

THE APPLICATION OF ADVANCED NUMERICAL TOOLS IN DESIGN FOR STOCKHOLM AGREEMENT UPGRADING

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ABSTRACT

Safety at Sea Ltd. (SaS) is an engineering consulting company specialised in stability, safety and design of ships and advanced marine vehicles. Safety at Sea was created to fully exploit the technology developed at the Ship Stability Research Centre of the Universities of Glasgow and Strathclyde (SSRC). This technology has been used to develop a niche in the upgrading of RORO vessels to SOLAS 90 and the Stockholm Agreement through a process known as Total Stability Assessment. This process includes damage stability upgrading using commercial static stability software in conjunction with numerical simulations of the dynamic behaviour of the damaged ship, before progressing to the physical damage survivability model tests. Once an upgrade solution has been optimised, a physical model for damage survivability is build for testing in the towing tank available to SSRC (Denny Tank at Dumbarton, a facility measuring 100mx6.7mx2.7m). Employing this approach, nearly 70 vessels have been tested by SaS, accounting for about 80% of the north European RORO fleet needing upgrading. The practical application of TSA is demonstrated in this paper through a comparative study addressing RORO damage survivability based on SOLAS 90, Stockholm Agreement, numerical simulations and physical model tests. It is also demonstrated how the correct application of TSA is conducive to optimal and inexpensive solutions, effectively reducing the average cost of upgrading to Stockholm Agreement to that of upgrading to SOLAS 90, for the majority of ships tested to date.

1. INTRODUCTION

Since the Estonia disaster, efforts have been focusing on the improvement of stability standards for Car/Passenger ferries. While international joint efforts have been conducive to introducing more rational damage stability standards based on vessel performance in realistic environmental conditions, for an immediate solution of the problem with existing ships, the IMO set up a panel of experts to consider the issues carefully and make suitable recommendations. Deriving from this, new stability requirements were proposed, such as the SOLAS 90 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 value, the number of persons carried and age. Furthermore, in the beginning of 1996, the North West European countries introduced the Stockholm Agreement standard, to be complied with dates ranging from 1 April 1997 to 1 October 2002 again depending on the vessel's A/Amax value. 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 to Stockholm Agreement has been allowed, which provides a non-prescriptive way of ensuring compliance by performing experiments of damaged ship models. This regulatory regime understandably left the shipping industry in a state of confusion and uncertainty concerning the available options and optimum choice to ensuring compliance. However, the industry responded to new standards positively by taking action towards improving the standards of existing ferries in a joint effort including operators, designers, research institutions and regulatory bodies.

In response to the challenge presented by the new regulations, the maritime industry, slowly but steadily, has favoured the model experiments route, implicitly demonstrating mistrust towards deterministic regulations. Blindly following this route, however, discourages systematic searching for practical and cost-effective solutions to upgrade existing ships as well as efforts towards the development of safe innovative designs to meet the demands of current and emerging markets. It is from these considerations that the SSRC developed in 1996 the TSA methodology. This design methodology exploits the high-tech numerical tools developed at SSRC to guide the design of RORO upgrading by predicting the behaviour of the vessel during the model tests. In practice, once compliance with SOLAS 90 has been assured by addressing those areas that show insufficient local static stability, the results of an array of simulations of the ship in various damaged condition is studied, to isolate improvements to the SOLAS 90 solution obtained that

would make survival of a target significant wave height (H_s) possible for the vessel. These improvements are thus guided by a sound physical understanding of damaged ship behaviour at sea and normally represent only minor adjustments to the SOLAS 90 solution. The upgraded design thus obtained is also assessed in terms of standard Stockholm Agreement calculations by evaluating the equivalent limiting H_s/KG according to this method and/or by comparing it in economic and practical terms with alternative solutions produced using direct calculations only. In most cases dealt with so far, this exercise proved that the TSA method produced solutions far less onerous than those that could be devised using direct Stockholm Agreement calculations.

Applying TSA, SSRC first and SaS later have designed upgrading solutions for approximately 80% of the North European passenger RORO fleet, with nearly 70 models tested in Dumbarton. In this paper, a brief account will be given of how TSA has been used by presenting the case of a typical RORO upgrading.

2. DESIGN FOR STOCKHOLM AGREEMENT COMPLIANCE

2.1 Stockholm Agreement Requirements

The Stockholm Agreement demands that a vessel satisfies SOLAS 90 with a constant height of water on deck as explained in the following. Based on a 4 m significant wave height, the height of water on deck should be:

- 0.5 m if the residual freeboard at the damage opening is 0.3 m or less;
- 0.0 m if the residual freeboard at the damage opening is 2.0 m or more;
- intermediate values can be determined by linear interpolation.

For ships operating in restricted areas where the significant wave height is less than 4 m, the height of water on deck will be:

- 0.0 m if the significant wave height is 1.5 m or less;
- intermediate values of height of water on deck for significant wave heights between 1.5 and 4 m can be determined by linear interpolation.

In practice this is equivalent to a linear interpolation over a surface as illustrated in Figure 1.

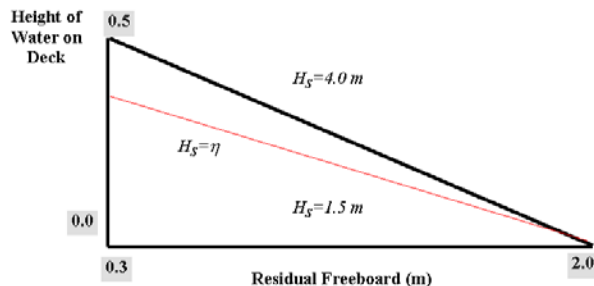


Figure 1: Stockholm Agreement (Height of Water on Deck)

As an alternative to Stockholm Agreement water on deck calculations, physical model experiments can be carried out to demonstrate whether a ship in the worst damage condition can survive the operational sea-state (the *equivalence* route). The worst damage case scenario is defined according to the area under the GZ curve (e.g., up to GZ max, according to some national authorities). If the worst damage case is outside $\pm 10\%L_{bp}$ amidships, additional experiments for the worst midship damage case (selected within this range to have the minimum freeboard at the damage location) should be carried out.

All physical model experiments must be carried out in accordance with the official model test procedure as specified in Appendix to the Annex of Resolution 14 of SOLAS 95. The model should be placed in beam seas and subjected to long crested irregular seas defined by the JONSWAP spectrum with a required significant wave height and two peak periods corresponding to “short” and “long” waves. Experiments last over 30 minutes in full scale and are repeated 5

times for each damage condition tested and for each sea state. Survival of all tests is required for compliance with Stockholm Agreement.

2.2 Total Stability Assessment

The basic idea behind the TSA involves assessing the damage survivability of the vessel through an iterative procedure, shown in Figure 2, involving all pertinent stability instruments, namely probabilistic (A/Amax; the main criterion to determine dates of compliance), deterministic (SOLAS 90 and Stockholm Agreement) and performance-based (numerical and physical model tests).

