail, according to Figure 113, Figure 114 and Figure 115, in the case of μ=0.75 the simulations resulted in 55 actual capsizes. The maximum wave height is 8.09 metres and the minimum is 0 metres. The damages span between 29.9 and 58.2 metres located across the entire length of the vessel. Also, 65% of the damages tend to capsize between 0 and 80 seconds. In particular, 8 damages are transient capsizes, and 47 progressive flooding cases. The cases which change from transient to progressive occupy a large fraction of the total volume with machinery rooms. For instance, 73% of the cases include up to 25% machinery rooms whereas 25% higher than 35% of machinery rooms. Furthermore, in the case of μ=0.85 the simulations resulted 62 actual capsizes.

Table 19: Breakdown of physical capsizes from simulations in calm water and waves along with minimum and maximum longitudinal damage extent.

	Total number of capsizes	Transient (TTC≤60s)	(TTC>60s)	Min/Max Lx (m)
Calm water (μ=85%)	69	58	11	29/58.2
Waves (μ=75%)	55	34	21	29/58.2
Waves (μ=85%)	62	41	21	29.9/58.2
Waves (μ=95%)	71	51	20	29.9/58.2

The maximum wave height is 8.09 meters and the minimum is 0 meters. The damages span between 29.9 and 58.2 meters located across the entire length of the vessel. Indicatively, 75% of the cases capsize below 80 seconds of simulation time. In particular, 44 cases are transient (if we consider a 60s threshold for transient nature) and 18 progressive flooding. In the case of μ=0.95 the simulations resulted in 71 actual capsizes. There, the maximum wave height is 4.89 metres and the minimum is 0 metres. The damages span between 29.9 and 58.2 metres located across the entire length of the vessel. Here again, 81% of the cases capsize below 80 seconds of simulation time. In particular, 55 cases are transient and 16 progressive flooding. Finally, as far as the calm water runs are concerned, the simulations resulted in 69 actual capsizes. The damages span between 29.9 and 58.2 metres and are located across the entire length of the vessel. Almost 84% of the cases are transient capsizes whereas 12% (9 cases) are progressive flooding cases.

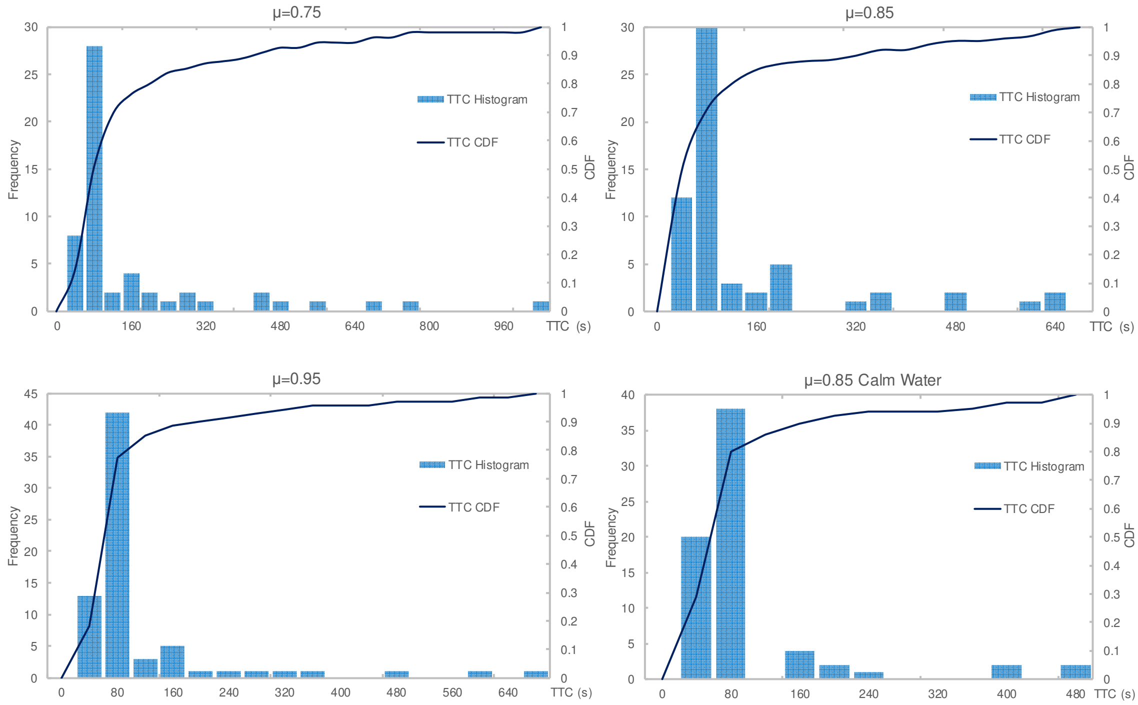


Figure 113: Cumulative distribution of Time To Capsize (TTC) for actual capsizes across the different permeability group runs.

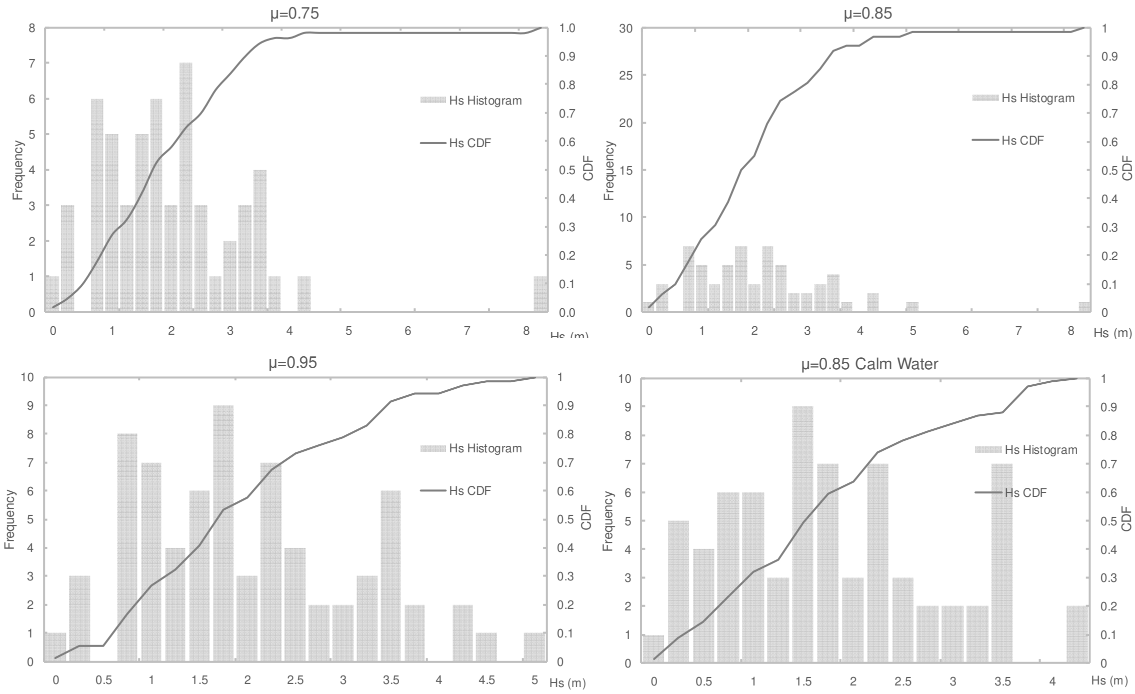


Figure 114: Cumulative distribution of significant wave height Hs (m) for actual capsizes across the different permeability group runs.

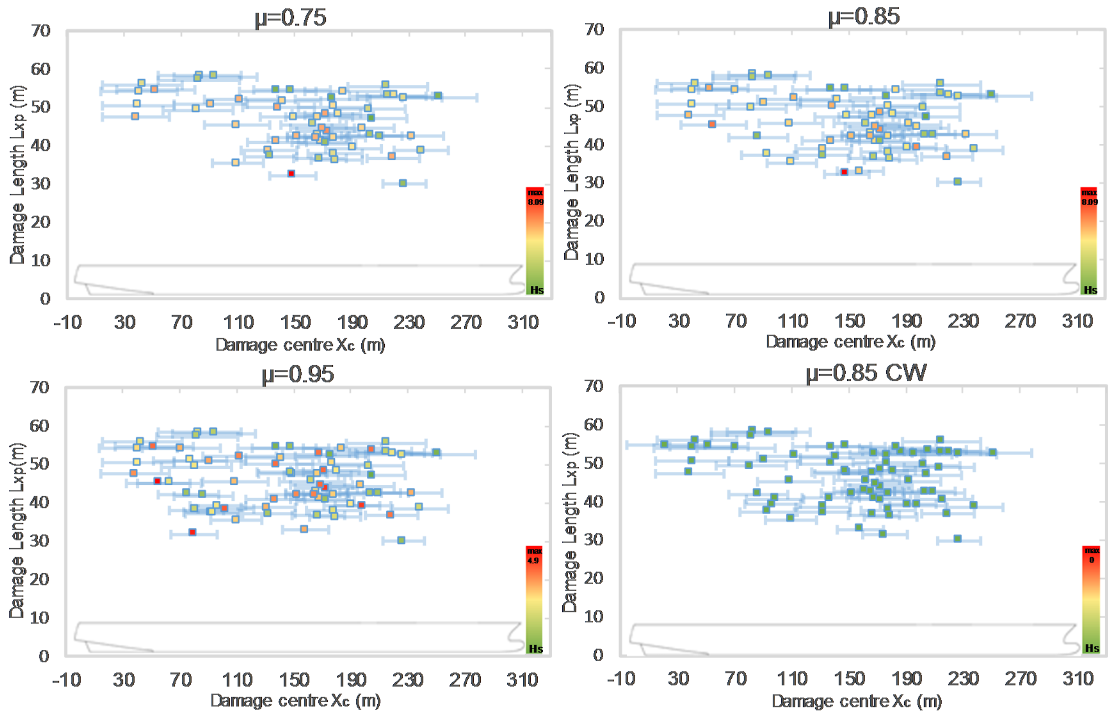


Figure 115: Illustration of damages depicting their longitudinal damage extent Lxp , damage centre Xc and wave height in gradient for the various permeability groups along with the Calm Water runs.

Building on the above, the impact of varying permeability on the mode of capsize and the Time To Capsize (TTC) can be proven significant. Two damage cases are analysed in more detail with a view to providing more evidence to justify this statement. Figure 116 shows the results of a 2-compartment equivalent damage located across the engine room of the vessel as depicted in Figure 111. As it is shown in the figures, the roll motion is exacerbated by gradually increasing permeability, whilst, the vessel reaches stationary state and survives in the case of the reduced permeability 0.75. In the case of 0.95 permeability, the vessels capsizes transiently within 215 seconds but in the case of 0.85 the flooding progresses until the vessel is lost after 800 seconds of simulation time. Figure 117 represents a 3-compartment equivalent damage, which spans across the aft shoulder of the vessel in consideration. The former damage case is occupied almost by 60% of machinery rooms whereas the second damage case by 43%. In spite of the fact that the water ingress fluctuation is limited because of the opening size (3-minute average final flooding rate of 14,556 tonnes) as opposed to the first case (12,388 tonnes) the manner in which permeability affects the vessel is quite similar. In a similar manner, for the case of 0.75 the vessel survives while for the cases of 0.85 and 0.95 it transiently capsizes after 43 and 146 seconds, respectively.

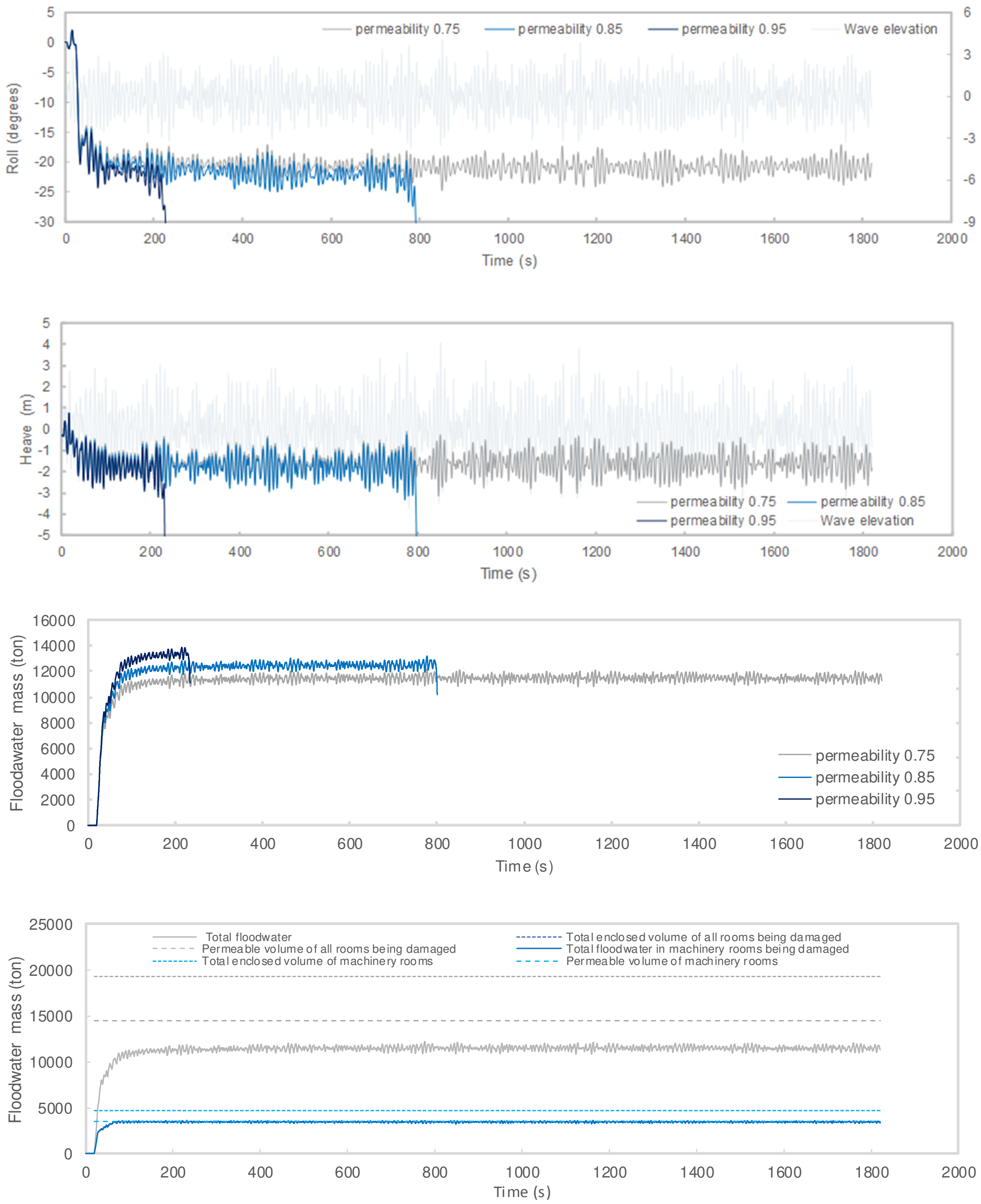


Figure 116: Damage 624 includes 45% of damaged machinery rooms which occupy 58.4% of the available floodable volume of the damage. The first three graphs provide an indication of the damaged ship motions and water accumulation (Roll, Heave and Floodwater mass) using different permeability values for a significant wave height of 1.5 meters. The last graph indicates the available and utilised floodable volume of the damaged machinery rooms and total damaged rooms in the case of 0.75 permeability.

