Stockholm Agreement – Past, Present & Future (Part I)

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SUMMARY

April 1, 2001 will mark the fourth anniversary of the Stockholm Agreement (SA), a period during which almost 80% of the Ro-Ro fleet in North West Europe will have been subjected to calculations, model testing and numerical simulations in the strife to meet these demanding new requirements. The experience gained has been invaluable in understanding better the problem at hand and is being utilised to shape new developments, likely to lead to more meaningful requirements. The North-South divide, however, continues to cause unrest, particularly at European level. Efforts to assess the status quo in North West Europe and use the information amassed so far as a means to predict the potential impact of introducing the SA in the South, led to a dedicated call by the Commission and to a contract being awarded to two closely collaborating teams, one at the Ship Stability Research Centre of the University of Strathclyde under the leadership of Professor Vassalos and one at the Ship Design Laboratory of the National Technical University of Athens, under the leadership of Professor Papanikolaou, representing the North and South of Europe, respectively. This background provided the incentive for an introspective look at the SA, with a view to ascertaining its status before embarking into future projections. This forms Part I of the SA related research with Part II aiming to cover the Commission study, due to be shortly finalised.

1. INTRODUCTION

The Ro-Ro concept provides the capability to carry a wide variety of cargoes in the same ship, thus being able to offer a competitive frequency with minimum port infrastructure or special shore-based equipment. Short sea routes are dominated by Ro-Ro ships with lorries, trailers, train wagons, containers, trade cars and passengers being transferred from the "outer" regions (UK, Ireland, Scandinavia and Finland) to the "main" land (continental Europe). Also in the Southern Europe corridors, the Ro-Ro freight service is progressively increasing in volume. The case for a long-distance Ro-Ro service to provide a European maritime highway has also been made several times before. This is particularly relevant and important in respect of fast sea transportation where again Ro-Ro ferries play a prominent role. The main concern with the Ro-Ro ship design, whether justified or not, relates to safety and with safety becoming of paramount importance, it is vital that a rational approach to safety is demonstrated, validated and adopted. This is the right way to ensuring both the survival and a meaningful evolution of Ro-Ro ships in the future. Along these lines, the maritime industry is acutely aware of recent shipping casualties involving Ro-Ro ferries, which have resulted in severe loss of life. Standards for Ro-Ro ship configuration, construction and operation have come under close scrutiny and new legislation has been put into place aimed at improving the safety of these vessels, notably SOLAS '90, [1] as the new global standard for all existing ferries with dates of compliance ranging from 1 October 1998 to 1 October 2010 depending on a combination of the vessel's A/Amax[1] value [2], the number of persons carried and age. However, since the great majority of Ro-Ro passenger ferries were designed and built prior to the coming-into-force of SOLAS '90, it is hardly surprising that few of them comply with the new

[1] The A/A_{max} calculation procedure, [2] is a simplified version of the probabilistic damage stability calculation of ships, [3] and was adopted by IMO as a means of trying to compare the survivability of one vessel against another in order to achieve a hierarchy for phasing-in purposes. It is not a survivability standard

requirements. Furthermore, concerted action to address the water-on-deck problem in the wake of the *Estonia* tragedy led IMO to set up a Panel of Experts (PoE) to consider the issues carefully and make suitable recommendations. However, the complexity of the problem and the need to take swift action to reassure the public that appropriate steps are taken to avoid a repeat of the *Estonia* disaster influenced and shaped to a large extent both the initial and final proposals. In this pace of developments and following considerable deliberations and debate, a new requirement for damage stability has been agreed among North West European Nations to account for the risk of accumulation of water on the Ro-Ro deck. This new requirement, known as the *Stockholm Agreement* [4], ameliorates the original proposals by demanding that a vessel satisfies SOLAS '90 requirements (allowing only for minor relaxation) with, in addition, water on deck by considering a constant height rather than a constant amount of water as was originally intended. The dates of compliance with the provisions of the agreement range from April 1, 1997 to October 1, 2002. However, in view of the uncertainties in the current state of knowledge concerning the ability of a vessel to survive damage in a given sea state, an alternative route has also been allowed which provides a non-prescriptive way of ensuring compliance, through the "*Equivalence*" route, by performing model experiments in accordance with the Model Test Method of SOLAS '95 Resolution 14, [5].

Deriving from systematic research over the past twelve years, numerical simulation models have been developed capable of predicting with good engineering accuracy the capsizal resistance of a damaged ship, of any type and compartmentation, in a realistic environment whilst accounting for progressive flooding. A comprehensive calibration/validation programme has allowed for sufficient confidence to be built up, rendering the developed models a valuable design "tool", [6]. This, in turn, offered the ferry industry the attractive possibility of utilising such "tools" to assessing the damage survivability of ferry safety by using numerical simulation programs to effectively plan or, in time, replace the model tests, the so called "*Numerical Equivalence*" route. Numerical simulation readily allows for a systematic identification of the most cost-effective and survivability-effective solutions to improving ferry safety and hence offers a means for overcoming the deficiency of the physical model tests route in searching for optimum solutions and an indispensable "tool" for the planning and undertaking of such tests.

The close involvement of ferry owners/operators in North Western Europe with research projects in the wake of the *Herald of Free Enterprise* and the *Estonia* accidents was instrumental in nurturing industry to firmly accept the "*Numerical Equivalence*" route as a viable alternative for assessing Ro-Ro vessel survivability. This afforded SU-SSRC a unique opportunity to develop in close collaboration with NTUA-SDL a rational approach to ferry safety with the capability of attending to the needs of the shipping industry cost-effectively and led to the establishment of what is termed a "Total Stability Assessment" (TSA) procedure. The procedure comprises assessment of a vessel's survivability utilising all the currently available instruments, namely: A.265 (VIII) + amendments (probabilistic procedure), SOLAS '90, Stockholm Agreement (prescriptive criteria) and safety "Equivalence" tests by means of physical model experiments and numerical simulations (performance-based criteria). A schematic illustration is provided in Figure 1. The tightening of legislation described above is coupled with serious considerations at IMO for regular application of risk assessment methods, for example, the *Formal Safety Assessment*. In this context, considerable attention has been focusing on the application of probabilistic procedures of damage stability assessment for the evaluation of Ro-Ro vessels and it appears more than likely that developments in the foreseeable future will most certainly adopt a framework of a probabilistic description. The regulatory regime described in the foregoing has understandably left the shipping industry in a state of confusion and uncertainty concerning the available options, approaches and optimum choice to ensure compliance and to ascertain the level of safety attained with regard to any such choice.

Stated specifically, a ship owner today is faced with the following choices concerning safety standards:

(i) Deterministic (SOLAS ’90) Vs probabilistic (A.265 (VIII))
(ii) Prescriptive (SOLAS ’90 + 50) Vs performance based (physical model experiments or numerical simulations)

Standards in each group are assumed to ensure an “equivalent” level of safety, correspondingly, whilst a serious attempt to demonstrate such equivalence is totally lacking. Adding to the confusion is the fact that the dates of compliance with deterministic/prescriptive standards are decided on the basis of a simplified probabilistic approach (calculation of A/A_{max}). In response to the challenge presented by this state of affairs, the maritime industry, slowly but steadily, appears to be favouring the model experiments route, implicitly demonstrating a preference towards performance-based safety standards over deterministic static stability standards when addressing the damage survivability of new concept designs. Not only is the introduction of performance standards a major development in assessing safety but it is also seen as beneficial from the industry as these readily allow consideration of alternative designs as well as a rapid implementation of technological innovation.

2. BACKGROUND

2.1 Historical Overview

Historically, most changes in international regulations for ship design and operation have been introduced as a result of major disasters with a large loss of life. The first notable of such disasters was the sinking of the *TITANIC*, which led a year later to the first International Convention for the Safety of Life at Sea in London. The first damage stability requirements were introduced, however, following the 1948 SOLAS Convention and the first specific criterion on residual stability standards at the 1960 SOLAS Convention with the requirement for a minimum residual GM (0.05m). This represented an attempt to introduce a margin to compensate for the upsetting environmental forces. "Additionally, in cases where the Administration considered the range of stability in the damaged condition to be doubtful, it could request further investigation to their satisfaction". Although this was a very vague statement, it was the first attempt to legislate on the range of stability in the damaged condition. It is interesting to mention that a new regulation on "Watertight Integrity above the Margin Line" was also introduced reflecting the general desire to do all that was reasonably practical to ensure survival after severe collision damage by taking all necessary measures to limit the entry and spread of water above the bulkhead deck. The first probabilistic damage stability rules for passenger vessels, deriving from the work of Kurt Wendel on “Subdivision of Ships”, [7] were introduced in the late sixties as an alternative to the deterministic requirements of SOLAS ‘60. Subsequently and at about the same time as the 1974 SOLAS Convention was introduced, the International Maritime Organisation (IMO), published Resolution A.265 (VIII). These regulations used a probabilistic approach to assessing damage location and extent drawing upon statistical data to derive estimates for the likelihood of particular damage cases. The method consists of the calculation of an *Attained Index of Subdivision*, A, for the ship which must be greater than or equal to a *Required Subdivision Index*, R, which is a function of ship length, passenger/crew numbers and lifeboat capacity. The Equivalent Regulations raised new damage stability criteria addressing equilibrium as well as recommending a minimum GZ of 0.05m to ensure sufficient residual stability during intermediate stages of flooding.

