Technische Universität Hamburg-Harburg
Institut für Entwerfen von Schiffen und Schiffssicherheit

SOLAS 2009 and IMO/Circ.1891 (Stockholm Agreement) Damage Stability Investigation of two ships and contrast of the requirements

Thesis to obtain the degree
Diplom-Ingenieur

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I hereby declare that I have written this thesis by myself and that I have not employed any other aids than those stated.

Hamburg, May 15th, 2006

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Contents

1 Introduction

Safety is an essential aspect of travelling the sea. In order to provide a certain safety standard a set of regulations has been developed forming the SOLAS [1] (Safety of life at sea), an international convention mandatory for all ships engaged in international trade. The convention is constantly being further developed to provide state of the art safety standards and to account for recent accidents. Since the first version of SOLAS adopted in 1914 following the sinking of the TITANIC, there have been four more versions of SOLAS. The present version was adopted in 1974. This version has since been amended 29 times, last of which has been in May 2004.

The International Maritime Organization (IMO) is the specialized agency of the United Nations devoted to maritime affairs. The Maritime Safety Committee (MSC) is the committee of the IMO concerned with ship's safety. Currently the IMO aims for harmonizing the damage stability regulations for passenger and cargo ships. Presently a passenger ship has to fulfil either the deterministic damage stability criteria of Chapter II-1, Part B, Reg. 8 of SOLAS or the probabilistic criteria of IMO Resolution A.265. A cargo ship's damage stability on the other hand is evaluated according to the probabilistic regulations stated in SOLAS, Chapter II-1, Part B-1, Reg. 25-1, pp.

In order to assess the level of damage stability for cargo ships and passenger ships the same way, the Sub-Committee for Stability, Loadline and Fishing vessels (SLF) of the MSC has developed harmonized regulations for both types of ships on the basis of the probabilistic method. The accepted draft for the new Chapter II-1 Part B, of SOLAS is MSC 80/24/Add.1, Annex 1 [2] and will in way of this thesis be referred to as SOLAS 2009.

The sinking of Ro-Ro passenger vessel ESTONIA in 1994 due to water on deck had led to the 15th amendment of SOLAS 1974, the Stockholm Agreement IMO/Circ.1891 [3], an accentuation of the SOLAS convention for Ro-Ro passenger vessels. The Stockholm Agreement requires the fulfilment of Chapter II-1, Part B, Reg. 8.2.3 of the current SOLAS under the influence of an assumed amount of water on bulkhead deck.

The thesis at hand deals with two RoRo passenger vessels which have been designed to comply with SOLAS incl. the Stockholm Agreement and assesses the Attained Index A according to SOLAS 2009. It also analyses the impacts of each IMO/Circ.1891 and SOLAS 2009 on the capability of a Ro-Ro passenger vessel to withstand water on deck. The aim is to investigate whether SOLAS 2009 establishes an equivalent level of safety to the current regulations.

1.1 Remit

1) The attained indices A as calculated according to SOLAS 2009 on the basis of the GMs from the limiting curves to meet IMO/Circ.1891 (Stockholm Agreement) will be compared with the required indices R according to SOLAS 2009.

Ships to be examined in the scope of this thesis:

<u>Vessel 1:</u>

GL-No.	94615
Name	NILS HOLGERSSON
	Passenger ship with cabins, Ro-Ro ship
	744 passengers + 56 Crew, Ro-Ro cargo space below bulkhead deck
L_{bp} / B / d [m]	175 / 29.5 / 6.2

<u>Vessel 2:</u>

	Project ship by Meyer-Werft
	Passenger ship with cabins, Ro-Ro ship
	2200 passengers, 92 Crew, no Ro-Ro cargo space below bulkhead deck
L_{bp} / B / d [m]	173.6 / 27.8 / 6.7

2) Comparison of the survivability criteria (factor s_i) from SOLAS 2009 and the IMO/Circ.1891 regarding Water on Deck. For this further criteria and the results from the EU research project HARDER, which have been considered when developing SOLAS 2009, will be regarded.

2 Regulations on damage stability

2.1 The current regulation

Currently evidence that a passenger ship complies with the requirements on damage stability can be provided in two ways.

One way is to show that the ship complies with SOLAS Chapter II-1, Part B, Reg. 8. The ship concerned has to be capable of withstanding the damage of a certain number of adjacent main compartments. The main compartments are separated by transverse watertight bulkheads. These bulkheads reach from the keel up to bulkhead deck. In case of a ship having a two compartment standard, the applicable stability criteria have to be complied with after flooding following damage of two adjacent compartments. No penetration of the ship greater than B/5 needs to be accounted. In case of a Ro-Ro passenger vessel sailing European waters, the Stockholm Agreement needs to be complied with additionally. Sufficient stability has to be provided under the influence of an assumed amount of water on the car deck. This accounts for the danger of capsize caused by the significant GM reduction due to large free surfaces on the large car decks of Ro-Ro passenger vessels. The impact of the Stockholm Agreement is compared to that of SOLAS 2009 in Chapter 6 of this thesis.

The second possibility for a passenger ship to comply with the current SOLAS is to meet the requirements of IMO resolution A.265, a probabilistic approach which will not be dealt with here.

2.2 MSC80/24/Add.1, Annex 1, the new Chapter II-1 of SOLAS

The following chapter introduces MSC80/24/Add.1, Annex 1, referred to as SOLAS 2009, as concerns damage stability regulations and as far as needed for the investigations in way of this thesis. This will be done following MSC80/24/Add.1, Annex 1 [2] and the draft of the explanatory notes [4], quoting them in extracts and using some of the illustrations contained.

When effective, SOLAS 2009 will be mandatory for both passenger and cargo ships. The level of safety in case of damage is assessed probabilistically in such manner that both the probability of occurrence p_i of a damage of certain extent, at a certain location as well as the chance of survival s_i after flooding following the damage follow a probability distribution. The probability distribution of the damages is based on a damage statistic. The probability of survival has been formulated under consideration of the relevant criteria affecting survivability. This method of assessing the damage stability leaves the designer of a ship more flexibility. Damage stability is considered sufficient, if the attained subdivision index A is not less than the required subdivision index R:

$$A \geq R\ .$$

2.2.1 The attained subdivision index A

The attained subdivision index A is obtained by the summation of the partial indices A_s, A_p and A_l (weighted as shown) calculated for the draughts d_s, d_p and d_l in accordance with formula

$$A = 0.4A_s + 0.4A_p + 0.2A_l\ .$$

Each partial index is a summation of contributions from all damage cases taken in consideration, using formula

$$A = \Sigma p_i s_i$$

where

- i — represents each compartment or group of compartments under consideration,
- p_i — accounts for the probability that only the compartment or group of compartments under consideration may be flooded, disregarding any horizontal subdivision and
- s_i — accounts for the probability of survival after flooding the compartment or group of compartments under consideration, and includes the effect of any horizontal subdivision.

The draughts for which the partial indices A_s, A_p and A_l are calculated are

- d_s — Deepest subdivision draught: the waterline which corresponds to the summer load line draught of the ship,
- d_l — Light service draught: the service draught corresponding to the lightest anticipated loading and associated tankage, including, however, such ballast as may be necessary for stability and/or immersion. Passenger ships should include the full complement of passengers and crew on board and
- d_p — Partial subdivision draught: the light service draught plus 60% of the difference between the light service draught and the deepest subdivision draught.

In the calculation of A, the level trim should be used for the deepest subdivision draught and the partial subdivision draught. The actual service trim shall be used for the light service draught. If in any service condition, the trim variation in comparison with the calculated trim is greater than

0.5% of L_s, one or more additional calculations of A are to be submitted for the same draughts but different trims so that, for all service conditions, the difference in trim in comparison with the reference trim used for one calculation will be less than 0.5% of L_s.

Subdivision length L_s is the greatest projected moulded length of that part of the ship at or below deck or decks limiting the vertical extent of flooding with the ship at the deepest subdivision draught. Its definition is clarified by the following illustration (Figure 2-1):

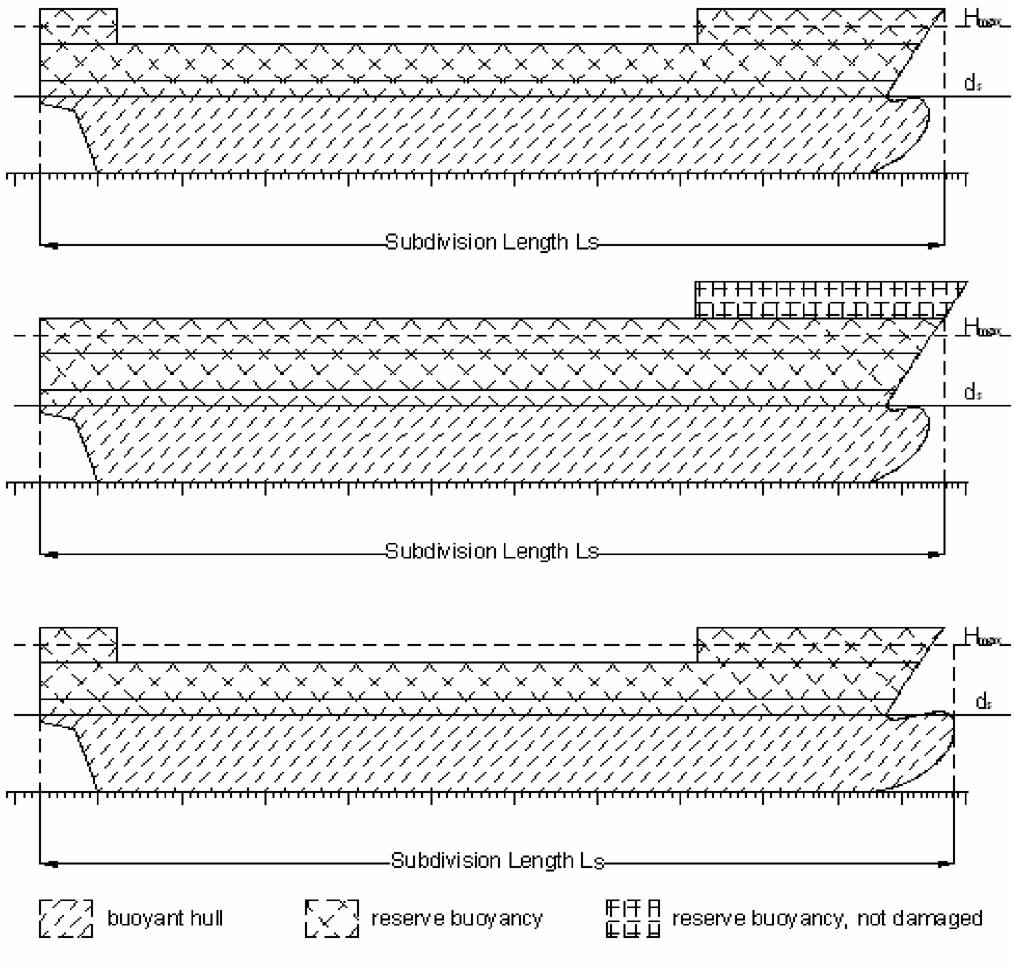

Figure 2-1: Definition of subdivision length L_s [4]

The particular floating conditions regarded for assessing the three partial indices A_s, A_p and A_l are pictured below:

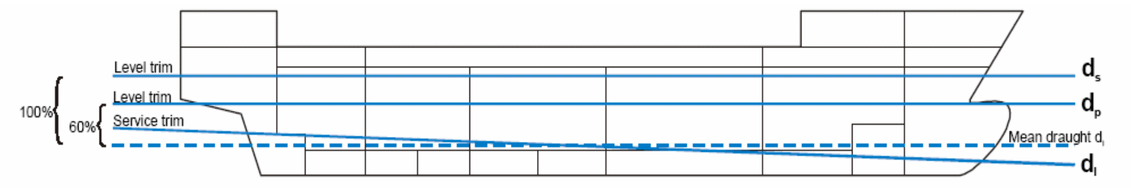

Figure 2-2: Illustration of floating conditions [4]

2.2.1.1 Probability p_i of occurrence

For the explanation of the following, the terms zone, damage and room are introduced. A zone is a longitudinal interval of the ship within the subdivision length. A damage is a number of rooms within the watertight arrangement opened to the sea or connected to rooms opened to the sea. The damage may be considered as being limited by watertight transverse, longitudinal and/or vertical structures. All damages that are considered may contribute to the attained index A. A room is a part of the watertight arrangement having a specific permeability.

For each damage the probability p_i of its occurrence is calculated. This probability is affected by

- the maximum damage length l_{max} = 60m, i.e. damage lengths greater than 60m have the probability $p_i = 0$,
- the l_{max} / L_s – ratio which does not need to exceed 10/33 which is another damage length limitation,
- the length of the damage and
- the location of the damage within the subdivision length.

The probability p_i is solely dependent on the geometry of the watertight subdivision of the ship as regarded for the damage generation.

The following figure exemplarily illustrates the possible single and multiple zone damages in a ship having been divided into 7 zones. The triangles in the bottom row resemble the probability of occurrence p_i of a damage involving exactly one zone. The rhombs in the row above the triangles resemble the probability that a damage involving exactly the two corresponding zones occurs. The area consisting of two adjacent triangles and the rhomb above them resembles the probability of occurrence of all possible combinations (namely three) of the two 1-zone and the single corresponding 2-zone damage. The probability p_i is calculated according to the applicable formulas of SOLAS 2009.

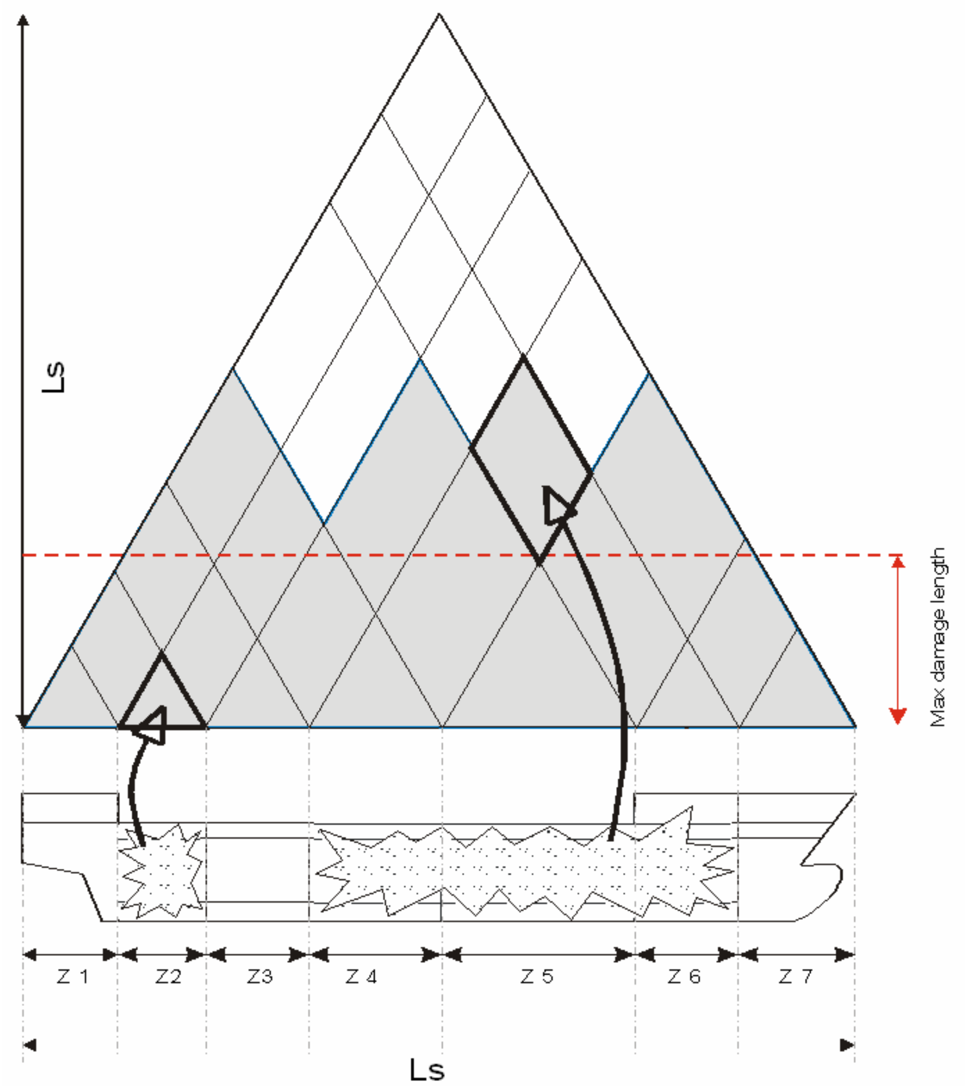

Figure 2-3: Illustration of the possible single and multiple damages in a ship [4]

The shaded area illustrates the effect of the maximum absolute damage length. The p_i - factor for a damage combining three or more adjacent zones equals zero as the length of such damage is greater than the maximum damage length of 60m.