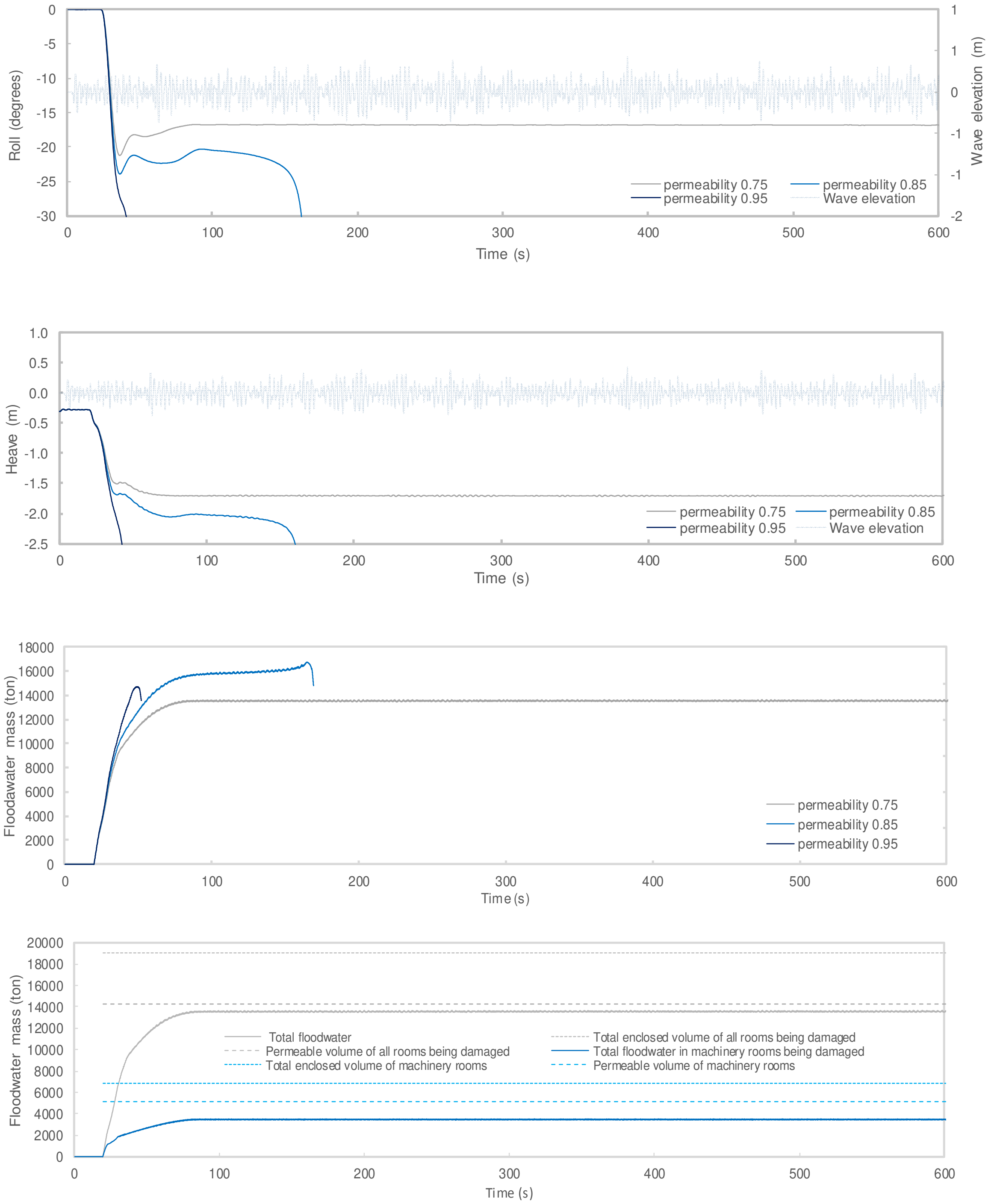


Figure 117: Damage 492 includes 30% of damaged machinery rooms which occupy 43.7% of the available floodable volume of the damage. The first three graphs provide an indication of the damaged ship motions and water accumulation (Roll, Heave and Floodwater mass) using different permeability values for a significant wave height of 0.5 meters. The last graph indicates the available and utilised floodable volume of the damaged machinery rooms and total rooms included in the case of 0.75 permeability.

8.5.Closing remarks

The chapter investigated methodically the impact of permeability on survivability by conducting a sensitivity assessment in two ways. Initially, static assessment is conducted on a number of sample ships and secondly dynamic simulations using a numerical time-domain platform. Deriving from the findings of the aforementioned research and results, a number of conclusions can be drawn. Static vulnerability assessment shows that cruise ships are sensitive to changes in permeability. Particularly, a maximum change in the Attained Index of the order of 18% is observed in the case of accommodation, while, 3% in the case of stores and finally almost 13% in the case of store spaces. The results have indicated that the impact of the accommodation spaces is larger than machinery spaces as opposed to the impact from stores, which is proven small. This is because the accommodation spaces are scattered along the length of the vessel and in locations above the watertight deck. In this sense and based on the impact of the floodwater mass, the centre of buoyant volume is affected dramatically, leading to large heel angles. In fact, the smaller the length and volume displacement of the vessel, the higher the impact on the Attained subdivision Index and ultimately survivability. As it has been pointed out through the sensitivity analysis, the available floodable volume plays a vital role in either case as it affects dramatically the slope of change of the Attained Index to the change of permeability. This, however, is again linked to the size of the vessel and the related watertight arrangement. Therefore, it can be concluded that the problem is ship-specific and any deductions on generalised solutions will be subject to a number of uncertainties.

On the other hand, in the case of dynamic simulations the impact has been witnessed to be significant. The large ship is shown to be very sensitive to alterations in the wave height with consequent impact on the critical wave height. The direct approach has indicated the impact on the Time To Capsize providing an indication of survivability equivalent to that of the static assessment. The Time To Capsize is increased dramatically when permeability is reduced and vice versa. Also, a minor decrease in permeability can bring about a decrease in the number of actual capsizes or change altogether the mode of capsize from transient to progressive flooding. This, in turn, can aid in the design phase of future cruise ships highlighting further vulnerabilities in the design. Finally, individual damage cases are provided to substantiate the argument showing a tendency to survive when permeability is reduced incrementally.

Chapter 9

Discussion

9.1.Opening remarks

The prevailing instruments of damage stability and survivability represent the end product of years of research and development in the field. The way currently damage stability and survivability is formulated leads to it being easily manipulated. Plethora of conceptual limitations, abundance of assumptions and compromises is the best way to describe the current status of the framework in place. Because of this, continuous effort is required to ameliorate these commensurate with the current state of knowledge and technological developments.

The research presented in the thesis paves the way in identifying definite improvements and contributions that can be implemented in the framework so as to accurately address survivability of large passenger ships. This, in turn, represents a paradigm shift from the past dichotomy between deterministic and probabilistic elements in the framework with the view of offering a platform that utilises actual data in the damage stability and survivability assessment.

The foregoing sections highlight the main contributions of the research in the field of damage stability of large passenger ships. In addition, a number of practical and conceptual encountered difficulties are addressed, offering new knowledge to address the various gaps that have identified along with the provision of recommendations for future research and developments in the field.

9.2.Contribution to the field

The thesis aimed at introducing a holistic approach to damage survivability assessment of large passenger ships by devising a platform that facilitates the adoption of new and modern knowledge and contemporary developments. The contribution in the field of damage stability and survivability assessment of large passenger ships is described in the following paragraphs, first at high level and then more specifically by addressing each of the thesis set objectives.

The first contribution to the field is the proposal of a holistic approach to address damage survivability of large size passenger ships, meaning both statistical and direct methods, using ship-specific formulations to account for ship-specific data and properties. In this respect, the proposed damage survivability assessment approaches are capable of incorporating actual and real data that cater for large passenger ships, their operational environment and profile for more accurate survivability assessment.

Another contribution relates to improving the knowledge about survivability of large passenger ships and particularly cruise ships. In addition, new methodologies are proposed to address survivability accurately and in a methodologically consistent manner by obtaining an in-depth understanding on the underlying dynamics which form a significant element for the implementation of similar future studies. As a result, more in-depth knowledge has been gained in the way SOLAS has been constructed to account for this type of vessels, including simplifying assumptions and approximations in addressing damage survivability.

The third contribution relates to the alteration and modification of the SOLAS damage stability framework into a platform capable of utilising modern knowledge and actual and real-time data. The presented approach, embraces available data either of operational or environmental nature and translates them into instruments of survivability and damage stability estimation. The developed holistic framework is not only limited to large passenger vessels as it can accommodate cargo or any other conventional ship types and their respective legislative frameworks (with some effort on ship-specific data and operational environments).

There are only a few sources covering thoroughly the state of the art and methodologies in the damage stability field of passenger ships. The thesis addressed, for the first time and in a comprehensive way, with inclusive discussions, all the shortcomings of the damage stability framework in place and highlighted the arising gaps that led to the undertaken research. This also constitutes a significant contribution in the field.

More specific contributions include the development of a cruise-ship specific survivability factor. The new s-factor accounts for the complex watertight architecture entailed in large cruise liners and it was established, for the first time, on the basis of solely numerical time-domain simulations, which are capable of capturing high degree of geometrical details (e.g. openings) and physical phenomena in waves. The new cruise ship-specific s-factor accounts more accurately for the effects of scale, which are attributed to the difference in ship size and damages.

Furthermore, the utilisation of the direct approach, as an alternative to the traditional statistical approach is not a new concept but it has been developed over the past 40 years. However, the key contribution presented in the thesis is the utilisation of such approach from a framework perspective. The robustness and efficiency of the entailed methodology applied in the thesis can be viewed as a legitimate alternative to the statutory compliance instruments currently used in SOLAS to assess damage survivability in waves. The benefits of the approach offered to the designers at forensic level and the utilisation of actual data form the methodology an ideal candidate for application in the form of Approval of Alternatives and Equivalents at design stage.

The consideration of actual wave statistics in the modelling of localised survivability methodologies is a new contribution to the field of damage stability. Typically, the level of safety is subjected to the actual operational environment the ships operate into. To this end, the thesis provided a modified approach that enhances the way the wave height limitations are assessed to account more accurately for different wave environments.

In the same manner, the utilisation of the actual operational profiles of ships comprising drafts, trims and permeabilities to accurately account survivability is a new significant contribution to the field. What is of high importance in this case is the adoption of actual data in the assessment of damage stability and survivability as input either to addresses static or dynamic calculations. The actual data provide accurate means to gauge survivability at design, forensic level or in actual operation for risk mitigation practices.

Deriving from the above, the utilisation of actual data in deriving ship-specific formulations and methodologies has proven that survivability can be more accurately calculated. This can provide an alternative route to the predominant damage stability assessment framework in a form of standard recommendations for future implementation in design, operation phase and emergencies.

9.3.Encountered difficulties

The following sections provide a number of difficulties met in the course of the research.

Modelling of survivability in waves

The survival assessment of passenger ships in waves is based on many parameters, most stochastic in nature. This renders modelling and analysis of such pertaining phenomenon difficult in specific circumstances. One of the encountered difficulties in modelling survivability in waves relates to the high resistance of cruise ships to capsize. Albeit their good ship design, the decrease in metacentric height employed to obtain the data required for modelling of survivability did not necessarily yield the required result. This, in turn, led to increasing KG to unrealistic sometimes values. The same practices have also been employed in the past within projects HARDER and GOALDS. To this end, many capsizes occurred in smaller simulation time due to water accumulation at higher decks resulting to higher degrees of roll in small period cycles. The availability and usage of preceded knowledge and experiences collected through past studies and throughout the thesis, can allow for more efficient and thorough assessments of damage survivability for this type of ships since the practices are now comprehensively documented.

There is only a number of parameters, which have been obtained through empirical experience and knowledge rather than a structured systematic analysis. Undoubtedly, in order to perform an accurate statistical analysis, a sufficient and adequate number of sample data is necessary. The population of the data in a quantitative and qualitative manner for the development of the s-factor following the aforementioned approach was a difficult task. A lot of effort has been exerted on identifying the ideal parameters and range of capsizes for the obtained data. Also, the design of the critical wave formulation was based on two governing parameters (because of historical data), which made the regression process cumbersome. The availability and fundamental understanding gained through the research on the parameters available to formulating the problem of damage survivability, form a good basis for the implementation of similar tasks in the future.

Numerical simulations and modelling practices

One of the main difficulties encountered during the performance of dynamic time-domain numerical simulations was the actual simulation time required for each of the runs in waves. Based on aforementioned sections, in order to create a rational comparative basis to the SOLAS 2009 s-factor, which is based on 30 minute exposure to beam seas in collision damages, an identical simulation time is required, that of 30 minutes (1800 seconds). Particularly on average, a 30 minute simulation time run would require approximately 20 to 35 minutes in real time for a large passenger ship (ratio varies from 0.7 to 0.95). This is very high time cost when considering thousands of simulations running simultaneously (2000 per damage type in our case, as described in chapter 5). Also, in the same manner another emerged issue concerned the memory required to store the results. The water accumulation files obtained from each simulation run including time histories require excessive storing capacity. Indicatively, for a 30 minute simulation run a total of 80 MB would be required.

With this in mind, dealing with extensive amount of data is paramount when considering a large number of numerical simulations. Therefore, a number of post and pre-processing scripts were developed to account for any storing and processing problems. With regards to the latter, the simulation geometry models of the cruise ships are numerically heavy since they incorporate large complexity of rooms, opening and sections. Therefore, a number of scripts and macros were developed that simplify the geometry in terms of knuckle points and sections.

Generally, the maximum simulation time (30 minutes) can be proven insufficient in assessing damages ensuing progressive flooding of large cruise ships pertaining to intricate geometry as the floodwater progression can take from minutes to hours. However, based on the findings of the thesis, and based on the approach employed in chapter 5, the time used was enough to capture the dynamic effects of waves on survivability and generate ship-specific formulations. Having identified ways of addressing the large amount of output and input data in the future, more in-depth analysis could be available incorporating the element of evacuation, which was not falling under the scope of the presented research. Based on the current standards for adequate evacuation (30 minutes), an increase in the simulation time would be essential in order to account for the effects of damage scale and quantification of the time to evacuate.

Availability of modern wave statistics

The availability and reliability of wave statistics in the development of the region-specific survivability factors were of significant importance. However, a difficulty emerged in attaining modern wave statistics pertaining to the last decade, from reliable sources. The data used in the formulation reflect relative old statistics of the wave environments of interest. Notwithstanding this, with the presence of modern and more accurate wave statistics pertaining to higher degree of detail for each area, survivability can be estimated in higher detail. The methodology adopted can be easily modified to reflect more accurate statistics. The impact from the presence of modern data in the analysis and developed methodology will be minor since the reliability of the data will not be subjected to significant alterations. However, this could enable to the designer more flexibility because of the relaxation the methodology would offer in the case of less severe wave environments.

Actual permeability values

The research on the impact of permeability was limited to a systematic and parametric sensitivity of different permeability purpose variations. For the consideration of actual permeability values catering for rooms such as machinery or stores, a detailed classification and taxonomy of items and spaces would be required, which would be computational laborious. Every item in a room is attributed to different permeability properties and water tightness which influence the overall volume permeability of each of the spaces and therefore more study would be required in this direction. In the presence of more accurate data representing actual permeable spaces of each different compartment types, the impact on the Attained Index and ultimately on survivability of large passenger ships would require future investigation.

9.4.Recommendations for future research

The thesis presented a holistic approach to damage survivability assessment of large passenger ships providing new contributions in the field and challenges as outlined earlier. Touching upon what has been discussed in the aforementioned and in light of the presented findings and research methodology adopted, a number of recommendations for future research are provided below:

- The consideration of external heeling moments in the current survivability assessment (as per SOLAS 2009) is considered static with fixed values and thus it does not constitute an accurate and adequate parameter of the equation. The variation of the external moments is random in nature; two examples in this case are the passenger movement distribution and the subjected wind moment, which can change based on the fetch of the area of operation. Thus, further research is necessitated in this direction in order to account accurately for the external moments and facilitate not only accurate damage stability and but also evacuation assessments.

- The dynamic effects entailed in the transient phase after damage of cruise ships in waves are pronounced. Therefore, the need to better quantify and evaluate the effects pertaining to the transient phase of flooding and capsize, whereas the consideration of survivability after or during transient flooding in the current framework would need addressing by means of advanced verification tools and particularly computational fluid dynamics.

- The calculation of the Attained subdivision Index represents an indication of the average survivability of a damaged vessel in waves. Saying this, the actual safety level of a vessel in consideration would need to account for crashworthiness, residual structural integrity and emergency measures and response for accurate risk estimation.

- Deriving from this, the Direct Approach to predicting survivability of passenger ships is proven efficient in this direction; however a better understanding of all the benefits should be gained through systematic analysis of all the pertaining elements and identification and quantification of the embedded uncertainties of such method.

- The calculation of the Time To Capsize can be achieved at a time computational numerical cost. Therefore, it would be essential to focus future efforts on identifying a method to ascertain the TTC in a time-efficient manner.

- To date, flooding accidents are classified based on the nature of damage to collision, grounding and foundering which drive rule-making. However, a unified approach to address ultimately flooding risk is absent from legislation. A suitably designed and adequately populated accident database, should aim to support the development of a unified approach to serious flooding risk and safety level of passenger ships.

- Building on the above, the flooding risk models currently in place address collisions and groundings separately. A holistic risk model accounting for only serious flooding events can link casual factors and controls for any type and nature of flooding accidents.

- The use of localised wave statistics has been proven a robust concept, however further investigation should be made on the level of focus on the area of operation. This could enable the development of parametric models, which despite the limitations of the current probabilistic framework (survivability is averaged for all damages based on pertinent sea states) can measure survivability at very high or low level. Also, modelling of proximity and vicinity to ports, important for survivability assessment, can be proven beneficial.