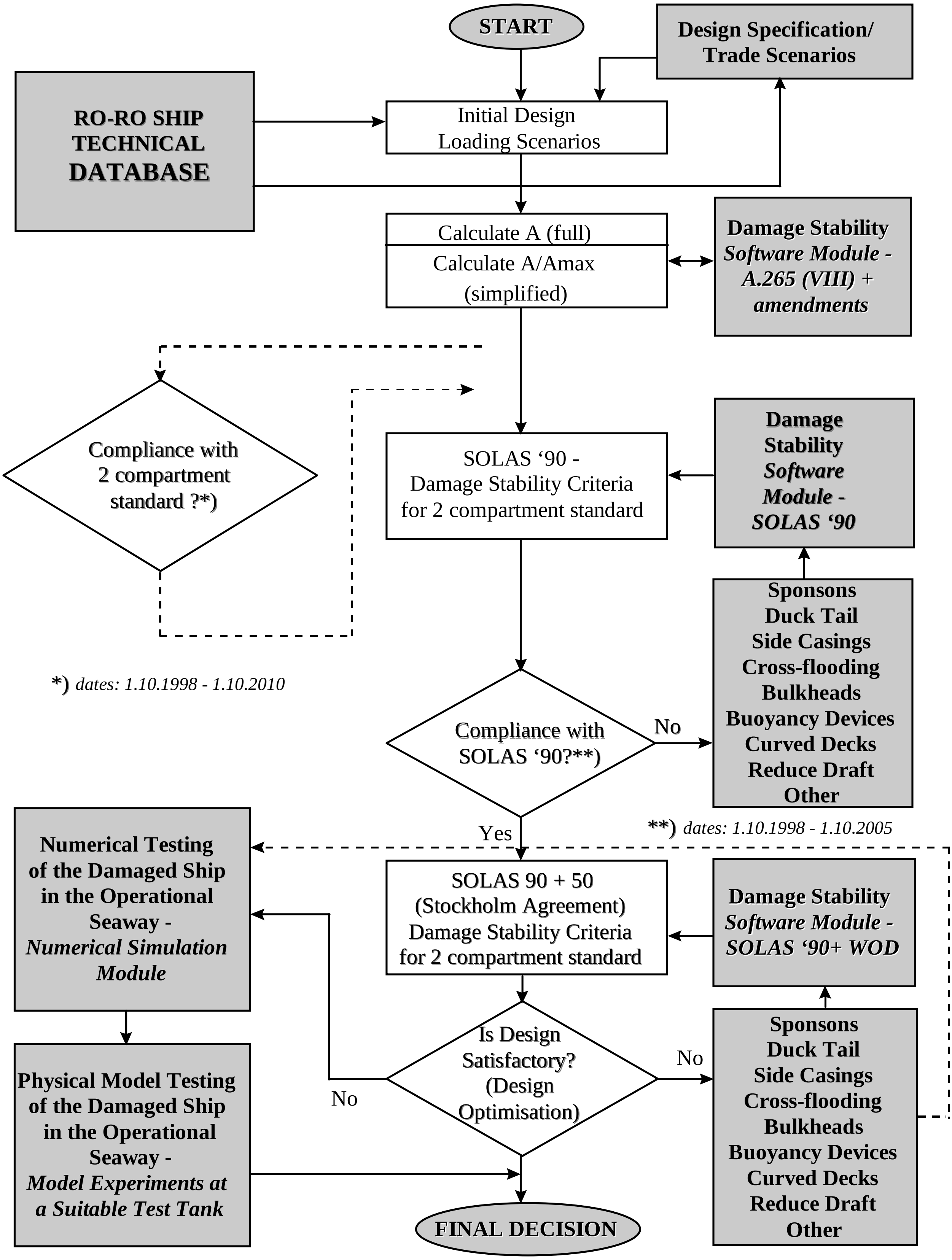


Figure 1: "Total Stability Assessment" Procedure

The next major step in the development of stability standards came in 1992 with the introduction of SOLAS part B-1 (in Chapter II-1), containing a probabilistic standard for cargo vessels, using the same principles embodied in the aforementioned regulations. The same principle is also the basis for the current IMO regulatory development of "Harmonisation of Damage Stability Provisions in SOLAS based on the Probabilistic Concept of Survival". The 1980 UK Passenger Ship Construction Regulations introduced requirements on the range of the residual stability curve as well as on the stability of the vessel at intermediate stages of flooding. The 1980 UK Passenger Ship Construction Regulations introduced requirements on the range of the residual stability curve as well as on the stability of the vessel at intermediate stages of flooding. The loss of the *Herald of Free Enterprise* in 1987 drew particular attention to Ro-Ro ferries in which the absence of watertight subdivision above the bulkhead deck is a particular feature. The implications of this feature were highlighted by the Court of Inquiry, which observed that the SOLAS Conventions and UK Passenger Ship Construction rules had been aimed primarily at conventional passenger ships in which there is normally a degree of subdivision above the bulkhead deck, albeit of unspecified ability to impede the spread of floodwater. In response to this, the UK Department of Transport issued Consultative Document No 3 in 1987, which outlined a level of residual stability that required all existing Ro-Ro ferries to demonstrate compliance with the 1984 Passenger Ship Construction Regulations. This standard had previously formed the basis of a submission by the UK and other Governments to IMO, which considered the question of passenger ship stability in some detail. This was the forerunner to SOLAS '90.

2.2 UK Ro-Ro Research Programme

In the wake of the *Herald of Free Enterprise* disaster, the need to evaluate the adequacy of the various standards in terms of providing sufficient residual stability to allow enough time for the orderly evacuation of passengers and crew in realistic sea states has prompted the UK Department of Transport to set up the Ro-Ro Research Programme comprising two phases. Phase I addressed the residual stability of existing vessels and the key reasons behind capsizes. To this end, theoretical studies were undertaken into the practical benefits and penalties of introducing a number of devices, [8], for improving the residual stability of existing Ro-Ro's. In addition, model experiments were carried out by the British Maritime Technology Ltd, [9] and the Danish Maritime Institute, [10] in order to gain an insight into the dynamic behaviour of a damaged vessel in realistic environmental conditions and of the progression of flood water through the ship. Phase II was set up with the following objectives in mind:

- To confirm the findings of Phase I in respect of the ability of a damaged vessel to resist capsize in a given sea state.
- To carry out damaged model tests, in which the enhancing devices assessed in Phase I would be modelled to determine the improvements in survivability achieved in realistic sea-going conditions.
- To confirm that damage in the region amidships is likely to lead to the most onerous situation in respect of the probability of capsize.
- To undertake theoretical studies into the nature of the capsize phenomenon, with a view to extrapolating the model test results to Ro-Ro passenger ships of different sizes and proportions.

Strathclyde was one of three organisations with the responsibility of developing and validating a theoretical capsize model which could predict the minimum stability needed by a damaged vessel to resist capsizing in a given sea state. This was subsequently to be used to establish limiting stability parameters that might form the basis for developing realistic survival criteria, [11].

2.3 Joint R&D Project

As the UK stood poised to share the findings from the Ro-Ro Research Programme with the rest of the world, the *Estonia* tragedy has once more shaken the foundations of shipping, forcing the profession to provide answers "immediately" and, in attempting to do so, to use the right expertise and experience to provide the right answers. The Nordic countries reacted quickly in undertaking this responsibility leading to a wider-based project within a very short period, taking onboard the fact that, in addressing the probability of a ship surviving a given damage, the problem of damage survivability does not end with quantifying the probability of damage and the consequences of damage. The *Estonia* disaster was the strongest indicator yet of the urgent need to define acceptable risks and maximum tolerable consequences as well as to identifying procedures for managing such consequences and dealing with residual risks. To this end, the principal aim of the project was to develop a proposal for a new probabilistic stability framework leading to improved safety for new vessels with particular reference to the damaged and flooded conditions. A second aim was the development and application of safety assessment procedures to Passenger/Ro-Ro vessels. Leading experts from Europe contributed to the technical work as shown in Figure 2.

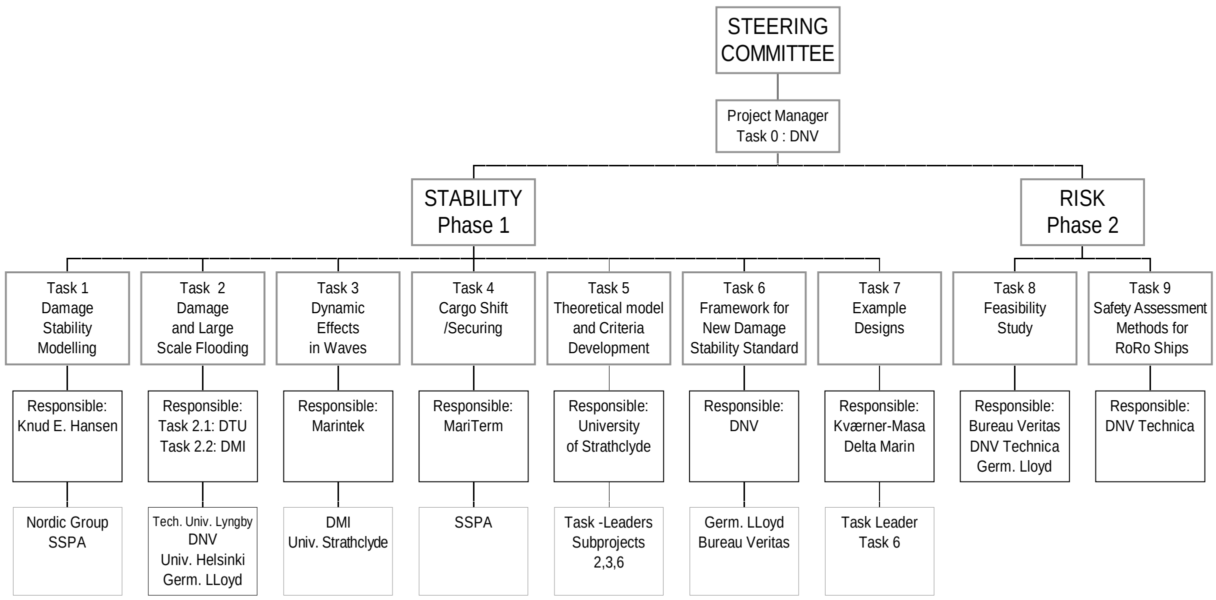
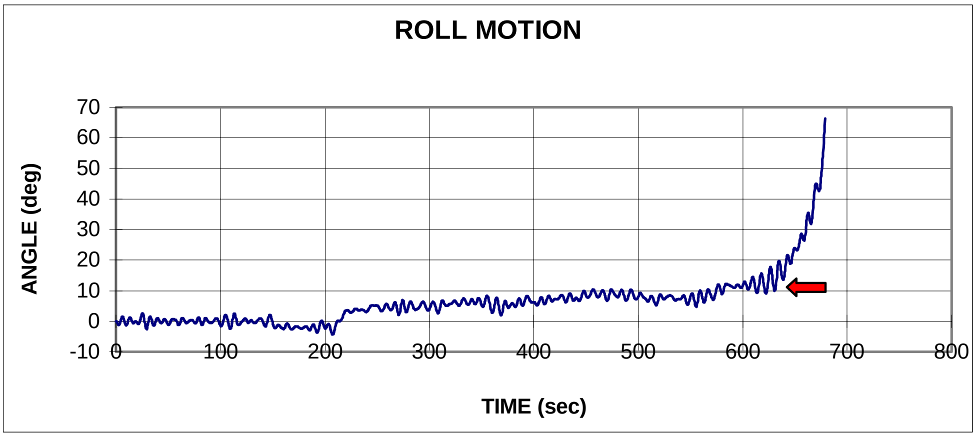