2.2.1.2 The probability s_i of survival

The other component of the attained index A is the probability of survival s_i. The s_i-factor regards the hydrostatic stability of every stage of flooding required for the particular damage case. Damage case is a damage as explained in paragraph 2.2.1.1 having occurred at one of the initial conditions d_s, d_p and d_l.

Flooding stage is any discrete step during the flooding process. Stages are required in damage cases where flooding of some rooms cannot be referred to as instantaneous. According to the explanatory notes [4] flooding is considered as not instantaneous if equalization lasts longer than 60 seconds. This might be the case where flooding of some rooms takes place after other rooms have been flooded to a certain degree or where cross flooding devices are provided.

The factor s_i shall be obtained from the formula

$$s_i = \text{minimum}\ \{s_{intermediate,i} \text{ or } s_{final,i} * s_{mom,i}\}$$

where

$s_{intermediate,i}$ is the probability to survive all intermediate flooding stages until the final equilibrium stage,

$s_{final,i}$ is the probability to survive in the final equilibrium stage of flooding and

$s_{mom,i}$ is the probability to survive heeling moments.

The factor s_i is calculated in accordance to the following notations:

θ_e is the equilibrium heel angle in any stage of flooding in degrees,

θ_v is the angle, in any stage of flooding, where the righting lever becomes negative, or to the angle at which an opening incapable of being closed weathertight becomes submerged,

GZ_{max} is the maximum positive righting lever, in metres, up to the angle θ_v and

Range is the range of positive righting levers, in degrees, measured from the angle θ_e. The positive range is to be taken up to the angle θ_v.

In case of the intermediate states s_i is to be calculated as follows:

$$s_{intermediate} = \left[\frac{GZ_{max}}{0.05} \cdot \frac{Range}{7}\right]^{\frac{1}{4}}$$

where

GZ_{max} is not to be taken as more than 0.05m and

Range is not to be taken as more than 7°.

The heel in intermediate stages may not exceed 15°, else $s_{intermediate}$ is to be taken as zero. Equalization through cross flooding pipes shall not take longer than 10min.

For the final stage the factor $s_{final,i}$ shall be obtained from the formula:

$$s_{final,i} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}}$$

where

GZ$_{max}$ is not to be taken as more than 0.12m,

Range is not to be taken as more than 16°,

K = 1 if $\theta_e \leq \theta_{min}$,

K = 0 if $\theta_e \geq \theta_{max}$,

$K = \sqrt{\frac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}$ otherwise,

where

θ_{min} is 7° for passenger ships and 25° for cargo ships and

θ_{max} is 15° for passenger ships and 30° for cargo ships.

The factor $s_{mom,i}$ is applicable only to passenger ships and shall be calculated at the final equilibrium from the formula

$$s_{mom,i} = \frac{(GZ_{max} - 0.04) \cdot \Delta}{M_{heel}}$$

where

Displacement is the intact displacement at the draught under consideration,

$s_{mom,i} \leq 1$,

M_{heel} is the maximum assumed heeling moment resulting from

the movement of passengers,

wind force or

from the launching of all fully loaded davit-launched survival craft on one side of the ship.

The displacement used for calculating the hydrostatics of the damaged hull is the displacement of the intact floating condition at the draught under consideration.

Where horizontal watertight boundaries are fitted above the waterline under consideration the s_i-value calculated for the lower compartment or group of compartments shall be obtained by multiplying the s_i-value as determined according to the formulas stated above by the reduction factor v_m, which represents the probability that the spaces above the horizontal subdivision will not be flooded.

Factor s_i is to be taken as zero amongst others in those cases where the final waterline, taking into account sinkage, heel and trim, immerses

the lower edge of openings through which progressive flooding may take place and such flooding is not accounted for in the calculation of factor s_i or

any part of the bulkhead deck in passenger ships considered a horizontal evacuation route.

2.2.1.3 Special requirements for passenger ships

While the above stated regulations apply for both passenger and cargo ships where not otherwise stated, there are some special requirements applicable solely to passenger ships.

According to these requirements a passenger ship intended to carry 400 persons or more has to provide a survivability factor $s_i = 1$ for all damage cases involving all compartments within 0,08L measured from the forward perpendicular.

Further on a passenger ship intended to carry 36 or more persons is to be capable of withstanding minor damages with specific extent along the side shell. The damage extent to be assumed depends on the number of persons the ship is permitted to carry and on the ship's subdivision length L_s. For ships carrying 400 or more persons, which are regarded in this thesis, a damage length of $0.03L_s$ but not less than 3m is to be assumed at any position along the side shell, in conjunction with a penetration inboard of 0.1B but not less than 0.75m measured inboard from the ship side, at right angle to the centreline at the level of d_s. The vertical extent of damage is to extend from the ship's moulded baseline to a position up to 12.5m above the position of the deepest subdivision draught as defined in regulation 2, unless a lesser vertical extent of damage were to give a lower value of s_i, in which case this reduced extent is to be used. The factor s_i for those damages is to be not less than 0.9 for each of the three loading conditions d_s, d_p and d_l.

This minor damage concept maintains some deterministic characteristics within the new mainly probabilistic SOLAS 2009.

2.2.2 The required subdivision index R

The required subdivision index R for passenger ships shall be determined as follows:

$$R = 1 - \frac{5000}{L_s + 2.5N + 15225}$$

where

N = $N_1 + 2N_2$,

N_1 = number of persons for whom lifeboats are provided and

N_2 = number of persons (including officers and crew) the ship is permitted to carry in excess of N_1.

The partial indices A_s, A_p and A_l are not to be less than 0.9R for passenger ships and 0.5R for cargo ships.

2.2.3 On the required subdivision index R

The following graphic shows the influence of the number of passengers and the number of lifeboats provided on the required index R for 3 passenger ships with subdivision lengths L_s = 100, 200 and 300m. Curves are plotted on the one hand for ships providing lifeboat space for 31% of the persons on board (which applies for Nils Holgersson and the Safedor project ship) and on the other hand for ships that provide lifeboats for 100% of the persons on board. The required indices for cargo ships with subdivision lengths L_s = 100, 200 and 300m calculated according to SOLAS, Chapter II-1, Part B-1, Reg. 25 are also plotted, because new SOLAS 2009 also applies to cargo ships. The required indices according to SOLAS, Chapter II-1, Part B-1, Reg. 25 do not depend on the number of persons on board or on the lifeboat space provided. The required index for cargo ships is calculated according to formula

$$R = (0.002 + 0.0009 L_s)^{\frac{1}{3}} \text{ [1].}$$

The difference in the required index R for a 200m-ship with 1500 persons on board for instance constitutes 0.031, when providing lifeboat space for either 31% (465 persons) or 100% of the persons on board. The formula for the required subdivision index for cargo ships to comply with SOLAS 2009 is

$$R = 1 - \frac{128}{L_s + 152}$$

Cargo ships have to attain a greater required index R according to SOLAS 2009 than according to the current SOLAS. The required indices for cargo ships to comply with the current SOLAS and SOLAS 2009 can not be directly compared to each other due to differences in the survivability factor s_i and the probability of occurrence p_i.

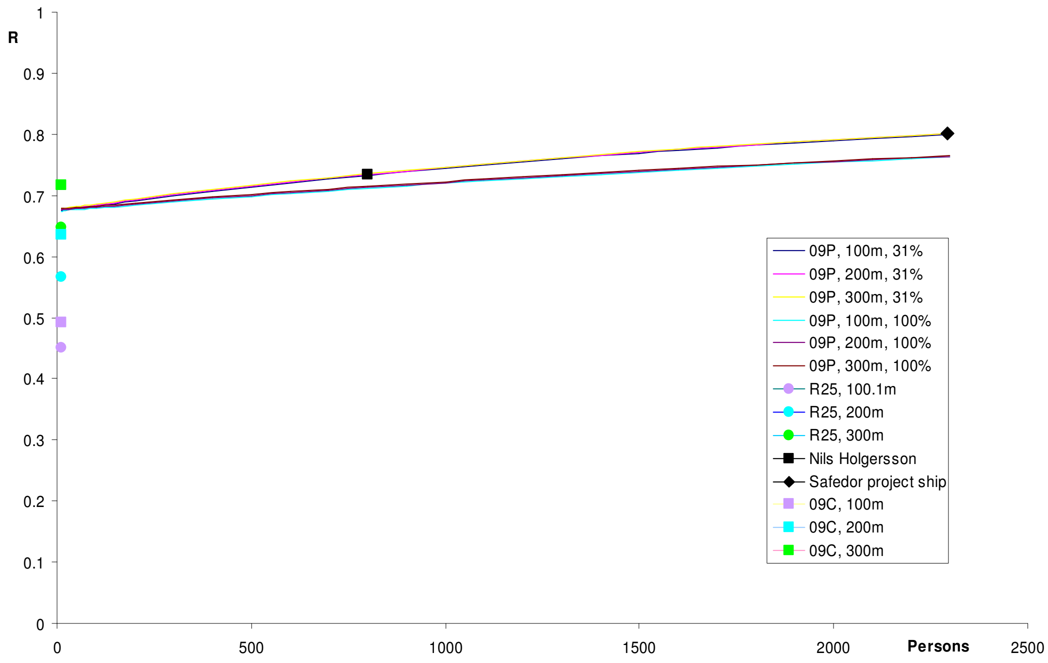

Figure 2-4: Influence of the number of passengers and the number of lifeboats provided on the required index R

3 The Procedure of Damage Stability Calculation

The damage stability calculations in way of this thesis have been carried out using the Naval Architectural Package NAPA. The damage stability regulations stated in SOLAS 2009 have been applied. This chapter explains the procedure of damage stability calculation in principle. Necessary data are stated and it is clarified what impact they have on the results. Chapters 5 and 5, which deal with the damage stability calculation of the two ships, will then give the results of the calculations.

First of all what is needed for the damage stability calculation is the hull definition of the ship. The geometrical information contained determines the ship's hydrostatics which directly influences the obtained s-factor.

The initial conditions represented by the draughts d_s, d_p and d_l are described by the draughts themselves as well as by the corresponding trims and GM-values. These data also have impact on the ship's hydrostatics. The GM-value has great influence on the s_i-factor, as the initial stability of a ship increases for greater GM-values and therefore the capability of the ship to avoid greater heeling angles increases. This goes hand in hand with the enhanced capability to keep openings dry which would result in $s_i = 0$ if becoming submerged.

Also the inner watertight structure of the ship needs to be considered. As explained in chapter 2.2.1.1, the damages are generated on the basis of that structure as far as it is considered. In each zone, there may be as many damages as there are different longitudinal, horizontal and transversal structural boundary combinations. According to the regulation, no greater penetration than B/2 needs to be considered. The maximum number of adjacent zones damaged in one damage is chosen by the user. If for instance the contribution of 7 zone damages to the attained index A can be neglected, the maximum number of adjacent zones would be set to 6.

Damages are named as follows:

[zone(s)].[ls].[hsu]-[hsd]

where: zone(s) = number of zone(s)

ls	=	Index of longitudinal subdivision limiting the damage; 0 = not limited
hsu	=	Index of horizontal subdivision limiting the damage; 0 = not limited
hsd	=	Index of horizontal subdivision limiting the damage downward, only for lesser extent damage cases

Where horizontal watertight boundaries above the waterline under consideration are taken into account, the s-value calculated for the lower compartment or group of compartments shall be obtained by multiplying the s-value as determined according to the formulas stated above by the reduction factor v_m, which represents the probability that the spaces above the horizontal subdivision will not be flooded. For instance if damage cases 5.1.1 and 5.1.0 exist and the horizontal boundary represented by the last numbers .1 and .0 lies above the waterline under consideration, damage case 5.1.1 might be allocated the factor $v_m = 0.6$ while damage case 5.1.0 gets the remaining 0.4. The sum of the factors v_m always is equal to 1. Each generated damage case contributes to the attained index A depending on its probability p_i of occurrence and probability of survival s_i.

The next necessary set of information is the room arrangement. It contains data about the rooms as the name, position, capacity and permeability of each room. The compartments (rooms or groups of rooms) that are inside the watertight hull are selected from the arrangement and located in the regarded watertight structure.

Flooding stages have been taken into consideration in those damage cases, where flooding of the rooms concerned could not be regarded as instantaneous. This applied on the one hand to those cases, where rooms within one damage are connected by cross flooding pipes and the calculated time for equalization is greater than 60s. On the other hand flooding stages have been considered, where a room involved in damage is divided by an "A"-class rated fire wall. According to the draft for the explanatory notes [4] for the new SOLAS, these fire walls are typical structures to significantly slow down equalization: "If a compartment contains decks, inner bulkheads, structural elements and doors of sufficient tightness and strength to seriously restrict the flow of water, for intermediate flooding stage calculation purposes it should be divided into corresponding non-watertight spaces." In case an extra cross flooding stage is taken into consideration, the flooding in the first stage is completed to the equilibrium either as if the cross flooding pipes were closed or as if the fire wall were undamaged. In the following cross flooding stage the openings of the pipes are regarded open or the fire wall is regarded collapsed and flooding proceeds until a new equilibrium is reached. The factor s_i is calculated for each stage and the least is regarded for the particular damage case. For calculating the hydrostatic properties of the ship at the end of each stage the lost buoyancy method is used.

According to SOLAS 2009 factor s_i has to be determined for the stage before equalization, too. To account for that, phases are assumed within every flooding stage. Assuming, the flooding process of a flooding stage is divided into 2 phases, the distance d between the water surface and the lowest point of the damaged rooms is calculated and divided into 3 equal parts. In the first phase the rooms are filled with water up to a waterline which is d/3 above the lowest point of the rooms. This waterline relates to a volume and moment of flood water causing a new floating position of the ship. The amount of flood water in phase 2 is obtained by filling the rooms up to a waterline, calculated by dividing the distance between the new external water surface and the water surface inside the rooms at the end of phase 1, by 2. The thereby added flood water gives a new floating position of the ship at the end of phase 2. The ship's hydrostatics at the end of a phase is calculated following the added-weight method. Finally the rooms are filled so, that they become full, which means that the water inside and outside the ship will have a common surface. That is then the end of the stage the phases had subdivided. The number of phases each stage is subdivided into is chosen for the entire damage stability calculation. In way of this thesis 0, 4, 5 and 10 phases have been accounted.

The displacement used to calculate the hydrostatic properties for stages and phases is the displacement of the intact condition.

The position, the degree of tightness and the connected spaces of all relevant openings also need to be considered. The openings may be watertight, weathertight or unprotected. The range of the righting lever curve is cut off as soon as an unprotected opening becomes submerged. This has impact on s_i by limiting the range and possibly also the maximum positive righting lever in the righting lever curve. The factor s_i is to be taken as zero in those cases where the final waterline immerses a weathertight opening through which progressive flooding may take place.

The openings representing cross flooding devices play a special role. The geometrical data of the pipes including their length, diameter and the sum of the resistance coefficients k are regarded. The time for equalization is determined as a function of the pipes' geometrical data and the floating position of the ship. If the calculated time for equalization exceeds 10min, the damage case is assigned the factor $s_i = 0$. The latest draft for the explanatory notes [4] for the new SOLAS however proposes to calculate s_{final} for the floating position the ship has achieved after 10min of equalization, in case the equalization time is longer than 10min. This procedure has not been employed in way of this thesis.

Due to the symmetry of the room arrangement of the ships regarded, the probabilistic as well as the deterministic damage stability calculations in way of this thesis have been performed for portside only.

4 Damage stability calculation of Nils Holgersson

Ro-pax ferry Nils Holgersson sails the Baltic Sea on short international voyage between Travemünde and Trelleborg. It has entered service on July 23rd, 2001. It has been designed to comply with the current SOLAS including the Stockholm Agreement with a Significant Wave Height of 4m.

This ship is capable of fulfilling a quasi 3-compartment standard in some zones in the mid ship region, whereas according to the current regulations it actually has to fulfil the 2-compartment standard. The reason for this specialty is a watertight sliding door connecting compartments 10 and 11 below bulkhead deck between shell and B/5-bulkhead. These doors connect two machinery spaces and could not be dispensed with. To account for the possibility that these doors might not be closed at sea and an occurring damage might flood three adjacent compartments, the authorities required to consider the two compartments concerned as one compartment. The effect of this measure is that a damage occurring at the transverse bulkhead separating zones 9 and 10 is assumed to cause flooding of zone 11 as well. The same applies for damage at the bulkhead between zones 11 and 12 due to which also zone 10 is flooded. These damages are depicted below. The rooms in zones 10 and 11 between B/5-bulkheads and shell are cross flooded. The small spaces remaining white in the damaged zone 12 are sea chests the buoyant hull had been reduced by.