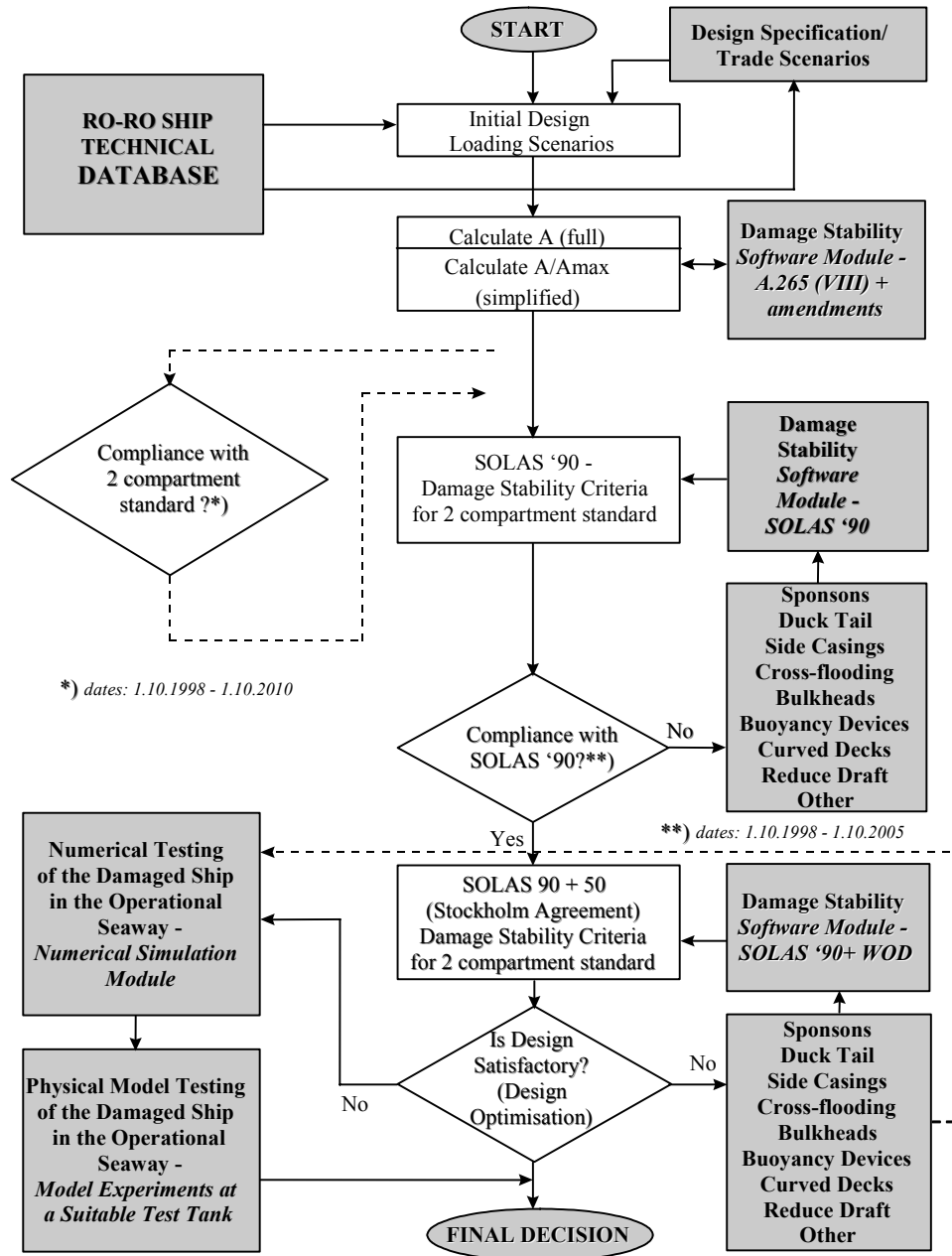


Figure 2: "Total Stability Assessment" Procedure

In brief, the methodology can be summarised in the following basic steps (it is here assumed that the A/Amax value of the vessel in question is known):

STEP 1: Compliance with SOLAS'90

This is the first step towards a successful upgrading design of a RORO vessel, which needs to be taken before proceeding with the numerical assessment of a design solution and the determination of the Hs achievable in the tank. Any design solution should satisfy the SOLAS 90 damage stability standards regardless of the damaged vessel performance in waves. Although traditionally this first stage of design has been carried out applying the deterministic SOLAS 90 standard, it can be equally addressed applying probabilistic methods, such as A.265 (VIII) + amendments.

STEP 1 thus involves optimisation of the required solution mainly in terms of static stability characteristics only, although SaS experience invariably leads to modifications that are also likely to improve the vessel survivability in waves. When this phase of the design optimisation is carried out according to deterministic rules, the value of the various GZ curve and margin line related parameters are used as guide to suggest possible modifications and improvements. If this process involves modifications to the external geometry of the ship, these are generally designed using software purposely developed at SaS (PolyCAD – see Figure 3).

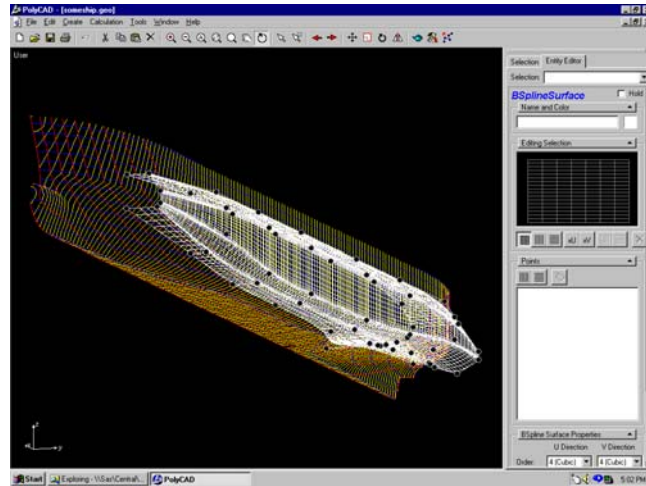


Figure 3: PolyCAD Definition of a Sponson

STEP 2: Numerical Simulation

Once a design solution complying with SOLAS 90 standards has been identified, the survivability of the damaged ship is investigated by means of numerical simulations and the limiting sea state in which the ship can survive is determined.

In order to do this, the internal and external geometry of the vessel are exported to SSRC software DAMSIM. An array of simulations is then set up and run (see Figure 4). If the numerical simulations indicate that the damaged ship can survive the target sea state without any further modifications to the design solution, then physical model tests can be performed as described in STEP 4. However, if the ship does not survive the required (normally operational) sea state, various improvements can be proposed and investigated employing DAMSIM, in order to identify an optimum solution that would provide the required level of survivability without compromising on practical applicability, cost or ease of operation.

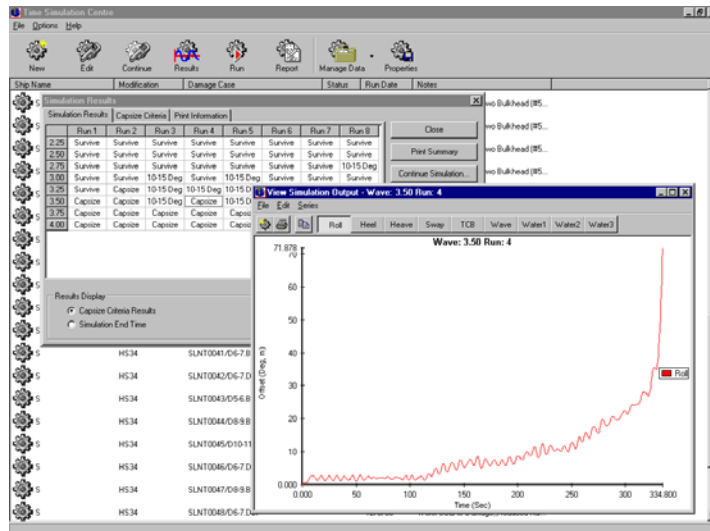


Figure 4: Typical Simulation Matrix and Results

Normally, the detailed information provided by the simulation software in terms of vessel motion and floodwater distribution is used as a guide to achieve this purpose (see Figure 5). This method is highly effective because this type of information allows an in-depth understanding of the damaged vessel dynamics which in turn is used to suggest the type of modifications necessary to achieve the most effective upgrading solution. The solution thus derived can then be model tested for compliance with the Stockholm Agreement, if compliance by direct calculation using the deterministic Stockholm Agreement method fails.

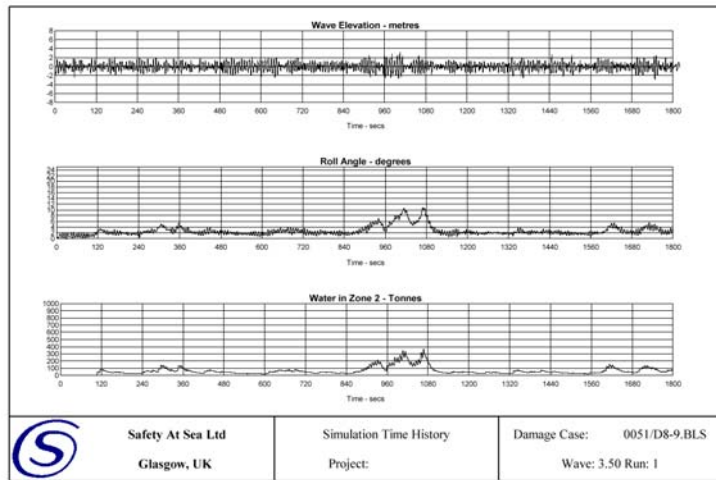


Figure 5: Typical Detailed Information Provided by DAMSIM

STEP 3: Compliance with Stockholm Agreement Requirements

This step involves an investigation on whether the damaged ship complies with the Stockholm Agreement requirements and only involves static stability calculations. STEP 3 is normally taken immediately after STEP 1 if the SOLAS 90 solution already provides a sufficient margin of stability to indicate a reasonable probability of achieving the target Hs by calculation without further modifications. If this test proves that the SOLAS 90 solution does not comply with the water on deck standards, then numerical tests are performed as described in STEP 2. In SaS and SSRC experience this type of check almost invariably reveals that the current Stockholm Agreement standard underestimates considerably the Hs achievable by typical RORO vessels when tank tested according to the *equivalent method*, particularly for damages other than amidships (see Figure 6).

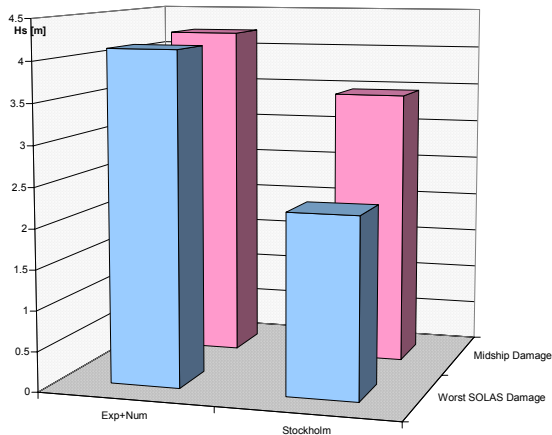


Figure 6: Comparison between Stockholm Agreement and Performance-Based Standards



Figure 7: A Typical RORO Model under Construction

STEP 4: Physical Model Tests

This step is required to demonstrate compliance with the Stockholm Agreement according to the *equivalence* route. However, it must be noted that this last step is employed within the TSA only to demonstrate Stockholm Agreement compliance to the national authorities. There is indeed a growing belief and sufficient evidence to demonstrate that

success using numerical simulations (*numerical equivalence* route) should suffice, although this is not yet officially recognised as a valid method of compliance.