Figure 2: Nordic Project Organisation

2.4 Survivability Measure – Critical Height of Water on Deck

The new damage stability framework proposed by the Joint North West European R&D Project is based on the probabilistic concept of survival. This means that the standard of survivability is expressed in terms of the probability that the vessel will survive, given a damage with water ingress has taken place. The total probability of survival depends on two factors: the probability that a compartment is being flooded and the probability that the vessel will survive flooding of that compartment. The concept itself is simple, but it takes a great deal of effort to establish correct formulation of these two factors, particularly when it involves large scale flooding of extensive undivided deck spaces such as the vehicle deck in Ro-Ro ferries. Concerning the latter and taking into account that there are many effects causing a vessel to capsize, the probability of survival can also be divided in two different factors: the probability to survive pure loss of stability, heeling moments, cargo shift and angle of heel and the probability to survive water accumulation on deck as a result of wave action. The calculation of this last factor, referred to as survival factor with water on deck, s_w, is based on a concept whereby the critical wave height at which the vessel will capsize is found, and s_w will simply be the probability that this wave height is not exceeded. Strictly speaking, this critical significant wave height cannot be determined uniquely because of the random nature of the sea. In connection to this, the term "Survivability Boundary" represents a contour within the capsize region ("Capsize Band") with equal probability of vessel capsize. Therefore, the main task in estimating the probability of survival with water on deck has been to formulate a connection between the critical sea state and parameters which can be readily calculated without resorting to numerical simulations or physical model experiments. Observations from the latter revealed that the dominant factor determining the behaviour of the vessel is the amount of floodwater accumulating on the vehicle deck, Figure 3. In case of large scale flooding, the vessel motions become subdued with the mean heel angle increasing slowly until a critical value is reached beyond which heeling increases exponentially and the vessel capsizes very rapidly. In this context, the term "*point of no-return*" is used as indicative of the fate of the vessel when this critical heel angle is attained. Put differently, the floodwater on the vehicle deck increases slowly, depending on the vessel and environmental conditions, until the amount accumulated reached a critical level that cannot be supported by the vessel/environment and the vessel capsizes quickly as a result. In relation to this, two points deserve emphasis. This amount is substantially less than the amount of water just before the vessel actually capsizes but is in excess of the amount required to statically capsize the ship. In this respect, the energy input on account of the waves helps the vessel sustain a larger amount of water than what her static restoring characteristics appear to dictate. Because of the nature of the capsize mode described above, it is not difficult to estimate the critical amount of water on deck at the point of no-return from experimental or numerical simulation records considering either the floodwater on the vehicle deck or the roll motion of the vessel as indicated by the arrow in Figure 3.



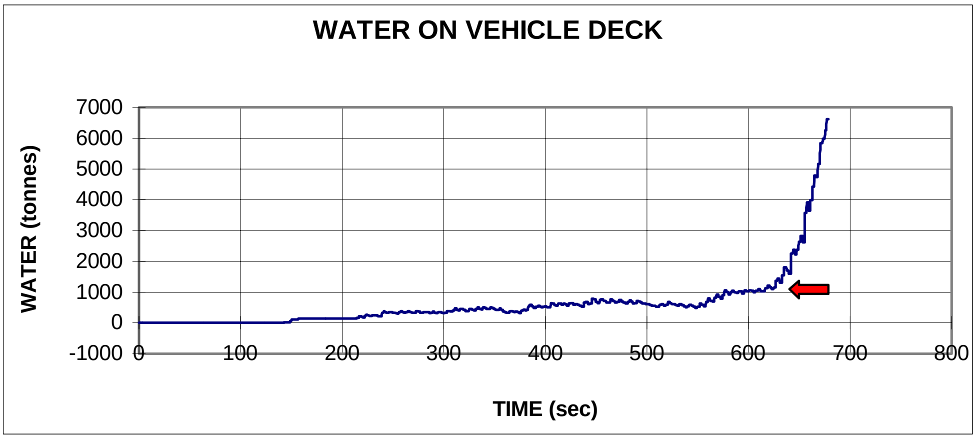


Figure 3: A Typical Capsize Mode with Water on Deck

A key observation from model experiments and numerical simulations was that vessel capsize occurs close to the angle where the righting moment has its maximum, i.e. θ_{max}, calculated traditionally by using the constant displacement method and allowing for free-flooding of the vehicle deck when the deck edge is submerged. This fact, coupled with observations from physical model experiments and the experience amassed from studying large numbers of numerical tests led to the development of a "*Static Equivalent Method - SEM*" which allows for the calculation of the critical amount of water on deck from static stability calculations. To this end, a flooding scenario is considered in which the ship is damaged only below the vehicle deck but with a certain amount of water on the (undamaged) deck inside the upper (intact) part of the ship. The critical amount of water on deck is then determined by the amount causing the ship to assume an angle of loll (angle of equilibrium) that equals the angle θ_{max}. Based on this, the volume of water on deck causing the vessel to assume an angle of loll that equals θ_{max}, was compared with the critical volume of water at the instant of capsize and a good correlation was found. The scenario described above and depicted in Figure 4, is believed to represent closely observations of the flooding process near the capsize boundary or when a stationary (steady) state is reached with the water on deck elevated at an average height, *h*, above the mean water plane, as a result of the wave action and vessel motions. It was subsequently shown that this height is a unique measure of ship survival in damaged condition - the higher the water elevation the higher the sea state needed to elevate the water to this level and the higher the capsizal resistance of the ship - that could be applied universally to all the arrangements studied, involving ship size and shape, subdivision arrangements and loading conditions. It follows, that the relationship between *h* and *Hs* will also be unique for a given ship, thus allowing the survivability of the vessel to be expressed as a function of the critical significant wave height as denoted below:

$$h_{\mathrm{crit}} = \mathrm{f}(Hs) = 0.085\,(Hs_{crit})^{1.3}$$

where, h_{crit} = the difference between the inner and outer waterline at the instant of capsize
Hs_{crit} = the critical significant wave height

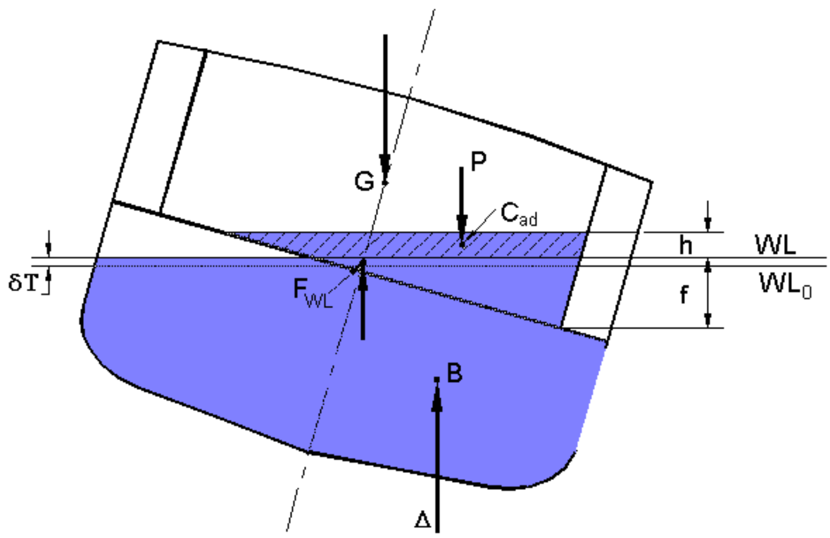


Figure 4: Stability of a Damaged Ship with Water Accumulated on Deck
(*Static Equivalent Method - SEM*)

This finding was the precursor to the subsequent developments that led to what subsequently became known as the Stockholm Agreement.

3. REGULATORY DEVELOPMENTS

3.1 PoE, Danish Proposals and the Stockholm Agreement

Whilst the developments described above were taking place, the prevailing climate following the *Estonia* disaster could not wait for the concept pertaining to SEM to be validated and nurtured to maturity. Instead, using the idea of the critical height of water on deck as the basis, the Joint Nordic Project commissioned a series of experiments at the Danish Maritime Institute, ([12], [13] and Table 1) aiming to produce evidence in support of the proposal of the PoE requiring a vessel to meet SOLAS '90 requirements with in addition of up to $0.5m^3/m^2$ water on deck. Results from these experiments were subsequently used by the Danish to formulate a proposal to the first Stockholm Conference on 27/28 January 1996, relating the amount of water on deck to a constant height rather a constant volume as was the case with the PoE proposal. This was again to be applied in a static and deterministic sense and was eventually accepted in the second Stockholm Conference one month later as the basis for taking into account water on deck in assessing the damage survivability of existing ships. Figure 5 summarises how to calculate the height of water on deck according to the Agreement, depending on the vessel residual freeboard and the operational sea state, characterised by the significant wave height, Hs.

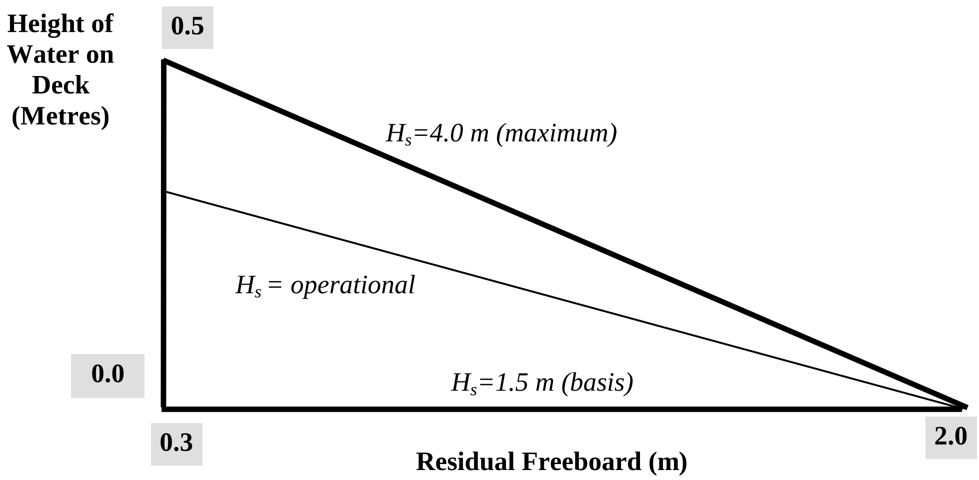


Figure 5: Stockholm Agreement (Height of water on Deck)

Table 1: Distribution of Test Results among Categories of Vessel Behaviour
(The 49 test cases considered by DMI in the aforementioned test programme, [11], [12])

Arrangement	Number of tests	Number of Capsizes	Survival Heel to Intact	Survival Heel to Damage
Open Deck	44	21	19	4
Open Deck with Bulkheads	7	1	3	**3**
Centre Casing	12	7	0	**5**
Centre Casing with Bulkhead	18 14	0 13	0 0	**18** **1**
Side Casings	14	5	1	**8**
Side Casings with Bulkhead	6 5	0 1	0 0	**6** **4**

3.2 The Model Test Method

As indicated earlier, in view of the obvious lack of in-depth understanding of the pertinent phenomena governing damage vessel behaviour in extreme sea-going conditions during large scale progressive flooding and uncertainties in the state of knowledge concerning damage survivability, the PoE recommended after some debate an alternative method of ensuring compliance through the "*Equivalence*" route, the Model Test Method of SOLAS '95 Resolution 14, [5]. The experimental set-up is depicted in Figure 6 below. The method itself has been subjected over the past two years to rigorous scientific scrutiny by a group of technical experts, known as the Gothenburg Technical Group, and a number of suggestions for improvement were recommended to the Gothenburg Group (the original signatories of the Stockholm Agreement) for a modified Model Test Method for assessing the damage survivability of new passenger/Ro-Ro vessels that could be used for new vessels following agreement initially among the member countries and subsequently within IMO. The adoption of performance-based standards and of first principles approaches to assessing ship safety is undoubtedly of paramount importance. In this respect, the Model test Method will prove invaluable in paving the right way forward.