- Survivability currently only uses the significant wave height from wave statistics however, the bivariate probability of encountering a given set of zero crossing periods and significant wave heights can have a significant effect on damage survivability assessment.

- Derivation of actual permeability values is essential for depiction of the actual and realistic permeable volume of different purpose rooms. This, in turn, can result in a more accurate prediction of survivability dynamically and aid in the damage stability assessment for statutory compliance purposes.

9.5. Closing remarks

This chapter elaborated on the findings of the research thesis on damage stability and survivability of passenger ships and recommended items for further research in the future. The damage stability and survivability of passenger ships is a vast area with further room for exploration and improvements. The final conclusions of the thesis are summarised in the next chapter.

Chapter 10

Conclusions

The current framework addressing damage survivability of large passenger ships, namely SOLAS, is ridden with a number of assumptions and unjustifiable compromises that are questionable and impose conceptual limitations. The thesis aimed at providing the rationale and means of enhancing the way damage survivability of passenger ships is currently estimated following a holistic approach.

In light of the findings of the aforementioned research, a number of conclusions can be drawn as follows:

i. The damage survivability of large passenger ships can be calculated in a holistic manner with the consideration of actual data pertaining to the operational profile, wave environment, room permeabitites and ship-specific data. This constitutes an accurate way of addressing survivability within either the statistical or direct approach to damage survivability of large passenger ships.

ii. The comprehensive review of the methodologies currently available to address damage survivability of large passenger ships led to the identification of a number of research gaps, which have been addressed through the presented research.

iii. A survivability factor catering specifically for cruise ships has been developed through using the statistical (traditional) approach to damage survivability of passenger ships in waves. To this end, the calculation of survivability is more accurate and accounts for the complex internal watertight architectures as entailed in large cruise liners. For this reason, the development of the survival factor formula is based solely on the results from numerical time-domain simulations, which in the past have been proven robust in capturing dynamic phenomena and intricate details. The s-factor considers variations in ship size and accounts for the damage size through the adoption and establishment of a scaling factor. The applicability of the new s-factor on cruise vessels has proven the concept to be robust. Also, in this quest, a critical significant wave height formulation has been devised linking the critical wave height with governing stability properties of the GZ curve.

iv. Survivability in waves can be assessed through employing the direct approach and adopting Monte Carlo sampling for a number of collision and grounding damages. In this line, the Flooding Survivability Index can be used to ascertain the risk derived from flooding of damages in waves as an alternative to the statutory compliance instruments currently present in SOLAS. The application of this method indicated higher survivability when compared to the statistical approach while, it has been understood that cruise ships pose high resistance to capsize in waves. The dynamic simulations offer additional information to address the ensuing potential risk at a forensic level and have indicated the existence of equivalent and more efficient routes to the establishment of higher safety level for passenger ships.

v. Localised wave statistics can support the development of region-specific survivability standards that can subsequently complement the current SOLAS framework for damage stability and survivability. The robustness of the concept has been demonstrated with application on a number of ships. The results show that areas with higher wave heights have higher impact on the Attained Index as opposed to areas with lower wave heights. The use of wave statistics as opposed to accident wave statistics results on increasing the magnitude of the critical wave height.

vi. A passenger ship-specific accident database has been developed namely “Accident at Sea Database” collecting wave statistics of the environment at the exact time and location the accidents occurred at. This research has indicated that Passenger ship-specific accident data can be used in order to derive a ship specific s-factor formulation that better accounts for this ship type.

vii. Actual data derived from ship operational profiles can be used to obtain accurate input in the assessment of damage stability. Also, the use of real loading condition data can be employed to generate weighting factors that represent the true operational profile of the vessel providing more accurate means of estimating survivability. As a result, two solutions have been envisaged that address both ships in operation and design phase.

viii. A systematic sensitivity on the permeability of different spaces has been performed using static and dynamic time-domain simulations for different size cruise ships. The results demonstrated that the variation of permeability in large spaces has significant effect while, change of permeability in small spaces can have large contribution to the global survivability of the vessels in waves. To this end, actual permeability values are necessitated in the current SOLAS framework for more reliable and accurate prediction of survivability.

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Appendix A: Complementing chapter 3

Stockholm Agreement (SA)

In the foregoing, a few remarks are provided on the Stockholm Agreement, which applies to RoRo ships. The Stockholm Agreement (IMO, 1996) (SA) does not correspond to any specific statistical or physical model. Nevertheless, it may be observed that the requirements for the residual freeboard and the limiting wave height are closely related to the research that led the SEM survivability model. Specifically, the requirements can be linked to the foregoing facts and assertions,

- The mechanism of capsize of a RoRo/RoPax ship involves steady accumulation of floodwater on a cargo deck(s)
- In order to prevent capsize with water on deck the ship should have sufficient reserve of stability
- About 90% recorded collisions have occurred in sea states below 2m Hs

Therefore, Stockholm Agreement is a measure aiming at preventing capsize either by restricting floodwater ingress into a vehicle deck (by ensuring large residual freeboard) or by maintaining substantial stability reserve (by ensuring positive stability with the additional mass on the vehicle deck).

Furthermore, although Stockholm Agreement is a deterministic provision and cannot be directly compared to the probabilistic frameworks of SOLAS, it seems reasonable to assume that the additional requirements for residual freeboard and stability might result in survivability of a measurable proportion damages exceeding the statutory one- and/or two-compartment standard.

Extended research from (Vassalos and Papanikolaou, 2002b, Vassalos and Papanikolaou, 2002a) comprised two studies. According to the first part, the comparative study between the available regulatory instruments indicated clearly that whilst SOLAS '90 represents meaningfully a level of safety, which is generally in agreement with that determined through performance-based standards, the Stockholm Agreement appears to be unrealistically stringent. This is also highlighted from (Tagg, 2014), where SA was considered the stringent standard in place while the later efforts of IMO SOLAS09 failed to provide a reasonable safety standard in the case of RoRo ships. In addition to this, the introduction of the Stockholm Agreement oriented attention on the safety of Ro-Ro passenger ships aiding in the promotion of a safety culture in shipping, pushing safety at the centre of the ship design process and instilling this to ship designers and operators as a through life-cycle vital.

In the second study (Vassalos and Papanikolaou, 2002a), the SSRC and NTUA assessed the impact of the standards of RoRo ships established in the North European countries. In light of the research, SOLAS '90 ships demonstrated to be capable of surviving sea states at higher than 2.5 meters significant wave height Hs and that in general accentuated that SOLAS90 is a good standard in place. The Stockholm Agreement demonstrated as unrealistically stringent, in general demanding levels of safety well beyond those determined through performance-based methods (model test method) and, at times, simply unattainable.

Safe Return to Port (SRtP)

The capsizing event of Costa Concordia along with the fire of engine room on board Carnival triumph indicate that hundred years after the tragic sinking of the ocean liner Titanic, passenger ships are still not adequately safe. This led the IMO Maritime Safety Committee to adopting a new philosophy and working approach for developing safety standards for passenger ships. Modern safety expectations are expressed as a set of specific safety goals and objectives, addressing design (prevention), operation (mitigation) and decision making in emergency situations with a principal safety goal: no loss of human life due to ship related accidents. IMO stipulates the following:
"A passenger ship shall be designed so that specified systems remain operational when the ship is subject to flooding of any single watertight compartment". (IMO, 2007b) MSC216 (82)

The term "Safe Return to Port (SRtP)" has been widely adopted in discussing this framework, which addresses all the basic elements pre-requisite to quantifying the safety level of a ship at sea. "Safe Return to Port" means new SOLAS regulations applicable to new passenger having a length of 120m or more or encompassing 3 or more Main Vertical Zones. As per these regulations, a passenger ship shall be designed so that the essential systems remain operational after a fire casualty which does not exceed casualty threshold or a flooding of any single watertight compartment and the ship is able to proceed to a safe port under their own power. This may sound simple in theory, but in reality poses a real challenge to ship designers. A casualty threshold includes a loss of space of fire origin up to the nearest "A" class division if the space is protected by a fixed fire-extinguishing system, or a loss of the space of origin and adjacent spaces up to the nearest "A" class divisions which are not part of the space of fire origin if it is not protected by a fixed fire-extinguishing system.

The four basic elements of the safe return to port concept are highlighted in the foregoing:

〉 Prevention/Protection: Emphasis must be placed on preventing the casualty from happening in the first place as well as on in-built safety to limit consequences. Attention must also be paid to the related international regulations addressing prevention of accidents.

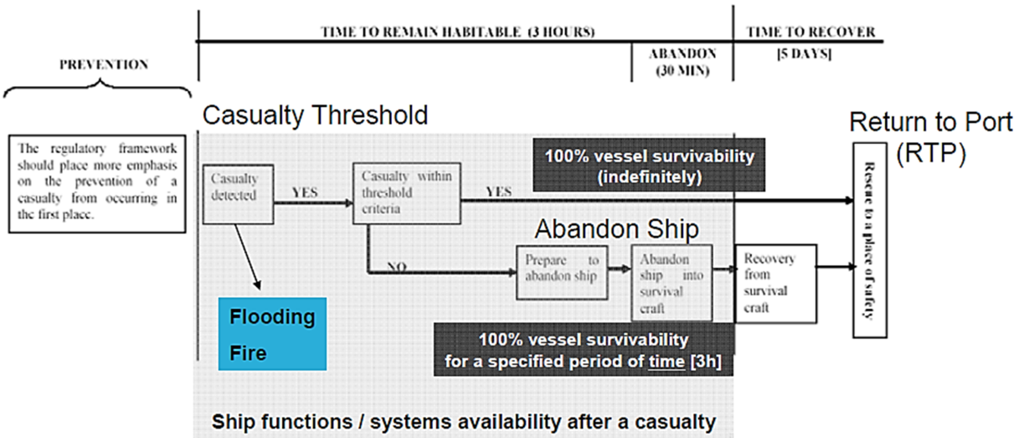


Figure 118: IMO (SLF47/48) framework for passenger ship safety. Safe Return to Port via achievement of specific goals (Vassalos, 2009a).

- Time-line Development: The new focus here is on the time-line development of different events. For the first time in the history of rulemaking, it is not only important to know whether a vessel will survive a given casualty in a given loading condition and operating environment, but also the time the vessel will remain habitable and the time it takes for safe and orderly abandonment and for recovery of the people on board.
- Casualty Threshold: This advocates the fact that the ship should be designed for improved survivability so that in the event of a casualty, persons can remain safely on board as the ship proceeds to port. In this respect and for design purposes only, a casualty threshold needs to be defined whereby a ship suffering a casualty below the defined threshold is expected to stay upright and afloat and be habitable for as long as necessary in order to return to port under its own power or wait for assistance. Currently it constitutes part of the design process to determine this value rationally, as it greatly influences the design arrangements.
- Emergency Systems Availability/Evacuation and Rescue: Should the casualty threshold be exceeded the ship must remain stable and afloat for sufficiently long time (3 hours recommended) to allow safe and orderly evacuation (assembly, disembarkation and abandoning) of passengers and crew. Emergency system availability is implicit in the framework in order to perform all requisite functions in any of the scenarios considered. In addition, the ship should be crewed, equipped and have arrangements in place to ensure the health, safety, medical care and security of

persons on board in the area of operation, taking into account climatic conditions and the availability of SAR functions until more specialised assistance is available.

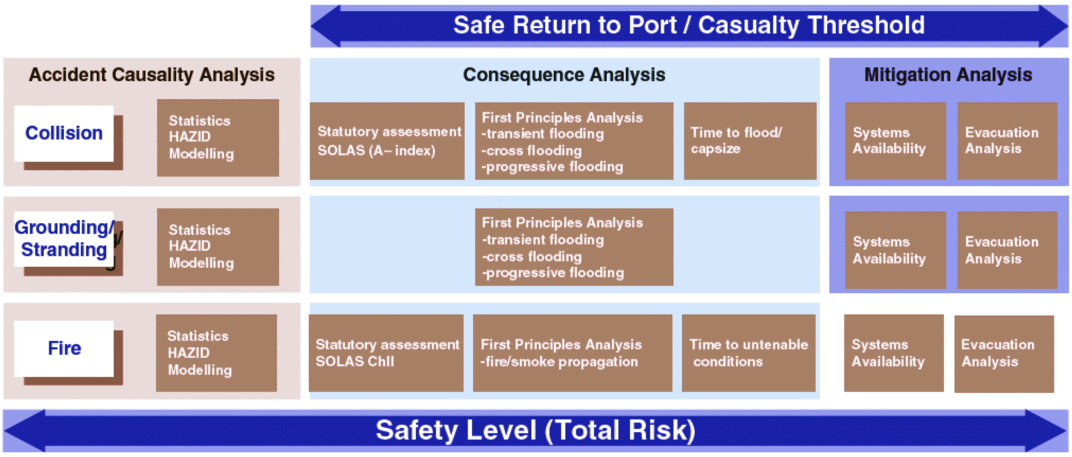


Figure 119: Risk-based design implementation with indication of the safety level (Vassalos, 2009a).

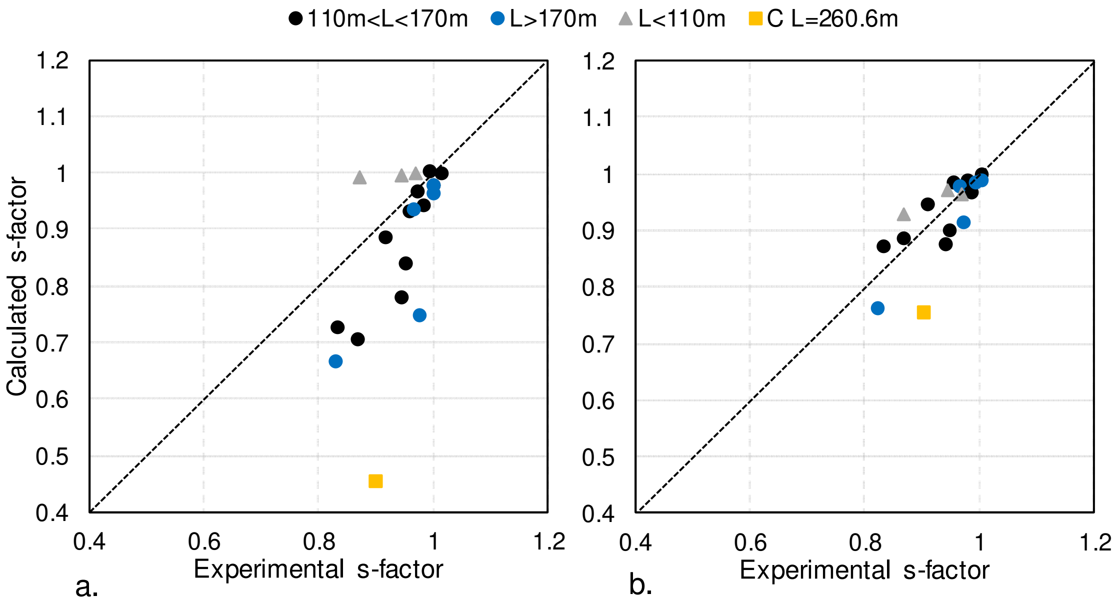


Figure 120: Comparison of calculated s-factor (regressed formula using targeting values) and experimental s-factor (using residual stability properties from experiments) for a) SOLAS 2009/HARDER formulation b) GOALDS proposed formulation. One point of the cruise ship is depicted with the yellow square while the rest of the points represent different size RoPax vessels.

Figure 120 indicates the correlation between obtained (projects HARDER (SOLAS'09) and GOALDS respectively) and experimental s-factors and experimental of survivability factors. As it can be observed, the obtained GOALDS s-factor formulation achieves better correlation to the experimental data. This demonstrates that the GOALDS formulation is efficient in the manner in which it facilitates for ship scaling effects.

PROTEUS (Numerical code for dynamic damage stability assessment)

PROTEUS is a state-of-the-art time-domain numerical simulation tool capable of handling complex geometries. It has been developed and validated on the basis of systematic research work conducted over the past 26 years (Turan, 1993, Letizia, 1996, Jasionowski, 2001).

Particularly, ship hydrodynamics, derived from properties of the intact hull, are based either on asymmetrical strip theory formulation with Rankine source distribution or NewDrift (Papanikolaou and Zaraphonitis, 2001), accounting for non-linearity pertaining to the instantaneous variation of the ship behaviour and large amplitude motions. The effects of floodwater dynamics are described by a full set of non-linear equations derived from the rigid-body theory. PROTEUS has the capability of modelling floodwater motions as a Free Mass on Potential Surface (FMPS) de-coupled system in an acceleration field but this has not been used in the presented research. Water ingress/egress is based on Bernoulli's equation (Jasionowski and Vassalos, 2001).