In order to prepare the model tests, drawings of a scaled model including the proposed structural alterations as determined in steps 1 to 3 are produced, ensuring that the stability characteristics of the model match those of the real ship. Following this design phase, the model is then constructed (Figure 7) following a standard process, developed in the light of the experience accrued over the past 15 years of this type of testing. Experiments are finally carried out in the wavemaking/towing tank according to the specifications laid down in the Stockholm Agreement.

2.3 SSRC Numerical Tools - DAMSIM

A number of specialised numerical tools are necessary in order to apply the TSA design procedure. In the following, a brief description is given of two of the codes employed, both developed by SaS and SSRC, before proceeding with the illustration of a worked example of the application of the TSA.

Since the dynamic behaviour of a damaged vessel and the progression of floodwater through it in a random sea are ever changing – rendering the dynamic system highly non-linear – the technique used to study this system is, of necessity, time simulation. The numerical experiments considered in TSA assume, as in the case of the standard Stockholm Agreement model tests, a stationary ship beam on to the oncoming waves with progressive flooding taking place through a standard SOLAS damage opening. During the simulation, SSRC software DAMSIM calculates the heave, sway and roll motion of the damaged ship under the action of random beam waves and instantaneous water ingress estimated as a function of wave elevation and ship motions. Because of the slow varying nature of pitch in the beam sea condition, this mode of motion is not taken directly into consideration as a fully dynamic degree of freedom. The static trim of the vessel is constantly updated instead, to take into account the effects of water accumulation. Also, because of the typical size of RORO vessels, it is assumed that floodwater dynamics would subside near to the capsize boundary and thus the free surface of floodwater in all compartments is always considered flat and horizontal, thus excluding all sloshing effects. These and other assumptions typifying DAMSIM have been extensively verified over the past 15 years and undergone vigorous validation/calibration during both the UK Ro-Ro Research [1] and the Joint North West European Project [2].

In order to effectively employ DAMSIM in a systematic assessment of a ship resistance to capsize, simulations are carried out for each design solution under investigation, for different damage cases and a number of loading conditions. For each of these cases, H_s is progressively increased up to the limit value characterising the area in the KG- H_s plane where the ship capsizes systematically, thus allowing for the definition of survival boundaries. These boundaries, together with additional information provided by the software in terms of time series of the vessel motion and the amount and location of floodwater in each compartment, constitute the basic information used to improve design solutions. Considerable effort has been spent towards development and refinement of this simulation program and confidence was gained over many years of numerical testing for the prediction of survival boundaries of a damaged vessel over the whole range of possible compartment arrangements, loading conditions, operating environments, and location of the damage opening, thus rendering DAMSIM a valuable design tool. Such claims have been substantiated by the impressive agreement achieved between theoretical and experimental results spanning a wide range of parametric variation as illustrated in Figures 8 and 9.

2.4 Case Study

In the following, an example of the practical application of TSA to the upgrading of an existing RORO ferry is presented. Details are given on the rationale leading to an optimised solution, highlighting the use of static and dynamic stability data in the search for a SOLAS 90 compliant solution by means of local and global modifications. Particular emphasis is put on the cost-benefit analysis performed on each solution, leading to the final selection.

The Problem:

This example ship was designed to comply with SOLAS 74 and operates in an area characterised by a significant wave height of 3.1 metres (required H_s). Principal particulars and general arrangement are shown in Table 1 and Figure 10, respectively. The value of A/A_{max} for this vessel before SOLAS 90 upgrading was 91.6% and the current owner wished her to be modified so that she would be able to operate in areas with H_s values up to 3.4 metres. The existing design did not comply with SOLAS 90 for most damage cases (see Table 2) over the vessel's operational KG and trim range because of generally poor static stability (range, GZ_{max} , area etc.).

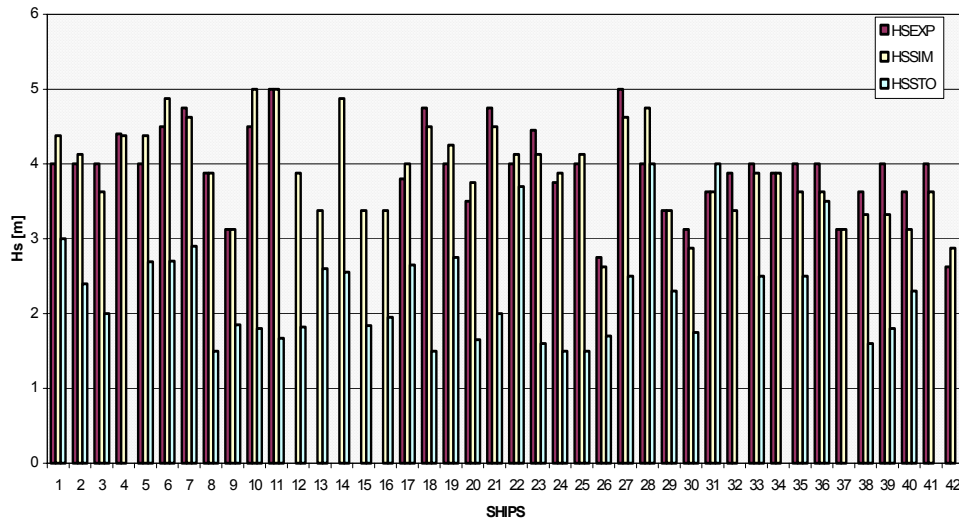


Figure 8: Comparison between Experimental Results (HSEXP), Numerical Simulations (HSSIM) and Stockholm Agreement Standard Calculations (HSSTO) – Worse SOLAS Damage

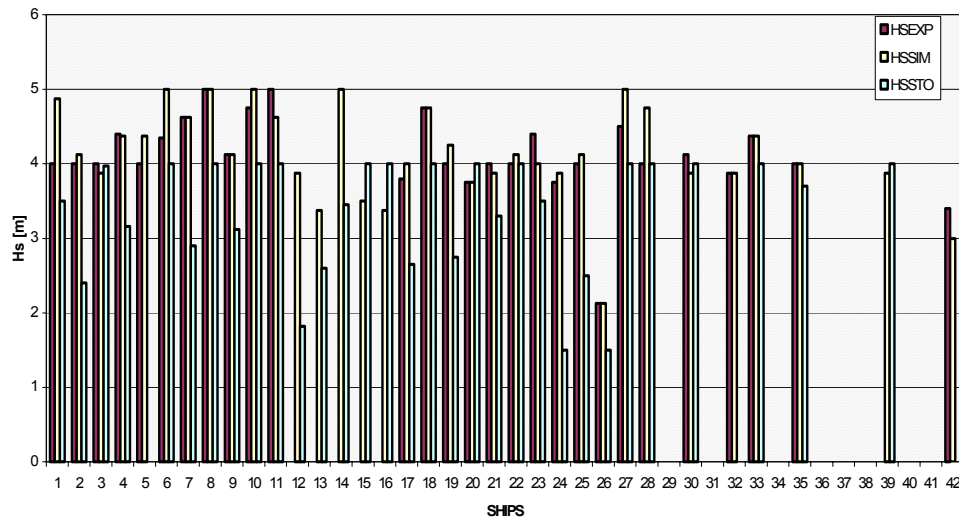


Figure 9: Comparison between Experimental Results (HSEXP), Numerical Simulations (HSSIM) and Stockholm Agreement Standard Calculations (HSSTO) – Midship Damage

The first step in the upgrading procedure is to find the least onerous set of alterations to comply with SOLAS 90 requirements. In the case of the ship in question, the design criteria imposed by her owner/operator were that the truck stowage arrangement on the vehicle deck was not to be reduced and that no external modifications were to be applied if at all possible. In addition, the current arrangement of the deck ramps and hanging car decks would have to be taken into consideration in positioning transverse barriers. For these reasons, a two-barrier on the car deck solution was proposed with the transverse barriers positioned so that no loss of cargo is incurred. The barriers were staggered in order to accommodate hanging car decks and two small buoyancy tanks and frame-size webbing on the vehicle deck were added in order to improve this arrangement in case where any of the barriers is damaged. This solution was devised bearing in mind both SOLAS 90 static stability criteria and the results obtained using DAMSIM.

Table 1: Principal particulars

Length Between Perpendiculars, L_{BP}	131.00 m
Beam, B	26.00 m
Maximum Draught, d	6.12 m
Depth to Car Deck	7.80 m
Depth to Upper Deck	18.00 m
Operational KG	12.31 m
Displacement, Δ	12759.50 tonnes

