A Realisable Concept of a Safe Haven Ro-Ro Design

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SUMMARY

A considerable amount of effort has been expended, particularly over the recent past, towards enhancing the safety of Ro-Ro vessels. The routes followed include proposals for a stricter regulatory regime, improvements on operational procedures, effective training of personnel onboard and the introduction of more efficient life saving and evacuation appliances and approaches. However attractive (and sometimes necessary) these measures might be, they do not address the root of the problem - namely the ship design concept itself. In this respect, it is particularly alarming to see proposals that undermine the meaningful evolution of the Ro-Ro concept, the most commercially successful ship design. With design-for-safety in mind this paper re-iterates the use of sheer and camber in the design of the Ro-Ro car deck as an efficient means to enhancing survivability drastically and cost-effectively. Two applications of this idea are considered: the first involving a combination of positive sheer with positive camber (PSPC) and the second negative shear with negative camber (NSNC) whilst employing the use of intelligent wash ports (IWP). The impressive enhancement of damage survivability is demonstrated by means of numerical simulation using the suite of software developed at SSRC. The latter is currently being extensively applied by the ferry industry for upgrading, retrofitting and design purposes in the strife of this industry to meet the new demanding survivability standards in the most effective way possible. Following a brief background and a description of the proposed survivability enhancing design ideas, the mathematical/numerical model used to perform the comparative study is briefly explained. The features of the Ro-Ro design and of the damage cases used in the analysis are described next before presenting and discussing the results for the basis ship flat deck (BSFD) design and the two alternatives considered.

BACKGROUND

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 turn-around 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). 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. As a result, the world fleet of Ro-Ro ships has steadily increased over the last 15 years to some 5,000. Over the same period there has been an encouraging reduction in the annual vessel casualty rate. However, the large number of serious casualties for this ship type and the overall loss of life have not shown the same improvement as the casualty rate. The maritime industry is acutely aware of recent shipping casualties involving Ro-Ro ferries, which have resulted in severe loss of life. These led to safety becoming the main concern with Ro-Ro vessels. Standards for Ro-Ro ship configuration, construction and operation have undergone 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. However, since the great majority of Ro-Ro passenger ships 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 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 to consider the issues carefully and make suitable recommendations. Following considerable deliberations and debate, a new requirement for damage stability has been agreed among north-western European Nations to account for the risk of accumulation of water on the Ro-Ro deck. This new requirement, known as the *Stockholm Agreement* [2], demands that vessels satisfy SOLAS '90 standards (allowing only for a minor relaxation) with, in addition, a constant height of water on deck. The net effect of these developments in legislation is a massive increase in survivability standards to a level many believe to be unattainable without destroying the very concept industry is extremely keen to defend.

Deriving from this, haphazard attempts to improve Ro-Ro safety by introducing ineffective survivability enhancement devices must give way to rational approaches. The ingenuity of designers must be called upon, and be nurtured, to pave the way towards practical designs for cost-effective safety, in order to ensure both the survival and a meaningful evolution of Ro-Ro ships in the future. Attempting to demonstrate that simple, cost-effective ideas, capable of ensuring the survivability of Ro-Ro vessels whilst retaining the Ro-Ro concept intact are there to be discovered, this paper features two configurations of the main deck, which if optimised could render Ro-Ro ships a safe haven. The analysis presented in the following provides ample evidence that such a concept can be realised and demonstrates beyond doubt the survivability effectiveness of one of the most traditional naval architecture design practices.

THE PROPOSED SURVIVABILITY ENHANCING DESIGN IDEAS

Earlier studies have clearly shown that the decisive factor affecting Ro-Ro damage survivability is the water accumulated on the main deck, [3]. Therefore, any measures to prevent or limit the water accumulation would result in a vessel with enhanced survivability. Should such measures prove effective with the ship damaged at high sea states, it could then be suggested that staying onboard the vessel would be the safest alternative in case of an accident that results in breaching of the hull. This is the idea of a safe haven ship. In the investigation considered here, the level of damage survivability aimed at is $H_s = 4$m over the whole range of feasible loading conditions. This is in accordance with the most severe damage stability requirement currently in force. The idea being advocated here is that of using a curved Ro-Ro deck, rather than a flat deck, (Figure 1), with or without intelligent wash ports as a means of channelling the water on deck to flow out. More specifically, the following two alternatives are examined:

<u>Alternative 1 (PSPC) – Figure 2:</u> Ro-Ro deck with positive sheer and positive camber.

Perceived advantages offered by this idea include:

- In the case of midship damage any water finding its way on the Ro-Ro deck would tend to concentrate in the vicinity of the damage opening because of the fore-and-aft sheer on the deck and flow out.

- In the case of damage forward or aft, the increased freeboard resulting from the deck sheer will ensure that less water reaches the Ro-Ro deck and hence survivability will be improved. Normally, the ensuing trim forward or aft, following respective damages will be conducive to water accumulation towards the vicinity of the damage opening and hence to water egress from the deck.

- Irrespective of the damage location, the presence of positive deck camber potentially provides two additional benefits. Water may flow towards the intact side of the ship resulting in an increased damaged freeboard and hence enhanced survivability. If the ship is inclined towards the damage, the presence of camber in principle impairs water inflow whilst assisting water outflow.

Alternative 2 (NSNC + IWP) – Figure 3: Ro-Ro deck with negative sheer and negative camber together with intelligent wash ports.

Intelligent wash ports are freeing ports with flaps, which passively allow only water outflow, their opening or closing depending on the pressure difference on either side of the flap. The use of these ports has been considered and abandoned on the basis of inconclusive research showing that the overall area of the freeing ports necessary to ensure effective outflow would be too large to offer an attractive solution. The idea put forward here is aimed at minimising the area of opening of the IWP's by utilising again a curved Ro-Ro deck. In a damage scenario resulting in progressive flooding of the Ro-Ro deck, there is a slow build up of water accumulation with the ship heel increasing equally slowly until a point is reached where the heeling effect of the water on deck exceeds the restoring capacity of the vessel. Beyond this point, capsize is inevitable and happens very quickly. Considering the above, if the capacity of IWP's were such as to offset the net inflow of water on deck for the range of loading and environmental conditions the ship is likely to operate in, survivability would be ensured and a safe haven ship could be realised.