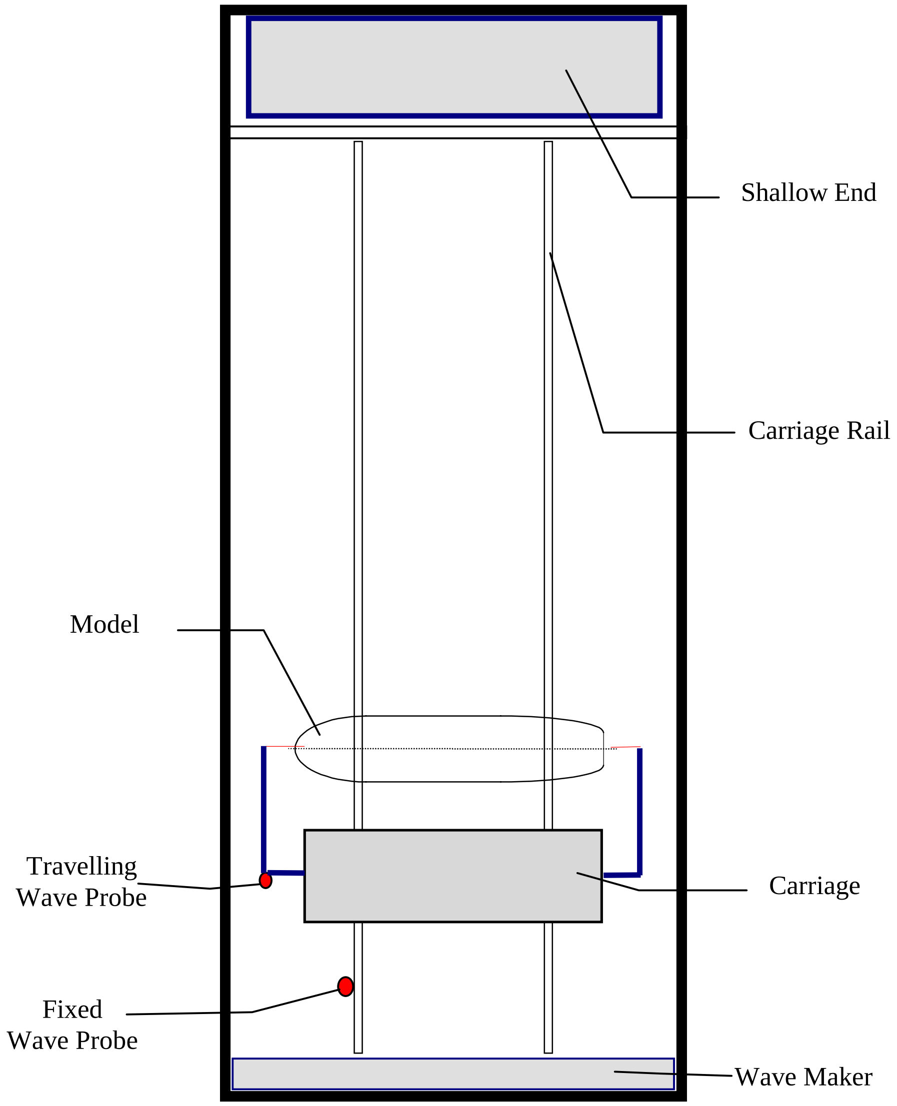


Figure 6: The Model Test method – Experimental Set-up

3.3 A critique of the Stockholm Agreement Requirements

The introduction of the Stockholm Agreement is closely associated with three unprecedented steps in the history of damage stability/survivability assessment:

- Water on deck was explicitly taken into account for the first time. This is remarkable in view of the knowledge that 85% of all deaths with ferry accidents relate to car deck flooding.
- The effect of waves, and this is even more remarkable, was explicitly taken into account also for the first time.
- It paved the way to the introduction of performance-based standards for assessing the damage survivability of ships (Model Test Method of SOLAS '95 Resolution 14).

All three steps represent gigantic improvements in the approach to addressing ferry safety but any potential benefits will have to be balanced against any likely costs that might be incurred through the introduction of inappropriate standards. There are certainly some obvious weaknesses in the requirements of the Agreement and this must be borne in mind when assessing Ro-Ro safety. Key among these include the following:

- The Stockholm Agreement was built on the presumption that a vessel designed (or modified) to SOLAS '90 standards ensures survival at sea states with Hs of only 1.5m. This was suggested in the face of uncertainty and lack of understanding of the phenomena involved. The evidence amassed so far and presented in the following suggests that this was a considerable underestimate.

- The maximum penalty of 0.5m height of water on deck is ill based. It is to be noted from Table 1 that the 49 tests used to measure water accumulation on the car deck comprised only 4 open-decked ships, the others having car decks with: 3 transverse bulkheads, 5 central casing, 19 central casing with transverse bulkheads, 8 side casings and 10 side casings with transverse bulkheads. It is straightforward to prove that the height of water accumulated on a subdivided deck is considerably larger than the height of water accumulated on open decks. More importantly, requirements based on subdivided decks are likely to promote designs with similar arrangements, which is contrary to the Ro-Ro concept itself.

- Furthermore, all the tests performed at DMI referred to midship damage, and the Stockholm Agreement was thus calibrated on the basis of this damage. As a result, and as the evidence accumulated so far and presented in the following clearly shows, the maximum disagreement between Stockholm Agreement and performance-based standards occurs when comparisons are made on damages outside ±0.1L from amidships, which are normally the worst damages, particularly when car decks are subdivided.

- Finally, the effect of water on deck is taken into account by a calculation method that does not preserve the physics of the problem, and being based on static and deterministic approaches, it tends to negate the potential for adopting rational approaches to safety through the introduction of operational sea states and performance-based standards.

4. SAFETY EQUIVALENCE OF THE STOCKHOLM AGREEMENT

4.1 Test Matrix

A sample of forty-two Ro-Ro vessels is utilised to form a suitable matrix that allows for meaningful comparisons between the various methods of assessing damage survivability as well as between the routes to ensuring compliance with current survivability standards. The main aim of this study is to present a critical evaluation of the emerging trends concerning the level of safety provided by the current damaged survivability standards for Ro-Ro vessels with the focus on the Stockholm Agreement requirements. More specifically, the study addresses the following methods and associated parameters:

- SOLAS '90 [GZ_{max}, Positive GZ Range, Area under GZ Curve]
- Stockholm Agreement Calculations [Limiting H_s]
- Numerical Simulations [Limiting H_s]
- Model Experiments [Limiting H_s]

In addition to the above, the residual freeboard and damaged GM_T are also considered. The sample of ships considered includes ships ranging in length from 85m to 205m and in damage stability standards from SOLAS '74 to SOLAS '90. The relevant details concerning the vessels in question together with the results pertaining to the damage survivability assessment according to the aforementioned methods are presented in Appendix A (available in "More MT Online" on the Web) with the operational sea states given in Table 2. Analysis of these results allowed for illustration of trends, consistency and relative significance between the methods used. A typical sample is shown in Figures 7 to 10.

4.2 Wave Environment

The wave environment used in the numerical simulations and physical model tests is representative of the North Sea and is modelled by using a JONSWAP spectrum as shown in the table below.

Table 2: Sea States (JONSWAP Spectrum with γ=3.3)

Significant Wave Height **H_s** (m)	Peak Period **T_p** (s)	Zero-crossing Period **T_0** (s)
1.0	4.00	3.13
1.5	4.90	3.83
2.0	5.66	4.42
2.5	6.33	4.95
3.0	6.93	5.42
4.0	8.00	6.25
5.0	8.95	7.00

$$H_s/L_p = 0.04\ (L_p = 25\,Hs);\quad T_p = \sqrt{\frac{2\pi\,Lp}{g}}\ \ (T_p = 4H_s^{1/2});\quad T_0 = \frac{T_P}{1.279}$$

4.3 Comparative Assessment of Ro-Ro Damage Survivability

Limiting Hs in the derived results represents the maximum sea state the damaged vessel can survive repeatedly. The norm that has been adopted in presenting the results of numerical simulations is to provide a capsize region rather than a capsize boundary to correctly reflect the fact that, because of the random nature of all the parameters determining a capsize event, a single boundary curve does not exist. A limiting Hs in the SA calculations is the maximum value of the significant wave height (and hence height of water on deck) in which the vessel fails any one of the relevant criteria. A close observation of Figures 7 to 10 combined with a careful study of Tables A1 to A3 of Appendix A leads to the following noteworthy points:

- The agreement between physical model tests and numerical tests is very impressive. With larger ships, in particular, the results between the two are identical. With the smaller size vessels, floodwater sloshing is more pronounced and so should be the damping effect on roll motion. Research to quantify the latter is currently under way.

- In general, ships that satisfy SOLAS '90 criteria "pass" the numerical/physical model tests and by implication will be deemed to be safe according to the "Equivalence" route. This is true for all the ships considered in this sample. There are exceptions, of course, and it has to be appreciated and understood that prescriptive criteria could not possibly represent reality meaningfully in all cases. This result is very encouraging, considering that SOLAS '90 has been adopted as the new global standard for all existing ferries. It is also somewhat surprising to see that the previously adopted conjecture that vessels constructed to meet SOLAS '90 standards were capable of avoiding rapid capsize after damage in moderate sea states with a significant wave height of only 1.5 m was a drastic underestimate. Results of ships meeting SOLAS '90 standards appear to be capable of surviving, on the average, sea states above 3m Hs. In this respect, SOLAS '90 provides the right platform for future developments.

- The critical parameter in achieving compliance with SOLAS '90 is usually GZ_{max}.

- The Stockholm Agreement standard is in general more difficult to satisfy than the numerical/physical model tests specified by the "Equivalence" route. The reason for this derives directly from the fact that the height of water on the vehicle deck postulated by this standard is unrealistic. Its derivation was influenced largely by results from vessels with vehicle deck configurations that were conducive to increased heights of water on deck, namely, ships with side casings and transverse bulkheads, [12], [13]. In only very few occasions, the limiting Hs calculated on the basis of the Stockholm Agreement exceeds that corresponding to the operational sea state. This is shown clearly in Figures 7 and 8, particularly so for the worst SOLAS damage.

- Examining Figure 9, it would appear that the trends between physical/numerical tests and Stockholm Agreement are in general similar with the best correlation resulting when considering GZ_{max}. However, a systematic study is required before any concrete conclusions can be derived concerning generalisations of such correlations. In addition, the Stockholm Agreement underestimates limiting Hs on the average by 2m for the worst SOLAS damage and by 1m for the midship damage.