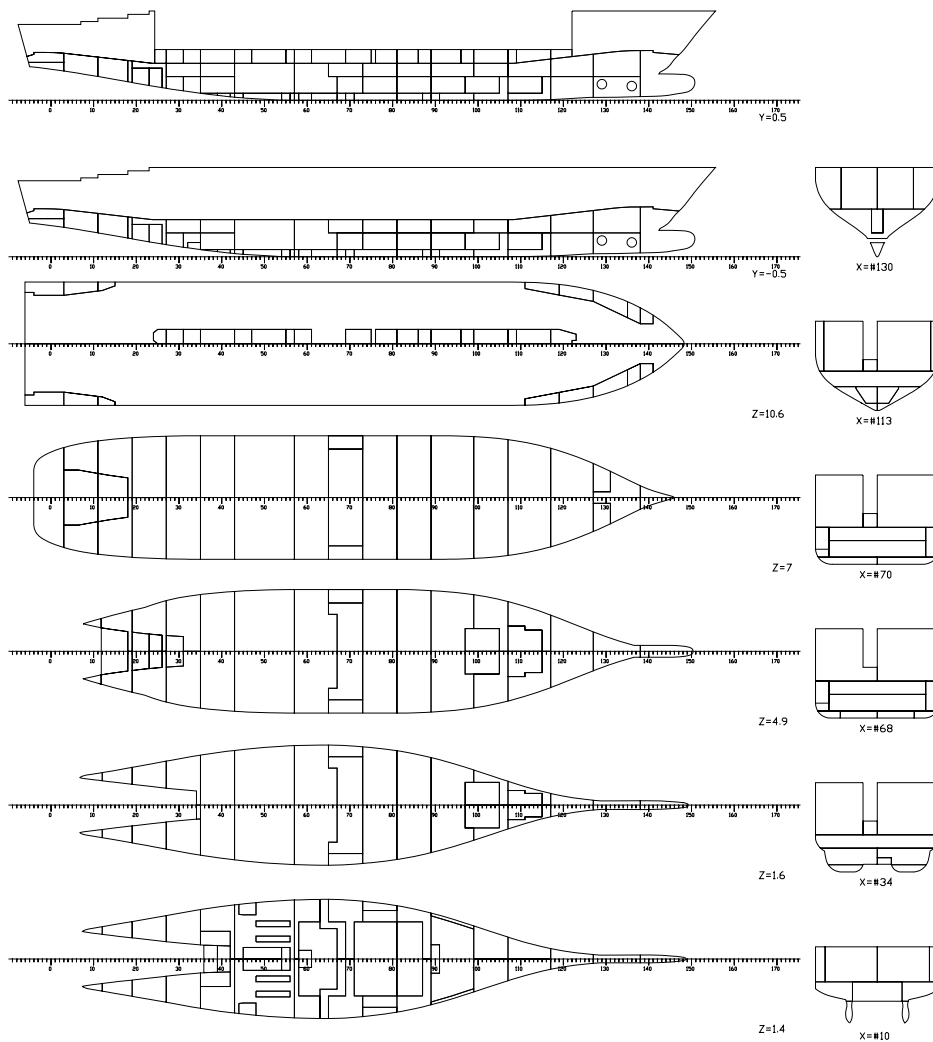


Figure 10: Arrangement of Existing Ship

Solution 1: The following is a list of all the modifications proposed for Solution 1:

SOLAS 90 and Stockholm Agreement Modifications

1. Car deck transverse barriers placed at frame #66 port, frame #69 starboard, frame #86.5m port and frame #89 starboard.
2. New buoyancy tanks added above the tween deck in compartment 12. Tank RS100 from frame #96 to frame #99 port; Tank RS101 cross-connected from frame #97 to frame #99 starboard.
3. Webbing added on car deck between frames #24-#57, #73-#86.5m and #96-#110. Webbing spaces are subdivided at frame #43.
4. Original side casings made watertight except for the vent compartments.

A diagram of these modifications is shown in Figure 12 and the summary SOLAS 90 results given in Table 3.

Table 2: SOLAS 90 calculations results for the existing ship

DAM	T m	TR m	HEEL degree	GZMAXR m	RANGE degree	AGZR rad*m	RESMRG m	STAT
D1-2 .BL	6.128	0.159	0.2	0.195	14.69	0.02965	1.50	OK
D2-3 .BL	6.153	1.017	1.2	0.148	11.99	0.01798	0.93	NOT MET
D2-3 .DB	6.152	0.967	0.9	0.154	12.49	0.01943	1.03	OK
D3-4 .BL	6.240	2.067	0.9	0.138	11.95	0.01778	0.54	NOT MET
D3-4 .DB	6.233	1.954	0.0	0.160	13.38	0.02254	0.79	OK
D4-5 .BL	6.341	2.199	1.5	0.131	10.96	0.01560	0.26	NOT MET
D4-5 .DB	6.328	2.060	0.0	0.168	13.29	0.02375	0.65	OK
D4-5 .BLA	6.364	2.360	0.0	0.184	13.52	0.02674	0.51	OK
D5-6 .BL	6.499	2.272	0.8	0.154	11.49	0.01930	0.24	NOT MET
D5-6 .DB	6.462	2.095	0.0	0.173	12.69	0.02357	0.51	OK
D6-7 .BL	6.883	2.119	0.2	0.128	9.84	0.01385	0.05	NOT MET
D6-7 .DB	6.759	1.876	0.0	0.132	10.29	0.01483	0.30	NOT MET
D7-8 .BL	7.016	1.187	0.0	0.139	9.98	0.01492	0.28	NOT MET
D7-8 .DB	6.863	1.047	0.0	0.133	10.03	0.01408	0.49	NOT MET
D8-9 .BL	6.631	0.088	3.3	0.069	6.83	0.00511	0.31	NOT MET
D8-9 .DB	6.513	0.074	4.0	0.049	5.73	0.00304	0.27	NOT MET
D9-10 .BL	6.766	-0.600	3.5	0.059	6.19	0.00402	0.08	NOT MET
D9-10 .DB	6.712	-0.560	3.2	0.068	6.85	0.00506	0.21	NOT MET
D10-11 .BL	6.845	-1.169	0.5	0.137	11.41	0.01650	0.58	NOT MET
D10-11 .DB	6.805	-1.096	0.0	0.151	12.29	0.01932	0.75	OK
D11-12 .BL	7.094	-2.314	0.0	0.081	9.50	0.00839	0.27	NOT MET
D11-12 .DB	6.983	-2.051	0.0	0.078	9.62	0.00816	0.42	NOT MET
D12-13 .BL	7.088	-2.864	0.0	0.050	8.43	0.00457	0.19	NOT MET
D12-13 .DB	7.005	-2.644	0.0	0.047	8.46	0.00419	0.31	NOT MET
D13-14 .BL	6.862	-2.775	0.0	0.049	9.00	0.00462	0.43	NOT MET
D14-15 .BL	6.851	-3.186	0.0	0.051	8.33	0.00463	0.38	NOT MET
D15-16 .BL	6.610	-2.346	0.0	0.127	11.80	0.01577	0.75	NOT MET
D16-17 .BL	6.353	-1.212	0.0	0.212	16.70	0.03674	1.18	OK

The numerical simulations carried out with DAMSIM to investigate the survivability of Solution 1 led to the conclusion that for the worst SOLAS damage, damage case D8-9.DBS, the survival boundary is greater than 3.75m, which provides a reasonable margin in terms of survival boundary with regards to the desired model test wave height of 3.4 m. Note that this damage case is within 10% L_{BP} from midship and thus the only one that would have to be tank tested.

Standard Stockholm Agreement calculations were also performed for this solution. The limiting KG curve according to these calculations is compared in Figure 11 with that of the same solution complying with SOLAS 90 and Stockholm Agreement via the experimental route. As it can be seen, the limiting KG curve determined using standard Stockholm Agreement calculations is well below the required operational KG. If Solution 1 were to meet this operational KG value using standard Stockholm Agreement calculations, the limiting significant wave height would have to be reduced from 3.4 to 1.7 m.