Perceived advantages deriving from the idea include:

- Negative deck camber assists in water accumulating near the ship centreline and hence reducing the ship heeling. This is very important, as the damaged freeboard is a critical parameter affecting ship survivability.

- Negative deck sheer assists water flow towards the ship ends where the heeling effect is further reduced due to reduced beam. Additionally, by locating IWP's at the ends water can flow out.

- Negative deck sheer results in increasing damaged freeboards particularly amidships where the ship is the most vulnerable when damaged at this location without having to raise the whole deck which would adversely affect the overall stability of the ship.

- The presence of IWP's would give a Ro-Ro ship a chance in case of accidents similar to the *Herald of Free Enterprise* and the *Estonia* where bow damage with forward speed rendered capsize inevitable and catastrophic.

To assess the survivability and effectiveness of these ideas, use is made of the North West European R&D Project on the "Safety of Passenger/Ro-Ro Vessels" and of the mathematical/numerical models developed at the Department of Ship and Marine Technology of the University of Strathclyde over the past 10 years.

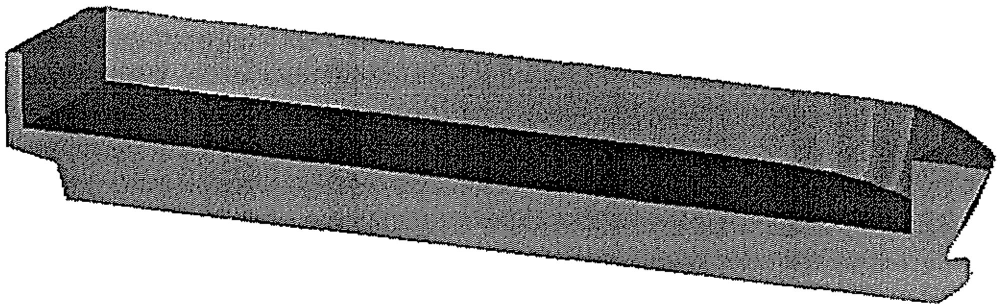


Figure 1 – Basis Ship Flat Deck (BSFD)

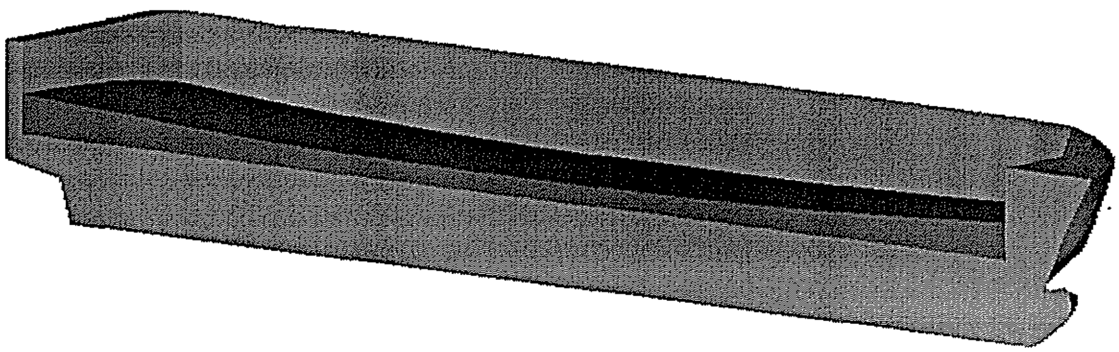


Figure 2 – Positive Sheer Positive Camber (PSPC)

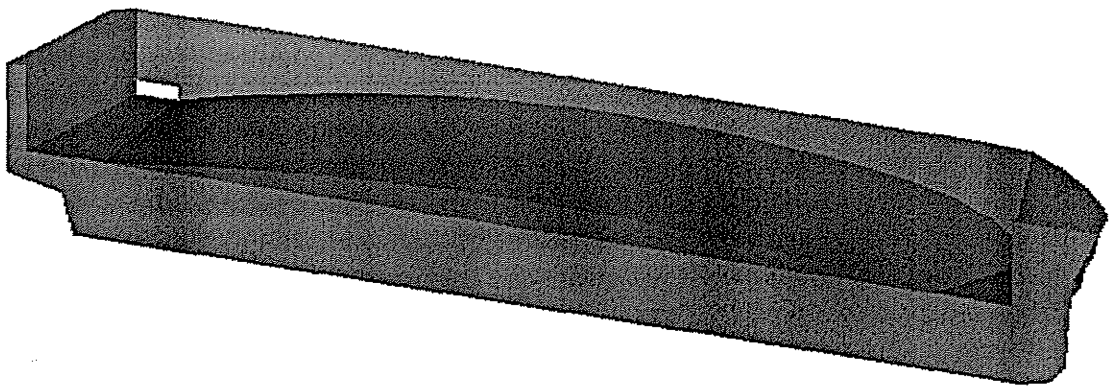


Figure 3 – Negative Sheer Negative Camber + Intelligent Wash Ports (NSNC + IWP)

MATHEMATICAL/NUMERICAL MODELS

Since the dynamic behaviour of the damaged vessel and the progression of the flood water through the damaged ship in a random seaway are ever changing, rendering the dynamic system highly non-linear, the technique used to study such behaviour is time simulation. The numerical experiment considered assumes a stationary ship, beam on to the oncoming waves, with progressive flooding taking place through the damage opening which could be of any shape, longitudinal and transverse extent and in any location throughout the vessel. The simulation begins with pre-defined initial conditions after which the damaged ship starts moving under the action of random beam waves. Instantaneous water ingress is considered by taking into account the wave elevation and ship motions, which are also estimated at each time step. For each case under investigation simulations are carried out for different loading conditions while the sea state used in the calculations is progressively increased to a limit where the ship capsizes systematically, thus allowing for a definition of survival boundaries. The complexity of the problem at hand dictates that several simplifications are adopted in both the mathematical formulation of the damaged vessel motions and of the water ingress in order to derive engineering solutions. The mathematical/numerical models developed at the

University of Strathclyde during the UK Ro-Ro Research Programme and subsequently the North-West European R&D Project have clearly demonstrated that acceptable accuracy could be attained with what appears to involve a high degree of simplification. In the majority of cases considered, a coupled sway-heave-roll model with instantaneous sinkage, heel and trim will normally suffice. Essentially this relates to a three-degree-of-freedom non-linear seakeeping model and a hydraulic water ingress model that allows for water inflow and outflow and associated gravitational forces in a semi-empirical manner, applicable to multiple-compartment flooding and to any vessel subdivision and deck arrangement.