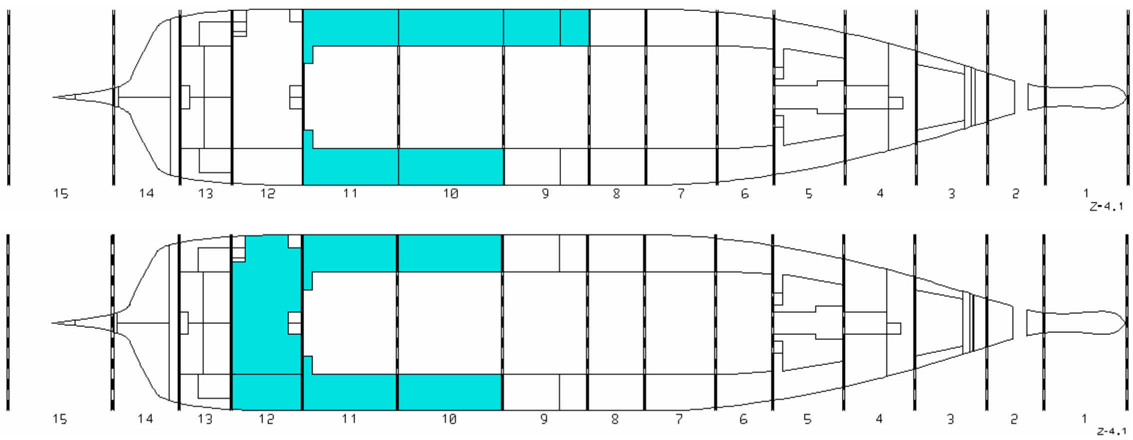

Figure 4-1: 3-zone damages

In order to compare the requirements of the current SOLAS and SOLAS 2009 as is scope of this thesis, the damage stability of Nils Holgersson has been assessed as follows: the mentioned 3-zone damages have been divided into corresponding 2-zone damages and the minimum GM-values, that were actually necessary for the ship to be able to comply with the current SOLAS damage stability criteria, were assessed. The 2-zone damages considered are shown below.

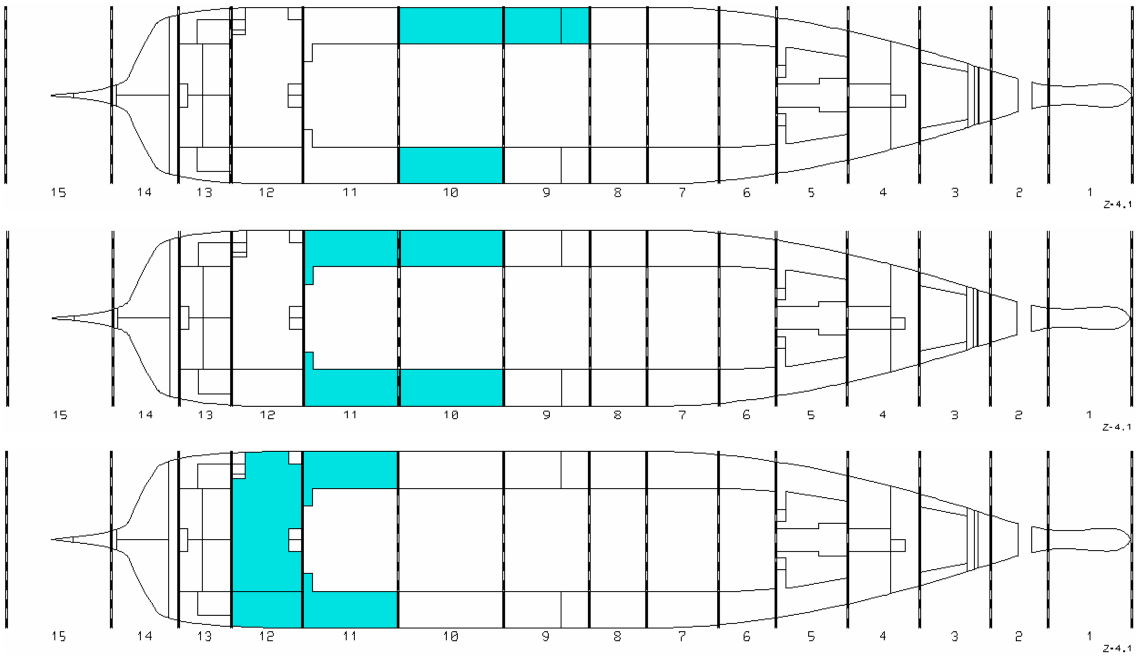

Figure 4-2: Corresponding 2-zone damages

4.1 Arguments for damage stability calculation

4.1.1 Main Dimensions

Length over all L_{oa}	= 190.77m
Length between perpendiculars L_{bp}	= 175.00m
Subdivision length L_s	= 188.31m
Breadth moulded B	= 29.50m
Depth moulded to 3rd deck (bulkhead deck) D	= 9.20m
Depth moulded to 5th deck (upper deck)	= 14.65m
Draught (design) d	= 6.20m
Deepest subdivision draught d_s	= 6.20m

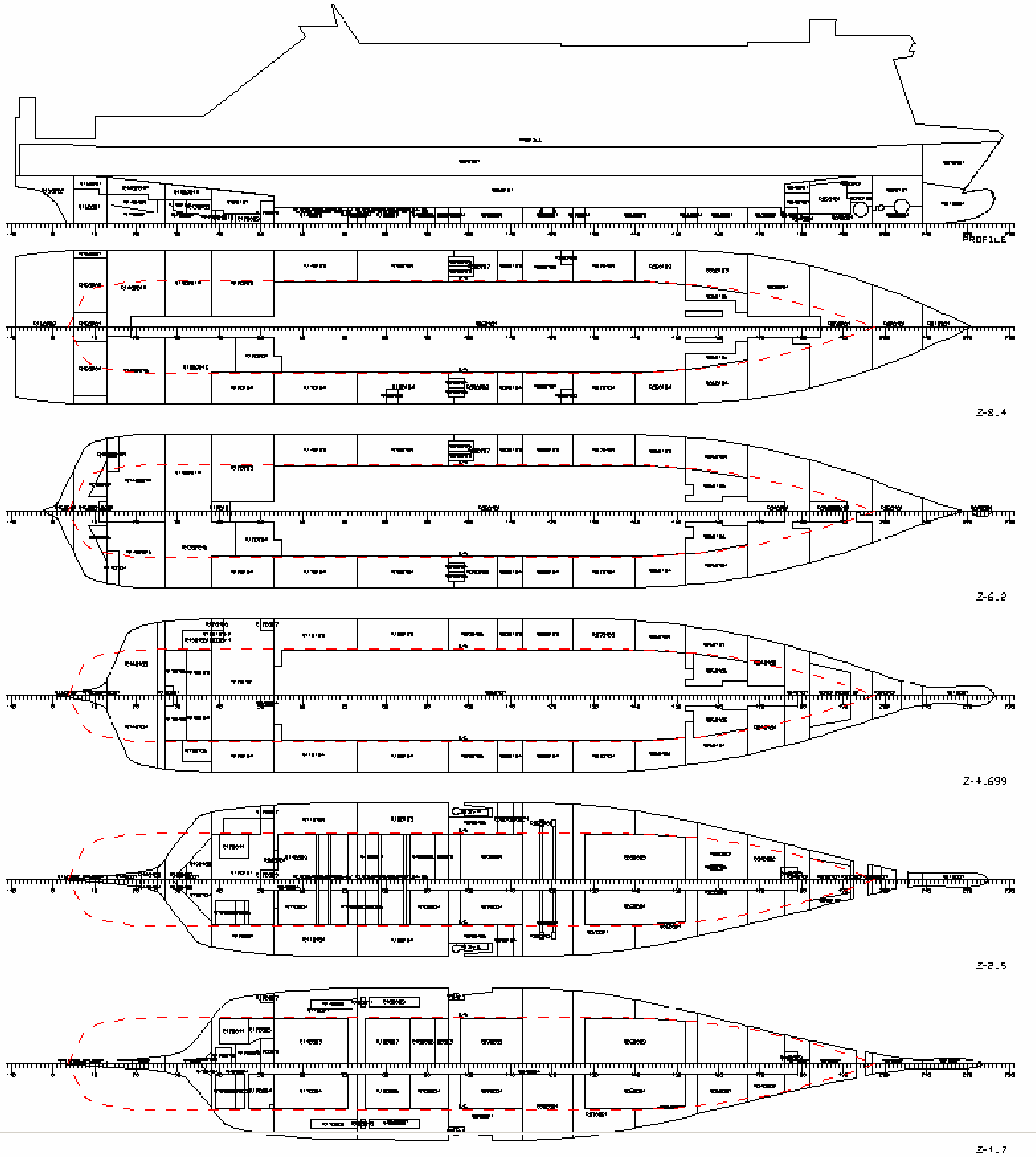

Figure 4-3: Room arrangement NILS HOLGERSSON

4.1.2 Number of passengers

NILS HOLGERSSON is permitted to carry 744 passengers and a crew of 56 making a total of 800 persons permitted on board. Lifeboats are provided for 250 persons (N_1) giving 550 persons in excess of N_1 (N_2).

4.1.3 Initial conditions

The minimum GM-values for the three draughts d_s, d_p and d_l of NILS HOLGERSSON have been obtained by performing a deterministic damage stability calculation according to the current SOLAS. This calculation employed newly generated damage cases, which divided the mentioned 3-compartment damage cases into cases combining only 2 compartments and led to new minimum GM-values.

The IMO intact criteria have also been considered as they have been in the approved stability booklet of the vessel. In the applicable draught interval the minimum GM is determined by the IMO weather criterion. The resulting limiting curves are displayed in the diagram below:

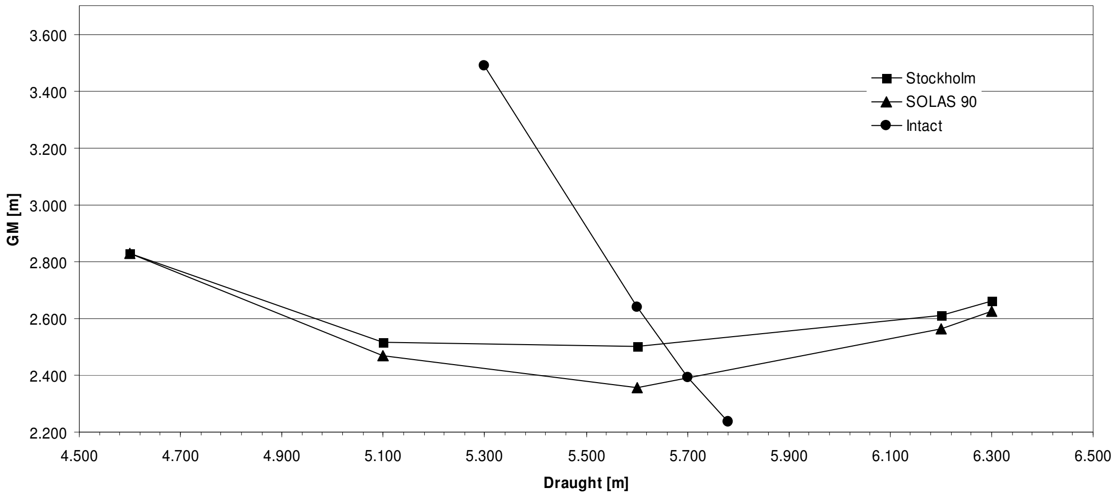

Figure 4-4: GM limiting curves

The resulting initial conditions are listed in the following table:

Draught [m]		Trim [m]	GM [m]
d_s	6.200	0.00	2.610
d_p	5.716	0.00	2.529
d_l	4.990	0.537	6.530

Table 1: Initial conditions

d_l corresponds to load case “ballast, arrival incl. passengers and crew, no trailers”,

d_p is calculated according to SOLAS 2009 as $d_l + 0{,}6d_s$ and

d_s corresponds to load case “departure, passengers, trailers”.

The GM-values for draughts d_s and d_p have been taken from the limiting GM-curves obtained by the damage stability calculation according to the current SOLAS. In case of draught d_l the GM has been taken from the existing load case, as this is the GM the ship has at that draught. This has been done to appreciate the higher GM of the loading condition and its favourable effect on the attained index A. The trims have also been taken from the loading conditions. In case of the load case corresponding to draught d_l the trim constituting 0.006m did not have to be considered for the calculations, because the difference in trim in comparison to the reference trim of 0.0m is less than 0.5% of L_s [2].

4.1.4 Heeling Moments

a) Passenger heeling moment

$$M_{passenger} = 0.075 \cdot N_p \cdot 12.75 tm$$

where

N_p: maximum number of passengers permitted on board (= 744 passengers) and the shift of the passengers constitutes 12,75m according to the approved damage stability calculation according to SOLAS 90.

$$M_{passenger} = 711 tm$$

b) Wind heeling moment

$$M_{wind} = (P \cdot A \cdot Z) / 9.806 tm$$

where

P: 120N/m² (= 0.01223t/m²),

A: projected lateral area above waterline,

Z: distance from centre of gravity of the lateral projected area above waterline to d/2 and

d: ship's draught

Draught [m]		$A_{lateral}$ [m²]	Z [m]	M_{wind} [tm]
d_s	6.20	4446	16.16	878
d_p	5.72	4534	16.14	895
d_l	4.99	4666	16.11	919

Table 2: M_{wind} for the three initial conditions

c) Davit-launched survival craft launching heeling Moment:

$$M_{survivalcraft} = 235tm$$

according to the stability booklet.

The Wind heeling moment M_{wind} is the greatest of the special moments and is therefore regarded for the calculation of $s_{mom,i}$.

4.1.5 Openings

For the probabilistic damage stability calculation the following openings have been taken into account:

- the openings representing unprotected, weathertight and watertight doors and exits situated on decks 1 to 4,
- weathertight air pipes according to the performed initial survey for load lines. In every zone of the watertight subdivision where air pipes are provided only the two lowest pipes closest to the terminals of the zone are considered for this damage stability calculation. The other pipes are omitted as they are assumed to become submerged when the above mentioned pipes are already under water and therefore do not have further impact on the attained index A,
- the ventilation openings according to the initial survey for load lines. They vent the machinery spaces and the cargo holds,
- at bulkhead deck level two weathertight openings as tracing points to account for the weathertight stern door and
- at bulkhead deck level two weathertight openings as tracing points to account for the weathertight inner bow door.

4.1.6 Zones and watertight subdivision

The zones for the probabilistic damage stability calculation have been defined on the basis of the 15 watertight compartments the ship had been subdivided into to comply with the current SOLAS and the Stockholm Agreement. Where transversal watertight boundaries separating rooms of considerable volume have been found within the compartments, additional watertight zone terminals have been entered giving a total of 22 damage zones.

As barriers for transverse penetration the B/5-bulkhead from the deterministic damage stability calculation. The side casings on bulkhead deck and the fore and aft ramps into the lower hold have been considered for the watertight subdivision. The weathertight sliding doors connecting some rooms in the side casing with the main hold and the ventilation ducts down onto bulkhead deck have been regarded in such way that the rooms are open to the main hold. Weathertight openings would have cut off the range of the righting lever curve when becoming submerged. That would have unjustifiably reduced the attained index A.