- Figure 10 clearly shows that the critical damage for compliance is the worst SOLAS damage. This result contrasts findings from earlier research where it was shown that the midship damage is the most onerous from survivability point of view. This discrepancy can be attributed to the positioning of bulkheads on the car deck.

- In several occasions what is defined to be worst damage according to SOLAS '90 calculations is not the worst damage from a survivability point of view. This is shown in Tables A1 to A3 of Appendix A where discrepancies up to 1m Hs can be noted.

The investigation presented in the foregoing continues with several other ships, thus offering unique opportunity to provide more convincing evidence of the correlation between safety standards as postulated by the current rules and survivability standards as dictated by the vessel's operational environment. Based on the investigation presented in the foregoing the following remarks can be made:

- The agreement between numerical and physical model tests has been impressive enough so far to warrant careful consideration for adopting the numerical tests as an alternative to physical model testing, for compliance.

- The results derived from this study show worrying inconsistencies between SOLAS '90 and Stockholm Agreement standards, which are <u>not</u> in favour of the ship owners/operators. At the current stage of research, the following findings must be noted:

  ⇒ SOLAS '90 is a "good" standard reflecting meaningfully the safety of Ro-Ro vessels at a level of safety that is generally in agreement with that determined through performance-based methods. However, it must not be overlooked that it is a deterministic standard and hence it could misrepresent the true level of a vessel's safety.

  ⇒ SA appears to be unrealistically stringent, in general, demanding levels of safety well beyond those determined through performance-based methods and, at times, simply not attainable.

Figure 7: Comparative Assessment of Ro-Ro Damage Survivability [Worst SOLAS Damage]

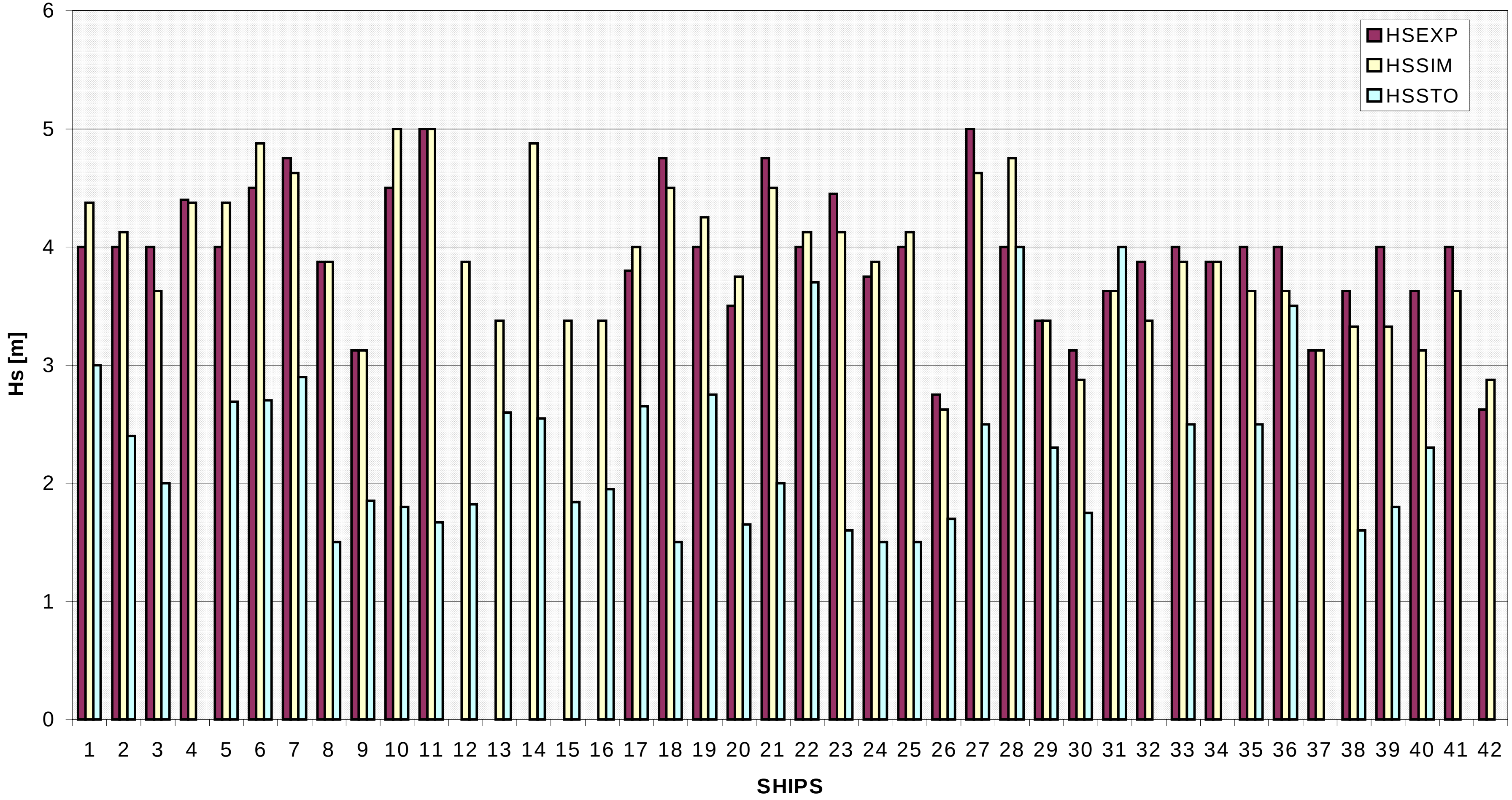


Figure 8: Comparative Assessment of Ro-Ro Damage Survivability [Midship Damage]