The model considered comprises the following:

$$\{[M(t)] + [A]\}\{\ddot{Q}\} + [B]\{\dot{Q}\} + [C]\{Q\} = \{F\}_{WIND} + \{F\}_{WAVE} + \{F\}_{WOD}$$

with, $[M(t)]$: Instantaneously varying mass and mass moment of inertia matrix.

$[A]$, $[B]$: Generalised added mass and damping matrices, calculated once at the beginning of the simulation at the frequency corresponding to the peak frequency of the wave spectrum chosen to represent the random sea state.

$[C]$: Instantaneous heave and roll restoring, taking into account ship motions, trim, sinkage and heel.

$\{F\}_{WIND}$: Regular or random wind excitation vector

$\{F\}_{WAVE}$: Regular or random wave excitation vector, using 2D or 3D potential flow theory.

$\{F\}_{WOD}$: Instantaneous heave force and trim and roll moments due to floodwater.

The latter is assumed to move in phase with the ship roll motion with an instantaneous free-surface parallel to the mean waterplane. This assumption is acceptable with large ferries since, owing to their low natural frequencies in roll, it is unlikely that flood water will be excited in resonance which is further spoiled as a result of progressive flooding. Indeed, when the water volume is sufficiently large to alter the vessel behaviour, small phase differences are expected between the flood water and ship roll motions. During simulation, the centre of gravity of the ship is assumed to be fixed and all subdivisions watertight.

Considerable effort has been expended to ensure the validity of the numerical simulation program in its ability to predict the capsizal resistance of a damaged vessel in a random sea whilst accounting for progressive flooding, over the whole range of possible applications. These include vessel type and compartmentation (above and below the bulkhead deck), loading condition and operating environment and location and characteristics of damage opening. Such claims have been substantiated by the impressive agreement achieved between theoretical and experimental results spanning a wide range of parameters, [3]. Typical results from ten ships, tested through the "Equivalent Safety" route by numerical and physical model experiments are shown in Figure 4 where the agreement between physical model tests and numerical tests is very convincing, [4]. This is a clear indication of the ability of the mathematical model used to accurately assess the capsizal resistance of a damaged Ro-Ro vessel subjected to large scale flooding. This derives from the accurate modelling of the dynamic system behaviour in the capsize region. This might at first sound surprising, considering how complex the processes involved are, but can be easily explained by the hydrostatically dominated nature of the capsize phenomenon relating to an extensively flooded vessel. With the exception of very few cases the results from both approaches are identical.

In general the agreement between numerical and experimental results has reached a level where any discrepancy of more than 0.25m in critical Hs between the two is considered unacceptable and is normally the cause of a thorough investigation until a satisfactory explanation is found. Typical cases include discrepancies, which are the result of differences in deck permeability of the order of 10% and in heel angle in the order of 0.5^0. The level of confidence in the results of numerical tests is clearly being demonstrated by some ferry owners/operators who proceed with retrofitting plans on the strength of numerical predictions. Efforts are currently under way to collect this and other relevant evidence to prepare a working paper for submission to IMO, aiming for approval to utilise numerical simulation as an alternative route to compliance with damage survivability standards.

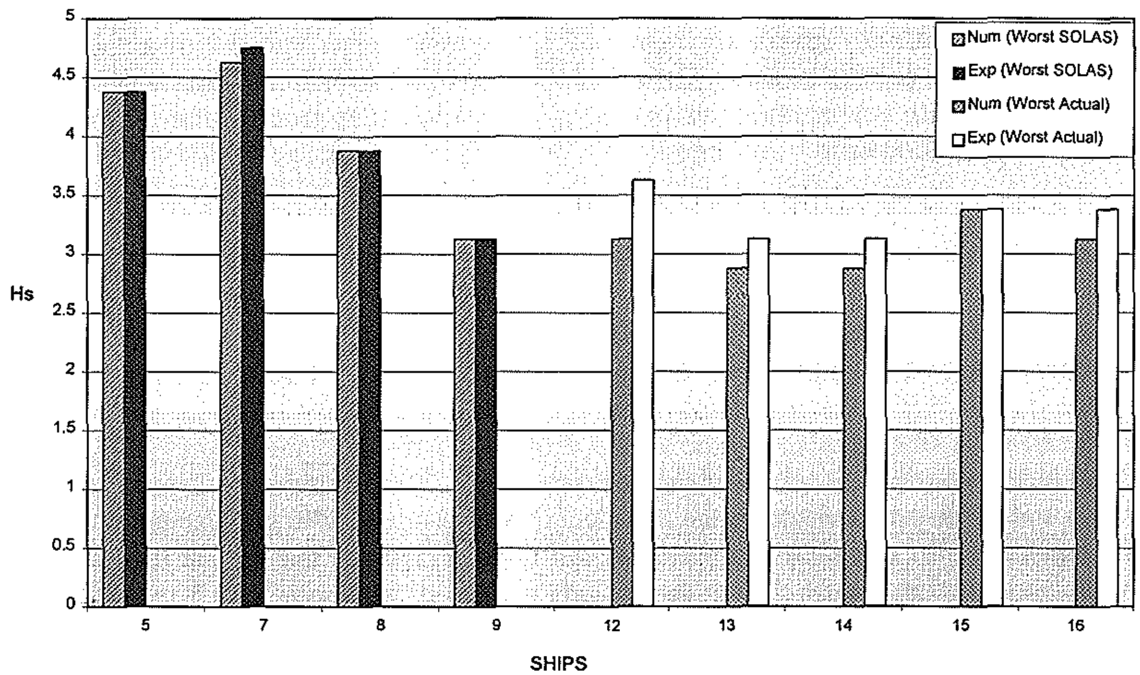


Figure 4 - Comparison Between Numerical and Experimental Results – Critical Hs

CASE STUDY

The case study presented here considers as a basis ship, the flat open deck Ro-Ro vessel NORA which is a generic design used in the North West European R&D Project. The two alternatives explained in the foregoing are also described in detail in this section, following a description of NORA. All three alternatives are illustrated in Figure 5.