All forces are predicted with conventional for Naval Architecture methods. The Froude-Krylov and restoring forces and moments can be integrated up to the instantaneous wave elevation or a conventional linear approach while, the radiation and diffraction forces and moments are derived from linear potential flow theory and expressed in time domain based on convolution and spectral techniques (Jasionowski and Vassalos, 2001). The correction for viscous effects on roll and yaw modes of motion is applied based on the well-established empirical methods and the second order drift and current effects are catered for through a set of parametric formulations. Naturally the gravity force and moment vectors correspond to ship and floodwater masses. The model includes a non-linear definition of the hydrodynamic coefficients varying with the vessel mean behaviour (heave, heel and trim) using the “database” approach. This in turn encompasses the generation of the hydrodynamic coefficients beforehand and uses interpolation between these forces during the actual simulations.

The equations of ship motions are solved for the position of the centre of gravity of the intact ship in gravity field and rotations of a vector through a 4th order Runge-Kutta-Feldberg integration scheme with a variable step size. Since the database generation usually requires extensive computational effort, particular attention has been paid towards enabling easy variation of the centre of gravity of the ship (particularly KG), without the requirement of regenerating the whole database. This has been achieved by formulating the equations of motions in a reference system located at an arbitrary location A and not, as is common practice, at the centre of gravity \G" of the ship. As mentioned earlier, the floodwater motion (velocity and acceleration) is modelled as a free mass point (Free Mass Potential Surface) on potential moving due to the acceleration field and it is geometrically restrained by predetermined potential surfaces of centre of buoyancy for given amount of floodwater (FMPS) (internal sloshing model). Alternatively, the floodwater mass centre position is predicted simply from the intersection of tank geometry and the water elevation inside the tank while the liquid free surface is assumed to be parallel to the sea level.

The output from PROTEUS includes time or frequency histories of the ship motions and accelerations, as well as floodwater mass, elevation and attitude in every modelled compartment of the ship. PROTEUS can perform Monte Carlo (MC) simulations estimating the likelihood of capsizing associated with the global range of damages along the ship length. As presented in the thesis, knowing that both the extents of damage and sea environment are random, a Monte Carlo sampling scheme can be employed to generate damage cases according to collision or grounding damage statistics.

Appendix B: Modelling of survivability in waves

The following tables summarise the results obtained through the time-domain numerical simulations for the purposes of the derivation of the the survivability factor employing the statistical approach to damage survivability for the four ships and different damages.

Ship A – D1

Hs crit	GMACT	KG	AGZ	MAXGZ	RANGEF	WFL	Heel
8.9	2.393	18.2	0.1157	0.38	21	10548.8	1.8
8.7	2.275	18.3	0.1006	0.34	20.7	10567.7	1.9
7.5	2.139	18.415	0.0842	0.3	20.3	10592	1.9
5.5	1.981	18.55	0.0662	0.25	19.7	10623.5	2
4.7	1.922	18.6	0.0599	0.24	19.5	10636.7	2.1
4.3	1.806	18.7	0.0479	0.2	19	10665.8	2.1
4	1.794	18.71	0.0468	0.2	19	10668.8	2.1
2.9	1.783	18.72	0.0456	0.2	18.9	10671.8	2.1
2.75	1.765	18.735	0.044	0.19	18.8	10676.4	2.1
2.5	1.759	18.74	0.0434	0.19	18.8	10678	2.2
2	1.748	18.75	0.0423	0.19	18.7	10681.2	2.2
2	1.742	18.755	0.0417	0.18	18.7	10682.7	2.2
1.9	1.736	18.76	0.0412	0.18	18.7	10684.3	2.2
1.75	1.722	18.775	0.0396	0.18	18.6	10698.1	2.2

Ship C – D1

Hscr	GM	GMA	KG	RAN	GZM	AGZ	RANG	GZMA	AFA	WFL
7	2.38	1.448	20.05	27.3	0.42	0.118	7	0.19	0.011	12809
7	2.33	1.394	20.1	27	0.4	0.111	6.9	0.18	0.010	12808
6	2.28	1.344	20.15	26.7	0.38	0.105	6.9	0.17	0.010	12806
5.55	2.23	1.294	20.2	26.3	0.37	0.099	6.8	0.16	0.009	12804
4.75	2.17	1.234	20.26	25.9	0.34	0.092	6.7	0.16	0.009	12801
4.75	2.17	1.231	20.26	25.9	0.34	0.092	6.7	0.15	0.009	12801
4.5	2.17	1.229	20.26	25.9	0.34	0.092	6.7	0.15	0.009	12801
3.3	2.16	1.224	20.27	25.8	0.34	0.091	6.7	0.15	0.009	12801
3	2.15	1.214	20.28	25.8	0.34	0.090	6.7	0.15	0.008	12800
2.5	2.14	1.204	20.29	25.7	0.33	0.089	6.6	0.15	0.008	12800
2.5	2.13	1.194	20.3	25.6	0.33	0.088	6.6	0.15	0.008	12800
1.25	2.12	1.184	20.31	25.6	0.33	0.086	6.6	0.15	0.008	12799
1.5	2.13	1.189	20.30	25.6	0.33	0.087	6.6	0.15	0.008	12799

Ship C – D2

Hs	GM	GMA	KG	RAN	GZM	AGZ	RANG	GZMA	AFA	WFL
4	2.17	0.747	20.26	18.7	0.21	0.038	3.3	0.05	0.001	9540.
7	2.28	0.757	20.15	20.6	0.25	0.049	4.6	0.07	0.002	9499.

Ship B – D1

Hs crit	GMprot	GMACT	KG	GZMAX	AGZ	RANGEF	WFL
5.5	5.57	2.808	23.6	0.35	0.0736	18.5	11506.6
3.5	5.37	2.659	23.8	0.27	0.0489	16.1	11866.7

Ship A - D2

Hs_crit	GM Initial	GMACT	KG	RANGE	GZ max	AGZ	WFl	Heel
6.4	1.626	0.908	19.2	21	0.16	0.0362	1165.9	7.7
5.75	1.615	0.896	19.25	20.8	0.15	0.0348	1171.1	8.1
4.8	1.572	0.836	19.3	19.9	0.14	0.0298	1192.6	8.9
4.25	1.552	0.812	19.32	19.5	0.13	0.0275	1203.3	9
7	1.772	1.09	19.1	23.5	0.21	0.055	1107.4	9.5
6.7	1.722	1.024	19.15	22.7	0.19	0.0483	1125.5	9.7

Ship A - D3

Hs_crit	GM Initial	GMACT	KG	RANGE	GZ max	AGZ	WFl	Heel
6.8	1.273	0.998	19.6	21.3	0.13	0.0326	4625.7	7.1
6	1.223	0.911	19.65	20.3	0.12	0.0271	4635.8	7.5
5.5	1.173	0.819	19.7	19.2	0.1	0.0219	4646.7	8
4.5	1.123	0.722	19.75	18	0.08	0.017	4658.7	8.5

Ship A – D4

Hs_crit	GM Initial	GMACT	KG	RANGE	GZ max	AGZ	WFl	Heel
5.5	2.536	0.899	18.65	23.3	0.19	0.0469	3477.6	9.1
5.2	2.486	0.846	18.7	22.2	0.16	0.0399	3506	9.6
5	2.436	0.792	18.75	21.2	0.14	0.0333	3537.3	10.2
4.6	2.416	0.77	18.77	20.8	0.13	0.0307	3550.7	10.5
3.5	2.411	0.765	18.77	20.6	0.13	0.03	3554.1	10.6
2.5	2.401	0.754	18.78	20.4	0.13	0.0288	3561.1	10.7

Ship A – D5

Hs_crit	GM Initial	GMACT	KG	RANGE	GZ max	AGZ	WFl	Heel
3	1.722	1.483	19.1	19	0.15	0.0332	10362.	7.3
3.5	1.822	1.736	19.05	20.3	0.18	0.0432	10337.	6.9
3.9	1.872	1.786	19	21	0.2	0.0485	10326.	6.7
4.5	1.972	1.885	18.9	22.1	0.23	0.0595	10304.	6.3
5.2	2.172	2.084	18.7	24.1	0.29	0.0837	10266.	5.7
6	2.372	2.302	18.5	25.9	0.36	0.1105	10234.	5.2

Ship A – D6

Hs_crit	GM Initial	GMACT	KG	RANGE	GZ max	AGZ	WFl	Heel
6.4	4.371	3.318	16.5	32.2	0.68	0.2445	12152.	6
6.2	4.221	3.169	16.65	30.9	0.61	0.2139	12186	6.3
5.5	4.171	3.119	16.7	30.5	0.59	0.2041	12197.	6.4
5	4.071	3.02	16.8	29.7	0.55	0.185	12222.	6.6
4.5	3.971	2.92	16.9	28.8	0.51	0.1666	12249.	6.8
3.8	3.876	2.834	16.95	28	0.47	0.1498	12276.	7.1
2.8	3.869	2.826	17	27.9	0.47	0.1486	12278.	7.1
1.5	3.821	2.773	17.05	27.5	0.45	0.1403	12292.	7.2

Ship C – D3								
Hs_crit	**GM Initial**	**GMACT**	**KG**	**RANGE**	**GZ max**	**AGZ**	**WFl**	**Heel**
7	0.639	0.658	21.8	13.8	0.07	0.0115	2121.1	9.7
5.5	0.589	0.607	21.8	12.4	0.06	0.0082	2130.9	10.5
5	0.539	0.555	21.9	10.7	0.04	0.0053	2143.2	11.5
4.8	0.489	0.502	21.9	8.6	0.03	0.0029	2158.3	12.6
2	0.439	0.449	22	6	0.01	0.001	2177.8	14

Ship C – D4								
Hs_crit	**GM Initial**	**GMACT**	**KG**	**RANGE**	**GZ max**	**AGZ**	**WFl**	**Heel**
7.9	2.239	1.457	20.2	24.3	0.42	0.1039	7685.8	6.8
7.1	1.939	1.158	20.5	21	0.31	0.0654	7645	8.5
6.9	1.739	1.045	20.7	18.1	0.23	0.043	7603.4	10.2
5.5	1.639	0.963	20.8	16.4	0.19	0.033	7574.4	11.3
4.4	1.539	0.948	20.9	14.4	0.16	0.024	7541.5	12.5
3.2	1.489	0.965	20.9	13.4	0.14	0.0199	7527.9	13.2
2.8	1.439	1.002	21	13.9	0.12	0.0161	7548.3	12.3
1.7	1.289	1.082	21.1	8.8	0.07	0.0066	7510.7	15.9
1	1.239	1.044	21.2	7.4	0.05	0.0041	7514.6	16.7

Ship C – D5								
Hs_crit	**GM Initial**	**GMACT**	**KG**	**RANGE**	**GZ max**	**AGZ**	**WFl**	**Heel**
5.8	2.739	1.894	19.7	28.3	0.44	0.132	10968.	2
4.7	2.689	1.845	19.7	28	0.43	0.1253	10967.	2.1
4.5	2.639	1.795	19.8	27.7	0.41	0.1186	10967.	2.1
3.5	2.439	1.595	20	26.4	0.33	0.0932	10964.	2.4
2.5	2.239	1.395	20.2	24.9	0.26	0.0697	10961.	2.7
2	2.139	1.295	20.3	24	0.23	0.0587	10959.	2.9
1.8	2.089	1.222	20.3	23.6	0.21	0.0534	10957.	3.1

Ship D – D1								
Hs_crit	**GM Initial**	**GMACT**	**KG**	**RANGE**	**GZ max**	**AGZ**	**WFl**	**Heel**
4.6	1.815	0.974	8.85	11	0.19	0.121	1928.8	5.5
4.7	1.865	1.025	8.8	11.3	0.21	0.1324	1926.7	5.2
4.8	1.965	1.123	8.7	11.8	0.24	0.1553	1923.2	4.8
4.9	2.065	1.219	8.6	12.2	0.26	0.1783	1920.3	4.4
5	2.165	1.316	8.5	12.5	0.29	0.2013	1917.8	4
5.1	2.265	1.413	8.4	12.8	0.32	0.2244	1915.6	3.8
5.25	2.365	1.51	8.3	13	0.35	0.2476	1913.6	3.5
5.4	2.465	1.608	8.2	13.2	0.38	0.2708	1911.9	3.3
5.8	2.665	1.805	8	13.6	0.44	0.3172	1909.1	2.9

Ship D – D2								
Hs_crit	**GM Initial**	**GMACT**	**KG**	**RANGE**	**GZ max**	**AGZ**	**WFl**	**Heel**
3.8	0.665	0.141	10	29.8	0.08	0.0206	1049.6	0
4.6	1.065	0.542	9.6	36.3	0.24	0.0865	1048.8	0
4.9	1.115	0.593	9.55	37	0.26	0.0964	1048.7	0
5	1.165	0.643	9.5	37.7	0.28	0.1067	1048.6	0
5.4	1.465	0.948	9.2	41.5	0.42	0.1758	1047.9	0
5.6	1.665	1.149	9	43.9	0.51	0.2289	1047.5	0
6.75	1.865	1.35	8.8	46.3	0.6	0.28	1047.1	0

Application of scaling using different basis ships

The robustness of the scaling factor approach has been examined through applying scaling using different basis ships namely ship C (Damage C2) and B (Damage B1). As it is apparent from the following results, scaling is successfully achieved in the two cases bringing the point sets close so that an accurate regression is feasible.

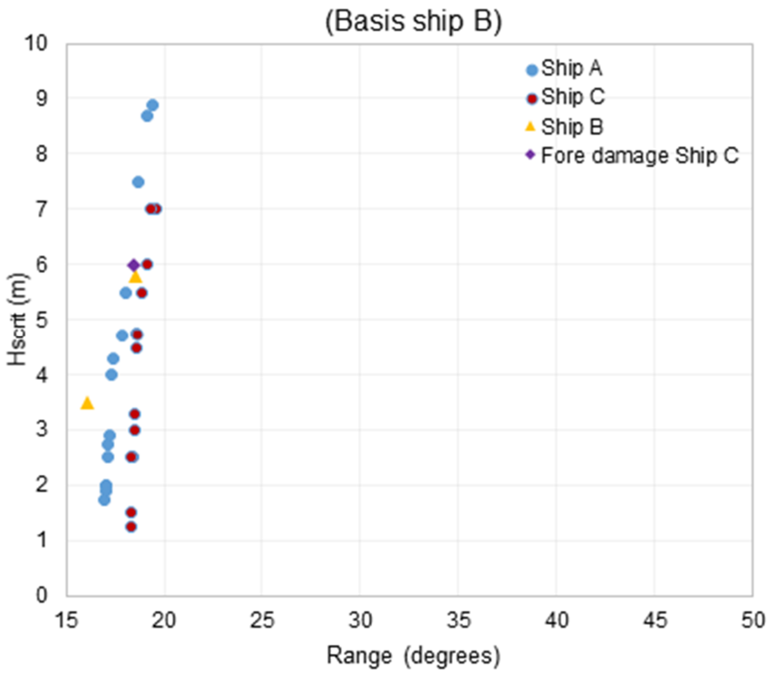


Figure 121: Application of scaling on sample ship results using ship B, damage B1 as basis for Hscrit and Range results.

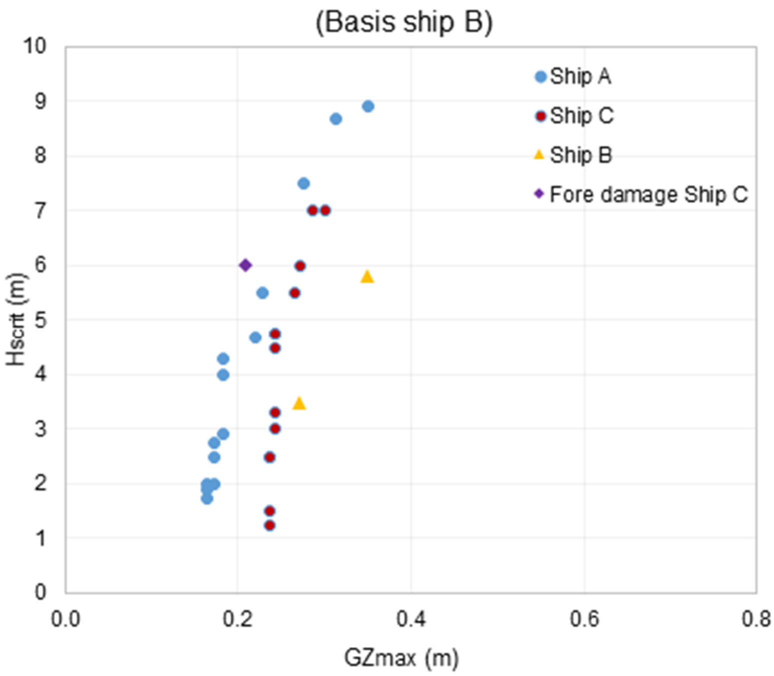


Figure 122: Application of scaling on sample ship results using ship B, damage B1 as basis for Hscrit and

GZmax results.