As horizontal watertight boundaries the double bottom for the most part and the bulkhead deck in parts have been considered. The bulkhead deck could not be considered where either the hinged covers covering the ramps leading from bulkhead deck down into the lower hold are situated or where air pipes penetrate the bulkhead deck and would conduct water onto the bulkhead deck if they were damaged from the bulkhead deck downwards and the ship was rolling. Only in zones 1, 2, 10 and 20, where neither air pipes nor hinged covers are situated, the bulkhead deck is considered watertight. Also the ramps have been regarded as watertight horizontal boundaries. The figure below depicts the damage zones and watertight subdivision of Nils Holgersson:

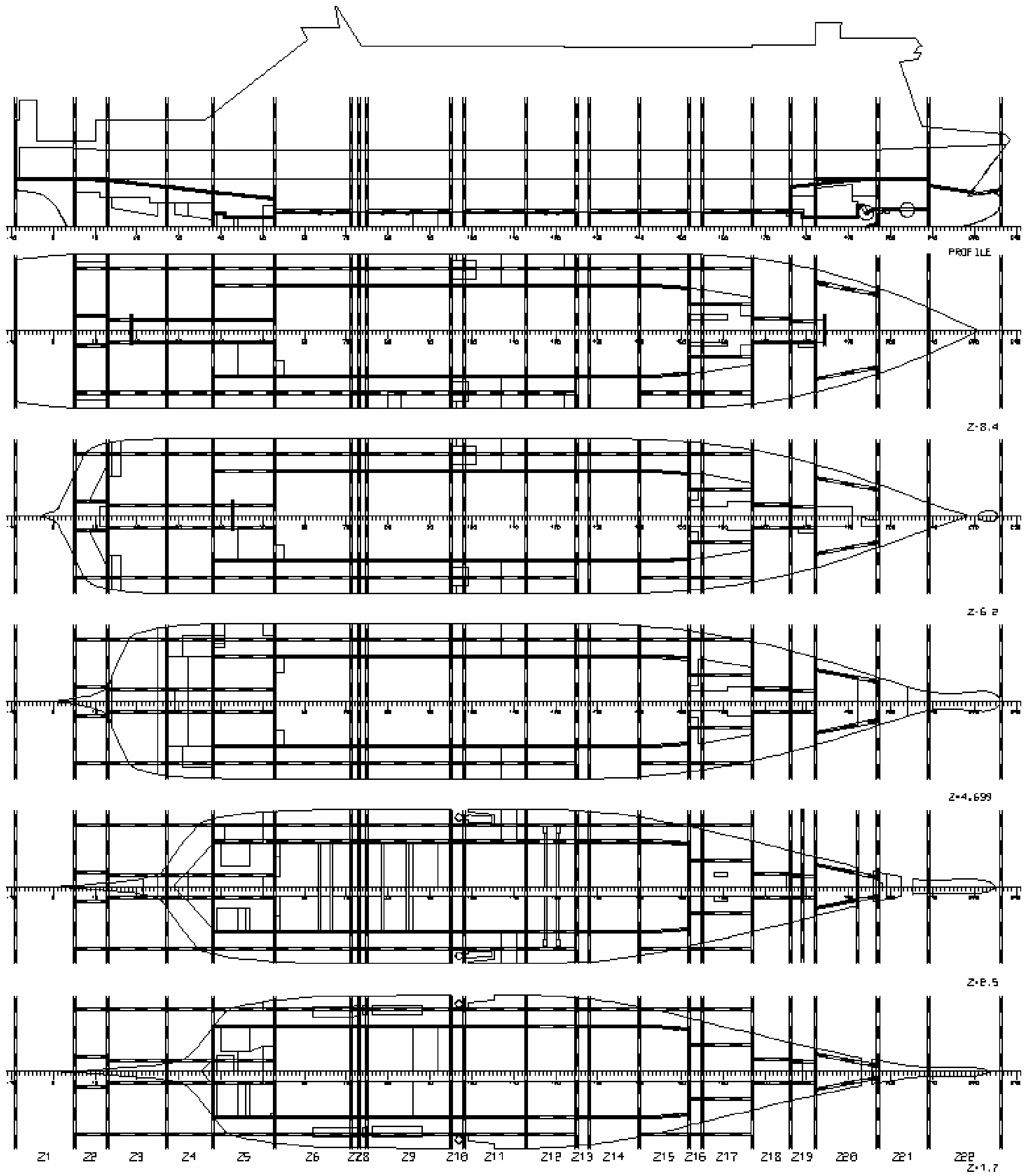

Figure 4-5: damage zones and watertight subdivision for damage stability calculation

4.1.7 Cross flooding devices

Nils Holgersson is equipped with cross flooding pipes without valves to decrease the angle of heel after damages to the ship’s side. The pipes are located in the double bottom of zones 6, 9 and 17 in groups of two or three pipes. Each group of pipes connects two rooms at the ship’s sides above the double bottom. In zone 9 heeling tanks are situated which are connected by pipes with valves. The rooms connected by pipes are listed in the table below:

Zone	number of pipes	Room portside / permeability	Room starboard / permeability
6	2	Machinery space / 0.85	Machinery space / 0.85
9	2	Machinery space / 0.85	Machinery space / 0.85
12	2	Heeling tank / 0.95	Heeling tank / 0.95
17	3	Stairs, accommodation / 0.95	Stairs, store / 0.95, 0.60

Table 3: Cross connected rooms

To account for the worst case, the heeling tank on portside has been regarded as full in the moment of damage. Two damage stability calculations have been performed: one has been performed assuming the master of the ship opened the valves of the pipes connecting the heeling tanks immediately after damage to decrease the angle of heel by flooding the starboard heeling tank. The other calculation was done considering the master did not take any measures. The same two procedures had been regarded during the deterministic damage stability calculation. They had not affected the limiting GM-values as neither of the damage cases considered required a higher GM than was required by the other deterministic damage cases. The probabilistic calculation resulting in the least attained index A is the one, where cross flooding does not take place. This calculation is regarded in way of this thesis.
The geometrical data of the pipes were regarded as they were built including their length, diameter and the sum of the friction coefficients k for inlet, outlet and pipe geometry according to the approved damage stability calculation.

4.1.8 Other input data

No escape routes needed to be considered, as no passengers are allowed on or below bulkhead deck when the ship is at sea.
To regard the not watertight bow visor, the room between bow visor and inner bow door has been removed from the buoyant hull. Two weathertight openings representing the tracing points of the also only weathertight inner bow door have been regarded.
In zones 3, 4, 5 and between zones 18 and 19 Nils Holgersson is equipped with “A”-class fire-rated walls to separate several auxiliary engine rooms, stair cases and crew recreation areas

from each other. These walls have been taken from the approved fire control plan. The deterministic damage stability calculation of NILS HOLGERSSON had been carried out regarding not all of these fire walls. This is common method according to which the deterministic damage stability calculation of passenger vessels is performed by yards and classification societies.

The probabilistic damage stability calculation has been carried out performing calculations for intermediate stages of flooding in the zones described.

4.1.9 Required Index R

To comply with the regulations of SOLAS 2009 Nils Holgersson has to reach an attained index A greater than the required index R = 0.73388. The required index R has been determined according to the formula stated in paragraph 2.2.2 and using the parameters listed in paragraphs 4.1.1 and 4.1.2.

4.2 Results

NILS HOLGERSSON attains an index A = 0.72669 and therefore does not reach the required index R by a small margin. For the attained index A damages with an extent of up to 6 zones have been considered. 6-zone damages contribute only 0.00275 to the attained index A so 7-zone damages did not need to be considered. No phases needed to be regarded as no damage case had in any phase a s_i less than the s_i at the end of the stage(s).

The three draughts contribute to the attained index A as follows:

Draught [m]		GM [m]	Index A	Weight coefficient	A*wcoeff.	A/R
d_s	6.200	2.610	0.65187	0.4	0.26075	0.888
d_p	5.716	2.529	0.68848	0.4	0.27539	0.938
d_l	4.990	6.530	0.95275	0.2	0.19055	1.298
Index A total:					0.72669	0.990

Table 4: Contribution of the draughts to the Attained index A

The graphic below displays the contribution of the 1- to 6- zone damages to the attained index.

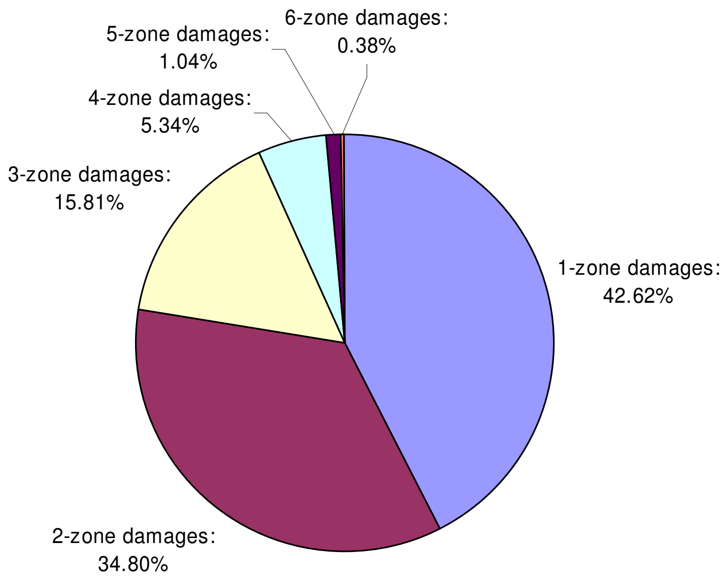

Figure 4-6: Contribution of the 1– to 6–zone damages to the attained index A

The following bar chart depicts the distribution of the survivability factor s_i for the 1- to 6-zone damages. The groups of the 2-, 3- and 4-zone damages contain more cases with $s_i = 1$ and still contribute less to the attained index A than the one zone damages. This is caused by the lesser probability of occurrence of these damages. The probability of occurrence p_i is clarified in the circular chart Figure 4-8. Many damage cases extending over 5 or 6 adjacent zones have a probability of survival of $s_i = 1$ despite of their large extent. This is caused first by the fact that there are 5 zones that extend only over 2-3 frames. Their extent is therefore not so big. Second, 98 of the 116 6-zone damage cases having $s_i = 1$ occur at the lightest service draught where the ship has the great GM of 6.53 m. Three, many of those damages either have little penetration depths or they occur at the ship's ends, where floodable volumes are small due to the hull's diminution.

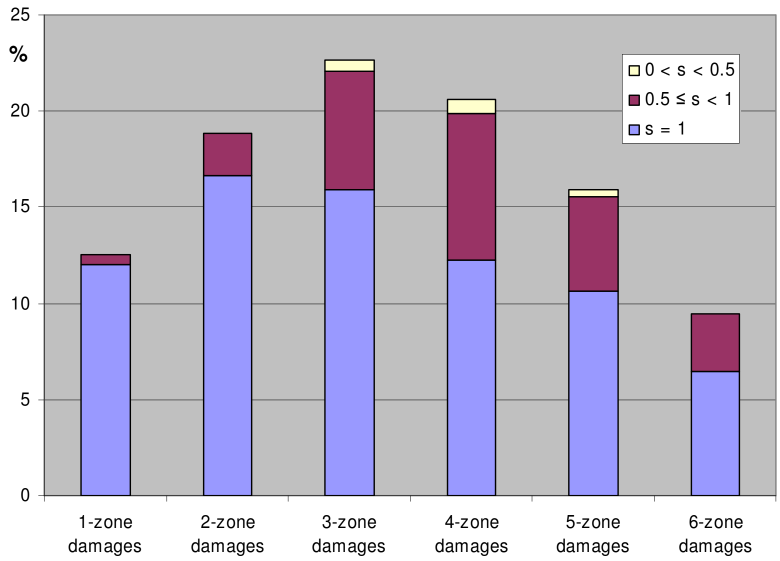

Figure 4-7: Distribution of survivability factor s_i for all damages

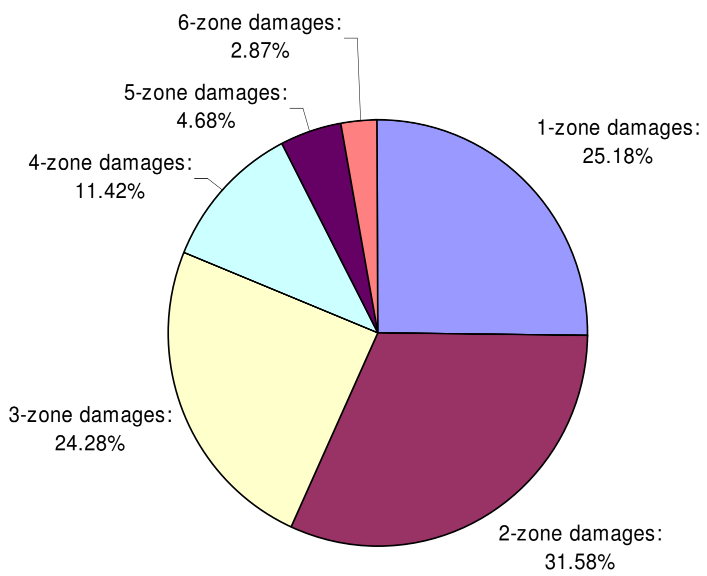

Figure 4-8: Probability of occurrence p_i of the 1- to 6- zone damage cases

4.2.1 Check of the special requirements

According to SOLAS 2009 passenger ship MV NILS HOLGERSSON has to meet two special requirements. First, it has to provide a survivability factor $s_i = 1$ for all damage cases involving all compartments within 0.08L measured from the forward perpendicular. Such damage includes zones 17 and 18. That requirement is fulfilled for all three draughts.
Second, a minor damage with a length of the greater of 3m or $0.03L_s = 5.65$m at any position of the side shell in conjunction with a penetration inboard of the greater of 0.75m or 0.1B = 2.95m shall be withstood in such way, that s_i is not less than 0.9 for each of the loading conditions d_s, d_p and d_l (paragraph 2.2.1.3). This requirement is not met at draughts d_s and d_p whereas it is met at draught d_l. At subdivision draught d_s the permitted cross flooding time of 10min is exceeded by 60 - 62s for four damage cases involving zones 7 and 8. At partial draught d_p the permitted cross flooding times are exceeded by 78 - 84s for the same four damage cases. For these cases s_i has been taken as zero. Cross flooding time is greater at partial draught as heel is greater and draught is less than is the case at d_s. This results in less pressure difference between the cross flooded compartments causing a greater time for equalization. The permitted cross flooding time according to the current SOLAS is 15min and is exceeded for none of the damage cases. Regarding the mentioned procedure for the calculation of s_{final} in case of equalization times exceeding 10min from the explanatory notes [4] as described in chapter 3 might influence the fulfilment of the minor damage criterion.

5 Damage stability calculation of the Safedor project ship

The ship dealt with in this chapter is a project status ship by courtesy of the shipyard Meyer Werft. It is a state of the art design from 2005 without a lower hold.

5.1 Minimum GM values

A deterministic damage stability calculation has been performed to obtain the minimum GM values employed for the following probabilistic damage stability calculation. Additionally, the recommended IMO intact criteria have been considered. The GMs have been obtained under consideration of the trims and draughts from the relevant load cases of the project. The load cases 1 (100% consumables, passengers, trailers) and 2 (10% consumables, full ballast water, passengers, no trailers) are regarded. In load case 1 the ship has a draught of 6.733m and level trim while in load case 2 it floats at a mean draught of 5.782m with a forward trim of 0.353m. The light service draft condition d_l has been allocated the draft and the GM the ship in fact has at the corresponding load case. To obtain the limiting GM values for draughts d_s and d_p the mentioned damage and intact criteria have been applied to the ship at the corresponding draughts at trim 0.0m.

5.1.1 Deterministic damage stability calculation

On the basis of the data submitted by the shipyard a deterministic damage stability calculation according to the current SOLAS has been performed. The ship has to fulfil the 2-compartment standard. A significant wave height of 4m has been accounted. The greatest of the three applicable heeling moments is the passenger heeling moment. It has been calculated according to formula

$$M_{passenger} = (0.075 \cdot N_p) \cdot (0.45 \cdot B) tm$$

where

N_p: maximum number of passengers permitted on board (=2200 passengers) and

B: Beam of the ship (= 27.80m),

resulting in passenger heeling moment $M_{passenger}$ = 2064tm. This formula was employed because data on relevant deck areas and muster stations were not submitted. The resulting minimum GM values can be found in chapter 5.1.3 together with the minimum GM values derived from the recommended intact criteria.

5.1.2 Recommended IMO intact criteria

For intact stability assessment the following criteria have been considered:

- the initial metacentric height GM_0 should not be less than 0.15m,
- the area under the righting lever curve up to 30° angle of heel or up to the angle of downflooding, if less than 30°, should not be less than 0.055mrad,
- the area under the righting lever curve up to 40° angle of heel or up to the angle of downflooding, if less than 40°, should not be less than 0.09mrad,
- the area under the righting lever curve between the angles of heel 30° and 40° or between 30° and the angle of downflooding if less than 40° should not be less than 0.03mrad,
- the righting lever should be at least 0.20m at an angle of heel equal to or greater than 30°,
- the maximum righting lever should occur at an angle of heel preferably exceeding 30° but not less than 25°,
- the angle of heel on account of crowding of passengers to one side should not exceed 10°. It has been assumed a shift of 0.45B, a weight of 75kg and 2200 passengers and
- the angle of heel on account of turning should not exceed 10°. The ship has been designed for a service speed of 27knots (= 13,89m/s).

Further on the IMO weather criterion has been considered. For that purpose the following wind profile has been defined:

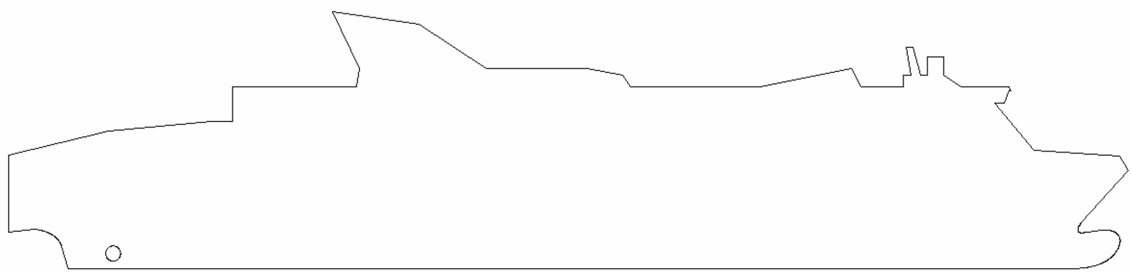

Figure 5-1: Illustration of the wind profile of the Safedor project ship

The area bilge keel area A_k resulting in factor k for the weather criterion has been assumed to constitute 60m². For that one 30cm height HP bilge keel of 100m length on each side of the ship has been considered.
The resulting GM-limiting curves can be found in Chapter 5.1.3.