Basis Ship

The principal design particulars of NORA are shown in Table 1 and the outline design with the original car deck configuration is illustrated in Figure A.1 of Appendix A.

Table 1: Principal Design Particulars of NORA

Length, L_{BP}	130.00 m
Beam, **B**	25.50 m

Depth to Car Deck, **D**	8.35 m
Draught, **T**	5.75 m
Displacement, Δ	12,000 tonnes
Block Coefficient, $\mathbf{C_B}$	0.612
Intact **KM**	14.26 m
Intact Freeboard, **F**	2.60 m

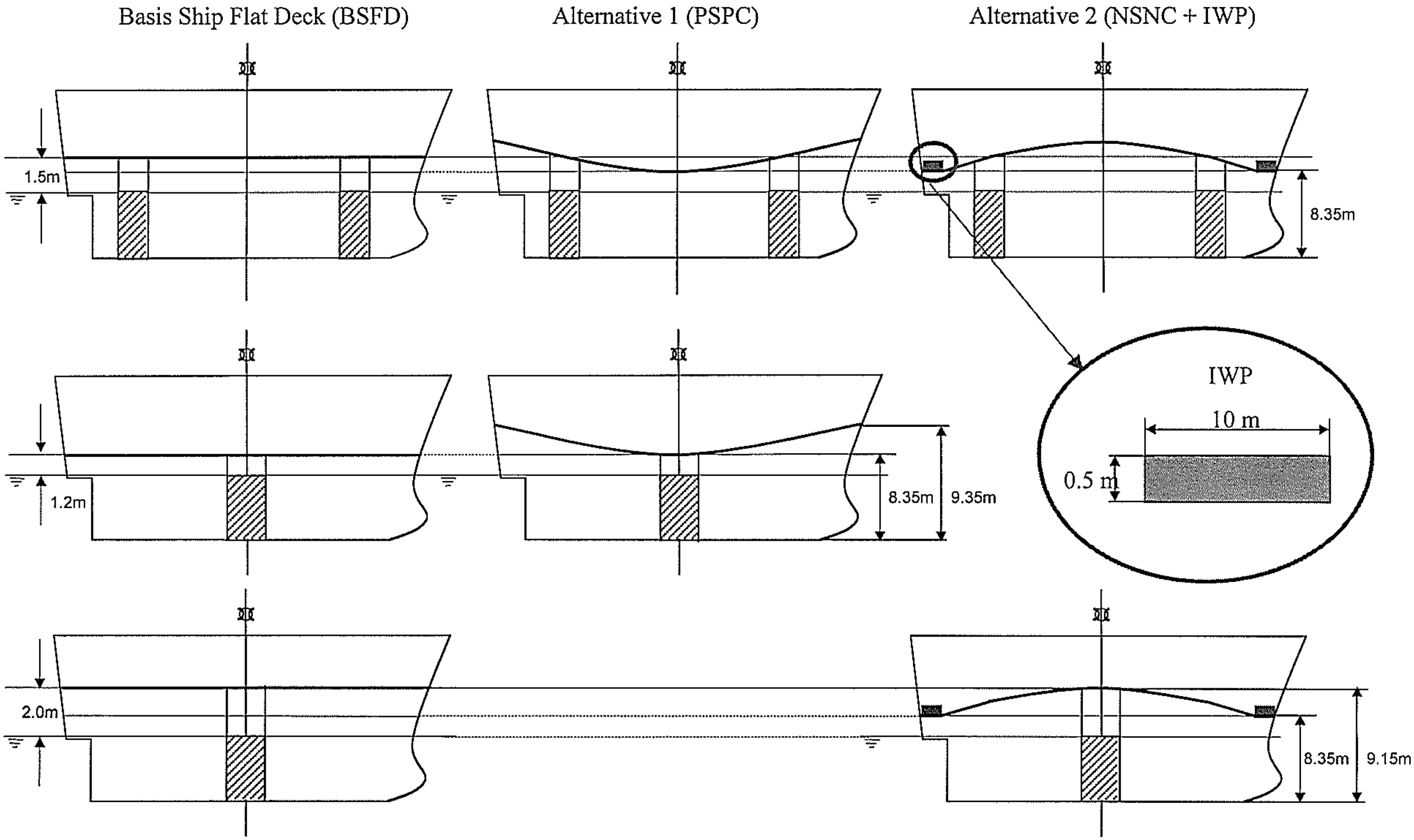
Alternative 1 (PSPC)

Details of this arrangement are shown in Figure A.2 of Appendix A. The sheer considered is parabolic in shape with maximum values of 1.0 m at the ends and 0.0 m amidships. The camber is also of parabolic shape with a maximum value of 0.2 m at the centreline of the vessel. This choice was made by taking the ratio of maximum sheer to maximum camber in proportion of the L/B ratio.

Alternative 2 (NSNC + IWP)

Details of this arrangement are shown in Figure A.3 of Appendix A. The negative sheer has now a maximum value of 0.8 m amidships at the side of the car deck reducing to 0.0 m at the location of the IWP. The maximum camber is again 0.2 m but with the negative camber considered here, this would correspond to a drop of 0.2 m along the ship centreline with the deck at side following the shape of the negative sheer. This configuration provides therefore for two flat deck portions along the ship length where the IWP's are located. The freeing ports considered in this case study are located at both sides of the ship at the stern and the bow as illustrated in Figure 5 with dimensions of 10.0 m in length by 0.5 m in height. The 20.0 m reduction in the sheered Ro-Ro deck length is the reason for considering a maximum camber of 0.8 m in this alternative rather than 1.0 m as in alternative 1. No optimisation study has been made to determine the most effective dimensions or location of the IWP's for the damage scenarios considered.