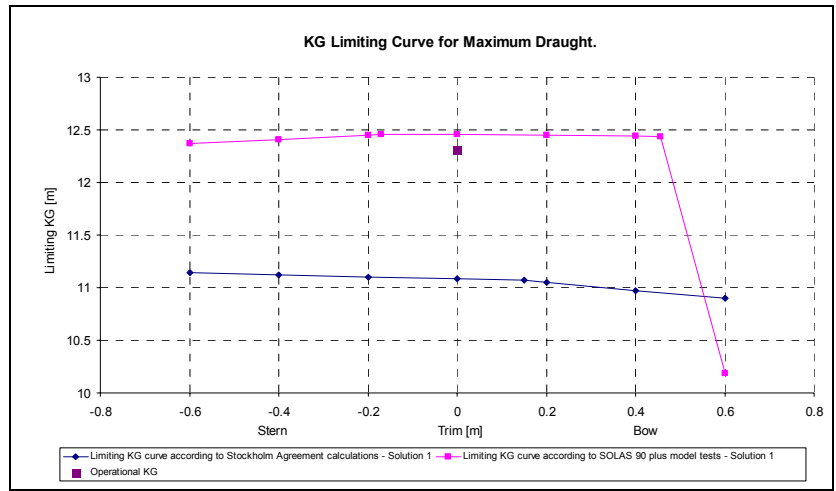


Figure 11: KG limiting curves for Solution 1

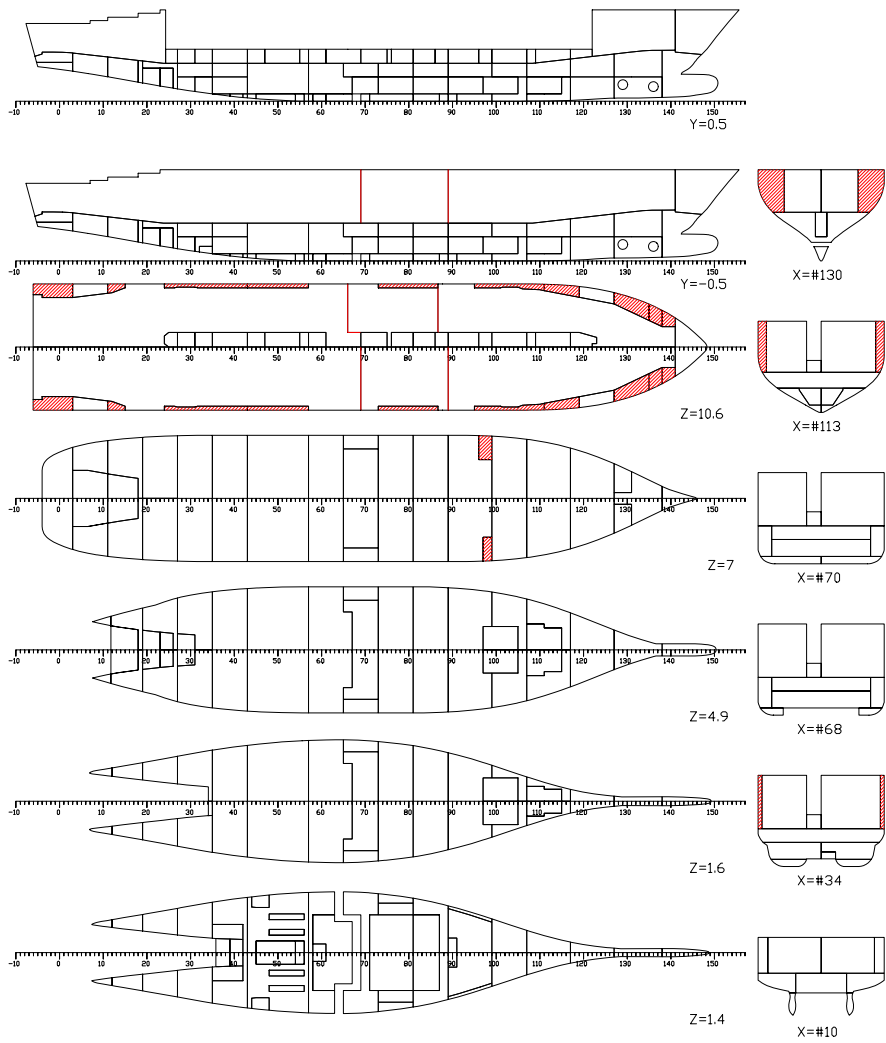


Figure 12: Arrangement of Solution 1

Table 3: SOLAS 90 calculations results for Solution 1

DAM	T m	TR m	HEEL degree	GZMAXR m	RANGE degree	AGZR rad*m	RESMRG m	STAT
D1-2.BLP	6.139	0.204	0.5	0.270	23.68	0.07608	1.40	OK
D1-2.BLS	6.139	0.204	-0.5	0.255	23.60	0.07310	1.40	OK
D2-3.DBP	6.246	1.176	0.9	0.185	22.38	0.05390	0.88	OK
D2-3.DBS	6.246	1.176	-0.9	0.182	22.45	0.05015	0.88	OK
D2-3.BLP	6.250	1.219	1.2	0.178	22.05	0.05142	0.79	OK
D2-3.BLS	6.250	1.219	-1.2	0.175	22.12	0.04763	0.79	OK
D3-4.DBP	6.313	1.408	0.0	0.222	23.67	0.06451	0.94	OK
D3-4.DBS	6.313	1.408	0.0	0.198	23.38	0.06078	0.94	OK
D3-4.BLP	6.325	1.501	1.0	0.205	22.23	0.05725	0.67	OK
D3-4.BLS	6.325	1.501	-1.0	0.179	22.30	0.05341	0.67	OK
D4-5.DBP	6.417	1.640	0.0	0.240	22.79	0.07322	0.75	OK
D4-5.DBS	6.417	1.640	0.0	0.232	22.89	0.06955	0.75	OK
D4-5.BLP	6.437	1.763	1.3	0.206	21.29	0.06017	0.39	OK
D4-5.BLS	6.438	1.764	-1.3	0.199	21.43	0.05671	0.41	OK
D5-6.DBP	6.511	1.568	0.0	0.284	22.95	0.08658	0.68	OK
D5-6.DBS	6.511	1.568	0.0	0.274	22.50	0.08256	0.69	OK
D5-6.BLP	6.556	1.717	0.7	0.274	22.13	0.08239	0.44	OK
D5-6.BLS	6.556	1.718	-0.6	0.265	21.57	0.07846	0.45	OK
D6-7.DBP	6.825	1.527	0.0	0.195	20.96	0.05327	0.38	OK
D6-7.DBS	6.825	1.527	0.0	0.185	21.00	0.04794	0.38	OK
D6-7.BLP	6.963	1.738	0.2	0.212	19.81	0.05819	0.12	OK
D6-7.BLS	6.963	1.738	-0.2	0.197	19.85	0.05216	0.12	OK
D7-8.DBP	6.926	0.920	0.0	0.195	21.00	0.05590	0.49	OK
D7-8.DBS	6.926	0.920	0.0	0.183	20.99	0.05061	0.49	OK
D7-8.BLP	7.061	1.054	0.1	0.236	20.07	0.06607	0.29	OK
D7-8.BLS	7.061	1.054	-0.1	0.217	20.07	0.06022	0.29	OK
D8-9.DBP	6.743	0.035	0.0	0.174	21.84	0.04260	0.97	OK
D8-9.DBS	6.743	0.035	0.0	0.171	21.75	0.03870	0.97	OK
D8-9.BLP	6.821	0.029	0.0	0.193	21.45	0.05102	0.89	OK
D8-9.BLS	6.821	0.029	0.0	0.188	21.35	0.04696	0.89	OK
D9-10.DBP	6.733	-0.470	0.0	0.543	22.53	0.09989	0.88	OK
D9-10.DBS	6.733	-0.470	0.0	0.547	22.52	0.10032	0.88	OK
D9-10.BLP	6.788	-0.499	0.5	0.569	21.72	0.10372	0.70	OK
D9-10.BLS	6.788	-0.499	-0.5	0.573	21.72	0.10415	0.70	OK
D9-10.DBS2	6.735	-0.465	0.0	0.177	21.63	0.04273	0.88	OK
D9-10.BLS2	6.789	-0.496	-0.5	0.174	20.81	0.04293	0.70	OK
D10-11.DBP1	6.713	-0.914	0.0	0.599	22.45	0.10993	0.79	OK
D10-11.DBS1	6.713	-0.914	0.0	0.603	22.40	0.11021	0.79	OK
D10-11.BLP1	6.748	-0.979	0.5	0.607	21.74	0.10954	0.62	OK
D10-11.BLS1	6.748	-0.979	-0.5	0.611	21.68	0.10980	0.62	OK
D10-11.DBP2	6.720	-0.910	0.0	0.226	22.35	0.06159	0.78	OK
D10-11.BLP2	6.751	-0.977	0.5	0.228	21.66	0.05895	0.62	OK
D11-12.DBP1	6.785	-1.613	0.0	0.176	22.09	0.04038	0.54	OK
D11-12.DBS1	6.784	-1.615	-0.3	0.203	21.57	0.04295	0.48	OK
D11-12.BLP1	6.879	-1.844	0.0	0.209	21.65	0.04518	0.39	OK
D11-12.BLS1	6.879	-1.846	-0.3	0.234	21.11	0.04729	0.33	OK
D11-12.DBP2	6.804	-1.665	0.0	0.327	21.99	0.05807	0.51	OK
D11-12.BLP2	6.898	-1.906	0.0	0.355	21.55	0.06342	0.36	OK
D12-13.DBP	6.817	-2.226	0.0	0.292	21.99	0.04448	0.36	OK
D12-13.DBS	6.817	-2.226	0.0	0.323	21.74	0.04903	0.36	OK
D12-13.BLP	6.884	-2.429	0.0	0.309	21.68	0.04831	0.25	OK
D12-13.BLS	6.884	-2.429	0.0	0.340	21.40	0.05270	0.25	OK
D13-14.BLP	6.697	-2.428	0.0	0.269	22.26	0.04033	0.43	OK
D13-14.BLS	6.697	-2.428	0.0	0.300	21.98	0.04535	0.43	OK
D14-15.BLP	6.659	-2.780	0.0	0.292	22.23	0.04285	0.39	OK
D14-15.BLS	6.659	-2.780	0.0	0.319	21.88	0.04808	0.39	OK
D15-16.BLP	6.468	-2.054	0.0	0.366	22.63	0.06807	0.75	OK
D15-16.BLS	6.468	-2.054	0.0	0.400	22.30	0.07301	0.75	OK
D16-17.BLP	6.207	-0.591	0.0	0.592	24.18	0.11442	1.37	OK
D16-17.BLS	6.207	-0.591	0.0	0.623	24.06	0.11730	1.37	OK

It is clear from these results that this solution could not be ratified unless model experiments were run to verify the predictions of the DAMSIM simulations. Indeed, a reduction of limiting KG in the range of 1.5 m also indicated very clearly that attempting to find a solution that would satisfy standard Stockholm Agreement calculations would almost certainly lead to much more onerous modifications. From experience with several other ferries operating in similar conditions, this result was expected. On the basis of these limiting KG curves, the physical model experiment route was therefore preferred for compliance with the Stockholm Agreement and hence model tests were planned and carried out accordingly. The results of these tests confirmed, once again, the numerical results produced by the DAMSIM simulations. The total cost for this upgrading design was later confirmed by the owner to be 878 kEURO with no loss of cargo or significant increase in running costs.