5.1.3 Resulting GM-limiting curves

The resulting minimum GM values from the deterministic damage stability calculation according to the current SOLAS (SOLAS), the minimum GMs needed to comply with the Stockholm Agreement (WOD) and the required GM-limiting values for the recommended IMO intact criteria (Intact) are summarized in the following diagram:

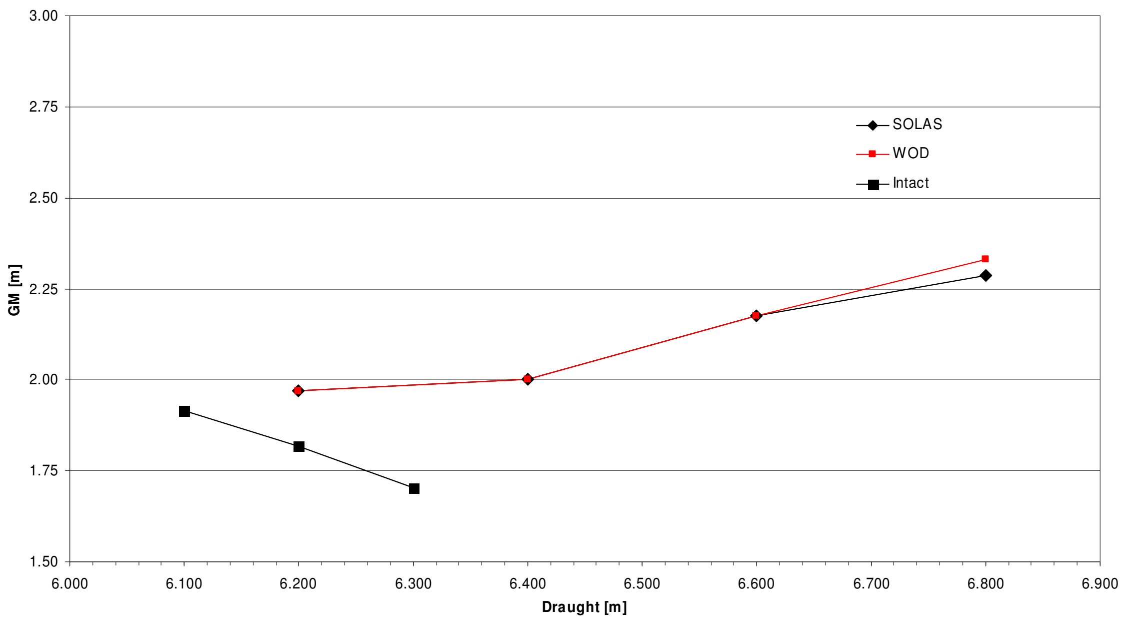

Figure 5-2: minimum GM values Safedor project ship

5.2 Probabilistic damage stability calculation

5.2.1 Main Dimensions

Length over all L_{oa}	= 187.91m
Length between perpendiculars L_{bp}	= 173.60m
Subdivision length L_s (without bowroom)	= 185.65m
Breadth moulded B	= 27.80m
Depth moulded to 3rd deck (freeboard deck) D	= 9.70m
Draught (design) T	= 6.60m
Deepest subdivision draught d_s	= 6.733m

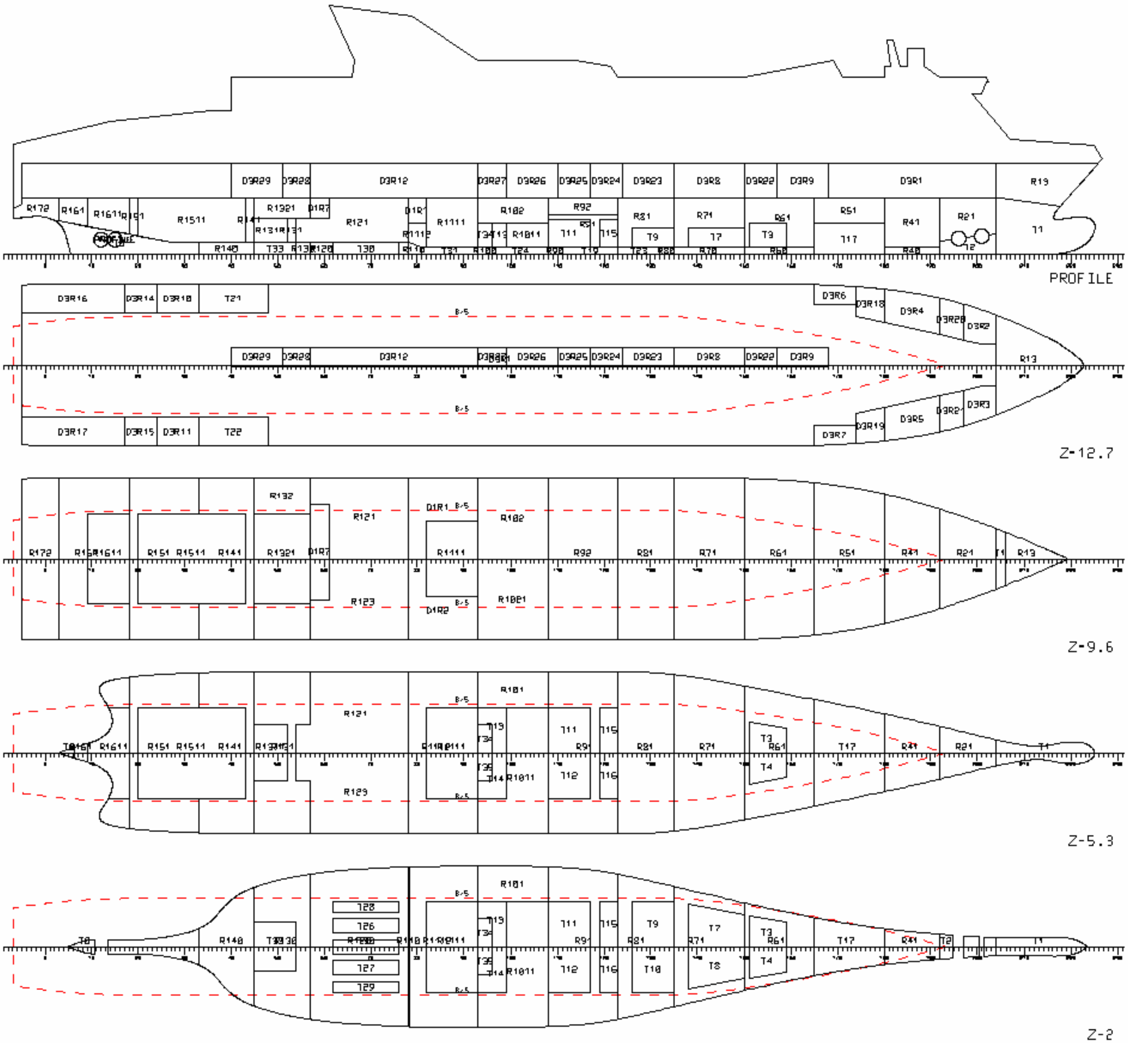

Figure 5-3: Room Arrangement Safedor project ship

5.2.2 Number of passengers

The Safedor project ship is designed to carry 2200 passengers and a crew of 92 making a total of 2292. Lifeboats are provided for 720 persons (N_1) giving 1572 persons in excess of N_1 (N_2).

5.2.3 Initial Conditions

	Draught [m]	GM [m]	Trim [m]
d_s	6.733	2.278	0.00
d_p	6.212	1.970	0.00
d_l	5.430	3.820	-0.353

Table 5: Initial conditions

d_l corresponds to the load case "10% consumables, full ballast water, passengers, no trailers",
d_p is calculated according to SOLAS 2009 as d_l + 0,6d_s and
d_s corresponds to the load case "100% consumables, passengers, trailers".

The GMs have been obtained by linear interpolation from the values forming the GM-limiting curves shown in the diagram in Figure 5-2: minimum GM values Safedor project. At draughts d_s and d_l GM is determined by the damage criteria of the current SOLAS and the Stockholm Agreement. The GM for draught d_l has been taken from the existing loading condition. This has been done to appreciate the higher GM of the loading condition and its favourable effect on the attained index A. The trim for draught d_l has also been taken from the loading condition.

5.2.4 Heeling moments

a) Passenger heeling moment

$$M_{passenger} = (0.075 \cdot N_p) \cdot (0.45 \cdot B)tm$$

where

N_p: maximum number of passengers permitted on board (=2200 passengers) and
B: Beam of the ship (= 27.80m).

$$M_{passenger} = 2064tm$$

b) Wind heeling moment

$$M_{wind} = (P \cdot A \cdot Z)/9.806tm$$

where

P: 120N/m² (= 0.01223t/m²),
A: projected lateral area above waterline,

Z: distance from centre of gravity of lateral projected area above waterline to d/2 and

d: ship's draught.

Draught [m]		$A_{lateral}$ [m²]	Z [m]	M_{wind} [m]
d_s	6.733	4232	15.70	813
d_p	6.212	4325	15.69	830
d_l	5.430	4464	15.67	855

Table 6 – M_{wind} for the three initial conditions

c) Davit-launched survival craft launching heeling Moment is considered negligible in comparison to $M_{passenger}$.

The Passenger heeling moment $M_{passenger}$ is the greatest of the special moments and is therefore regarded for the calculation of $s_{mom,i}$.

5.2.5 Openings

For the probabilistic damage stability calculation the following openings have been taken into account:

- the openings that have been submitted by the shipyard representing emergency exits and lifts at 13.23m above basis,
- at 760mm above bulkhead deck weathertight air pipes from tanks and void spaces into the watertight centre casing where this is present,
- at bulkhead deck level two weathertight openings as tracing points to account for the weathertight stern door and
- at bulkhead deck level two weathertight openings as tracing points to account for the weathertight inner bow door.

5.2.6 Zones and watertight subdivision

The zones for the probabilistic damage stability calculation have been defined on the basis of the 16 watertight compartments the ship had been subdivided into to comply with the current

SOLAS. Additional zone terminals have been defined where large watertight volumes would else have been flooded simultaneously. A total of 25 zones were defined.

As barriers for transverse penetration the B/5-bulkhead, the tank boundaries in zones 6 and 7 that do not coincide with the B/5-bulkhead and the side casings and centre casings in parts have been considered for the watertight subdivision. In zone 8 Room D1R7 has been regarded as watertight and considered for the damage generation.

As horizontal watertight boundaries the double bottom and the bulkhead deck have been considered. The figure below depicts the regarded boundaries of the Safedor project ship.

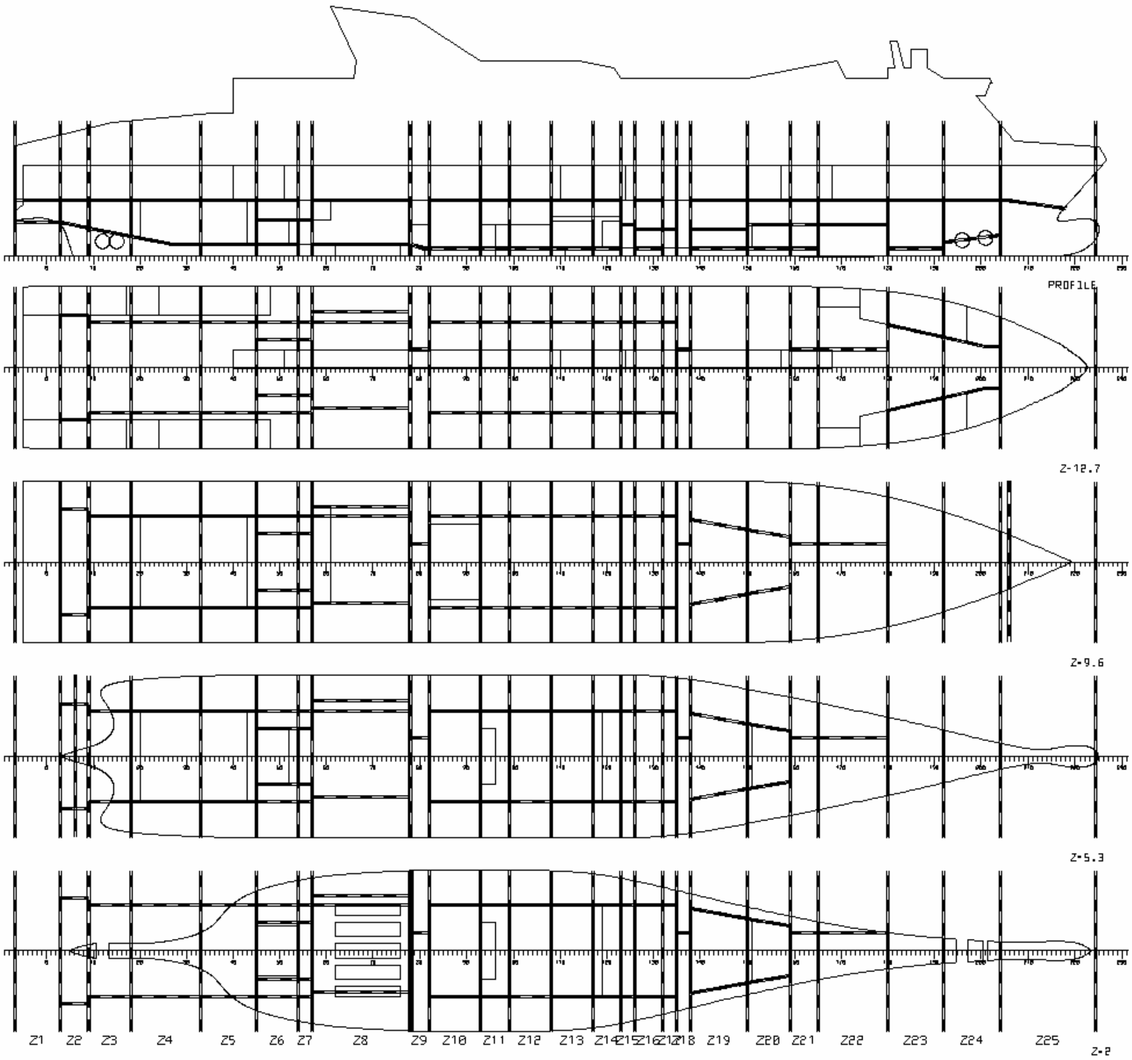

Figure 5-4: Regarded watertight boundaries of the Safedor project ship

5.2.7 Other input data

No escape routes needed to be considered on bulkhead deck, as no passengers are allowed on or below bulkhead deck when the ship is at sea.

To regard the not watertight closable bow visor, the room between bow visor and inner bow door has been removed from the buoyant hull. Two weathertight openings representing tracing points of the also only weathertight inner bow door have been considered.

The Safedor project ship has zones that due to the purpose of the rooms contained have been regarded to be equipped with "A" class fire-rated walls according to SOLAS Part C Chapter II-2, Reg. 9. These compartments are three engine room compartments ranging from side to side and are situated on the tank top in zones 7 to 12 between $0.23L_s$ and $0.47L_s$. The walls regarded separate the two main propulsion plants and several engine stores, auxiliary engine rooms, the engine control room, separator rooms, corridors and workshops from each other. The deterministic damage stability calculation of the Safedor project ship has been carried not regarding these fire walls. This is common method according to which the deterministic damage stability calculation of passenger vessels is performed and which has been applied in both the designing process at the yard and the calculation in way of this thesis.

The probabilistic damage stability calculation has been carried out performing calculations for intermediate stages of flooding in the machinery compartments described.

5.2.8 Required index

To comply with the regulations of SOLAS 2009 the Safedor Project ship has to reach an attained index A of at least the required index R = 0.80056. The required index R has been determined according to the formula stated in paragraph 2.2.2 and using the parameters listed in paragraphs 5.2.1 and 5.2.2.

5.3 Results

The calculations have been performed regarding 0, 4, 5 and 10 phases within every flooding stage. The results were as follows:

Number of phases	attained index A
0	0.80568
4	0.79660
5	0.79613
10	0.79591

Table 7 – correlation number of phases - attained indices A

The calculation of a damage stability calculation with x phases takes (x+1) -times longer than it takes without phases. In this particular case the calculation considering 4 phases for instance took about 9h. The number of 5 phases was believed to be the best compromise between achieving a sufficiently precise result and a reasonable calculation time.

The Safedor project ship attains an index A = 0.79613 and therefore does not reach the required index by a small margin. For the attained index A damages involving up to 7 adjacent zones have been considered. 7-zone damages contribute 0.00334 to the attained index so 8-zone damages did not need to be considered.