Figure 5 – Case Study Alternatives



Particulars of Damage

To evaluate the effectiveness of the proposed ideas in enhancing Ro-Ro damage survivability, it was thought appropriate to consider a relatively low damaged freeboard for the basis ship, for ease of illustration of the survivability enhancing effect of the proposed ideas. To this end, the basis ship damaged freeboard was taken to be 1.2 m. Furthermore to eliminate any bias in the results deriving from the difference in the damage freeboards due to the presence of deck sheer, it was considered appropriate to compare the survivability of the various alternatives at the same damaged freeboard. This was achieved by raising in each case the car deck artificially to the right level. In this respect, it is to be noted that the damaged freeboard for both the fore and aft damages at the location of damage is approximately 1.5 m in both alternatives whilst for the midship damage of alternative 2 the damaged freeboard is 2.0 m.

Deriving from the above, the damage cases considered in this case study are given in the Table 2 below referring to all the alternatives and are illustrated in Figure A.4 of Appendix A.

Table 2: Particulars of Damaged Cases

Damage Case	Damaged Freeboard (m)	Damaged Compartment Length (m)	Compartment Location (m)	Damaged KM (m)
Aft	1.5	18.00	-47.00 ÷ -29.00	13.71
Midship	1.2	29.20	-22.43 ÷ 10.00	13.45
	2.0	29.20	-13.80 ÷ 0.50	
Forward	1.5	19.30	19.65 ÷ 43.35	13.23

Parametric Investigation

Considering the damage cases described in the foregoing over the range of possible operational and environmental conditions leads to the test matrix shown in Table 3. With the operational KG at 11.5 m, a ± 0.5 m variation was thought to be representative for the KG operational envelop appropriate to this vessel.

Table 3: Test Matrix

	FLAT DECK			ALTERNATIVE 1		ALTERNATIVE 2	
KG (m)	Damaged Freeboard (m)			Damaged Freeboard (m)		Damaged Freeboard (m)	
	1.2 amidships	1.5 fore &aft	2.0 amidships	1.2 amidships	1.5 fore & aft	1.5 fore & aft	2.0 amidships
11.0	X	X	X	X	X	X	X
11.5	X	X	X	X	X	X	X
12.0	X	X	X	X	X	X	X

WAVE ENVIRONMENT

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

Table 4: 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	6.99

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

Numerical survivability tests have been undertaken for a significant wave height resolution of 0.25 m. Limiting Hs in the derived results represents the maximum sea state that can be survived repeatedly in each damaged case considered. The norm adopted in presenting the results of numerical simulations and model experiments 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.

RESULTS AND DISCUSSION

The results are presented as survivability bands in the form of critical Hs (i.e. significant wave height characterising a limited sea state from survivability point of view) versus KG, allowing for comparisons between the basis ship and the two alternatives proposed at the corresponding KG and freeboard.

Flat Deck (BSFD) Vs Alternative 1 (PSPC)

Midship Damage – Figure 6a

For open deck Ro-Ro vessels, damage amidships is the most onerous and hence it constitutes the critical damage concerning survivability. This is clearly demonstrated in Figure 6 where the basis ship appears to have very low capsizal resistance, barely managing to survive 3.0 m Hs, even at low KG's. Introducing positive sheer and camber on the deck at levels that could easily be realised, however, results in increasing the damage survivability of the vessel over the required 4.0 m Hs, even at high KG's.

Fore & Aft Damages – Figures 6b & 6c

For open deck Ro-Ro vessels fore and aft damages are normally less onerous than midship damage, as indicated above. It is interesting, however, to demonstrate that even by increasing the damaged freeboard of the basis ship at a level corresponding to the height of the sheered deck at the damage location, alternative 1 still results in a clear improvement of survivability for both damage cases.

Flat Deck (BSFD) Vs Alternative 2 (NSNC + IWP)

Midship Damage – Figure 7a

The importance of freeboard in improving damage survivability is clearly demonstrated in Figure 6, where by increasing the damaged freeboard of the basis ship to 2.0 m, the vessel is capable of surviving over 4.0 m sea states almost throughout the range of possible loading conditions. This example explains clearly and justifies in a way the drive inherent in recent criteria and approaches for assessing survivability towards higher freeboards. However the introduction of curved decks as described in alternative 2 together with moderately sized freeing ports improves survivability beyond these levels by an average of 1.0 m Hs over the whole range considered.

Fore & Aft Damages – Figures 7b & 7c

The potential advantages deriving from alternative 2 are clearly demonstrated in Figure 7 where survival to extreme sea states appears to be realisable, throughout the possible range of interest and well above the survival levels offered by alternative 1.