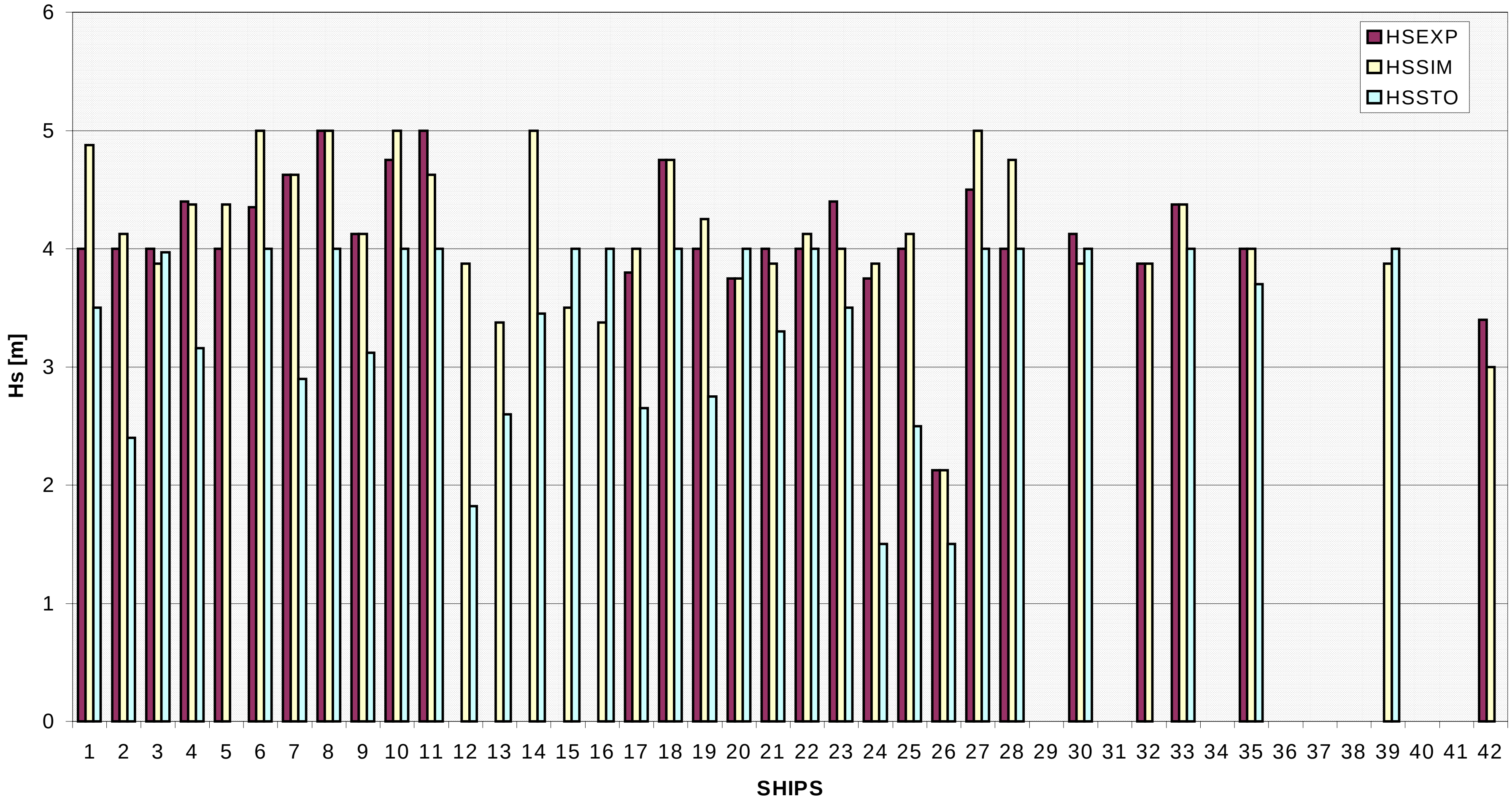


Figure 9a: **Worst SOLAS Damage**

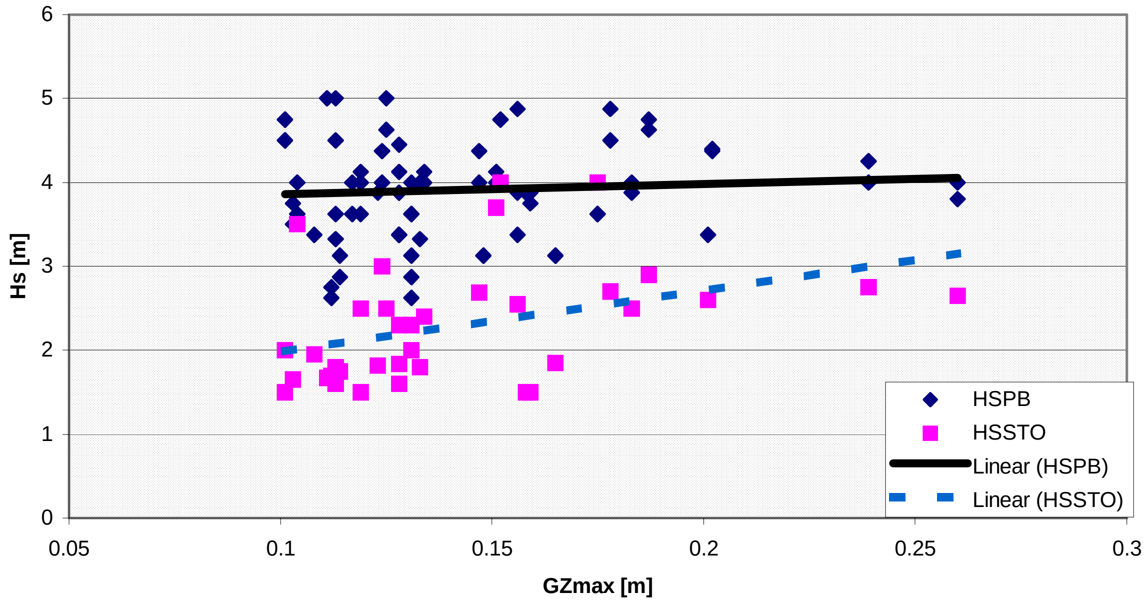


Figure 9b: **Midship Damage**

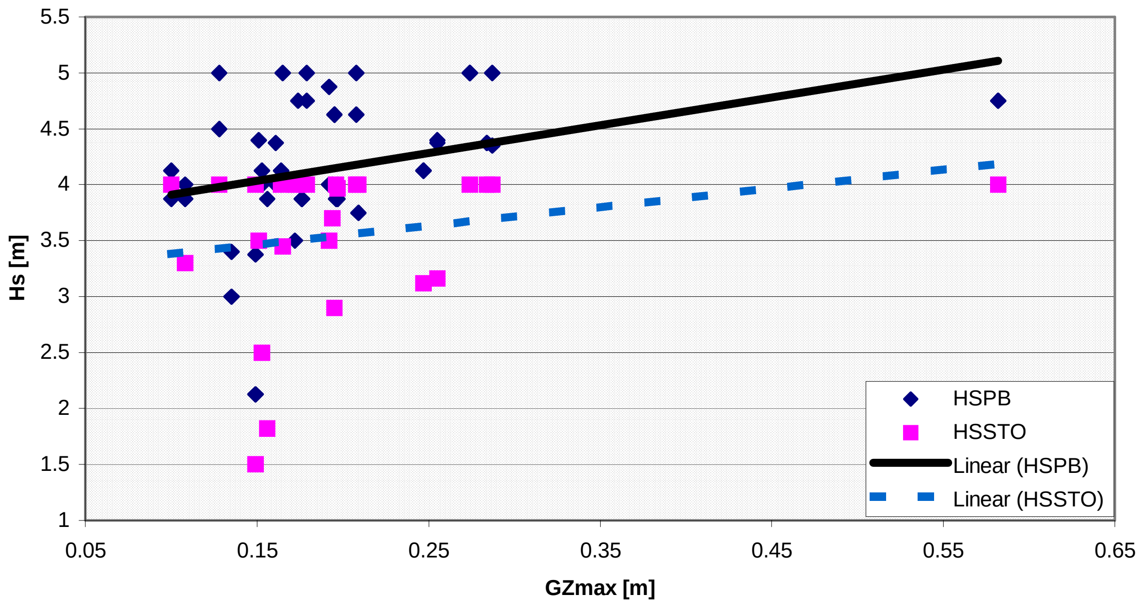
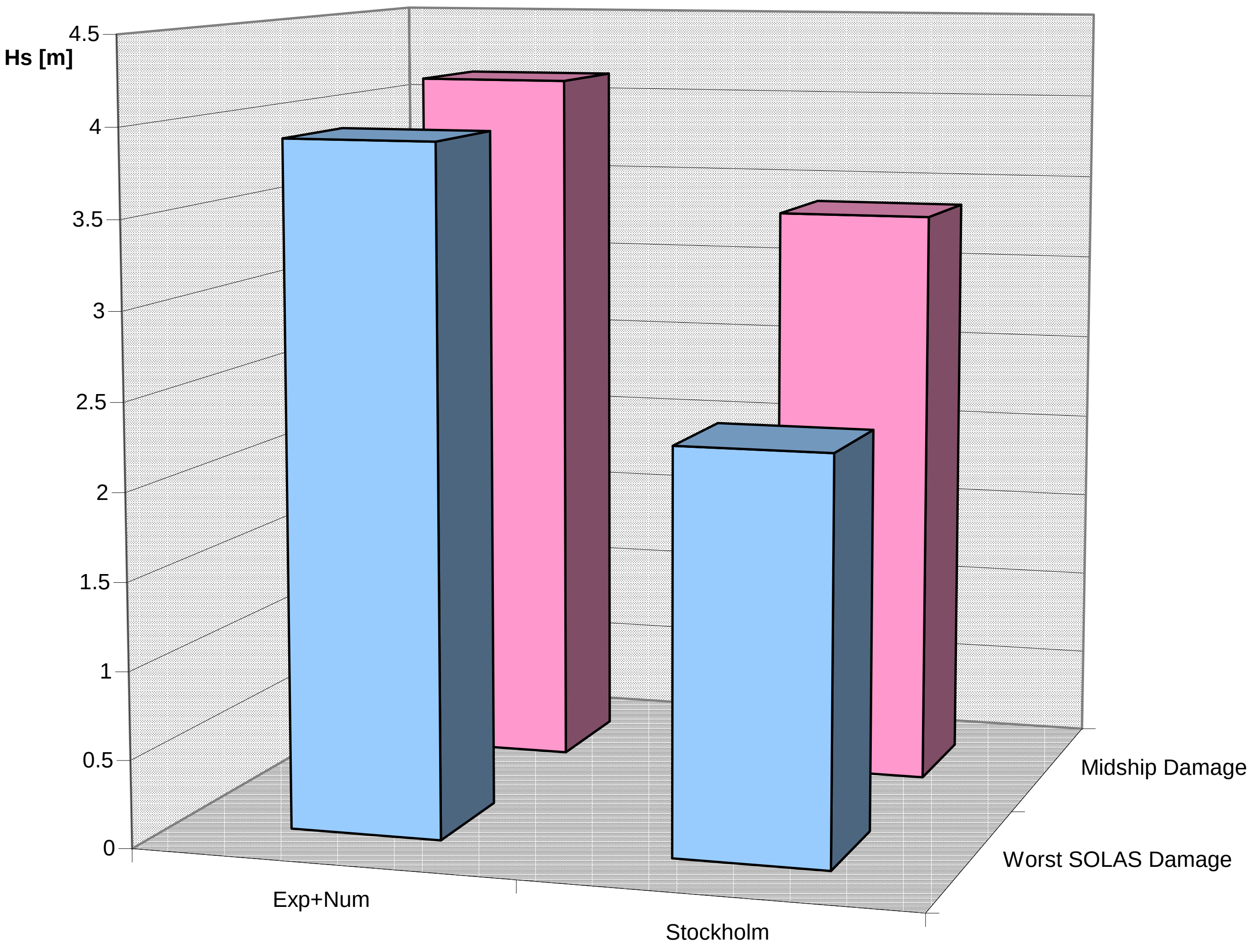


Figure 10: Comparison between Stockholm Agreement and Perfomrnace-Based Standards



5. PRACTICAL IMPACT

In addition to upgrading concerning damage stability safety standards, operational safety is as big a challenge for designers and operators in the adversity of increasing competition where lower costs, increased earning capacity and enhanced safety standards, all conflicting criteria, are becoming key factors to success. Deriving from this, the practical impact on the design and operation of existing Ro-Ro passenger ships deriving from the formal application of the provisions of the Stockholm agreement is in general severe, depending on the ship and area of operation. Relevant costs include running costs (e.g., effect of increased resistance on fuel costs following external modifications of the ship geometry), operational costs (e.g., effect on line length and on turnaround times following modification of internal ship layout) and other less straightforward to quantify effects (e.g., comfort related implications because of the normally increased vessel restoring stiffness as a result of the upgrading process). The governing factors that determine the ensuing costs comprise the following:

1. **Current Stability Standard** (of the ship in question): In general ships complying with SOLAS '90 two compartment standard, or the equivalent A.265 probabilistic standard, might be required to undergo very little or no modification, when exploiting the 'optimisation' route, outlined in Figure 1 (TSA). SOLAS '74 and especially SOLAS '60 ships, on the other hand, are expected to undergo more severe modifications, which might give rise to technically and/or economically unviable solutions.
2. **Ship Characteristics**: Independently of the currently valid stability standard, the practical impact on existing ships will depend to a large extent on the actual intact and damage stability characteristics, especially type of compartmentation and compartment standard, intact and damage freeboard and intact and damage GM values. Ships with B/5 longitudinal BHDs under the Ro-Ro deck will in general be less affected, as they comply with the design philosophy resulting form SOLAS '90 provisions.
3. **Area of Operation**: Considering the entire European route network without restrictions, the most severe impact concerns ships operating in the Northern North Sea and Irish Sea, characterised by relevant significant wave heights of 4.0m for the purposes of compliance with the provisions of SA. On the same basis, severe impact is also expected for ships on the routes to Madeira, Azores (serviced form Portugal) and Canary Islands (serviced from Spain), if the area of application of the Stockholm Agreement is extended to South Europe.
4. **Technical Solutions Applied**: There is a great variety of possible technical solutions leading to compliance with the provisions of the Stockholm Agreement, greatly depending on the extent of the required modifications (factors 1 and 2 above) and the expertise of the technical consultant. Approaches are normally classified according to the choice of the survivability-enhancing device (e.g., structural modifications referring to changes in the internal and/or external ship geometry), operational measures (reducing draught/payload, increasing displacement/payload via external modifications, lowering operational KG, changing route to one with less severe operational sea states or a combination of these) and finally to the mode of achieving compliance (model test method or calculation method). Concerning the latter, formal application of the requirements of the SA, without optimisation, is likely to lead to ineffective modifications and economically unviable solutions. An indicative list of possible technical solutions is given in Table 3 below.

Table 3: Technical Solutions Adopted by the Sample of Retrofitted Ro-Ro/passenger Ships

ITEM	TECHICAL INFORMATION
Transverse Doors on the Car Deck	Major modification as it effects the overall cost, survivability and operation significantly
Ducktail	Major modification as it effects the overall cost, survivability and operation significantly
Ducktail Sponsons	Major modification as it effects the overall cost, survivability and operation significantly
Side Sponsons	Major modification as it effects the overall cost, survivability and operation significantly
Side Casings	It could be major or minor conversion depending on cost and effect on cargo capacity
Making existing rooms watertight on the Car Deck	Minor
Internal Tank – Re-arrangement	Minor
Buoyancy Tanks	Minor
Additional Subdivisions	Minor or major, depending on the location and size of the conversion
Making existing rooms watertight below the Car Deck	Minor
B/5 Longitudinal Bulkheads	Minor or major depending on the location and size of the conversion
Cross-flooding Arrangement	Minor
Heeling Tanks	Minor
FW tanks	Minor
Ballast Tanks	Minor
Stabilising Tanks	Minor
Scupper Arrangements	Minor
Additional Centre Casing on Car deck	Minor
Stern Boxes	Minor
In Flooding Valves	Minor
New Bulbous bow	Major
Foam Fillings in void tanks	Major

Some indicative cost values regarding compliance with the provisions of SOLAS ’90 and the SA and addressing initial and operational cost are also shown, based on data of ships operating in NW Europe. Table 4 refers to ships already converted for compliance with the provisions of Stockholm Agreement, without exploiting the possibility of optimisation within the ‘Total Stability Assessment Procedure’. Table 5 refers to data of ships operating in UK waters, deriving from an investigation on possible compliance with the provisions of SOLAS ‘90. It is of interest to note that the practical impact concerning compliance of Ro-Ro/passenger vessels with the requirements of SOLAS ‘90 are at approximately the same level as those required for compliance with the SA provisions, much in agreement with the conclusions derived from performance-based criteria concerning the level of survivability attained by SOLAS’90 ships. Finally, Table 6 refers to a sample of 42 ships operating in NW Europe that have been investigated at SSRC for possible compliance with the provisions of SA. Typical examples shown different levels of modification are shown in Figures 11 to 13.