The following table lists the distribution of the attained index over the three draughts:

Draught [m]		GM [m]	Index A	Weight coefficient	A*wcoeff.	A/R
d_s	6.733	2.278	0.74770	0.4	0.29908	0.933
d_p	6.212	1.970	0.76248	0.4	0.30499	0.952
d_l	5.430	3.820	0.96029	0.2	0.19206	1.200
Index A total:					0.79613	0.994

Table 8: Contribution of the draughts to the attained index A

The contribution of the 1- to 7-zone damages to the attained index A is illustrated in the following diagram:

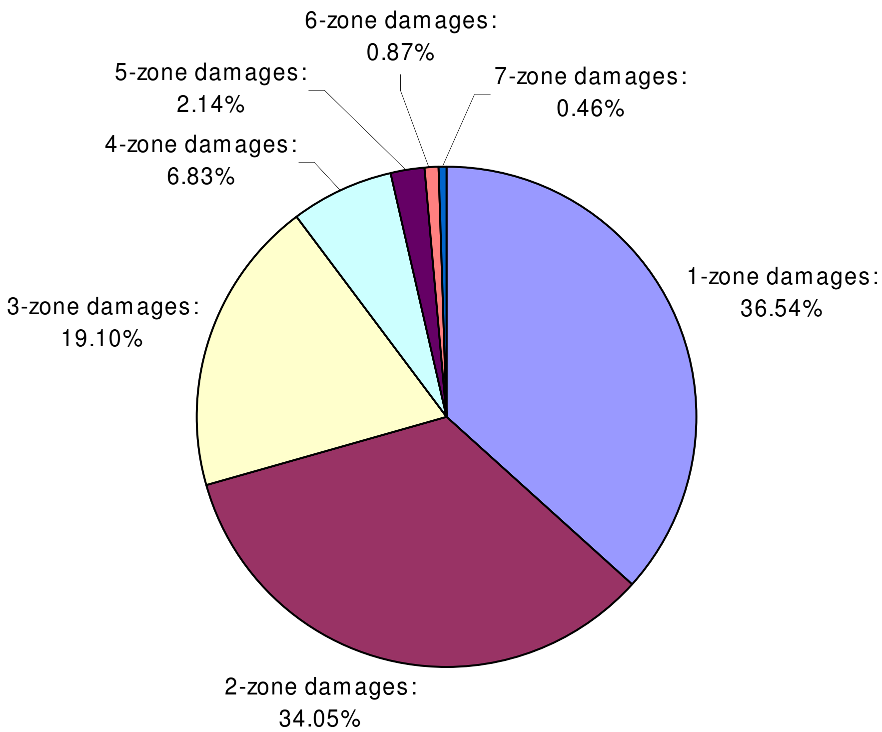

Figure 5-5: Contribution of the damages to the attained index A

The following bar chart displays the distribution of the s_i-factor for the 1- to 6-zone damage cases. It attracts attention that the Safedor project ship has hardly any damage cases with s_i below 0.5 and little below 1. If she survives a damage case, this case almost always attains a high survivability factor. This is due to the way the rooms are arranged below bulkhead deck. As can be seen in Figure 5-3, the Safedor project ship has many rooms reaching from one side of the ship to the other which are connected by large cross section ducts. Flooding stages did not need to be regarded for these rooms as times for equalization constitute roughly 10-30s. Where rooms or tanks are not symmetrical to the centre line, they mostly are either rather small or situated close to the centre line. The effect of this way of arranging rooms is to obtain symmetrical flooding for very many damage cases. These damage cases obtain the mentioned high s_i-factors if survived at all.

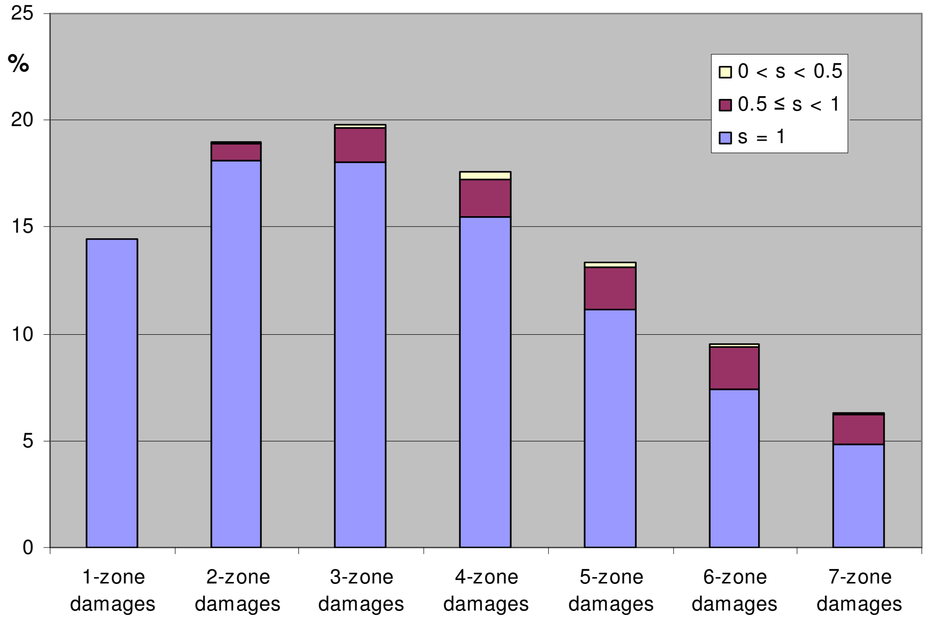

Figure 5-6: Distribution of the survivability factor s_i

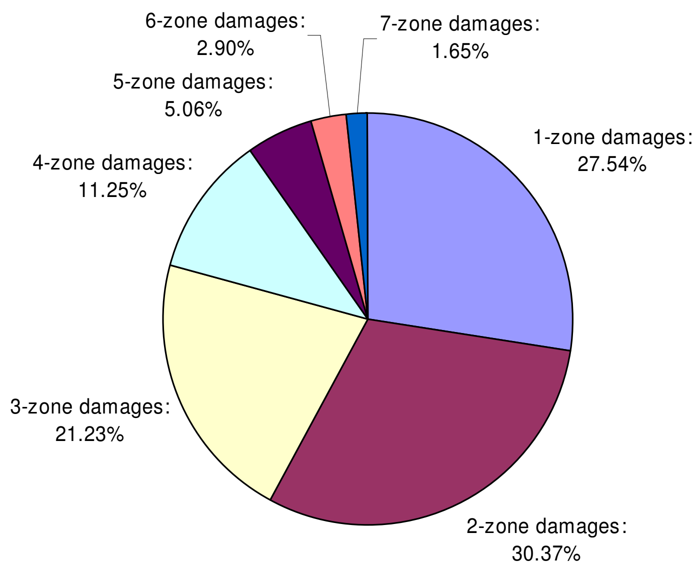

Figure 5-7: Probability of occurrence p_i of the 1- to 6-zone damages

5.3.1 Check of the special requirements

First, the survivability factor s_i equals 1 for all damage cases involving all compartments within 0.08L measured from the forward perpendicular. Such damage includes zones 24 and 25. That requirement is fulfilled for all three draughts.
Second, the minor damages with a length of the greater of 3m or $0.03L_s$ = 5.57m at any position of the side shell in conjunction with a penetration inboard of the greater of 0.75m or 0.1B = 2.78m are not withstood in that way, that s_i is greater than or equal to 0.9R when calculated according to reg. 7-2 for each of the loading conditions d_s, d_p and d_l. This requirement is not met for draughts d_p and d_s. Some damage cases involving those zones where the mentioned "A" class fire-rated walls have been regarded in the engine room compartments have s-values below 0.9 because of too little righting levers at the end of stage 1 before the fire wall is assumed to collapse.

5.3.2 Investigation of the flooding phases

Below three significant damage cases are shown where the floating condition of the Safedor project ship after damage attains a lesser s_i in one of the phases considered than at the equilibrium at the end of the intermediate or the final stage of flooding. Three mechanisms leading to this were observed. Each of the three damage cases is used to clarify one of the mechanisms. First, a table listing properties of the floating position is given. Second, the floating position and the filling degree for significant flooding phases are depicted together with the corresponding righting lever curve.

5.3.2.1 Damage case 1:

Stage	Phase	Draught [m]	Heel [°]	GZ [m]	Range [°]	si
1	1	6.80	1.68	0.72	50.3	1
1	2	6.88	3.16	0.63	48.3	1
1	3	6.94	4.48	0.55	46	1
1	4	7.01	5.83	0.48	43.5	1
1	5	7.06	7.22	0.40	40.9	1
1	EQ	7.14	10.47	0.02	4.9	0.741
2	1	7.18	10.88	0.01	3.3	0.570
2	2	7.25	9.45	0.04	6.1	0.886
2	3	7.33	7.87	0.09	10.4	1
2	4	7.40	6.16	0.15	14.3	1
2	5	7.48	3.62	0.23	19.9	1
2	EQ	7.54	1.17	0.19	18.8	1

Table 9 – properties of floating position damage case 1

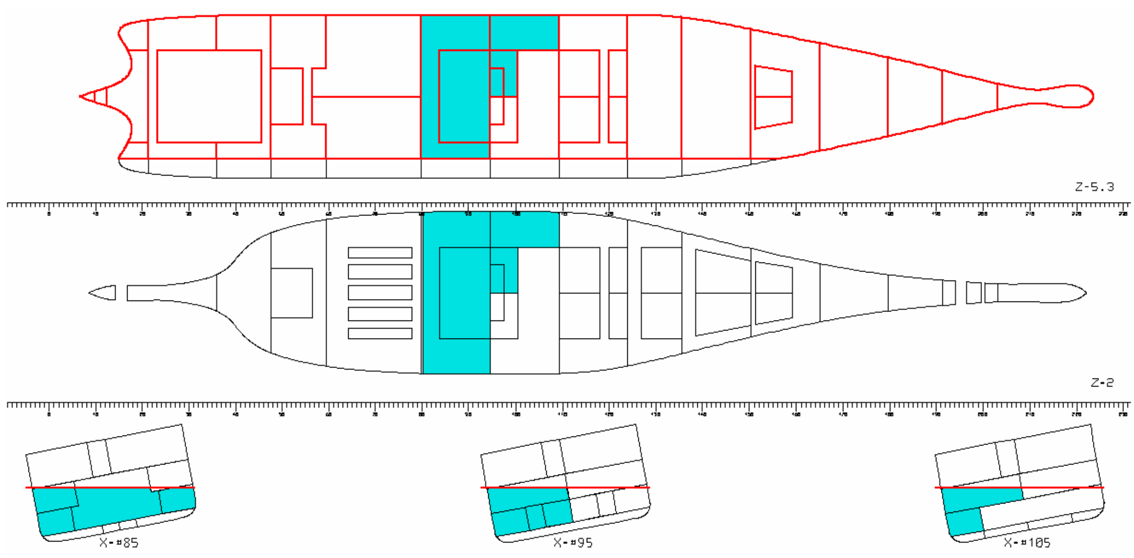

Figure 5-8: Floating position in stage 1, phase EQ

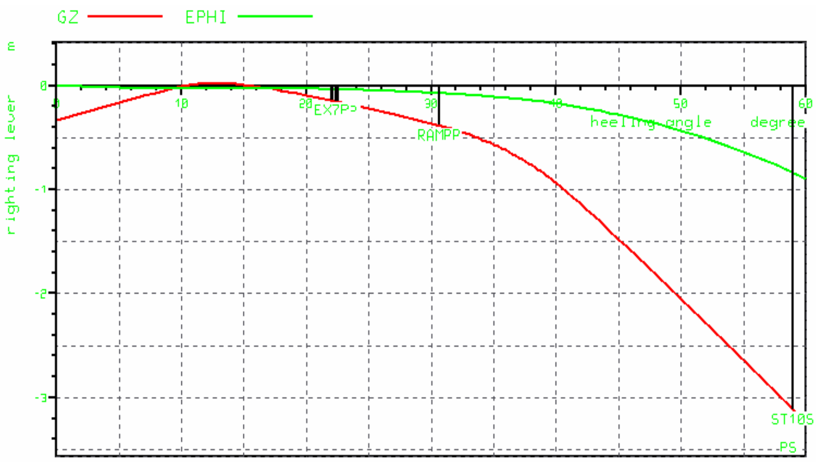

Figure 5-9: Righting lever curve in stage 1, phase EQ

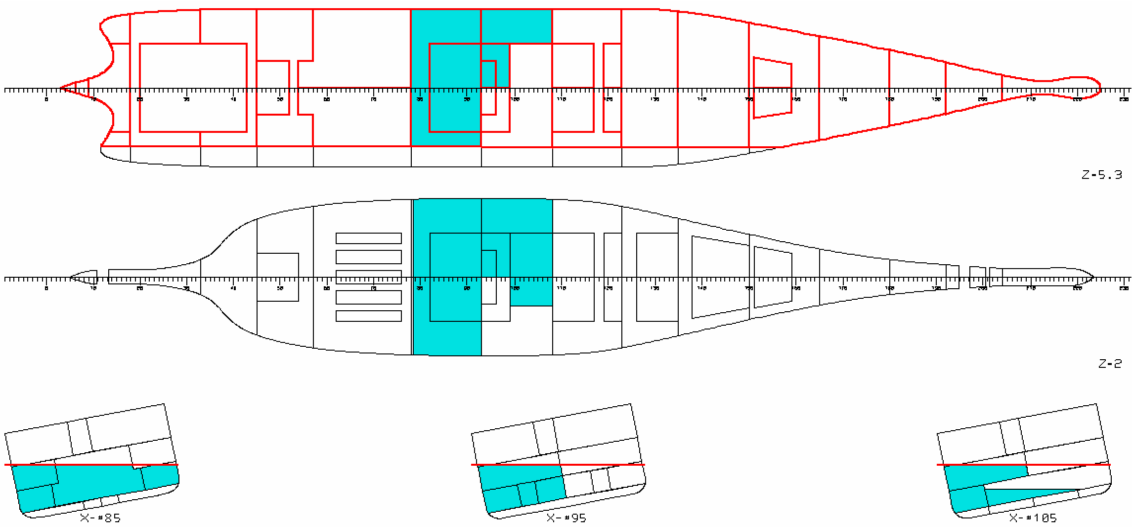

Figure 5-10: Floating position in stage 2, phase 1

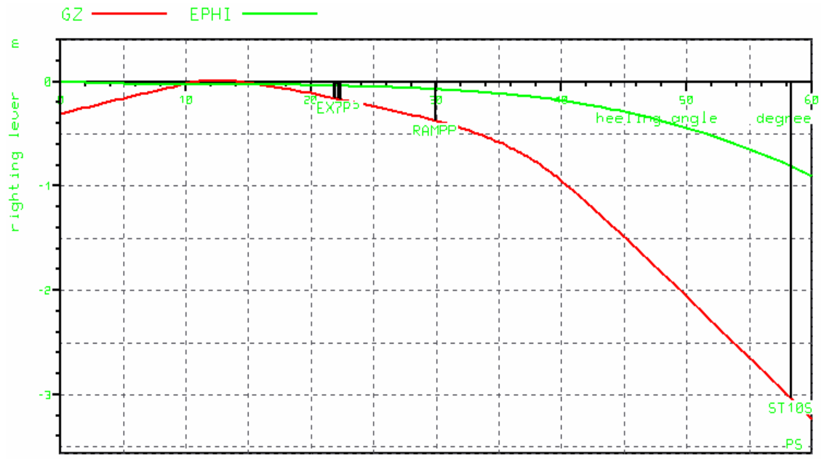

Figure 5-11: Righting lever curve in stage 2, phase 1

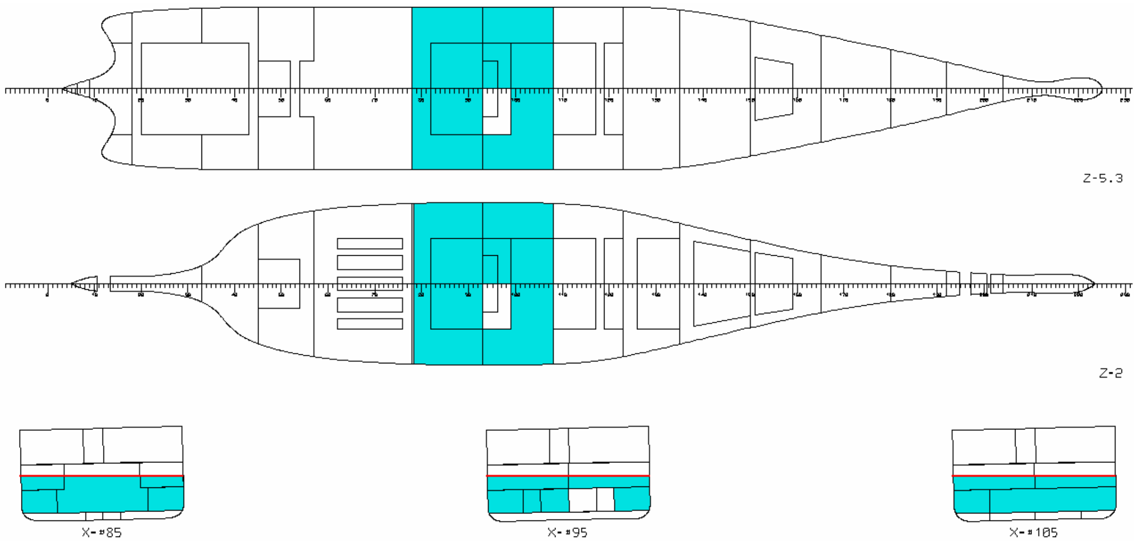

Figure 5-12: Floating position in stage 2, phase EQ

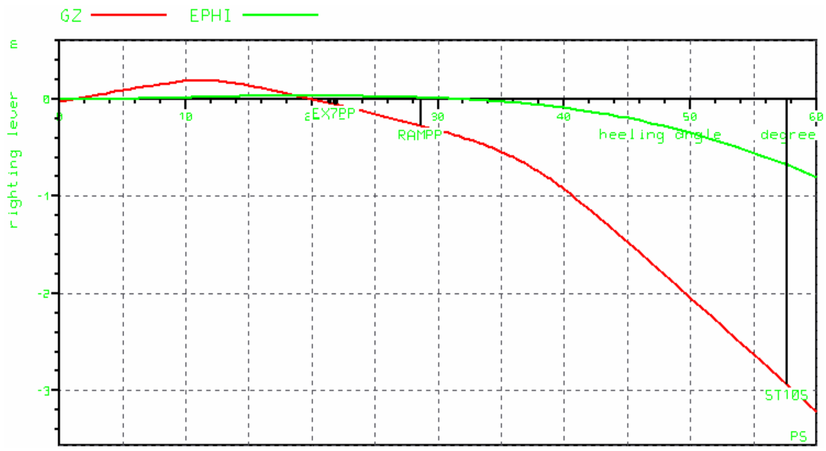

Figure 5-13: Righting lever curve in stage 2, phase EQ

Damage case 1 is a lesser extent damage case with the double bottom remaining undamaged. This case attains its least s_i in flooding stage 2, phase 1 due to the little remaining righting lever GZ.