Figure 6a - MIDSHIP DAMAGE
Freeboard = 1.20 m

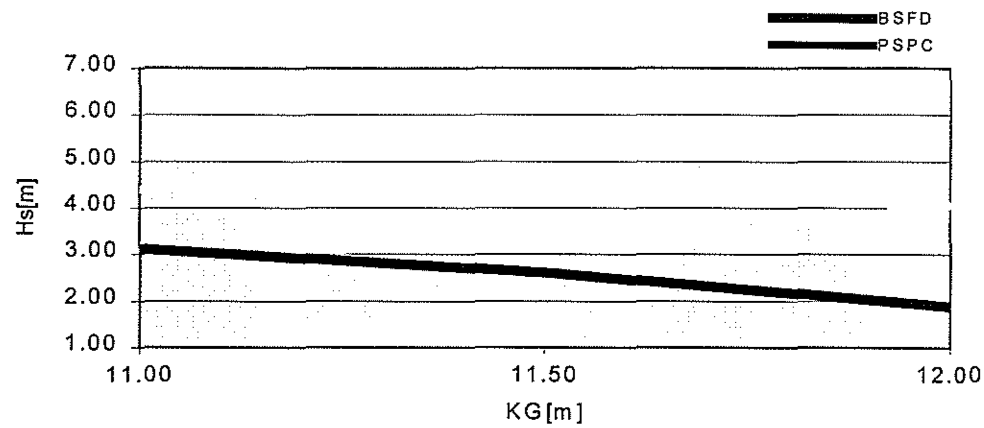


Figure 6b - AFT DAMAGE
Freeboard = 1.50 m

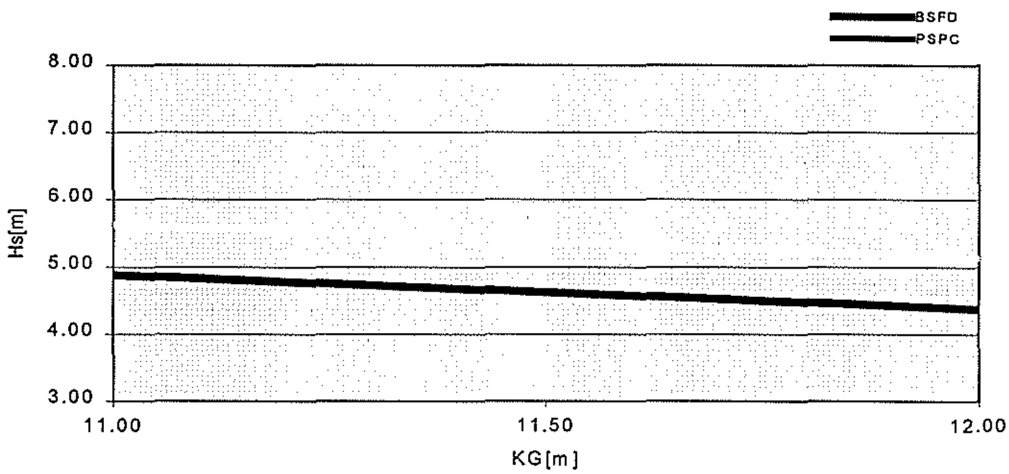


Figure 6c - FORWARD DAMAGE
Freeboard = 1.50 m

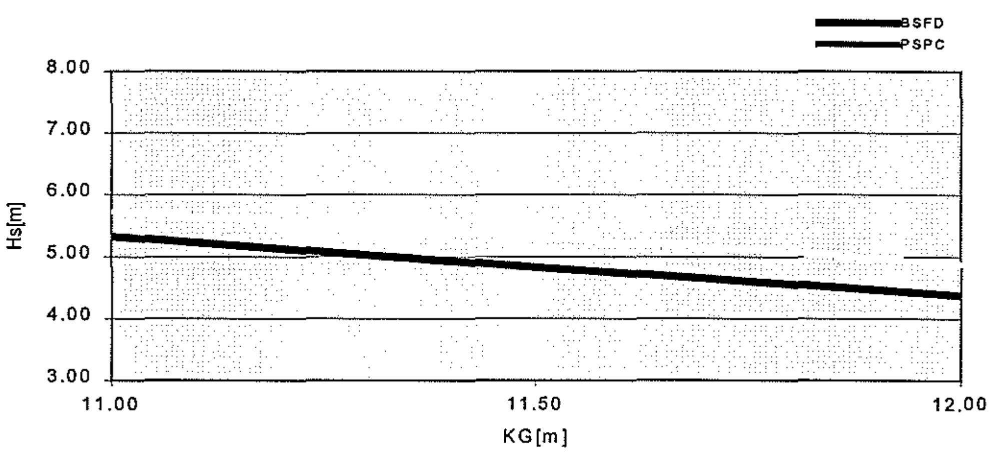


Figure 6 – Comparison Between Basis Ship (BSFD) and Alternative 1 (PSPC)