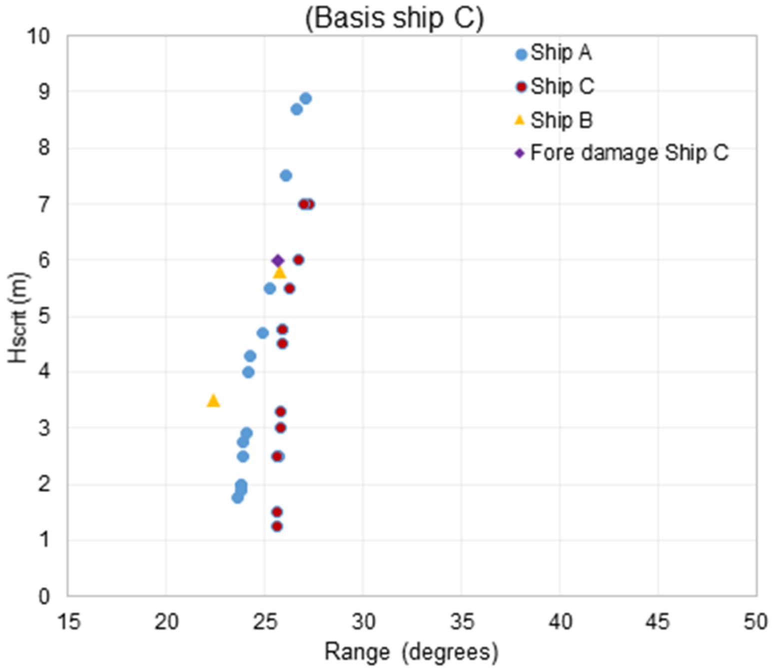


Figure 123: Application of scaling on sample ship results using ship C, damage C2 as basis for Hscrit and Range results.

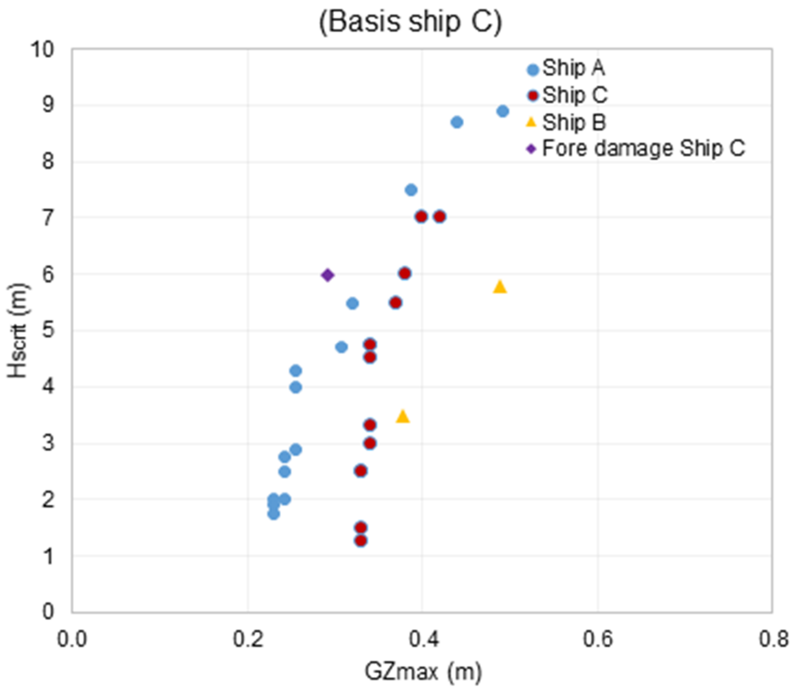


Figure 124: Application of scaling on sample ship results using ship C, damage C2 as basis for Hscrit and GZmax results.

Appendix C: Accidents at Sea Database

No#	Ship type	Damage type	Ship Length (m)	Ship GT	Accident Year	Hs (m) (Time of accident)	Tz (s) (Time of accident)
1	cruise ship	Collision	207.3	41662	2005	2.08	5.79
2	cruise ship	Collision	294.1	91740	2005	1.1	5.41
3	cruise ship	Collision	280.6	80439	2005	2.91	7.99
4	cruise ship	Collision	301.4	82910	2006	1.87	5.54
5	cruise ship	Collision	260.6	70367	2007	1.11	3.97
6	cruise ship	Collision	174	70367	2007	0.45	3.48
7	cruise ship	Collision	251.3	58.625	2007	0.51	3.99
8	cruise ship	Collision	229.8	50764	2007	1	3.94
9	cruise ship	Collision	220.6	52926	2008	0.87	4.03
10	cruise ship	Collision	293.8	92627	2008	0.87	4.03
11	cruise ship	Collision	208	47413	2008	0.12	3.41
12	cruise ship	Collision	104.8	4333	2009	0.05	2.81
13	cruise ship	Collision	301.4	82910	2009	0.13	2.92
14	cruise ship	Collision	292.5	85942	2009	0.13	2.92
15	cruise ship	Collision	145	15067	2010	1.69	5.56
16	cruise ship	Collision	214.7	33930	2010	0.49	3.44
17	cruise ship	Collision	288.6	113561	2011	0.54	3.59
18	cruise ship	Collision	294	90901	2013	1.75	5.85
19	cruise ship	Collision	272.8	101509	2013	1.45	4.17
20	cruise ship	Collision	262.5	77302	2013	0.7	3.46
21	cruise ship	Grounding	240.4	46087	2005	1.7	5.68
22	cruise ship	Grounding	122.73	8378	2005	1.42	7.25
23	cruise ship	Grounding	240.4	46087	2005	2.44	6.34
24	cruise ship	Grounding	117.4	7478	2005	0.55	3.4
25	cruise ship	Grounding	217.91	43537	2006	2.84	5.8
26	cruise ship	Grounding	223.4	47263	2006	0.5	3.84
27	cruise ship	Grounding	245.1	70285	2006	3.56	6.44
28	cruise ship	Grounding	142.95	22412	2007	0.97	5.2
29	cruise ship	Grounding	294	90963	2007	1.29	4.22
30	cruise ship	Grounding	208	47413	2009	0.04	2.88
31	cruise ship	Grounding	176.26	20704	2009	0.09	4.14
32	cruise ship	Grounding	88.32	4077	2009	4.22	6.86
33	cruise ship	Grounding	289.6	114147	2012	1.22	5.68
34	cruise ship	Grounding	142.1	10992	2013	0.95	4.55
35	RoPax	Collision	136	14588	2005	2.2	5.26
36	RoPax	Collision	96	3934	2005	2.42	5.43
37	RoPax	Collision	160	21535	2005	0.16	4.61

38	RoPax	Collision	157.6	20921	2005	0.4	4.19
39	RoPax	Collision	151.1	22940	2005	2.72	7.45
40	RoPax	Collision	214	36825	2005	2.58	5.84
41	RoPax	Collision	122.9	11193	2006	0.55	3.4
42	RoPax	Collision	84.2	7799	2006	0.68	4.82
43	RoPax	Collision	158	18653	2006	0.26	5.49
44	RoPax	Collision	154.9	28727	2006	0.39	4.64
45	RoPax	Collision	95.8	4511	2006	0.49	3.44
46	RoPax	Collision	213.2	48622	2007	0.51	3.79
47	RoPax	Collision	139.1	8845	2007	1.56	4.51
48	RoPax	Collision	96	3934	2007	1.84	5.38
49	RoPax	Collision	186	26847	2007	0.78	4.14
50	RoPax	Collision	145.8	13493	2007		9.17
51	RoPax	Collision	154.9	28727	2007	0.27	3.56
52	RoPax	Collision	179.3	26790	2007	0.6	4.19
53	RoPax	Collision	150.4	15848	2007	0.6	4.19
54	RoPax	Collision	179.4	31598	2007	1.35	5.24
55	RoPax	Collision	139.7	5753	2008	2.24	6.18
56	RoPax	Collision	118.1	4140	2008	0.48	4.57
57	RoPax	Collision	173	15223	2008	2.7	5.94
58	RoPax	Collision	203.3	30285	2008	0.95	7.62
59	RoPax	Collision	212.1	48915	2008	1.26	7.41
60	RoPax	Collision	204	32694	2008	2.84	5.57
61	RoPax	Collision	218.8	45923	2008	0.4	3.06
62	RoPax	Collision	183	33313	2008	0.4	3.06
63	RoPax	Collision	173.7	23933	2009	0.82	4.37
64	RoPax	Collision	187.1	27362	2009	0.85	5.09
65	RoPax	Collision	195.8	29746	2009	0.5	4.76
66	RoPax	Collision	179.7	30635	2010	0.43	8.32
67	RoPax	Collision	188.1	33724	2010	0.01	3.9
68	RoPax	Collision	169.4	34384	2010	0.01	3.9
69	RoPax	Collision	186.4	26904	2010	0.38	4.66
70	RoPax	Collision	135.8	15690	2010	2.93	6.28
71	RoPax	Collision	175	36093	2010	2.01	5.74
72	RoPax	Collision	136	14588	2011	1.22	4.5
73	RoPax	Collision	157.9	18653	2011	0.19	5.88
74	RoPax	Collision	150.9	19468	2011	0.9	3.68
75	RoPax	Collision	98	6554	2012	0.39	4.47
76	RoPax	Collision	186.5	21856	2012	0.93	4.65
77	RoPax	Collision	118.4	9042	2012	1.88	4.84
78	RoPax	Collision	190	36468	2012	0.3	3.89
79	RoPax	Collision	96	3934	2012	0.64	3.82
80	RoPax	Collision	186	33940	2012	1.08	4.05

81	RoPax	Collision	179.7	28138	2012	1.08	4.05
82	RoPax	Collision	96	5695	2013	1.14	6.93
83	RoPax	Collision	241.3	51837	2013	1.22	4.9
84	RoPax	Collision	199	25518	2013	0.7	3.46
85	RoPax	Grounding	162.7	21188	2005	4.44	7.5
86	RoPax	Grounding	154.9	28727	2005	0.22	5.28
87	RoPax	Grounding	186	21856	2005	0.54	5.09
88	RoPax	Grounding	112	8780	2006	0.97	5.36
89	RoPax	Grounding	173	13526	2006	0.68	3.86
90	RoPax	Grounding	123.3	11386	2007	0.42	6.43
91	RoPax	Grounding	165.7	35966	2007	1.15	10.69
92	RoPax	Grounding	133	16140	2007	0.91	6.27
93	RoPax	Grounding	154.9	28727	2008	1.11	5.48
94	RoPax	Grounding	179.7	30635	2008	3.74	7.87
95	RoPax	Grounding	192.9	23824	2008	1.5	4.68
96	RoPax	Grounding	109	5505	2008	0.82	4.55
97	RoPax	Grounding	121.8	11205	2009	1.62	8
98	RoPax	Grounding	84.9	3296	2009	1.93	5.99
99	RoPax	Grounding	203.3	30285	2009	2.4	5.48
100	RoPax	Grounding	211.9	31730	2009	0.22	4.08
101	RoPax	Grounding	121.8	11204	2011	0.99	8.55
102	RoPax	Grounding	142.9	20024	2011	1.53	4.7
103	RoPax	Grounding	129.5	6904	2011	0.89	8.73
104	RoPax	Grounding	212	47592	2011	3.16	8.05
105	RoPax	Grounding	121.8	11204	2013	1.47	4.63
106	RoPax	Grounding	150.9	19468	2013	0.43	4.42
107	RoPax	Grounding	93	5695	2013	1.35	7.04
108	RoPax	Grounding	200	28460	2013	0.92	5.13
109	RoPax	Grounding	72.8	2118	2010	3.97	8.62
110	RoPax	Grounding	79.4	2434	2005	0.56	3.87
111	RoPax	Grounding	70.4	1698	2006	1.88	6.16
112	RoPax	Grounding	70	1676	2008	0.52	3.68
113	RoPax	Grounding	78.7	1859	2008	1.6	7.53
114	RoPax	Grounding	46	1226	2008	0.46	3.48
115	RoPax	Grounding	58	1121	2010	0.57	4.1
116	RoPax	Grounding	70	1676	2010	1.28	4.63
117	RoPax	Grounding	58	1121	2010	1.34	6.91
118	RoPax	Collision	67.85	1743	2005	0.38	5.07
119	RoPax	Collision	67.85	2268	2005	0.38	5.07
120	RoPax	Collision	213.96	39798	2006	0.78	4.34
121	RoPax	Collision	125	11720	2010	5.43	9.93
122	RoPax	Collision	73.2	2286	2010	1.35	10.12
123	RoPax	Collision	142	15187	2009	0.45	3.38

124	RoPax	Collision	200.2	42705	2012	0.53	4.14
125	cruise ship	Collision	220.6	52926	2010	1.35	4.82
126	cruise ship	Grounding	72.8	2183	2009	1.35	8.45
127	cruise ship	Grounding	49.7	1268	2007	0.53	4.22
128	cruise ship	Grounding	63.1	1471	2007	1.58	4.77
129	cruise ship	Grounding	69.7	1815	2009	1.71	6.55

Appendix D: Impact of permeability

The following graphs provide an illustration of impact on the Attained subdivision Index for the three different damage stability loading conditions namely Adl, Adp and Ads for each of the sample ships along with an indication of their respective floodable volumes.

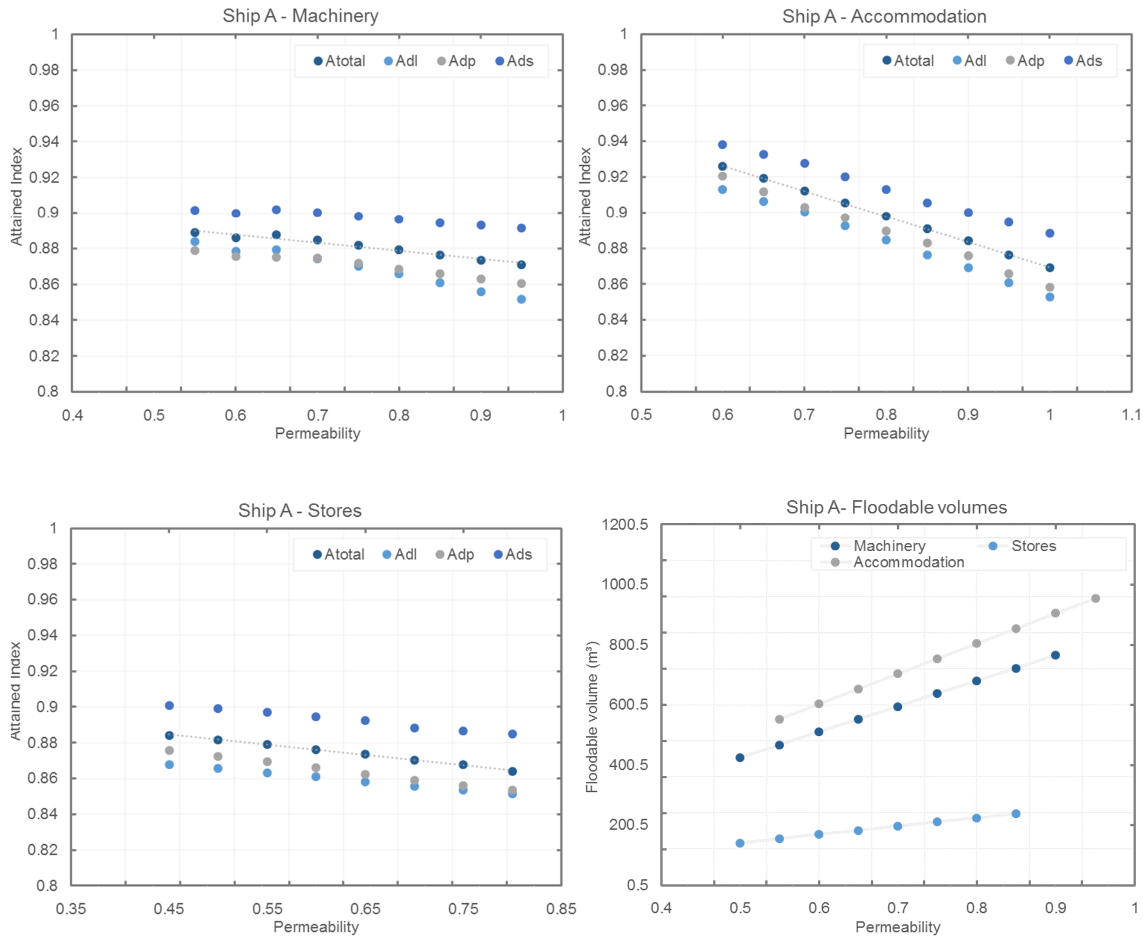
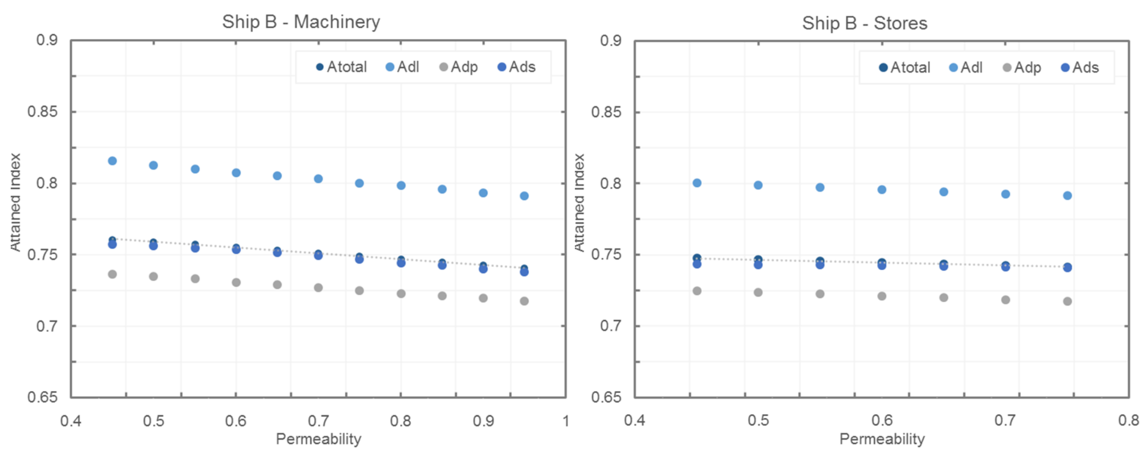