Flooding stage 1 fills two rooms on portside between frames 94 and 109, before at the beginning of stage 2 the firewalls collapse and flooding continues to starboard.

The ship has reached a heeled floating position at the end of stage 1, (phase EQ) (Figure 5-8). The buoyancy of the hull has at that stage been reduced by the buoyancy of the damaged rooms damaged (lost buoyancy method). When in stage 2, phase 1 (Figure 5-10) flood water fills the parts of the rooms further to starboard, this water causes an extra heeling moment reducing the righting lever of the ship. The end of this phase is the moment at which the ship has the least stability for this damage case. The flood water added during the next phase (phase 2), lowers the centre of gravity of the flood water and increases the draught, resulting in an increasing righting lever, as can be seen from Table 9. Figure 5-12 shows the final equilibrium of this damage case.

5.3.2.2 Damage case 2:

Stage	Phase	Draught [m]	Heel [°]	GZ [m]	Range [°]	si
1	1	6.86	2.15	0.70	49.9	1
1	2	6.98	3.27	0.61	48.2	1
1	3	7.11	3.90	0.52	46.4	1
1	4	7.25	4.29	0.43	44.6	1
1	5	7.38	4.66	0.37	42.7	1
1	EQ	7.54	6.48	0.11	12.1	1
2	1	---	---	---	---	0
(2)	(2)	(7.58)	(5.79)	(0.13)	(15.2)	(1)
(2)	(3)	(7.60)	(5.23)	(0.15)	(16.6)	(1)
(2)	(4)	(7.62)	(4.61)	(0.17)	(18.1)	(1)
(2)	(5)	(7.64)	(4.06)	(0.18)	(19.5)	(1)
(2)	(EQ)	(7.64)	(4.24)	(0.13)	(14.6)	(0.932)

Table 10 – properties of floating position damage case 2

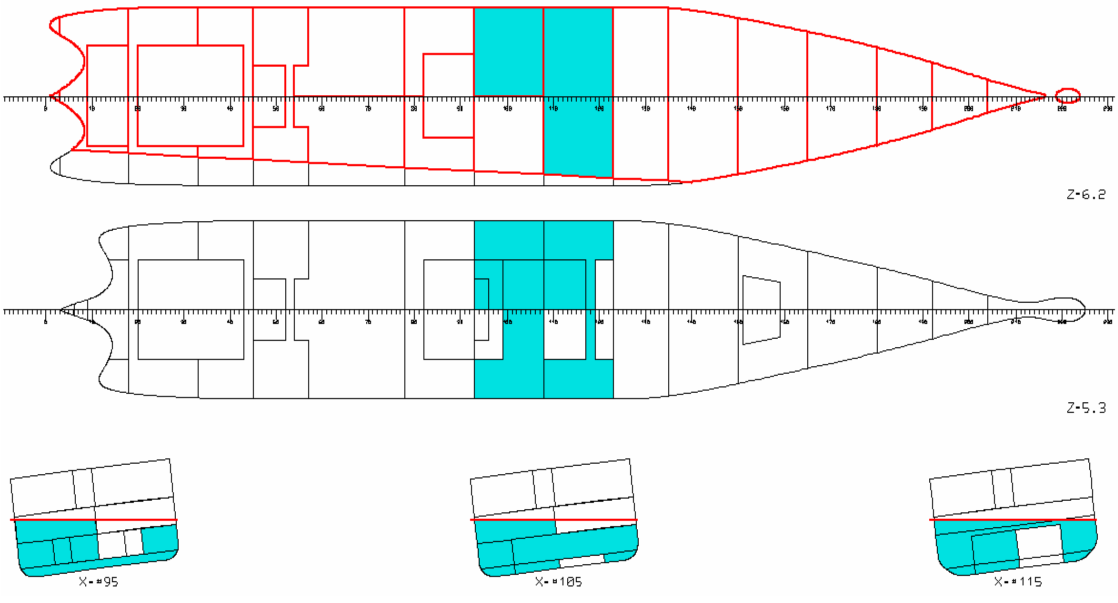

Figure 5-14: Floating position in stage 1, phase EQ

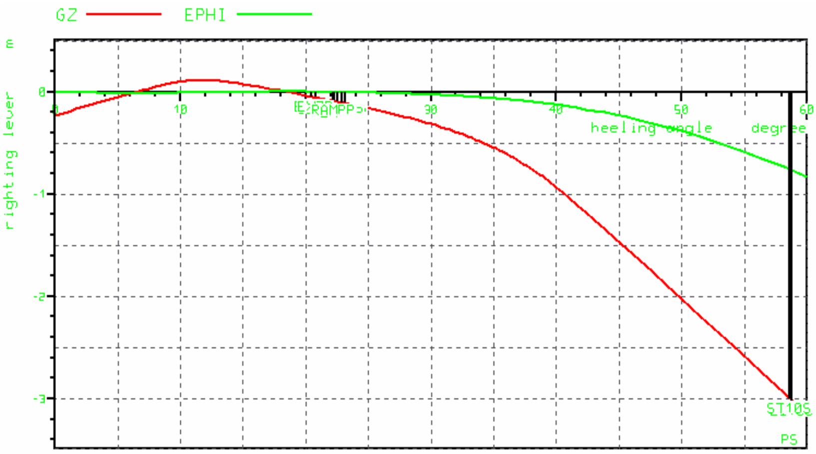

Figure 5-15: Righting lever curve in stage 1, phase EQ

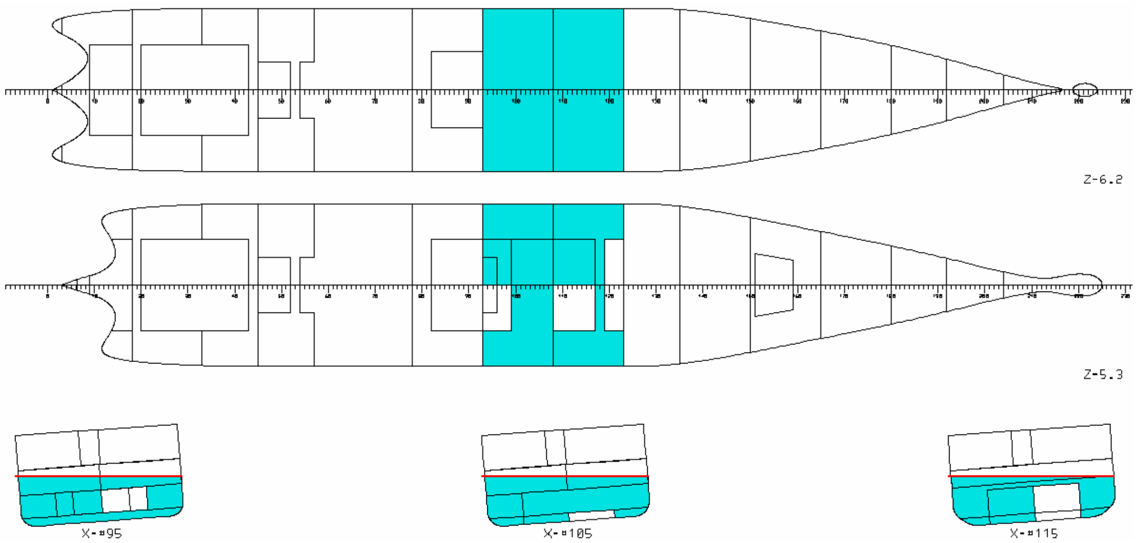

Figure 5-16: Floating position in stage 2, phase EQ

Damage case 2 is a damage case extending from the shell to the centre line and from the basis up to the upper limit of the buoyant hull. This case attains its least s_i, namely zero, at stage 2, phase 2.

Flooding stage 1 fills the portside room between frames 93 and 98, before at the beginning of stage 2 the firewalls collapse and flooding continues to starboard.

The observed mechanism is similar to the one explained by means of damage case 1. The difference is that the heeling moment caused by the flood water entering the ship during phase 1 of stage 2 reduces the stability of the ship to zero. The ship is lost and s_i becomes zero. The floating position shown in Figure 5-16 can not be achieved, it has just been shown to clarify the flooding process. No graphic could of course be shown for stage 2, phase 1. Also the phases in Table 10, where the data are put in brackets, are in fact not achieved.

5.3.2.3 Damage case 3:

Stage	Phase	Draught [m]	Heel [°]	GZ [m]	Range [°]	s_i
1	1	6.84	0.23	0.71	24.8	1
1	2	6.97	0.63	0.58	23.7	1
1	3	7.13	1.41	0.43	22.1	1
1	4	7.29	6.55	0.22	15.7	1
1	5	7.32	14.62	0.13	5.8	0.954
1	EQ	8.49	2.72	0.35	15.4	0.990

Table 11 – properties of floating position damage case 3

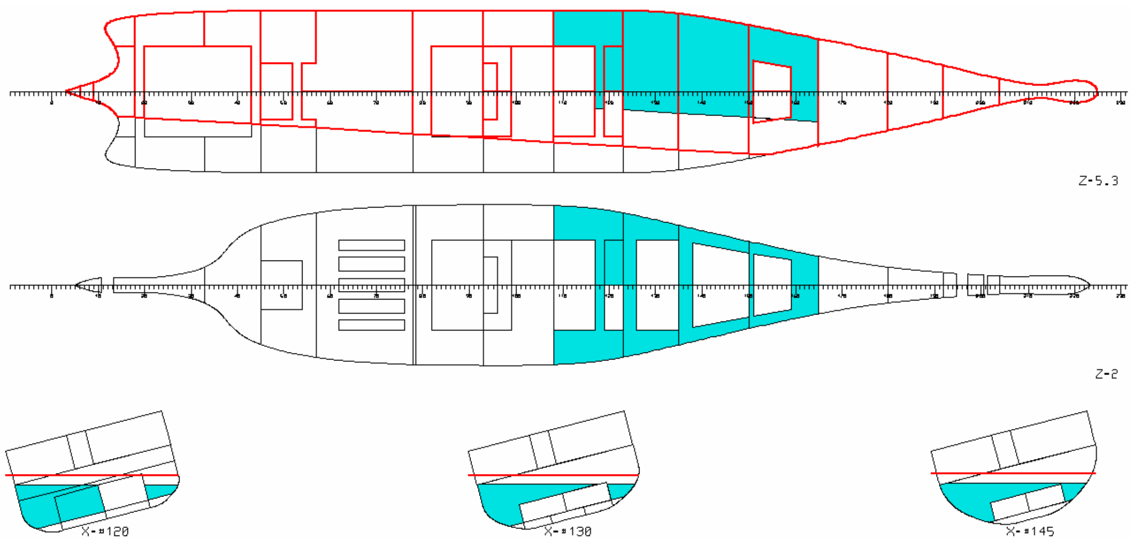

Figure 5-17: Floating position in stage 1, phase 5

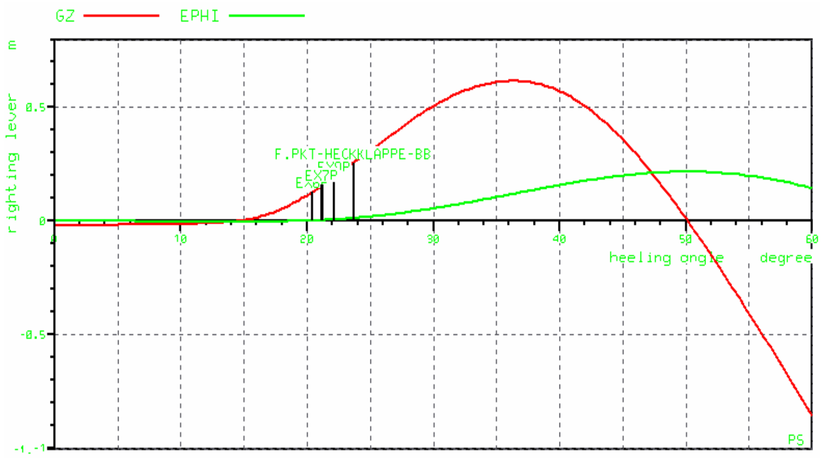

Figure 5-18: Righting lever curve in stage 1, phase 5

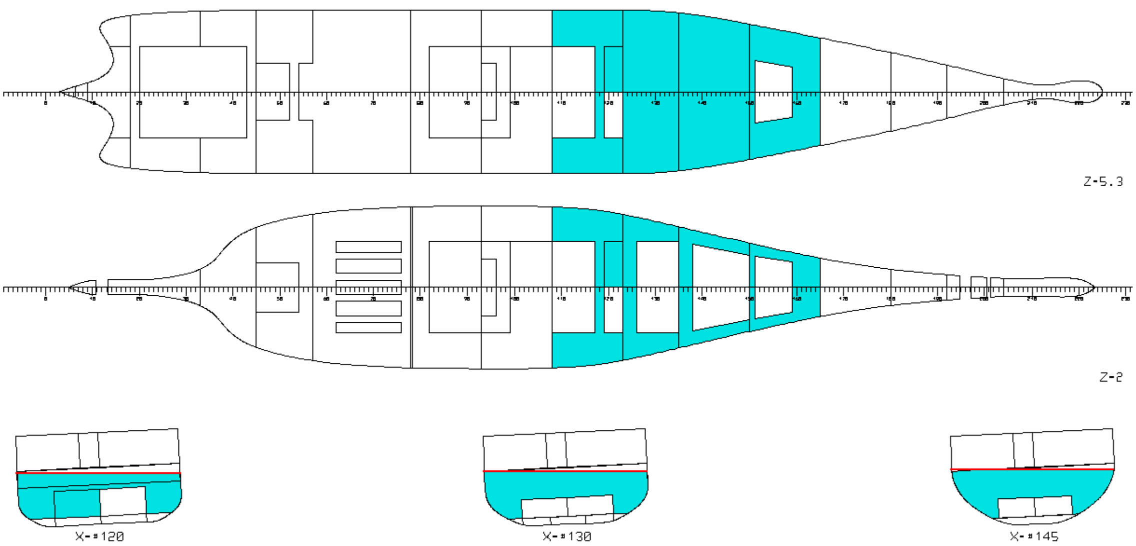

Figure 5-19: Floating position in stage 1, phase EQ

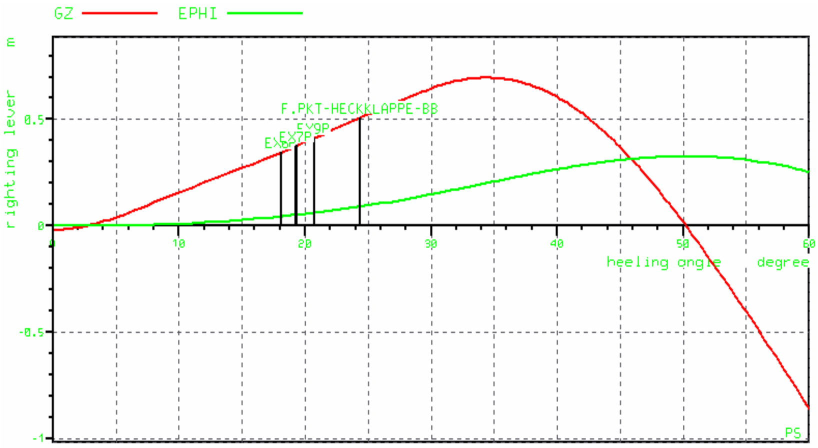

Figure 5-20: Floating position in stage 1, phase EQ

Damage case 3 is again a lesser extent damage case with the double bottom remaining undamaged. This damage attains its least s_i in flooding stage 1, phase 5 due to much lesser righting lever at phase 5 than at equilibrium. No additional flooding stages needed to be considered, as flooding was regarded instantaneous.

This damage is characterized by a great heel to portside at phase 5 due to the asymmetry of flooding caused by the portside tank between frames 119 and 123. At phase 5, the free surface of flood water is greater and the draught lesser as at the equilibrium as can be seen from figures Figure 5-17 and Figure 5-19 and from Table 11. The lesser righting lever and the greater heel cause a lesser s_i for the intermediate phase than for the final equilibrium.