Figure 7a - MIDSHIP DAMAGE
Freeboard = 2.00 m

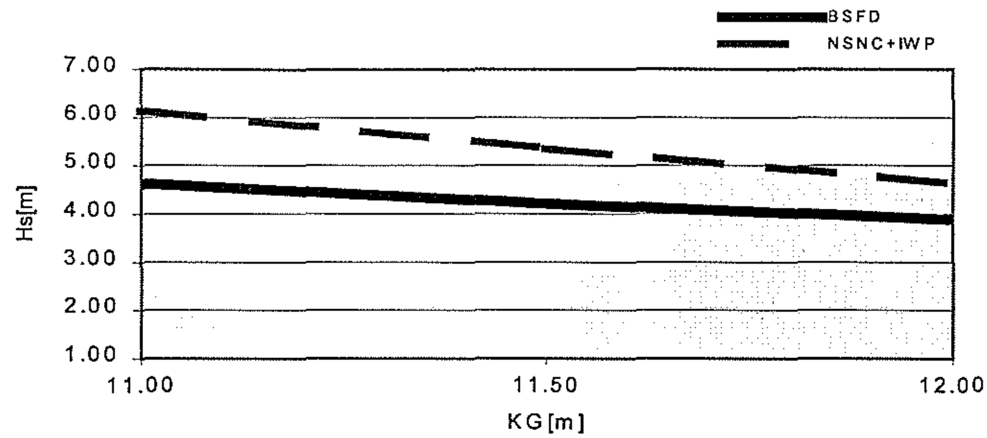


Figure 7b - AFT DAMAGE
Freeboard = 1.50 m

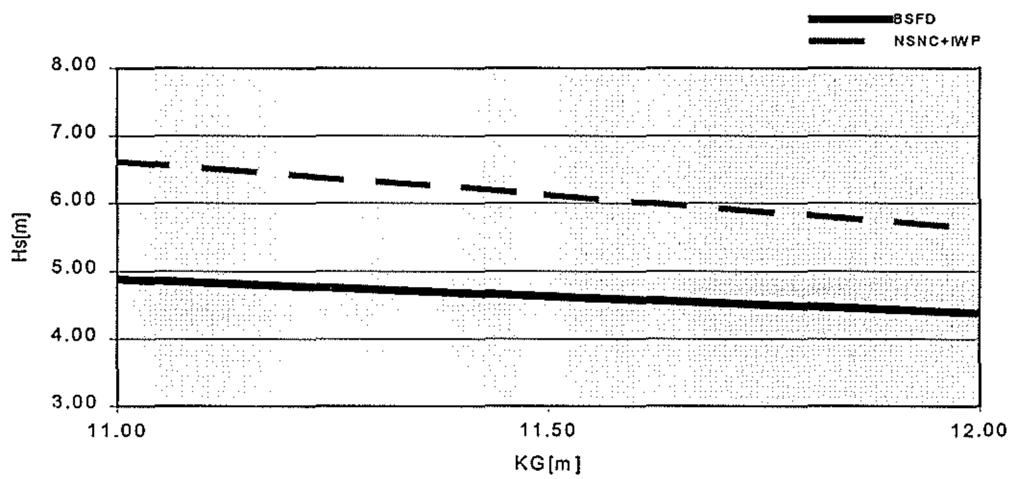


Figure 7c - FORWARD DAMAGE
Freeboard = 1.50 m

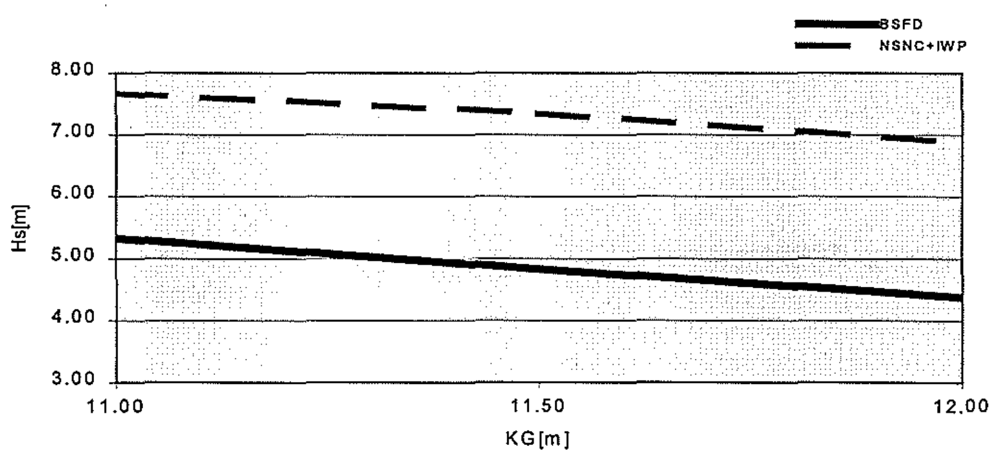


Figure 7 – Comparison Between Basis Ship (BSFD) and Alternative 2 (NSNC + IWP)

CONCLUDING REMARKS

Considering that the proposed design alternatives have not been optimally applied and hence the potential improvements on Ro-Ro damage survivability could be even more pronounced renders the results achieved from the introduction of such simple ideas even more impressive. The parametric investigation undertaken in the foregoing leaves little doubt that curved decks optimally designed to resist flooding and assist outflow could help realise Ro-Ro designs which can achieve acceptably high levels of survivability when damaged whilst preserving the flexibility and operational advantages offered by the open undivided Ro-Ro decks.

The results presented in this study help demonstrate to all concerned that cost-effective ship safety cannot be achieved solely by regulations, particularly when the latter derive from lack of understanding, experience or knowledge of the problem at hand.

Give the designers a chance and they will pave the way to safer ships!

REFERENCES

[1] **IMO Resolution MSC.12 (56) (Annex),** "Amendments to the International Convention for the Safety of Life at Sea, 1974: Chapter II-1 – Regulation 8", adopted on 28 October 1988.

[2] **IMO Resolution 14,** "Regional Agreements on Specific Stability Requirements for Ro-Ro Passenger Ships" – (Annex: Stability Requirements Pertaining to the Agreement), adopted on 29 November 1995.

[3] **Vassalos, D, Pawlowski, M, and Turan, O:** "A Theoretical Investigation on the Capsizal Resistance of Passenger RoRo Vessels and Proposal of Survival Criteria", Final Report, The Joint North West European Project, University of Strathclyde, Department of Ship and Marine Technology, March 1996.

[4] **Vassalos, D:** "Damage Survivability of Passenger/Ro-Ro Vessels by Numerical and Physical Model Testing", WEMT'98, Rotterdam, May 1998.