Figure 125: Ship A – Impact on Attained subdivision Index for machinery, stores and accommodation spaces along with the variation of the floodable volume in each case respectively



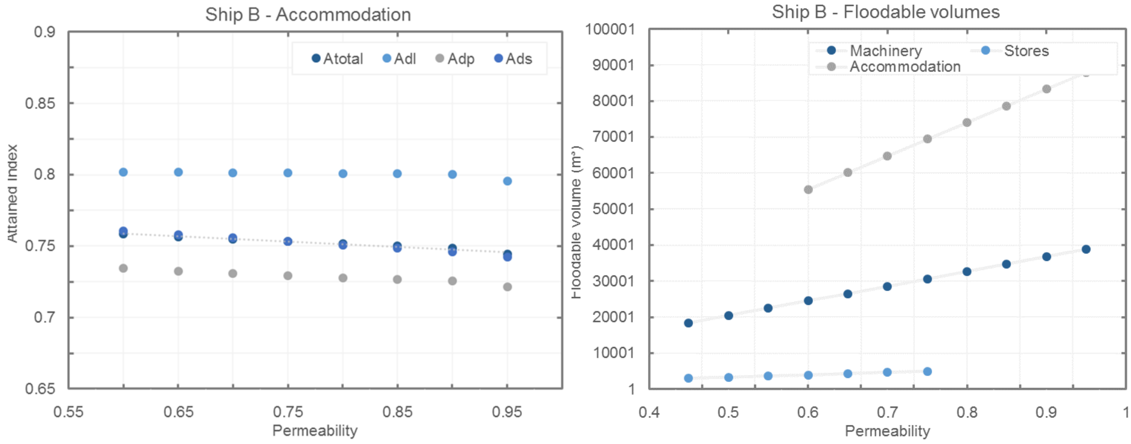


Figure 126: Ship B – Impact on Attained subdivision Index for machinery, stores and accommodation spaces along with the variation of the floodable volume in each case respectively

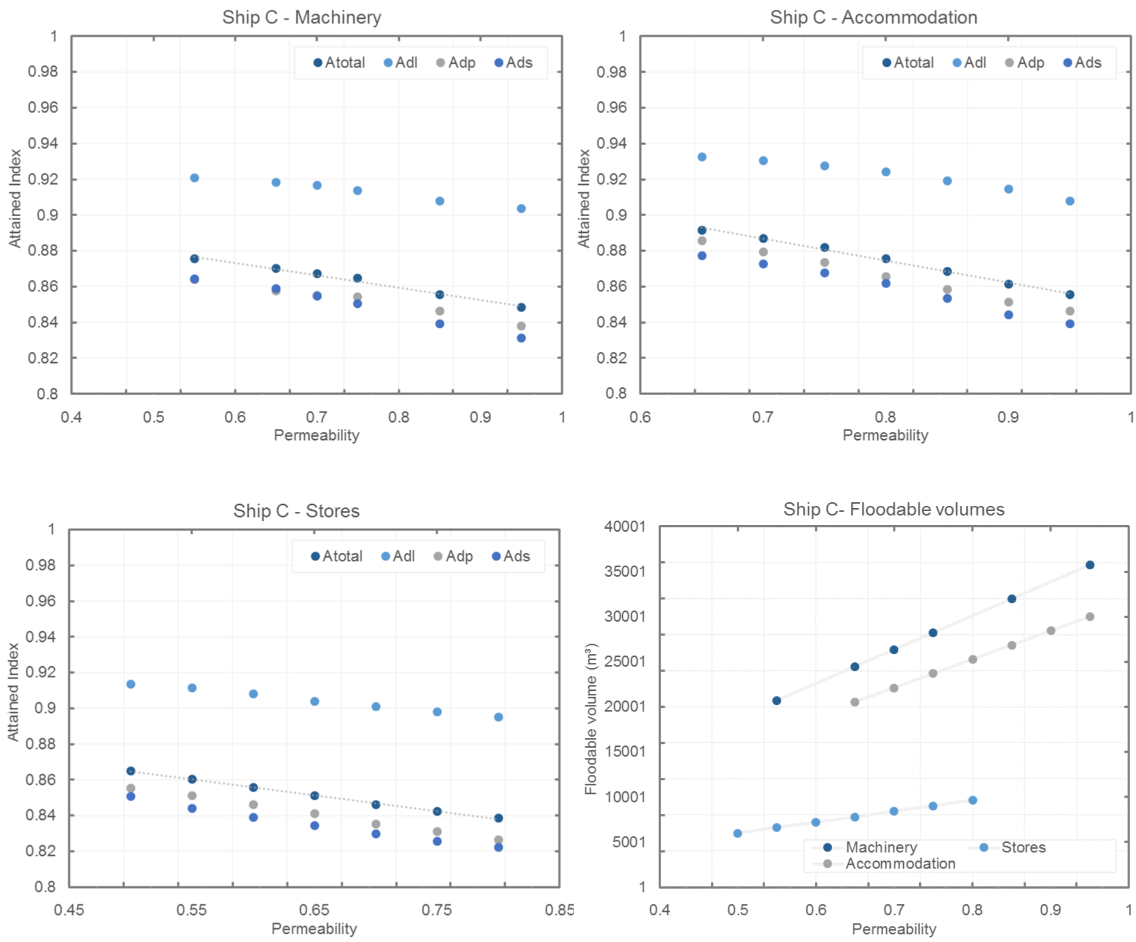


Figure 127: Ship C – Impact on Attained subdivision Index for machinery, stores and accommodation spaces along with the variation of the floodable volume in each case respectively

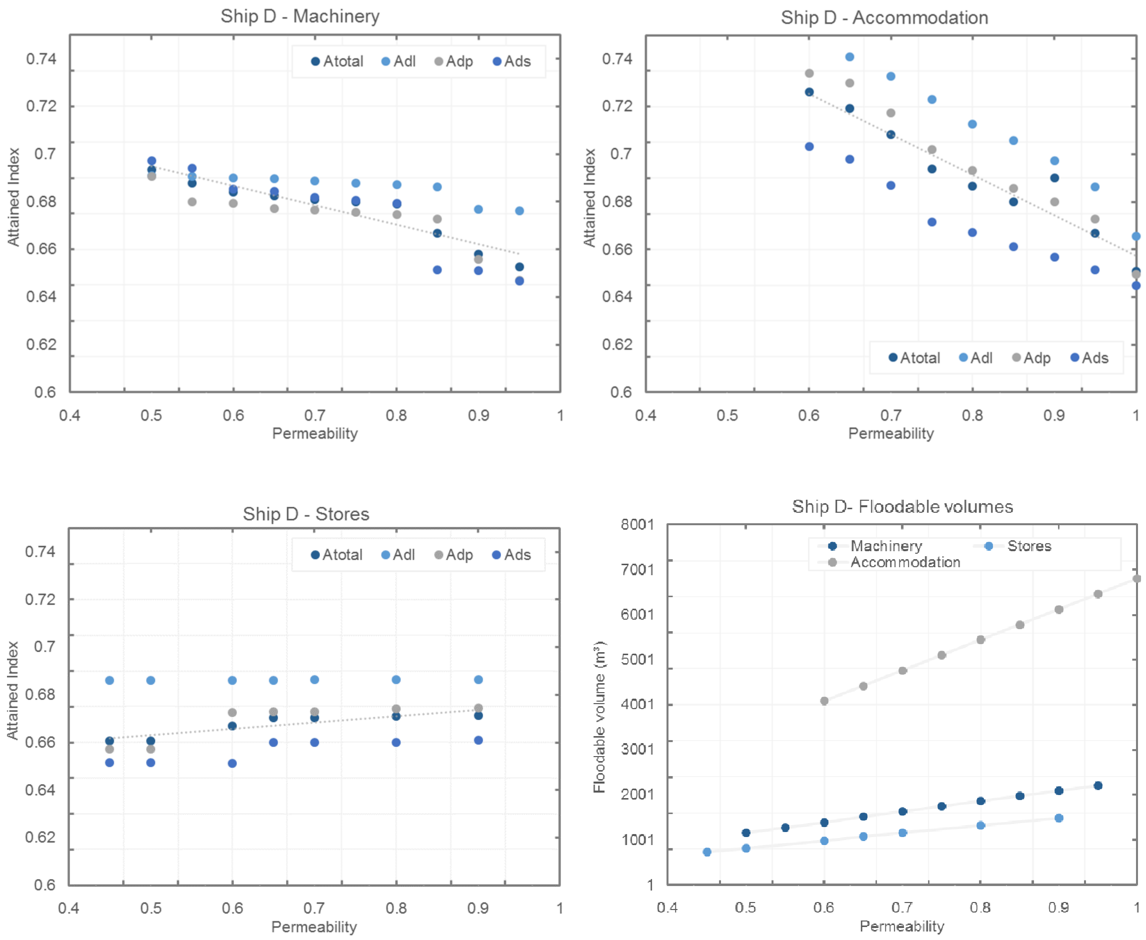
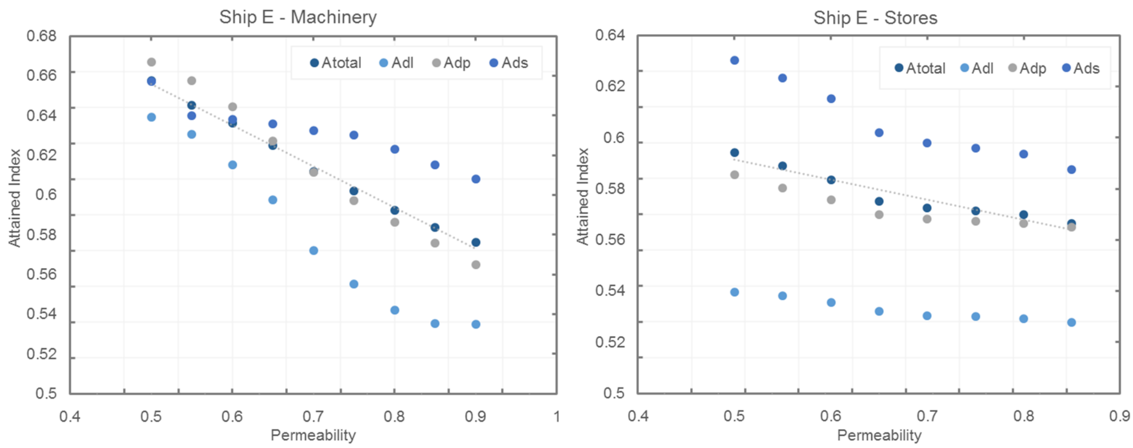


Figure 128: Ship D – Impact on Attained subdivision Index for machinery, stores and accommodation spaces along with the variation of the floodable volume in each case respectively



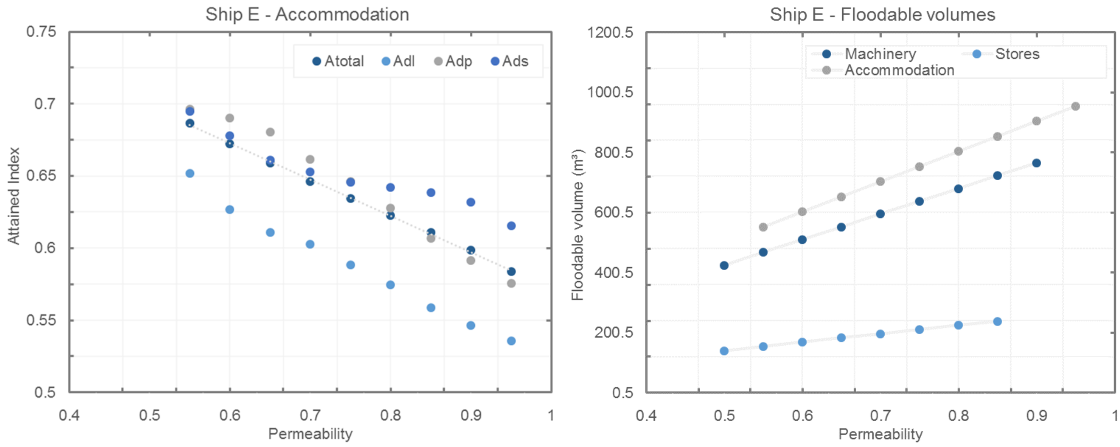


Figure 129: Ship E – Impact on Attained subdivision Index for machinery, stores and accommodation spaces along with the variation of the floodable volume in each case respectively

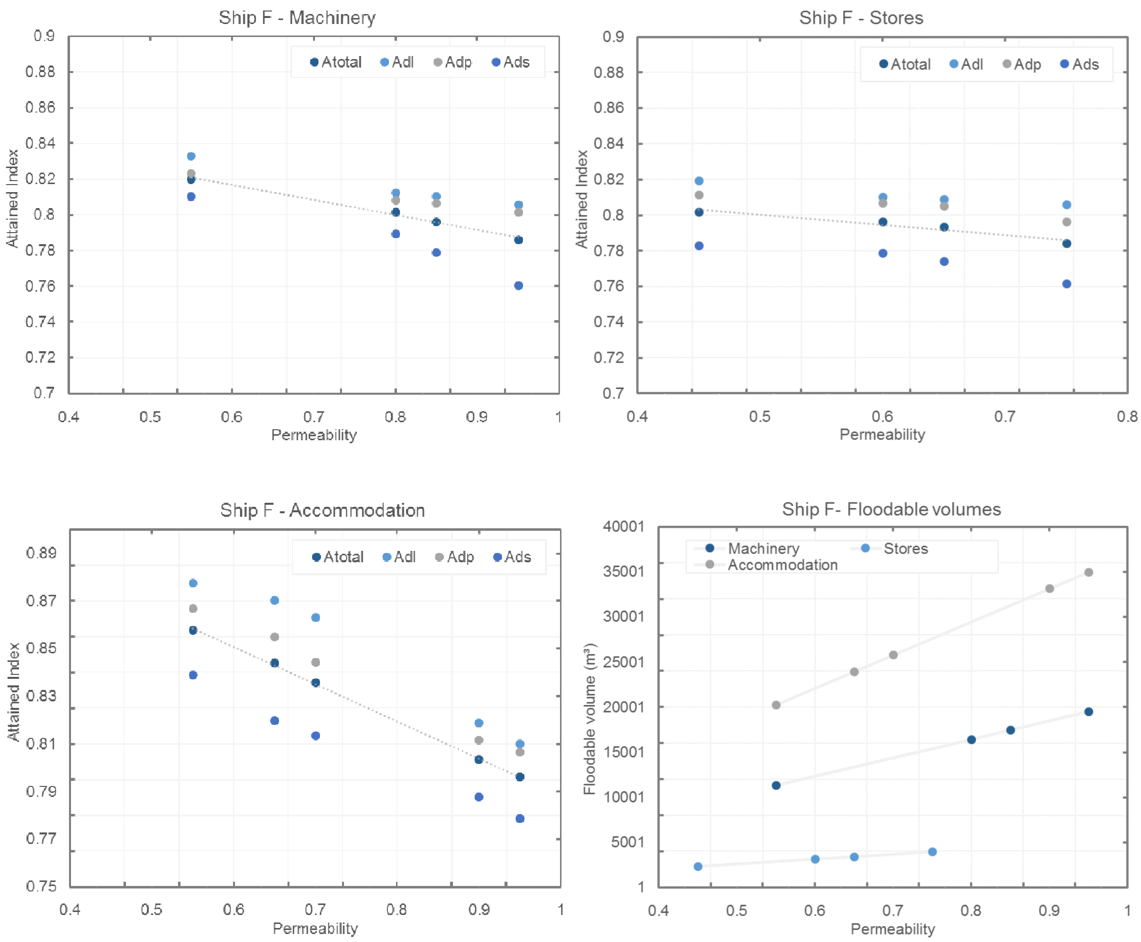


Figure 130: Ship F – Impact on Attained subdivision Index for machinery, stores and accommodation spaces along with the variation of the floodable volume in each case respectively

The following graphs provide the slope of the change of Attained Index and the permeability for each of the damage stability loading conditions namely Adl, Adp and Ads.