Because of the limiting KG results shown in Figure 11, no effort was made at the time to devise alternatives to Solution 1, thus minimising design costs. In order to emphasise the tremendous economic value of the TSA methodology, two alternative solutions have nevertheless been studied for this paper, only utilising standard Stockholm Agreement calculations. The first of these alternative solutions attempts to satisfy the Stockholm Agreement using only a combination of barriers on the vehicle deck and other internal modifications. Although the original customer requirements were taken into account for this solution, it was impossible to finalise a barrier set-up that would not affect the ship cargo-carrying capacity. The second solution utilises instead side sponsons to satisfy the Stockholm Agreement. As mentioned earlier, the customer did not favour this type of solutions because of its possible effects on passenger comfort and because of its costs. Nevertheless it should be noted that a similar modification has been designed by other consultants for a sister ship operating in similar environmental conditions (see Figure 13).

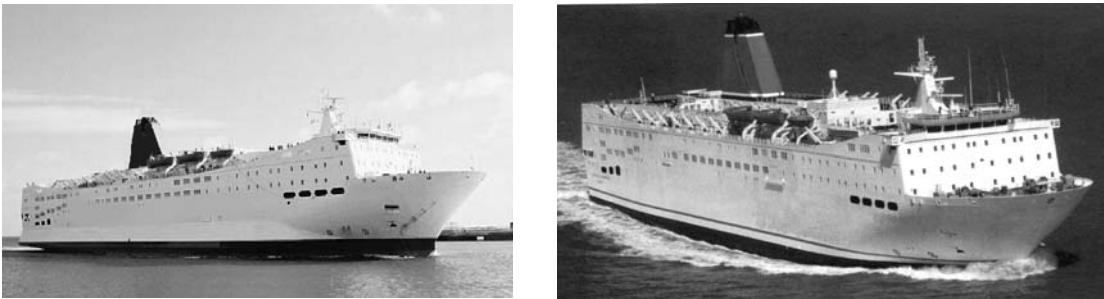


Figure 13: Sponsons modifications adopted for sister ship (left) compared to vessel modified by TSA (right).

Solution 2: The following is a list of all the modifications proposed for Solution 2:

SOLAS 90 and Stockholm Agreement Modifications

1. Car deck transverse barriers placed at frame #35, frame #57, frame #86.5 and frame #107.
2. Car deck longitudinal barrier placed between frame #61 and frame#69.
3. New buoyancy tanks added above the tween deck in compartment 12. Tank RS100 from frame #96 to frame #99 port; Tank RS101 cross-connected from frame #97 to frame #99 starboard.
4. Original side casings made watertight except for the vent compartments.

The arrangement of these modifications is shown in Figure 15 with the summary Stockholm Agreement results given in Table 4. The limiting KG curve according to these calculations is given in Figure 14 together with the corresponding curves calculated for Solution 1. Even after careful positioning of the four transverse barriers this solution limits the trailer length capacity of deck 3 to about 85% of its original value, whilst that of the hanging car deck 4 can only be retained by undertaking extensive modifications of this deck. Furthermore, as it can be seen from Figure 14, even with four sets of transverse barriers on the vehicle deck, watertight side casings and buoyancy tanks, it is still necessary to reduce the operational KG from 12.31 m to 12.22 m using additional ballast water, in order to meet the Stockholm Agreement requirements. This is possible without increase in maximum draught only because of the loss in payload on deck 3. In summary, it is clear that Solution 2 would be expensive to implement (on the basis of the cost estimates reported in [3] the total cost of upgrading for this solution would be around 1400 kEURO without including the modifications to hanging car deck 4) and at best would reduce the vessel's payload by 15%.