Table 4: Indicative Costs of Compliance with the Provisions of Stockholm Agreement (Based on Data of NW European Operators [14])

	Bow/Stern Door Reinforcement	**Transverse Doors/BHDs**	**Longitudinal BHDs**	**Sponsons/ Ducktails**	**Cross-Flooding Drainage/ Miscellaneous**
Design Procurement Installation	Mio ($ US) 0.25-0.60	Mio ($ US) 0.60-1.80	Mio ($ US) 0.60-1.80	Mio ($ US) 0.60-3.60	Mio ($ US) 0.12-1.20
Loss of Payload (lane length)	Tonnes 2-10	Tonnes 30-80 (5-10% on lane length)	Tonnes 30-80	Tonnes 50-400	Tonnes 0-20
Loss of Revenue	Not checked	Mio ($ US) 1.2/yr	Mio ($ US) 2.4/yr	Not checked	Not checked
Loss of Speed	0	0	0	1-2 knots	0
Manning	0	Mio ($ US) 0.12/yr	Mio ($ US) 0.12/yr	0	Mio ($ US) 0.06/yr
Maintenance	Mio ($ US) 0.06/yr	Mio ($ US) 0.06/yr	Mio ($ US) 0.024/yr	0	Mio ($ US) 0.024/yr

Notes
1. Indicative costs are likely to change significantly from ship to ship
2. Indicative costs refer to ships that underwent conversion for compliance with the provisions of SA without adopting any design optimisation.

Table 5: Indicative Costs of Compliance with the Provisions of SOLAS '90 (Based on Data of 15 NW European Ships according to a UK Study [16])

LOA/yr of built	**Modification**	**Initial Cost Mio [$ US]**	**Increased Running costs/yr Mio [$ US]**
158.43 m/ 1974	Doors on Car Deck	3.410	1.838
169.50m/ 1987	Doors on Car Deck	4.203	0
131.70m/ 1976	Sponsons*	3.122	0.050
80.40m/ 1988	Sponsons	2.024	0
137.01m/ 1978	Raise main deck	3.188	0.464
170.59m/ 1977	Buoyant wing tanks	1.797	***
126.50m/ 1967	Cross-flooding	0.166	0
129.85m/ 1968	Nil	0.017	0
120.71m/ 1979	Buoyant wing tanks	0.961	0.712
131.02m/ 1980	Doors	0.745	0.414
119.51m/ 1975	Sponsons**	3.125	0.041
119.87m/ 1976	Sponsons	4.322	0.133
107.60m/ 1975	Weathertight deck or…	0.133	0
107.60m/ 1975	Sponsons	4.090	4.3
161.50m/ 1987	Weathertight deck or…	0.166	0
161.50m/ 1987	Sponsons	3.585	8.280
116.13m/ 1974	Sponsons	3.043	1.515

Notes

1. Indicated costs are based on data for 15 UK flag ships operating in NW Europe (North Sea, Irish Sea and Channel). Basis ships are considered to comply with the SOLAS '74 stability standard.
2. Proposed modification solutions are not optimal and in some cases so severe, that removal form service and replacement appears necessary.
3. * 0.083 Mio [$ US] to be added for berth modifications
   ** 0.828 Mio [$ US] to be added for berth modifications
   *** 0.265 Mio [$ US]/yr savings due to increased payload

Table 6: Sample of Ships tested by SSRC for compliance with Stockholm Agreement & Proposed Modifications following the TSA Procedure

Ship No.	Previous Stability Standard	Modifications to Stockholm Agreement Requirements
Ship 1	SOLAS'90	None
Ship 2	SOLAS'90	None
Ship 3	SOLAS'90	None
Ship 4	SOLAS'74	Small buoyancy boxes on the car deck
Ship 5	SOLAS'90	None
Ship 6	SOLAS'74	2 transverse bulkheads on the car deck Modification to internal tank arrangement Extended side casings
Ship 7	SOLAS'74	2 transverse bulkheads on the car deck Minor modifications below the car deck
Ship 8	SOLAS'74	Large sponsons 2 transverse bulkheads on the car deck Modification to internal tank arrangement
Ship 9	SOLAS'74	Large sponsons (≈ 100m)
Ship 10	SOLAS'74	2 transverse bulkheads on the car deck Longitudinal bulkheads on the car deck along the CL
Ship 11	SOLAS'74	Optimised subdivision of existing side casings
Ship 12	SOLAS'74	1 transverse bulkhead on the car deck Extended side casings
Ship 13	SOLAS'74	2 transverse bulkheads on the car deck Sponsons
Ship 14	SOLAS'74	Relocation of existing car deck barrier
Ship 15	SOLAS'74	2 transverse bulkheads on the car deck Sponsons (≈ 60m)
Ship 16	SOLAS'74	Relocation of existing car deck barrier Sponsons with optimised subdivision
Ship 17	SOLAS'74	Large sponsons
Ship 18	SOLAS'90	2 transverse bulkheads on the car deck Extended side casings
Ship 19	SOLAS'74	Large sponsons Extended side casings
Ship 20	SOLAS'74	1 transverse bulkhead on the car deck Modification to internal tank arrangement
Ship 21	SOLAS'74	4 transverse bulkheads on the car deck
Ship 22	SOLAS'74	2 transverse bulkheads on the car deck Modification to internal tank arrangement

Ship 23	SOLAS'74	2 transverse bulkheads on the car deck Anti heeling tanks Extended side casings
Ship 24	SOLAS'74	1 transverse bulkhead on the car deck
Ship 25	SOLAS'74	Modification to internal tank arrangement
Ship 26	SOLAS'74	Ducktail
Ship 27	SOLAS'90	None
Ship 28	SOLAS'90	None
Ship 29	SOLAS'74	2 transverse bulkheads on the car deck Web side casings Modification to internal tank arrangement
Ship 30	SOLAS'74	Large midship side casings 1 transverse bulkhead on the car deck Modification to internal tank arrangement
Ship 31	SOLAS'74	2 transverse bulkheads on the car deck Web side casings Modification to internal tank arrangement
Ship 32	SOLAS'74	Stern boxes 1 transverse bulkhead on the car deck Modification to internal tank arrangement
Ship 33	SOLAS'90	None
Ship 34	SOLAS'74	2 transverse bulkheads on the car deck Large stern side casings Modification to internal tank arrangement Anti trimming tanks
Ship 35	SOLAS'74	1 transverse bulkhead on the car deck Modification to internal tank arrangement Ducktail
Ship 36	SOLAS'74	2 transverse bulkheads on the car deck Modification to internal tank arrangement
Ship 37	SOLAS'74	1 transverse bulkhead on the car deck Ducktail/ Sponson hybrid Modification to internal tank arrangement Modification to forward sections of the hull
Ship 38	SOLAS'90	None
Ship 39	SOLAS'74	Large sponsons (≈ 100m)
Ship 40	SOLAS'90	None
Ship 41	SOLAS'74	1 transverse bulkhead on the car deck Anti trimming tanks
Ship 42	SOLAS'74	2 transverse bulkheads on the car deck Modification to internal tank arrangement Extended side casings