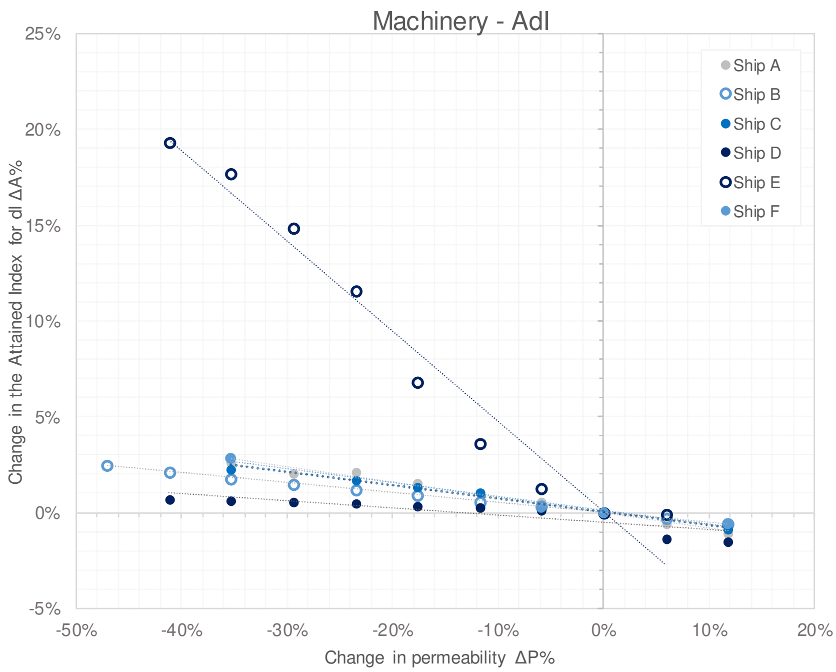


Figure 131: Change of slope of Attained index for the lightest condition and permeability for the case of machinery spaces.

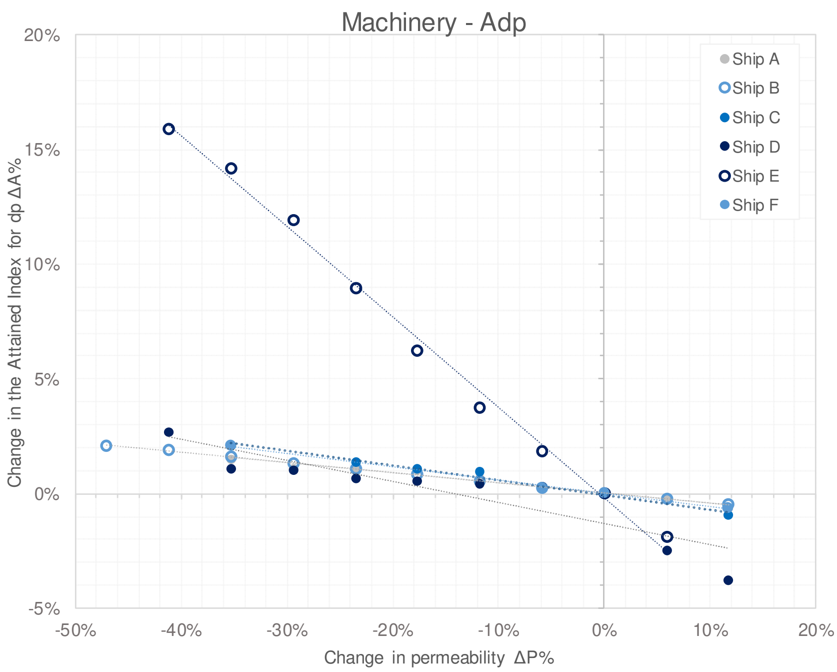


Figure 132: Change of slope of Attained index for the partial condition and permeability for the case of machinery spaces.

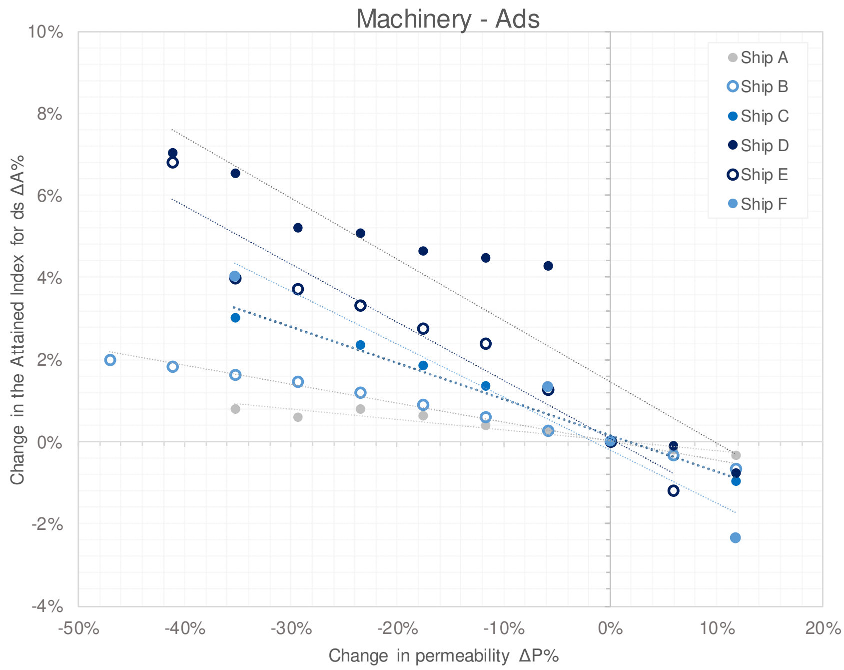


Figure 133: Change of slope of Attained index for the deepest condition and permeability for the case of machinery spaces.

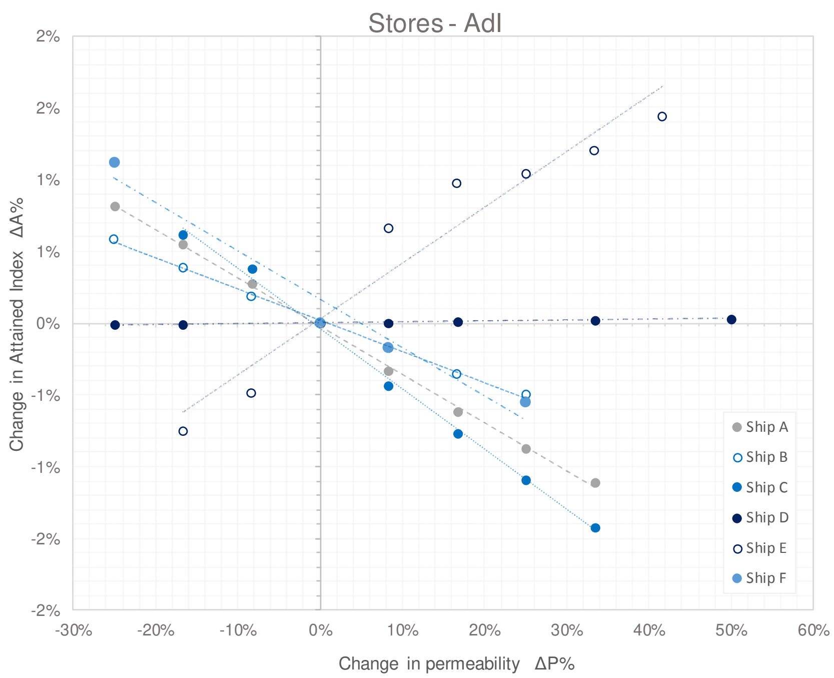


Figure 134: Change of slope of Attained index for the lightest condition and permeability for the case of store spaces.

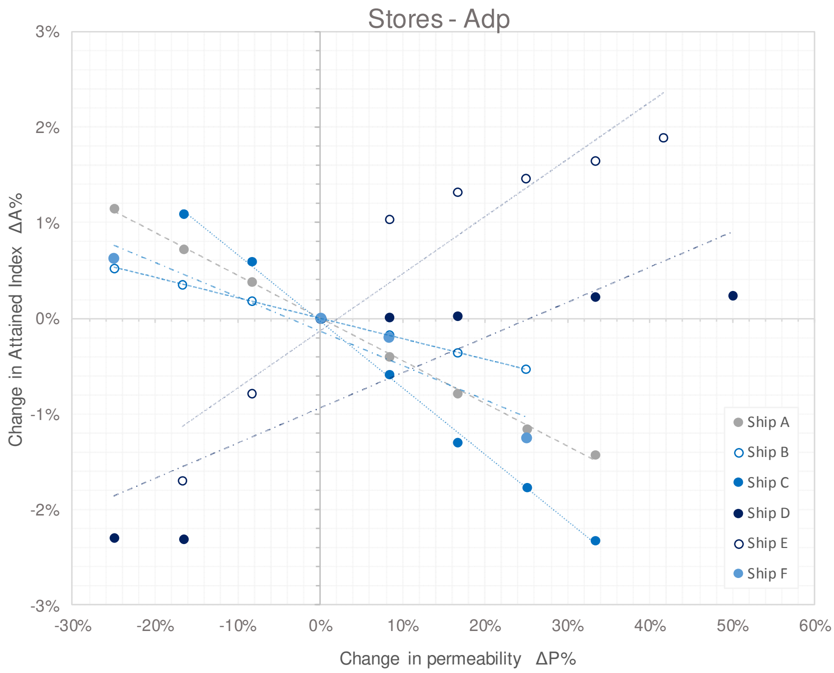


Figure 135: Change of slope of Attained index for the partial condition and permeability for the case of store spaces.

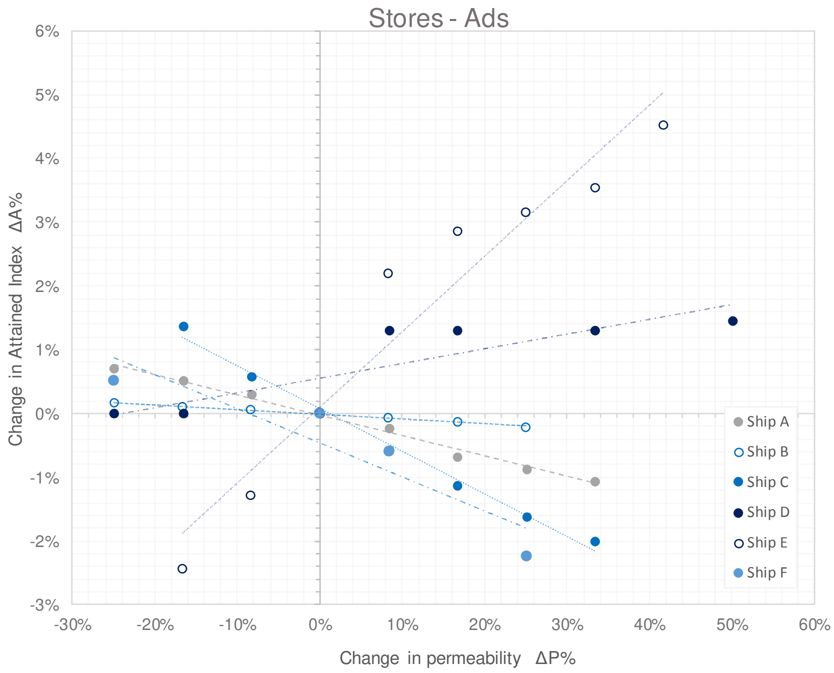


Figure 136: Change of slope of Attained index for the deepest condition and permeability for the case of store spaces.

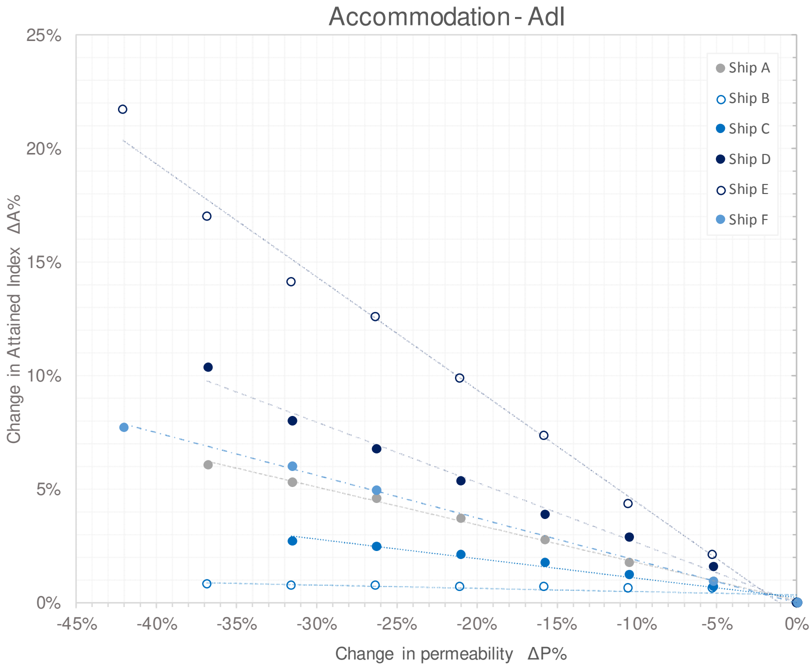


Figure 137: Change of slope of Attained index for the lightest condition and permeability for the case of accommodation spaces.

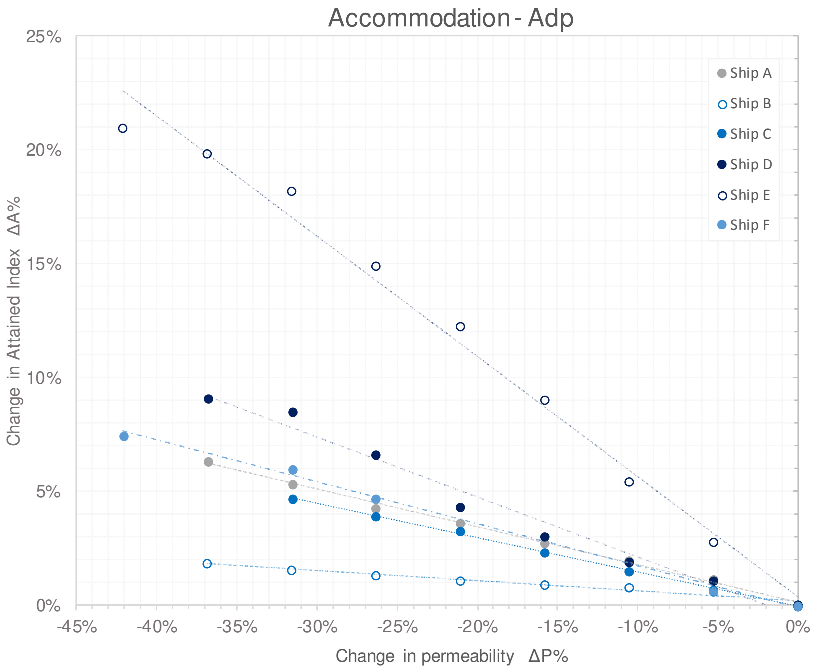


Figure 138: Change of slope of Attained index for the partial condition and permeability for the case of accommodation spaces.