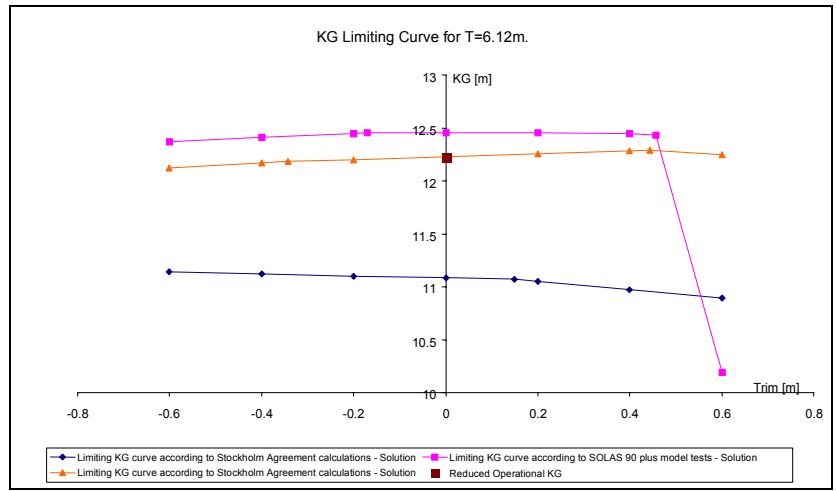


Figure 14: KG limiting curves comparison for Solution 2

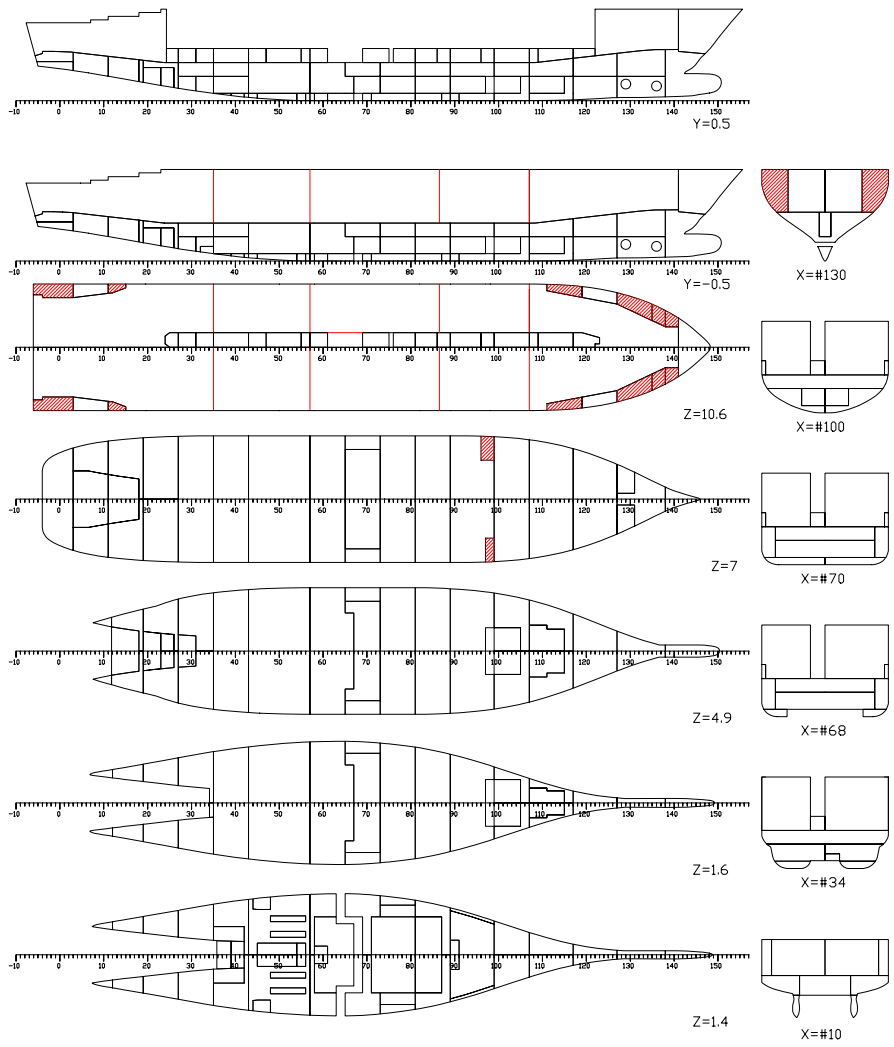


Figure 15: Arrangement of Solution 2

Table 4: Stockholm Agreement calculations results for Solution 2

DAM	T m	TR m degree	HEEL	GZMAXR m	RANGE degree	AGZR rad*m	RESMRG m	STAT
S1-2 .BLP	6.140	0.202	0.5	0.63	39.5	0.1042	1.41	OK
S1-2 .BLS	6.140	0.202	-0.5	0.63	39.5	0.1042	1.41	OK
S2-3 .DBP	6.250	1.207	1.2	0.63	38.8	0.0834	0.78	OK
S2-3 .DBS	6.250	1.208	-1.2	0.62	38.8	0.0834	0.78	OK
S2-3 .BLP	6.255	1.263	1.7	0.62	38.3	0.0799	0.65	OK
S2-3 .BLS	6.255	1.259	-1.7	0.62	38.3	0.0799	0.66	OK
S3-4 .DBP	6.332	1.494	0.0	0.64	40.0	0.0834	0.89	OK
S3-4 .DBS	6.328	1.494	-0.8	0.63	39.2	0.0837	0.72	OK
S3-4 .BLP	6.337	1.605	2.6	0.63	37.4	0.0735	0.25	OK
S3-4 .BLS	6.337	1.605	-2.5	0.62	37.5	0.0736	0.26	OK
S4-5 .DBP	6.439	1.751	0.0	0.59	40.0	0.0914	0.70	OK
S4-5 .DBS	6.439	1.750	0.0	0.59	40.0	0.0925	0.70	OK
S4-5 .BLP	6.455	1.901	2.9	0.58	37.1	0.0747	-0.05	OK
S4-5 .BLS	6.456	1.900	-2.8	0.57	37.2	0.0761	-0.02	OK
S5-6 .DBP	6.541	1.694	1.7	0.21	38.3	0.0607	0.22	OK
S5-6 .DBS	6.545	1.708	-1.8	0.21	38.2	0.0585	0.19	OK
S5-6 .BLP	6.588	1.855	2.8	0.18	37.2	0.0505	-0.13	OK
S5-6 .BLS	6.592	1.872	-2.9	0.18	37.1	0.0484	-0.17	OK
S6-7 .DBP	6.844	1.561	0.9	1.03	39.1	0.1084	0.14	OK
S6-7 .DBS	6.850	1.572	-1.1	1.03	38.9	0.1053	0.10	OK
S6-7 .BLP	6.984	1.775	1.2	1.14	38.8	0.1312	-0.12	OK
S6-7 .BLS	6.991	1.788	-1.3	1.13	38.7	0.1284	-0.16	OK
S7-8 .DBP	6.958	0.933	2.2	0.22	37.8	0.0487	-0.05	OK
S7-8 .DBS	6.970	0.930	-3.0	0.16	37.0	0.0342	-0.26	OK
S7-8 .BLP	7.100	1.073	2.1	0.30	37.9	0.0606	-0.22	OK
S7-8 .BLS	7.116	1.075	-2.8	0.24	37.2	0.0459	-0.41	OK
S8-9 .DBP	6.759	0.018	1.0	0.50	39.0	0.0911	0.72	OK
S8-9 .DBS	6.767	0.002	-1.5	0.45	38.5	0.0813	0.60	OK
S8-9 .BLP	6.839	0.011	1.0	0.54	39.0	0.1042	0.66	OK
S8-9 .BLS	6.848	-0.005	-1.4	0.50	38.6	0.0939	0.55	OK
S9-10 .DBP	6.749	-0.488	1.1	0.51	38.9	0.0931	0.63	OK
S9-10 .DBS	6.757	-0.503	-1.6	0.46	38.4	0.0833	0.50	OK
S9-10 .BLP	6.804	-0.525	1.7	0.52	38.3	0.0952	0.43	OK
S9-10 .BLS	6.813	-0.543	-2.3	0.47	37.7	0.0834	0.28	OK
S9-10 .DBS2	6.757	-0.503	-1.6	0.46	38.4	0.0833	0.50	OK
S9-10 .BLS2	6.813	-0.543	-2.3	0.47	37.7	0.0834	0.28	OK
S10-11 .DBP1	6.740	-1.002	1.9	0.31	38.1	0.0601	0.32	OK
S10-11 .DBS1	6.751	-1.057	-3.1	0.21	36.9	0.0401	0.04	OK
S10-11 .BLP1	6.775	-1.082	2.6	0.30	37.4	0.0560	0.10	OK
S10-11 .BLS1	6.784	-1.156	-4.0	0.20	36.0	0.0339	-0.22	OK
S10-11 .DBP2	6.713	-0.913	0.0	1.32	40.0	0.1440	0.79	OK
S10-11 .BLP2	6.775	-1.083	2.7	0.26	37.3	0.0520	0.09	OK
S11-12 .DBP1	6.811	-1.737	3.0	0.22	37.0	0.0320	-0.18	OK
S11-12 .DBS1	6.794	-1.922	-6.8	0.14	33.2	0.0154	-1.07	OK
S11-12 .BLP1	6.912	-1.978	2.7	0.31	37.3	0.0481	-0.26	OK
S11-12 .BLS1	6.907	-2.166	-6.6	0.18	33.4	0.0195	-1.19	OK
S12-13 .DBP	6.810	-2.334	3.7	0.46	36.3	0.0570	-0.48	OK
S12-13 .DBS	6.801	-2.424	-5.4	0.41	34.6	0.0458	-0.88	OK
S12-13 .BLP	6.886	-2.520	3.3	0.49	36.7	0.0615	-0.50	OK
S12-13 .BLS	6.883	-2.597	-4.7	0.44	35.3	0.0504	-0.85	OK
S13-14 .BLP	6.704	-2.640	4.4	0.23	35.6	0.0248	-0.59	OK
S13-14 .BLS	6.687	-2.811	-6.9	0.20	33.1	0.0179	-1.20	OK
S14-15 .BLP	6.679	-3.070	4.9	0.38	35.1	0.0405	-0.80	OK
S14-15 .BLS	6.684	-3.107	-5.2	0.35	34.8	0.0363	-0.87	OK
S15-16 .BLP	6.468	-2.052	0.0	0.54	40.0	0.0919	0.75	OK
S15-16 .BLS	6.468	-2.052	0.0	0.50	40.0	0.0866	0.75	OK
S16-17 .BLP	6.208	-0.583	0.0	0.70	40.0	0.1274	1.37	OK
S16-17 .BLS	6.208	-0.583	0.0	0.67	40.0	0.1248	1.37	OK

Solution 3: The following is a list of all the modifications proposed for Solution 3:

SOLAS 90 and Stockholm Agreement Modifications

1. Structural side sponsons extending from frame #-6 to frame #135 of 1.7 m width.

The arrangement of these modifications is shown in Figure 17 with the summary Stockholm Agreement results given in Table 6. The limiting KG curve according to these calculations is given in Figure 16 together with the corresponding curves calculated for Solution 1. The values in Table 6 and Figure 16 clearly show that Solution 3 could be a possible alternative to Solution 1 in terms of Stockholm Agreement compliance. It is also clear that the large sponsons used in Solution 3 help to retain the original payload capability of the vessel, although no increase in payload capability was obtained for the design in question. In fact, the sponsons presented in this paper were designed with emphasis on minimising the adverse effect of these large external structures on the vessel intact GM. In order to do so, the sponson width at waterline was minimised, only achieving an underwater volume of the sponson sufficiently large to counterbalance the weight of the structure itself. Although the design optimisation has not been fully carried out, it soon became clear after a few design iterations that values of intact GM lower than 3.5 m would be difficult to obtain. Evidently this would unacceptably affect passenger comfort.

Finally, it must be noted that no attempt has been made during the design of these sponsons to optimise their shape in order to minimise the increase in resistance, an expected result when fitting these structures. Nevertheless, from previous experience with faired sponson forms, properly optimised for minimal resistance, a 3 to 4% increase in resistance can be expected, equivalent to 1 to 2% reduction in vessel speed assuming equal powering. This increased operational cost needs to be added to an initial cost of upgrading which is in the range of 3000 kEURO, according to data from [3].

Synthesis:

In order to better appreciate the economical impact of the TSA design methodology, the results of the exercise presented in the foregoing have been summarised in Table 5. The limiting KG at maximum draught and even keel is provided as a measure of benefit (both in safety and operational terms) for each solution. Considering the results reported, it is fairly straightforward to conclude that Solution 1 is by far the most economic, safety- and cost-effective of the three considered in this paper and with the least impact on the vessel performance. On the basis of this, the advantages of employing the TSA methodology in upgrading existing RORO vessels for compliance with the Stockholm Agreement should be self-evident.

Table 5: Cost-benefit analysis

Solution	Upgrading Cost	Operational Performance Implications	Limiting KG
Solution 1	878 kEURO	None	12.454 m
Solution 2	1400 kEURO	15% loss of payload	12.223 m
Solution 3	3000 kEURO	Loss of passenger comfort, loss of speed/increase in running costs	12.456 m