APPENDIX A

DESCRIPTION OF DESIGN ALTERNATIVES AND DAMAGED CASES

Figure A.1: Basis Ship

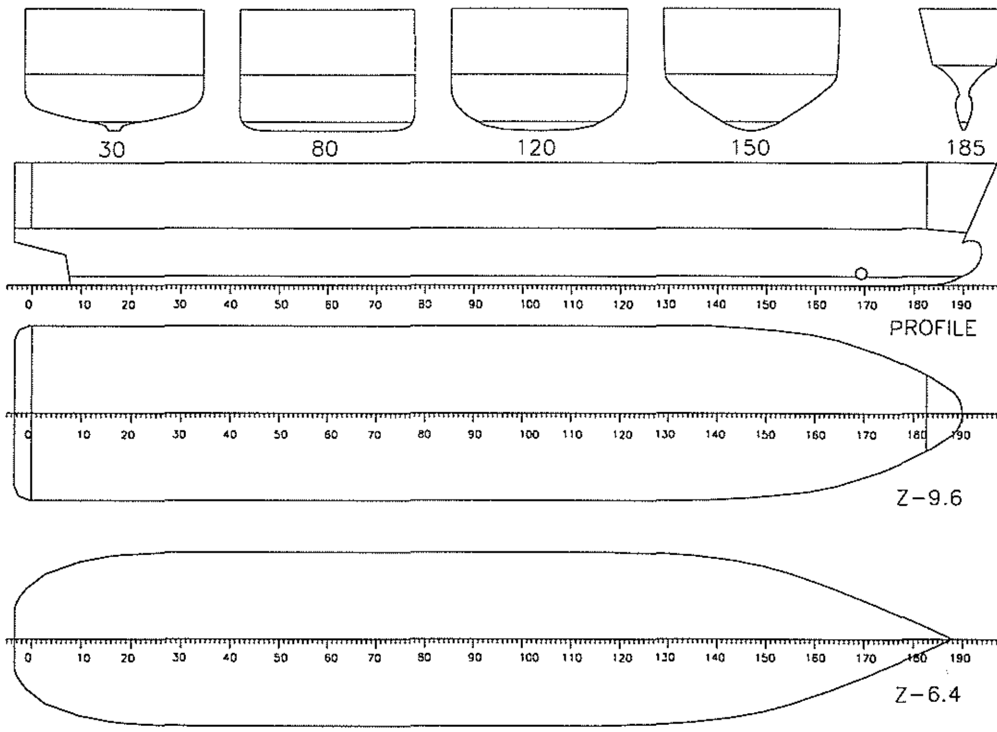


Figure A.2: Alternative 1

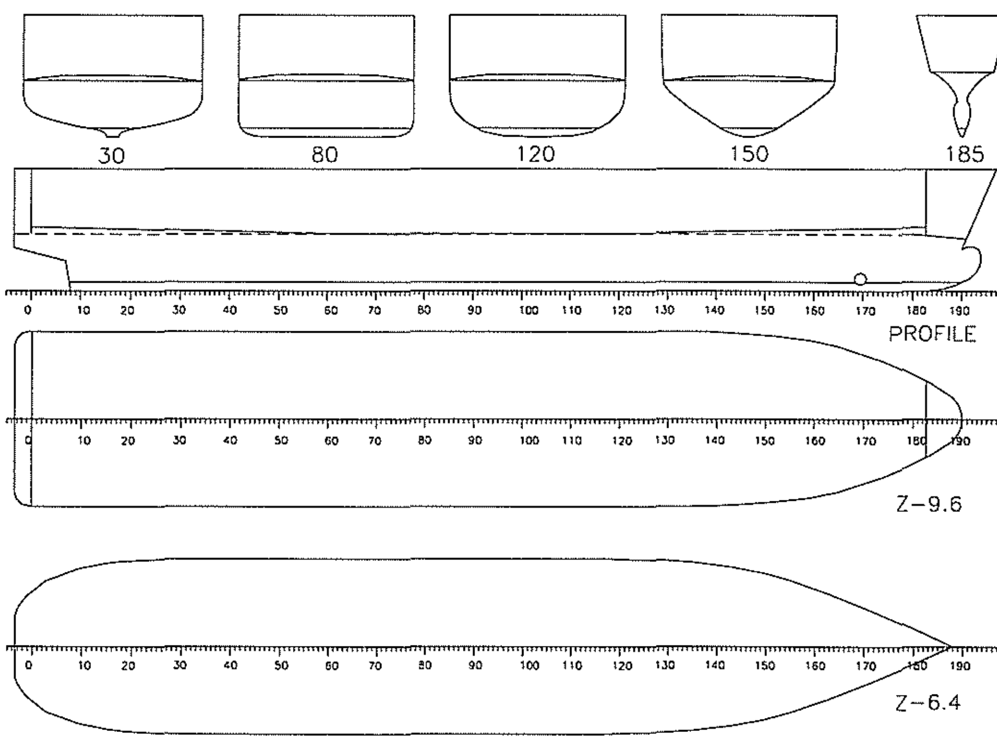


Figure A.3: Alternative 2

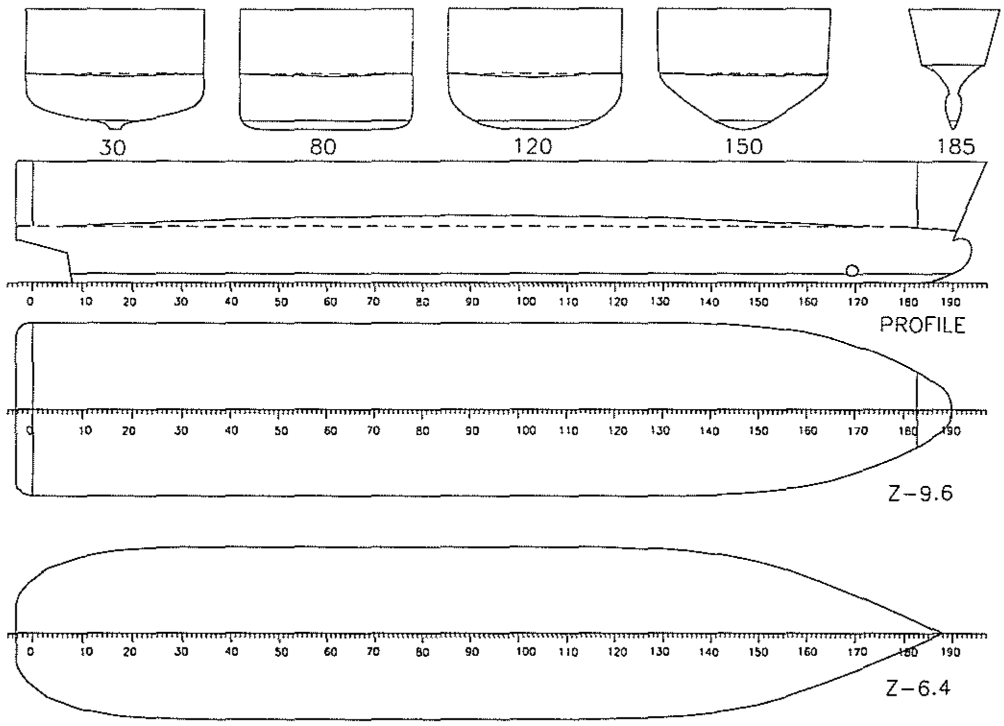


Figure A.4: Damage cases - Aft, Midship and Forward