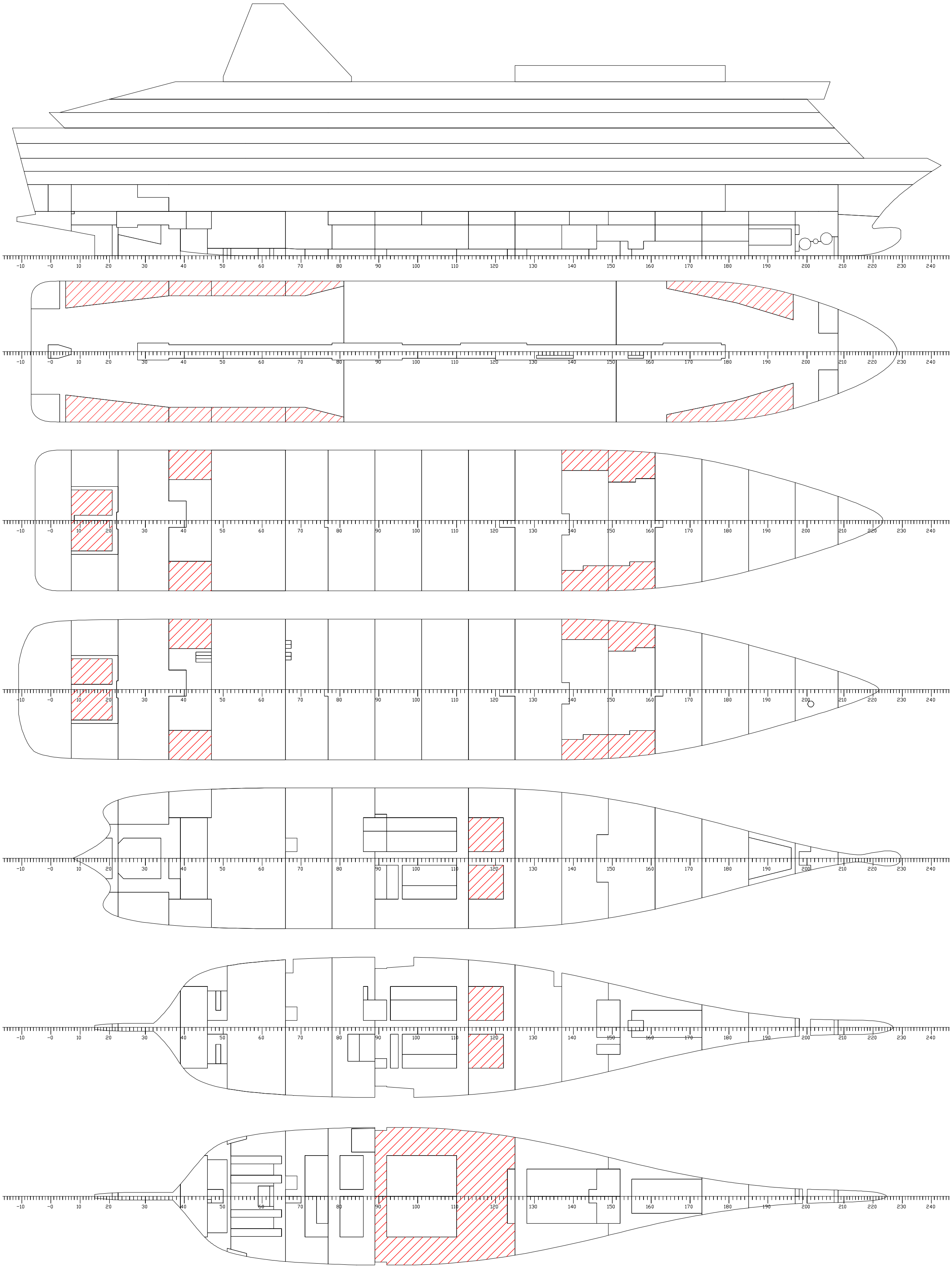


Figure 11: Complex Modification – Ship 34

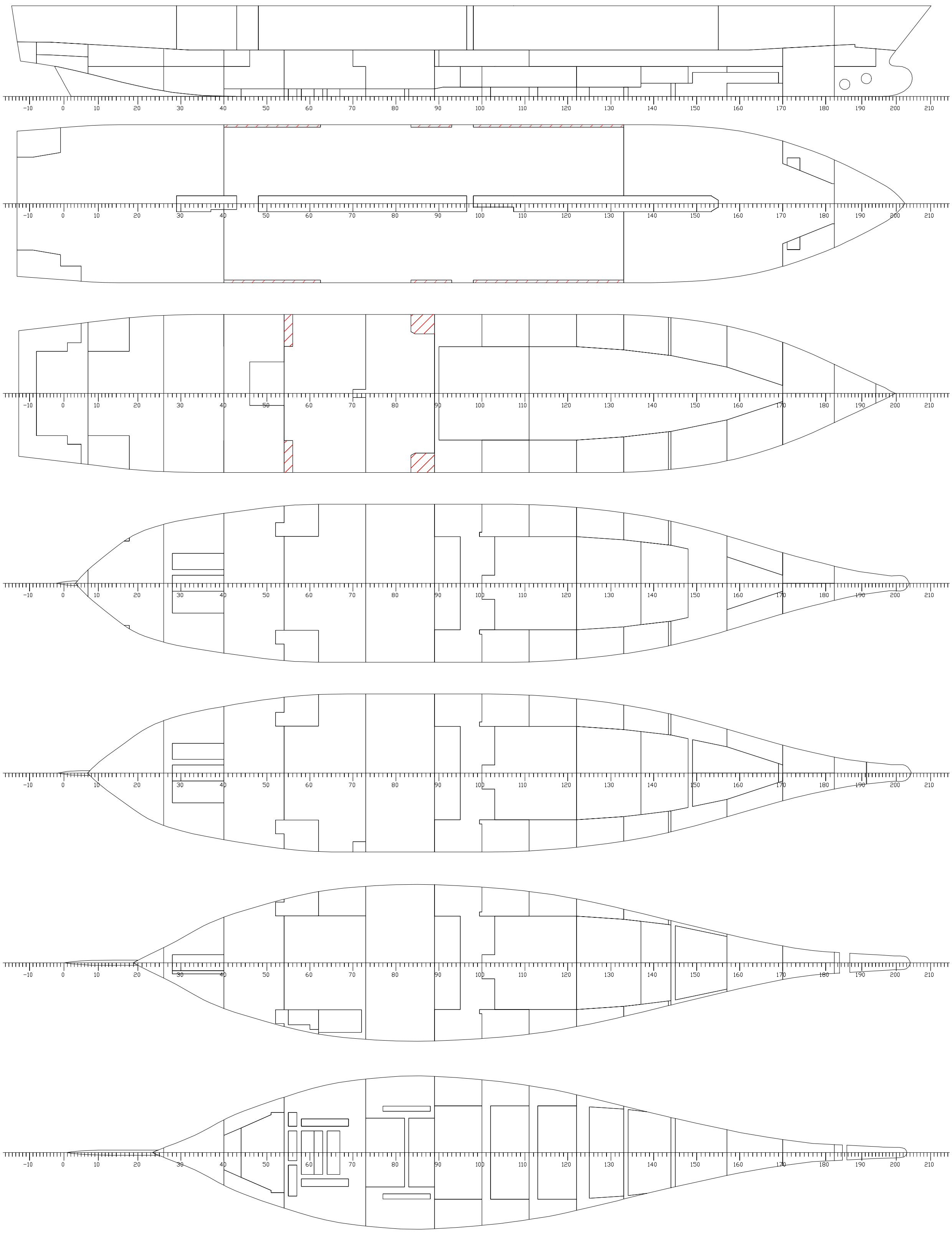


Figure 12: Medium Complexity Modification – Ship 36

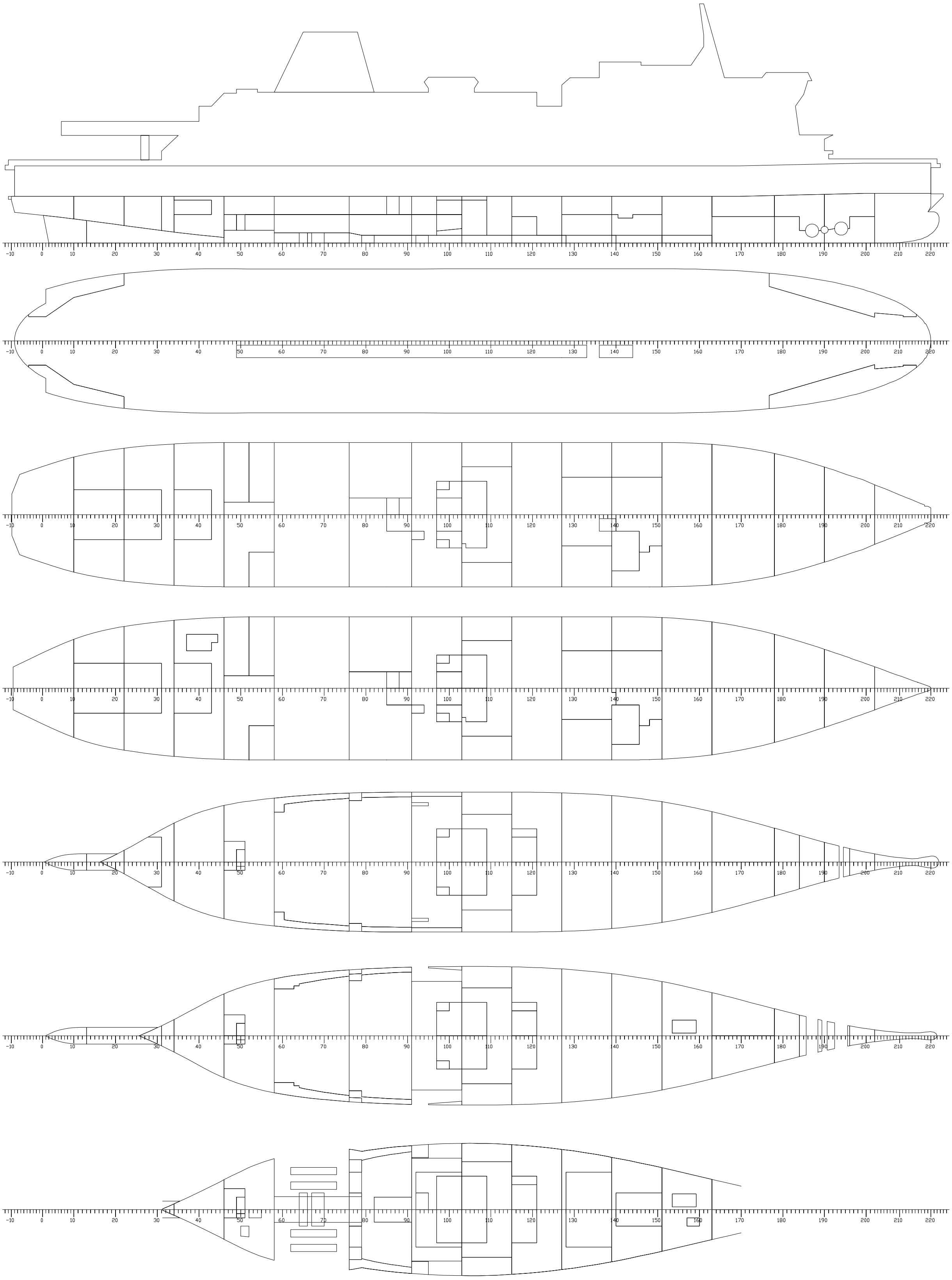


Figure 13: No Modification – Ship 33

6. CONCLUDING REMARKS

Based on the research work described in the foregoing and in the light of past developments, the experience being gained and of future expectations, the following conclusions may be drawn:

- In the wake of the Herald of Free Enterprise and the Estonia disasters, the regulatory Authorities have introduced demanding safety standards for passenger Ro-Ro vessels, notably SOLAS '90 as the new global standard and the Stockholm Agreement, a regional agreement among North West European nations that require these vessels to meet SOLAS '90 standards with up to 0.5m of water on the car deck.

- The Stockholm Agreement represents a major milestone in the history of rule development for assessing ship damage stability by taking explicitly into account the effect of water on the Ro-Ro deck, by linking damage survivability explicitly to operational sea states and by paving the way to performance-based standards and to first-principles approaches to ship safety.

- Evidence amassed in the route to compliance allowed for a comparative assessment between the available regulatory instruments showing 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.

- The introduction of the Stockholm Agreement forced attention on the safety of Ro-Ro passenger ships and in so doing it helped promote a safety culture in shipping, pushing safety firmly at the centre of the ship design process and establishing it firmly in the minds of ship designers and operators as a through life-cycle imperative. The influence of this shift of attention to safety coupled with technological developments and the need to adapt to the rapidly changing drivers of shipping are likely to have profound effects on Ro-Ro ship design, construction and operation.

- The impact of the Stockholm Agreement on the existing fleet of North West Europe has been much more positive than most people feared. Shippers have either found a cost-effective way to compliance through performance-based approaches (numerical simulations and model experiments), raising the safety of their fleet to its rightful level, or cut their losses and opted for new, modern, safer, more efficient ship designs. Either way shipping is undergoing a "face lift" and is looking much better for it.

- The North-South divide concerning safety of Ro-Ro passenger ships continues to troubles shippers and regulators alike and a way forward is actively being sought. Serving this need, an SSRC-NTUA partnership has undertaken on behalf of the European Commission a study to assess the impact of the Stockholm Agreement on the areas covered by it with the view to evaluating the likely impact of introducing it to areas not covered by it. This introspection on the Stockholm Agreement will prove invaluable in paving the way forward. The results of the Commission study, due to be finalised shortly, will form Part II of this paper.

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