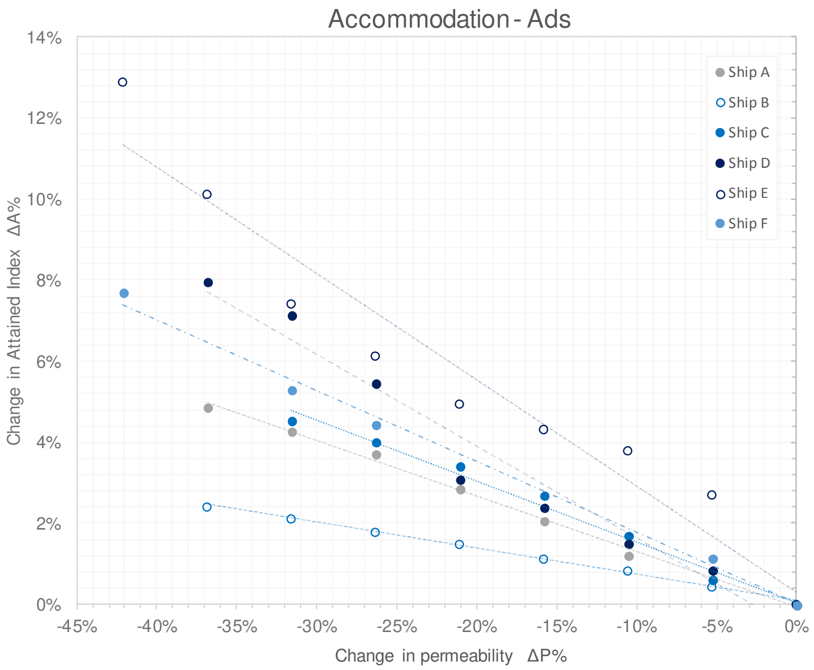


Figure 139: Change of slope of Attained index for the deepest condition and permeability for the case of accommodation spaces.

Table 20: Regression fit accuracies and parameters for the three damage stability loading conditions

	$\frac{\Delta A}{\Delta \mu}(L_{OA}) = a \cdot L_{OA}^{b} + c$				$\frac{\Delta A}{\Delta \mu}(V_{displacement}) = a \cdot V_{displacement}^{b} + c$			
	Atotal	Adl	Adp	Ads	Atotal	Adl	Adp	Ads
a	839.00	1.16E+14	31670.0	0.00	413.80	1.02E+14	11260.00	0.00
b	-1.97	-8.09	-2.78	2.34	-0.98	-4.39	-1.38	0.80
c	0.05	0.06	0.05	0.15	0.05	0.06	0.05	0.16
SSE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
R-sqr	0.98	0.99	1.00	0.65	0.98	0.99	1.00	0.62
RMSE	0.02	0.02	0.01	0.04	0.02	0.02	0.01	0.04

Table 21 : Regression fit accuracies and parameters for the three damage stability loading conditions

	$\frac{\Delta A}{\Delta \mu}(L_{OA}) = a \cdot L_{OA}^{b} + c$				$\frac{\Delta A}{\Delta \mu}(V_{displacement}) = a \cdot V_{displacement}^{b} + c$			
	Atotal	Adl	Adp	Ads	Atotal	Adl	Adp	Ads

a	-1.5E+12	0.0	-1.9E+13	3.30E+13	-4E+12	-1.6E-1	-1.2E+13	-1.1E+13
b	-7.4	5.9	-8.1	-8.1	-4.2	3.1	-4.3	-4.2
c	0.02	0.00	0.02	0.01	0.02	0.01	0.02	0.01
SSE	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
R-sqr	0.42	0.01	0.50	0.74	0.42	0.04	0.50	0.74
RMSE	0.06	0.05	0.04	0.04	0.06	0.04	0.04	0.04

Table 22: Regression fit accuracies and parameters for the three damage stability loading conditions

	$\frac{\Delta A}{\Delta \mu}(L_{OA}) = a \cdot L_{OA}^{b} + c$				$\frac{\Delta A}{\Delta \mu}(V_{displacement}) = a \cdot V_{displacement}^{b} + c$			
	Atotal	Adl	Adp	Ads	Atotal	Adl	Adp	Ads
a	132.60	3.97	8.06	0.00	56.50	3.89	6.37	0.00
b	-1.48	-0.10	-0.61	2.31	-0.69	-0.04	-0.30	0.88
c	0.10	-2.17	-0.14	0.26	0.10	-2.34	-0.12	0.26
SSE	0.01	0.02	0.01	0.00	0.01	0.01	0.01	0.00
R-sqr	0.86	0.89	0.94	0.94	0.86	0.90	0.95	0.96
RMSE	0.06	0.07	0.05	0.02	0.06	0.07	0.05	0.02

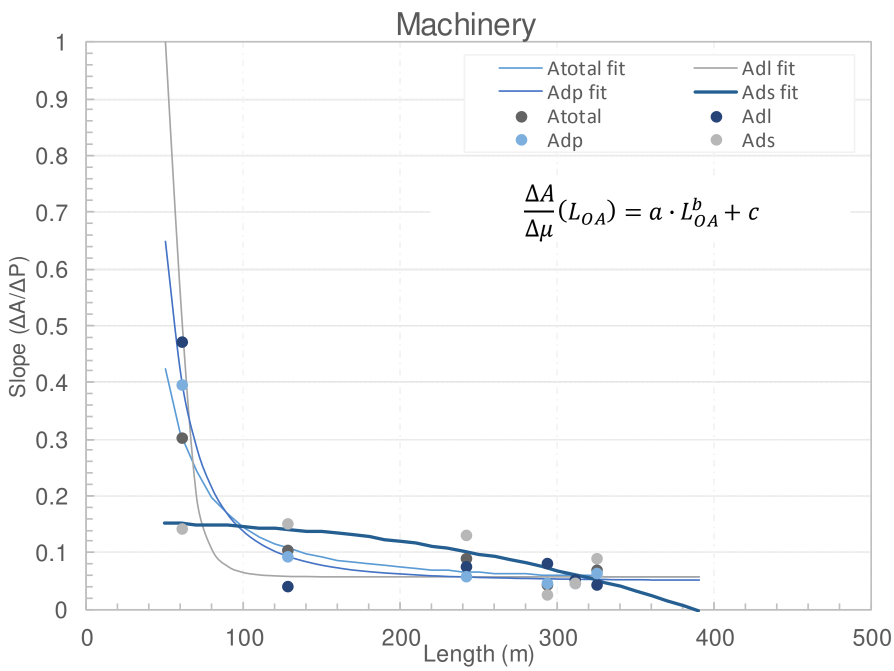


Figure 140: Regression fit with respect to length for all damage stability loading conditions in the case of machinery spaces

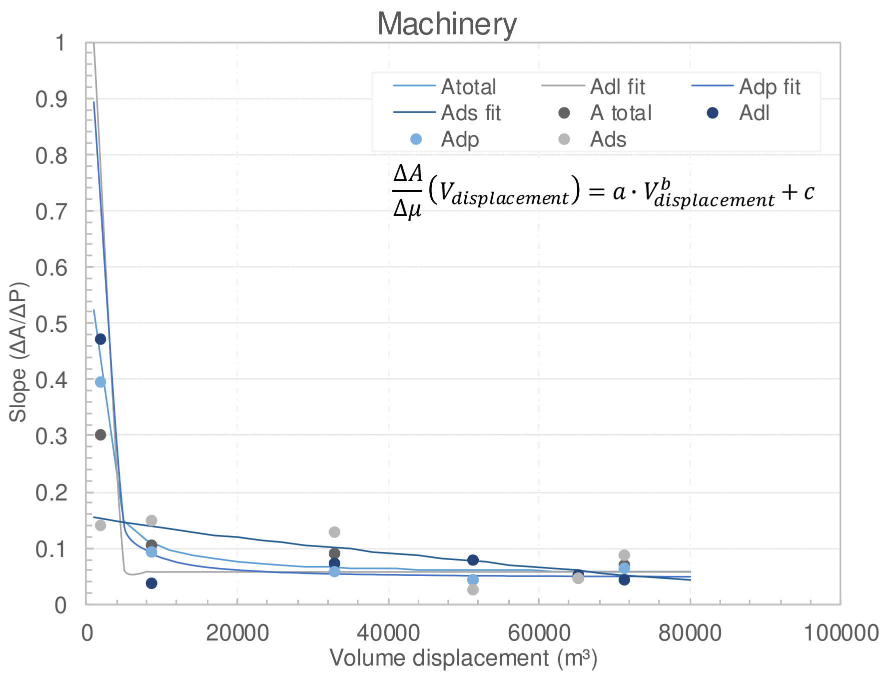


Figure 141: Regression fit with respect to volume displacement for all damage stability loading conditions in the case of machinery spaces

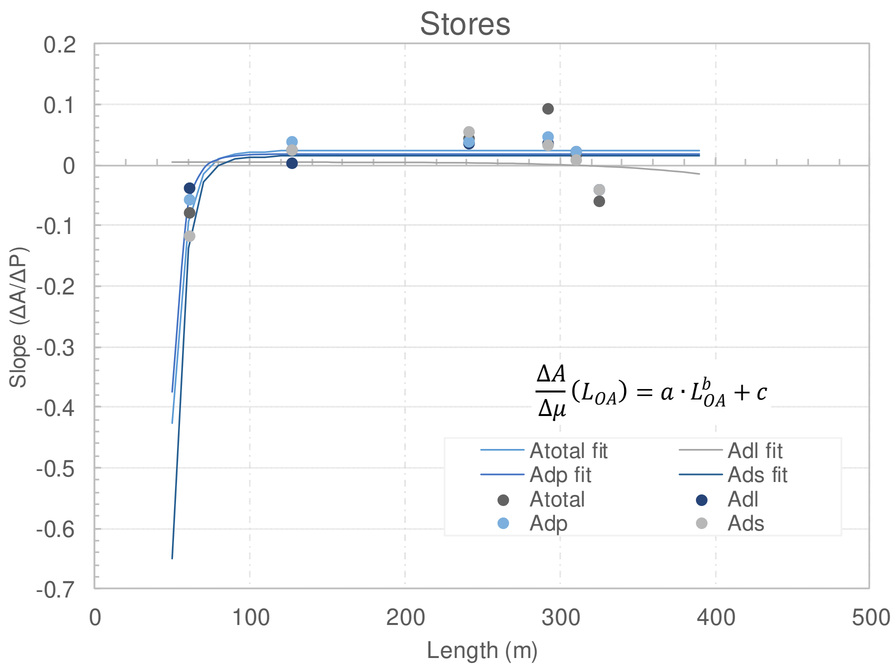


Figure 142: Regression fit with respect to length for all damage stability loading conditions in the case of store spaces

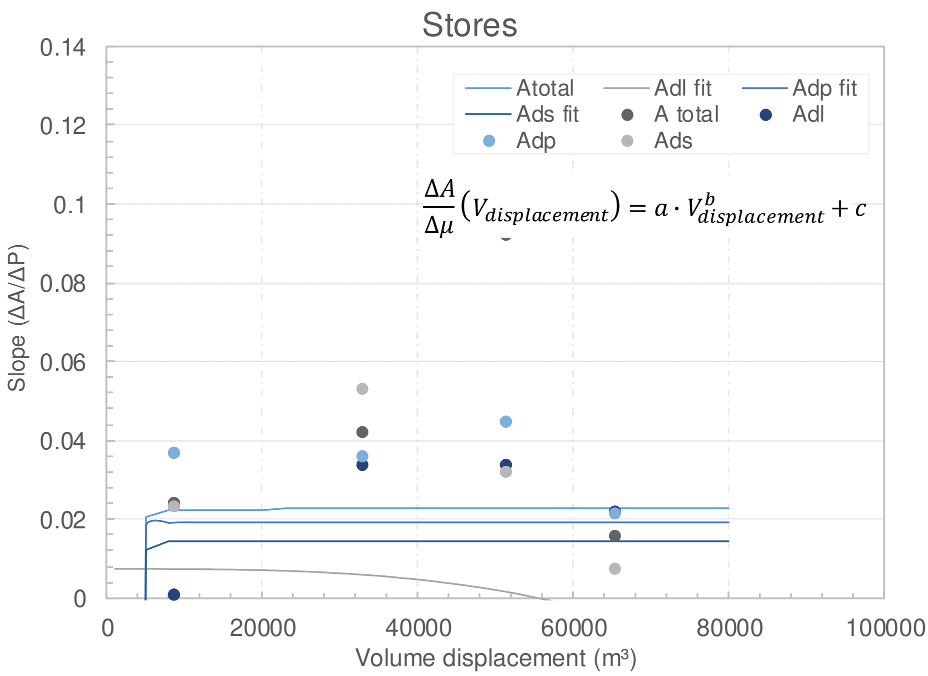


Figure 143: Regression fit with respect to volume displacement for all damage stability loading conditions in the case of store spaces

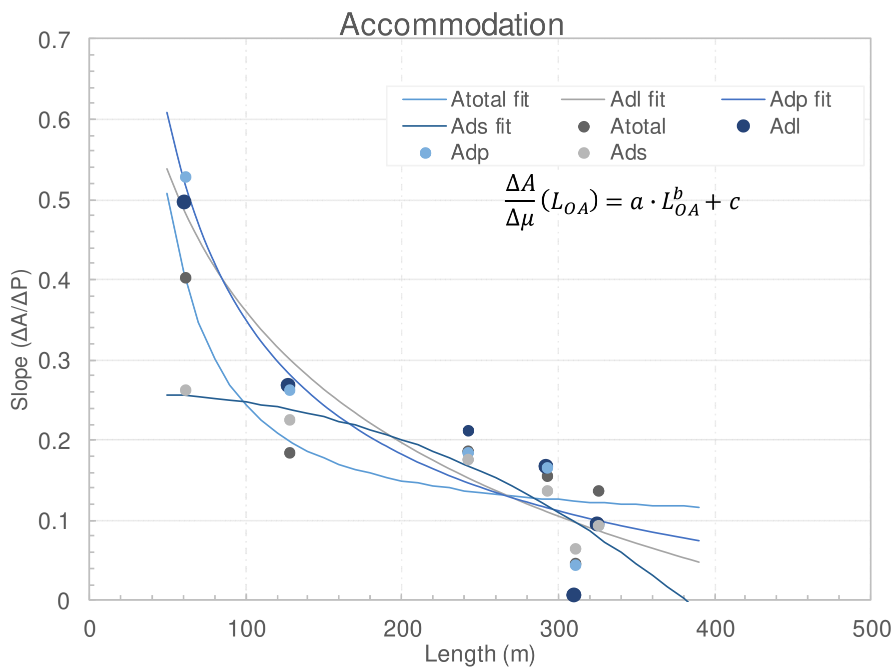


Figure 144: Regression fit with respect to length for all damage stability loading conditions in the case of accommodation spaces

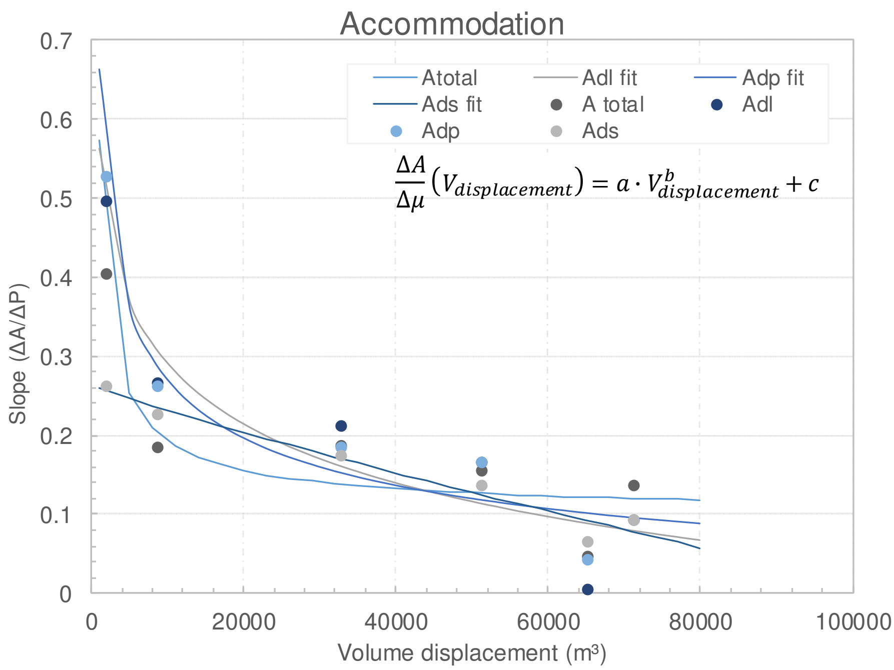


Figure 145: Regression fit with respect to volume displacement for all damage stability loading conditions in the case of accommodation spaces