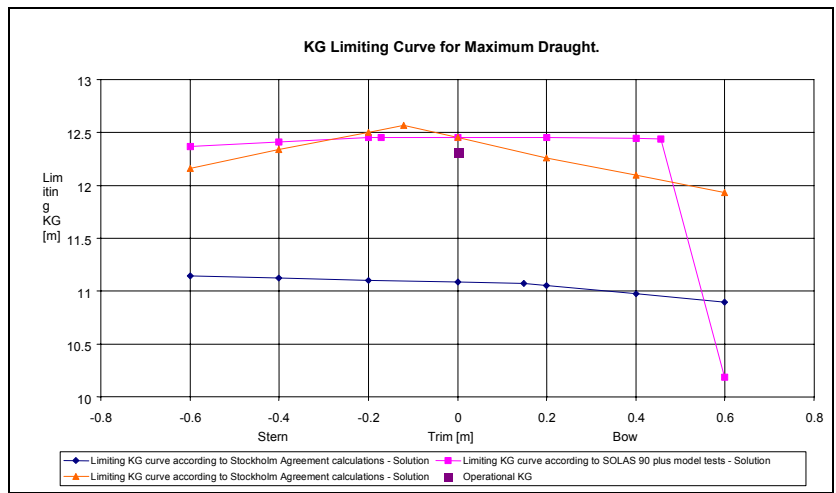


Figure 16: KG limiting curves comparison for Solution 3

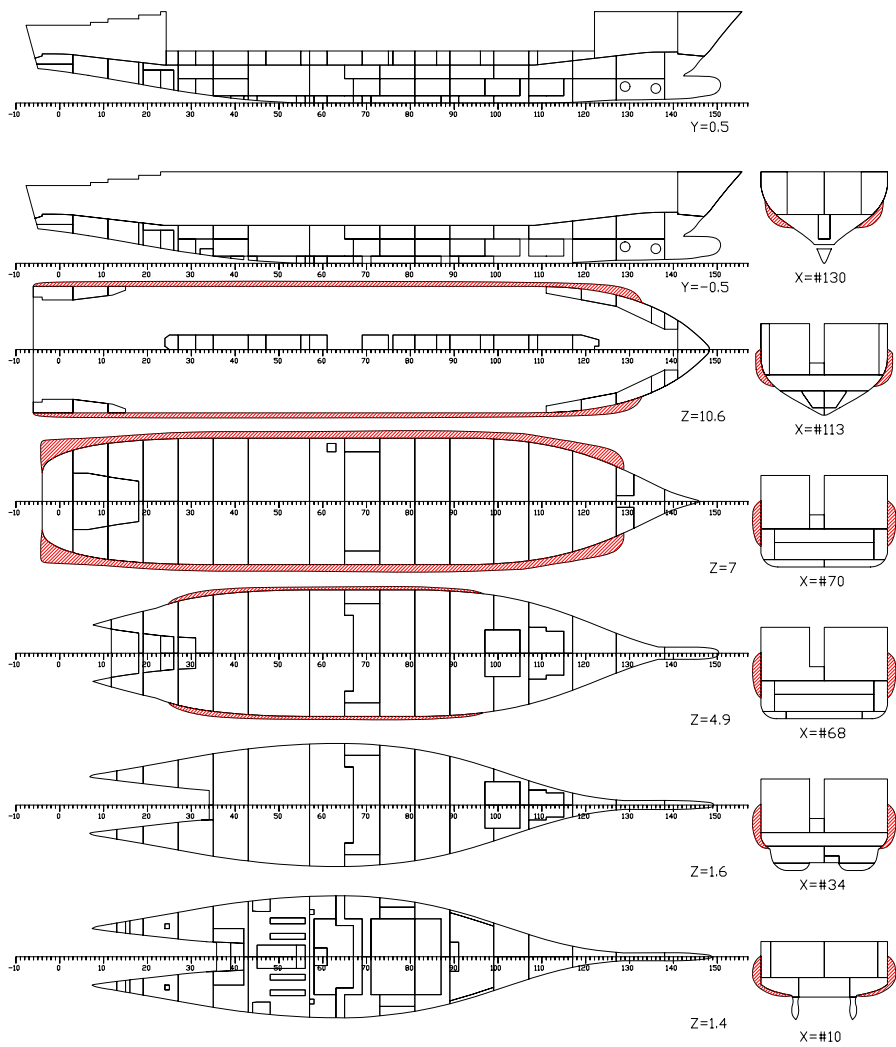


Figure 17: Arrangement of Solution 3

Table 6: Stockholm Agreement calculations results for Solution 3

DAM	T m	TR m degree	HEEL	GZMAXR m	RANGE degree	AGZR rad*m	RESMRG m	STAT
S1-2.BLP	6.144	-0.227	0.3	0.79	36.4	0.2357	1.43	OK
S1-2.BLS	6.143	-0.218	0.0	0.83	33.7	0.2469	1.51	OK
S2-3.DBP	6.267	-1.134	1.4	0.65	32.3	0.1853	0.76	OK
S2-3.DBS	6.269	-1.144	-1.4	0.62	27.2	0.1679	0.74	OK
S2-3.BLP	6.271	-1.161	1.5	0.64	32.0	0.1820	0.73	OK
S2-3.BLS	6.273	-1.171	-1.5	0.61	26.9	0.1642	0.70	OK
S3-4.DBP	6.400	-1.413	2.6	0.48	28.4	0.1295	0.24	OK
S3-4.DBS	6.409	-1.430	-3.0	0.43	22.8	0.1041	0.14	OK
S3-4.BLP	6.417	-1.488	3.2	0.45	27.1	0.1174	0.08	OK
S3-4.BLS	6.425	-1.522	-3.5	0.39	21.6	0.0911	-0.02	OK
S4-5.DBP	6.522	-1.645	3.1	0.44	24.2	0.1074	-0.06	OK
S4-5.DBS	6.532	-1.667	-3.5	0.37	19.2	0.0794	-0.18	OK
S4-5.BLP	6.557	-1.770	4.0	0.36	21.7	0.0831	-0.36	OK
S4-5.BLS	6.570	-1.800	-4.4	0.29	16.6	0.0540	-0.48	OK
S5-6.DBP	6.595	-1.537	2.1	0.52	26.7	0.1354	0.13	OK
S5-6.DBS	6.604	-1.528	-2.7	0.46	21.4	0.1066	-0.02	OK
S5-6.BLP	6.649	-1.680	2.8	0.48	25.1	0.1199	-0.14	OK
S5-6.BLS	6.660	-1.687	-3.4	0.40	19.6	0.0875	-0.29	OK
S6-7.DBP	6.891	-1.480	2.9	0.39	21.8	0.0907	-0.33	OK
S6-7.DBS	6.906	-1.493	-3.5	0.29	16.7	0.0556	-0.49	OK
S6-7.BLP	7.045	-1.738	3.3	0.34	21.3	0.0798	-0.67	OK
S6-7.BLS	7.072	-1.759	-4.3	0.20	14.8	0.0347	-0.93	OK
S7-8.DBP	6.972	-0.853	3.3	0.36	21.2	0.0822	-0.30	OK
S7-8.DBS	6.990	-0.863	-3.8	0.27	16.0	0.0486	-0.43	OK
S7-8.BLP	7.148	-1.023	3.6	0.33	21.2	0.0762	-0.61	OK
S7-8.BLS	7.177	-1.034	-4.4	0.20	14.8	0.0348	-0.82	OK
S8-9.DBP	6.777	0.029	2.5	0.47	27.1	0.1228	0.36	OK
S8-9.DBS	6.789	0.036	-2.8	0.40	21.0	0.0926	0.29	OK
S8-9.BLP	6.883	0.024	2.5	0.48	27.0	0.1246	0.25	OK
S8-9.BLS	6.896	0.032	-2.9	0.39	20.8	0.0898	0.15	OK
S9-10.DBP	6.773	0.522	2.4	0.48	28.7	0.1272	0.30	OK
S9-10.DBS	6.784	0.534	-2.7	0.41	22.3	0.0986	0.22	OK
S9-10.BLP	6.830	0.552	2.7	0.46	27.9	0.1205	0.17	OK
S9-10.BLS	6.843	0.565	-3.0	0.38	21.3	0.0884	0.07	OK
S9-10.DBS2	6.784	0.534	-2.7	0.41	22.3	0.0986	0.22	OK
S9-10.BLS2	6.843	0.565	-3.0	0.38	21.3	0.0884	0.07	OK
S10-11.DBP1	6.767	0.958	2.3	0.48	30.3	0.1299	0.21	OK
S10-11.DBS1	6.777	0.969	-2.7	0.41	23.4	0.1014	0.11	OK
S10-11.BLP1	6.805	1.018	2.7	0.45	29.6	0.1212	0.08	OK
S10-11.BLS1	6.816	1.035	-3.1	0.38	22.5	0.0909	-0.02	OK
S10-11.DBP2	6.751	0.950	1.1	0.60	34.8	0.1685	0.49	OK
S10-11.BLP2	6.790	1.014	1.4	0.58	34.4	0.1635	0.39	OK
S11-12.DBP1	6.905	1.775	2.1	0.30	28.2	0.0799	-0.09	OK
S11-12.DBS1	6.910	1.785	-3.1	0.25	19.8	0.0539	-0.30	OK
S11-12.BLP1	7.019	2.059	1.1	0.28	29.6	0.0733	-0.05	OK
S11-12.BLS1	7.015	2.034	-3.2	0.22	19.0	0.0437	-0.50	OK
S12-13.DBP	6.916	2.271	0.0	0.33	32.3	0.0882	0.25	OK
S12-13.DBS	6.902	2.240	-3.2	0.25	22.0	0.0597	-0.44	OK
S12-13.BLP	6.991	2.471	0.0	0.30	32.5	0.0828	0.13	OK
S12-13.BLS	6.981	2.446	-3.3	0.22	21.3	0.0519	-0.58	OK
S13-14.BLP	6.881	2.690	0.0	0.24	31.1	0.0623	0.19	OK
S13-14.BLS	6.861	2.689	-4.0	0.17	18.2	0.0326	-0.68	OK
S14-15.BLP	6.704	2.518	0.0	0.51	38.4	0.1362	0.40	OK
S14-15.BLS	6.706	2.527	-1.0	0.39	30.9	0.1104	0.19	OK
S15-16.BLP	6.399	1.473	0.0	0.81	40.0	0.2494	0.96	OK
S15-16.BLS	6.399	1.473	0.0	0.78	36.7	0.2328	0.96	OK
S16-17.BLP	6.194	0.451	0.0	0.99	40.0	0.2929	1.42	OK
S16-17.BLS	6.194	0.451	0.0	0.95	37.8	0.2823	1.42	OK

3. CONCLUDING REMARKS

On the basis of the case presented in the foregoing and the wide ranging experience amassed from the upgrading of nearly 70 vessels the following remarks can be made:

- Advanced numerical models developed at the Ship Stability Research Centre of the Universities of Glasgow and Strathclyde are routinely used at Safety At Sea Ltd to predict with good engineering accuracy the dynamic stability of damaged RORO ferries, taking account of the operational environment in realistic terms. These tools are employed within a design methodology known as Total Stability Assessment to ensure optimal cost-effective and safety-effective design solutions.
- The TSA has repeatedly proven invaluable to North European ferry operators in the strife to enhancing the safety of their fleet, providing substantial and verifiable evidence both of the need to use advance tools and of the capability of these tools to used with confidence in practical ship design and operation

4. REFERENCES

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