6 SOLAS 2009 and IMO/Circ.1891: Contrast of the requirements

In the calculations performed, the two ships do not attain their required indices R according to the new SOLAS. From that the conclusion can be drawn that SOLAS 2009 for these two ships and for the stated input data provides at least the level of safety as the current SOLAS incl. the Stockholm Agreement IMO/Circ.1891 [3] does. This chapter attempts to provide explanations. It deals with the development of the survivability factor s_i and the required index R, discusses differences between the two regulations and uses the results from the performed damage stability calculations of the two ships.

6.1 SOLAS 74 and IMO/Circ.1891

The regional agreement IMO/Circ.1891 increases the safety level for RoRo passenger ships sailing European waters compared to the current SOLAS. It considers the effect of an assumed amount of water on RoRo deck (WoD). The water level assumed depends on the residual freeboard f_r in damaged condition and the significant wave height H_s of the sea area sailed. In the final equilibrium after damage and under the influence of this assumed amount of water RoRo passenger vessels concerned have to comply with Chapter II-1, Part B, Reg. 8.2.3 of the current SOLAS. IMO/Circ.1891 therefore is a set of requirements on top of the current SOLAS. The effects on the ship design of the affected vessels were on the one hand measures to avoid WoD by providing higher RoRo decks or aspiring symmetrical flooding following damage and on the other to increase stability to withstand the effect of WoD.

To show the impact of the Stockholm Agreement, another probabilistic damage stability calculation according to SOLAS 2009, has been performed for each of the two ships, this time using the GMs from the GM–limiting curves the ships needed to comply with the current SOLAS without the Stockholm Agreement (limiting curves Figure 4-4 and Figure 5-2).

For Nils Holgersson the GMs to comply with the current SOLAS without the Stockholm Agreement are 0.046m for d_s and 0.133m for d_p lower than needed for complying with the Stockholm Agreement.

Draught [m]		SOLAS incl. Stockholm		SOLAS without Stockholm	
		GM [m]	A*wcoeff.	GM [m]	A*wcoeff.
d_s	6.20	2.610	0.26075	2.564	0.25830
d_p	5.72	2.529	0.27539	2.396	0.26664
d_l	4.99	6.530	0.19055	6.530	0.19055
R = 0.73388			**A = 0.72669**		**A = 0.71549**

Table 12: GMs and results for Nils Holgersson

The effect of the assumed water on deck according to the Stockholm Agreement is relevant at all draughts for Nils Holgersson. The distance from the water surface to bulkhead deck in the intact condition is about 3m. As Nils Holgersson heels for the critical damage cases (see 6.2.3.1), the residual freeboard f_r in damaged condition is small so according to the regulation water on deck has to be assumed.

N.B.: The expression critical damage case is used for that damage case determining the minimum GM of the ship at the draught under consideration by requiring the greatest GM of all damage cases considered to fulfil the criteria.

For the Safedor project ship GMs are reduced by 0.028m for the deepest subdivision draught d_s only so the effect of the assumed water on deck according to the Stockholm Agreement is relevant only at that draught.

Draught [m]		SOLAS incl. Stockholm		SOLAS without Stockholm	
		GM [m]	A*wcoeff.	GM [m]	A*wcoeff.
d_s	6.733	2.278	0.29908	2.250	0.25830
d_p	6.212	2.970	0.30499	2.970	0.26664
d_l	5.430	3.820	0.19206	3.820	0.19055
R = 0.80056			**A = 0.79613**		**A = 0.79549**

Table 13: GMs and results for the Safedor Project ship

The distance from the water surface to bulkhead deck in the intact condition is about 3m for the Safedor project ship, but for this vessel the Stockholm Agreement has almost no effect due to the high residual freeboard f_r resulting from symmetrical flooding for the critical damages (see 6.2.3.2).

The difference between the results for the GMs from the current SOLAS and the Stockholm Agreement GMs is therefore lesser for the Safedor project ship (0.08%) than for Nils Holgersson (1.6%).

6.2 SOLAS 2009 and the current SOLAS incl. IMO/Circ.1891

Elementary differences between the current, deterministic SOLAS and the probabilistic SOLAS 2009 as concern their procedure of evaluating the level of safety make it impossible to directly compare the provided level of safety. Some elementary differences are the following:

Damage stability calculation according to SOLAS 2009 considers all damage cases within the grid of the watertight subdivision as far as it is considered. Each of these damage cases contributes to the attained index A as explained in chapter 3. The deterministic damage stability calculation according to the current SOLAS considers only damages extending between the transverse bulkheads forming the watertight compartments the lengths of which are very limited and considers penetration of the hull only to B/5 from the shell inwards. SOLAS 2009 therefore considers the complex watertight structure of the ship more precisely. Surviving the damages survival of which is sufficient to comply with the current SOLAS is by far not sufficient to attain the required index R of the SOLAS 2009.

In the current SOLAS the floating conditions of the ship after the damages considered either meet the relevant criteria or they do not. No gradual rating by the degree of fulfilling the criteria within a certain range is possible as it is in SOLAS 2009.

The following deals with the development of factors s_i and R to clarify, how SOLAS 2009 has been developed to provide a higher level of safety than the current SOLAS.

6.2.1 On the development of the survivability factor s_i

The working group on Subdivision and Damage Stability (SDS) of the SLF had proposed in the 47th session of the SLF to estimate the survivability of all ships by referring to the properties of the righting lever curve (GZ-curve) of the damaged ship. This procedure was later adopted by the MSC for SOLAS 2009. The line of arguments leading to that decision is explained in the following to help understand how water on deck of Ro-Ro-vessels is accounted for. This is done utilizing the HARDER report on work package 3.3.2, Generalized S_w Factor, [5] and the paper

On the Water on Deck Effect (WoD) by Sigmund Rusaas [6], quoting them in extracts and using some of the illustrations contained.

During research in way of the HARDER project [5] model tests have been carried out using seven models representing a range of different types, sizes and forms of ships representative of the fleet. One aim was to quantify the key issues pertaining to capsize mechanisms as a function of design and operational parameters.

The ships regarded have been divided into three groups. High freeboard ships, low freeboard Ro-Ro-ships and low freeboard conventional ships. As the seastate in times of collisions is almost always characterized by a significant wave height H_s of below 4m, and since the relative motion of the ship at the damage opening has been observed to be roughly $H_s/2$, damage freeboards of about 2m or higher will be called high freeboards.

During research for the HARDER project, the water on deck effect (WoD-effect) was accounted for by using the static equivalent method (SEM). SEM statically develops the critical volume of water on the vehicle deck of a RoRo ship that will reduce the damage GZ curve to zero. Less water on deck is considered survivable, more water is assumed to cause capsize.

This method was employed to calculate the dynamic water head h and the freeboard f at the critical angle θ for the low freeboard RoRo ships. High freeboard ships during research in way of HARDER were not subjected to WoD type capsize mechanisms.

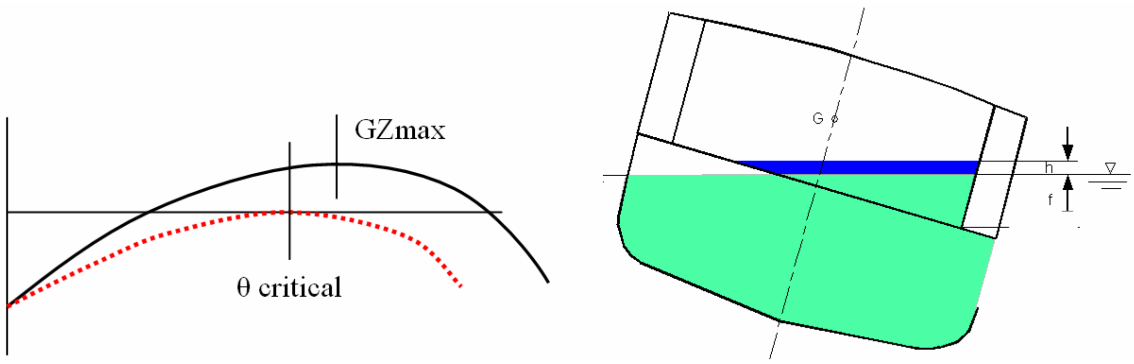

Figure 6-1: Definitions of critical angle θ, dynamic head h and freeboard f [5]

The values of h and f are then statistically correlated with the survival seastate boundary from the damage stability model tests. SEM had been developed assuming, that the properties of the righting lever curve such as GZ_{max}, Range or GZ area could not be used to predict the survivability of damaged RoRo ships. In its report [5] HARDER also correlates the critical wave height H_s at which capsize occurred to these properties of the righting lever curves of all investigated RoRo- and conventional ships at the moment of capsize.

In his paper On the Water on Deck Effect [6] Sigmund Rusaas, chairman of the HARDER research project, considers the results from the HARDER project and explains why the SEM method does not provide any significant effect compared with a pure GZ approach. When comparing the H_s - GZ_{max} curves from HARDER for conventional and RoRo ships, one finds that GZ_{max} of 0.12m represents about H_s = 4m for a conventional ship and about H_s = 2m for a RoRo ship.

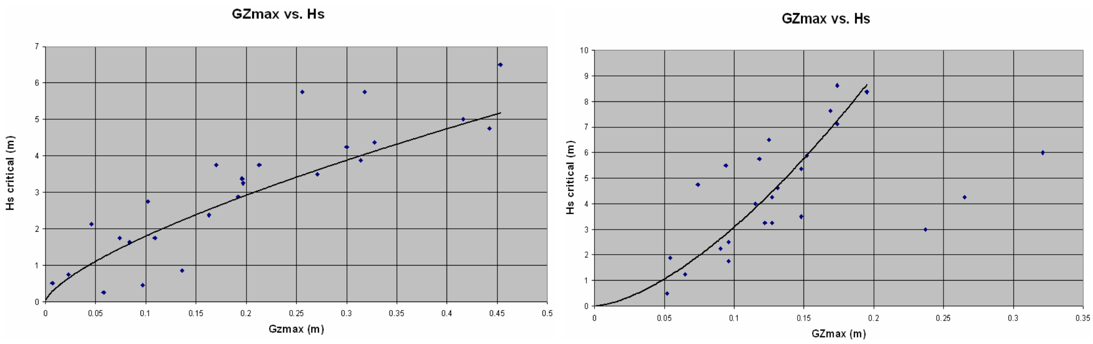

Figure 6-2: H_s - GZ_{max} curves (trend lines) for RoRo (left) and conventional ships (right) [5]

From the wave height statistics considered it is seen, that approximately 90% of the collisions occur, when H_s is less than 2m and virtually none occur, when H_s exceeds 4m. Reducing H_s from 4m to 2m therefore represents a reduction in the s-factor of 10%.

Converting the trend lines from Figure 2-1 into equivalent s-factors gives the following figure:

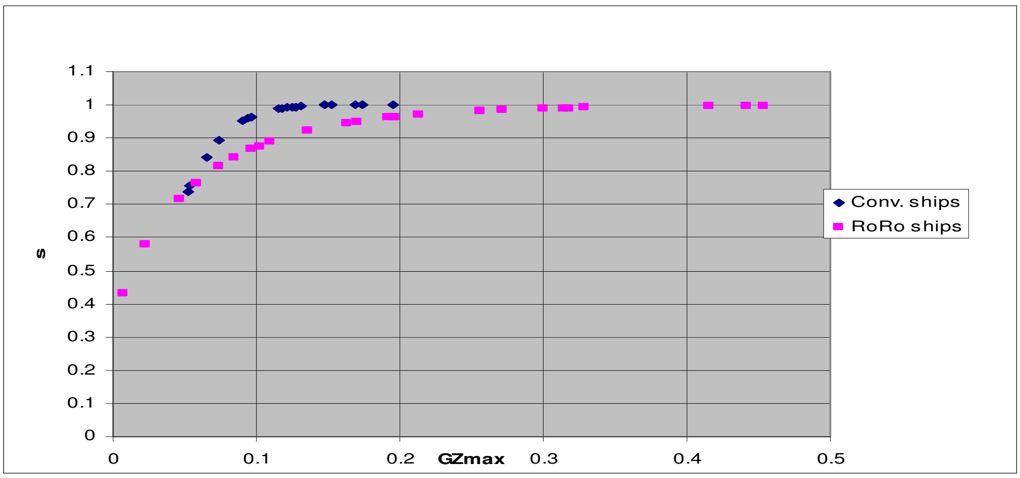

Figure 6-3: Equivalent s-factors for the trend lines [6]

The maximum expected difference in the s-factor including any WoD effect or not is in the order of 10%. This difference lies in the area between GZ_{max} = 0.05m and 0.2m (H_s = 1m to H_s = 3m). Below and above this area any WoD effect is believed to be negligible.

From the GZ approach for the survivability factor as developed from the background data in HARDER

$$s = \left(\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right)^{\frac{1}{4}},$$

the critical wave height H_s can be derived. The resulting values for H_s follow the trend lines shown in Figure 6-2.

The reason why the GZ approach obviously finds such universal application lies probably in the range parameter which is included in the GZ approach. This is considered to be caused by the observed behaviour that damages with low freeboard (e.g. a RoRo deck) generally give a lesser Range / GZ_{max} - ratio than if the freeboard is greater.

Mr. Rusaas concludes, that the GZ approach, probably because of the Range parameter, predicts the critical wave height also for RoRo ships with better accuracy than originally expected. Following his arguments, the largest expected difference in the s-factor lies in the order of 10% including the WoD effect or not. This difference may be expected in the relative narrow area between H_s = 1m to H_s = 3m. Below and above this area any WoD effect is believed to be marginal. Assuming that at most 10% of the damage cases may be in this critical area, the maximum expected effect of WoD would approximately be 1% in the attained index. The norm is considerably less. Extensive validation work for the HARDER project showed that it made hardly any difference in the results whether SEM was employed or not.

These arguments convinced the majority of the stability experts from the SLF and the IMO not to consider SEM for the survivability criteria of SOLAS 2009. Other alternatives such as the FB factor method were dispensed with for similar reasoning.

The Stockholm Agreement which had been adopted to account for WoD can therefore also be considered dispensable for SOLAS 2009 designs.

6.2.2 Differences between SOLAS 2009 and the current SOLAS as concerns the survivability criteria (factor s_i)

What can be directly compared are the survivability criteria of the regulations. In the following, differences between them are listed. The criteria of the current SOLAS are not stated in detail here but reference is made to SOLAS, Edition 2004 [1]. For easier comparison of the regulations the strictly speaking incorrect but significant expression $s_i = 1$ is used to describe the floating positions that meet the requirements of the deterministic SOLAS.

		current SOLAS incl. Stockholm Agreement	new SOLAS 2009	
		pass requirement ($s_i = 1$)	$s_i = 1$	$0 \leq s_i < 1$
final stage of flooding (1)	i) Range	Range $\geq 10° – 15°$ (2)	Range $\geq 16°$	$0° \leq$ Range $< 16°$
	ii) Area	min 0.015mrad – 0.0225mrad (2)	---	---
	iii) Heel	Heel $\leq 12°$ (3)	Heel $\leq 7°$	$15° \geq$ Heel $> 7°$
	iv) GZ_{max}	$\frac{M_{heel}}{\Delta} + 0.04m$, min 0.1m	0.12m	$0 \leq GZ_{max} < 0.12m$
intermediate stages of flooding	v) Range	Range $\geq 7°$	Range $\geq 7°$	$0° \leq$ Range $< 7°$
	vi) Heel	Heel $\leq 15°$	Heel $\leq 15°$	Heel $\leq 15°$
	vii) GZ_{max}	$GZ_{max} \geq 0.05m$	$GZ_{max} \geq 0.05m$	$0 \leq GZ_{max} < 0.05m$
	viii) cross flood. time	max 15min	max 10min	max 10min
General differences	SOLAS 2009 requires flooding stages at structures that seriously restrict the flow of water as for instance “A”-rated fire walls			
	SOLAS 2009 does not permit flooding of escape routes / hatches			
	SOLAS 2009 considers increased permeabilities for cargo spaces dependent on the draught under consideration			

Table 14: comparison of the criteria for the survivability factor s_i

(1) In SOLAS 2009, s_i for the final stage of flooding is obtained by multiplying $s_{final,i}$ by $s_{mom,i}$, so criteria i) – iv), not only the righting lever criterion GZ_{max} are influenced by the heeling moment M_{heel}

(2) Range may be reduced up to 10°, if the area under the GZ-curve is increased by the ratio $\frac{15}{\text{Range}}$.

(3) applicable for ships having to fulfil the 2-compartment standard

6.2.3 Discussion of the differences between SOLAS 2009 and the current SOLAS as concerns the survivability factor for selected damage cases

The critical damage cases from the deterministic damage stability calculation according to the current SOLAS incl. the Stockholm Agreement are shown and the obtained results according to both regulations are investigated. For the precise explanation of the damage stability criteria of the current SOLAS reference is made to SOLAS [1]. Relevant data on the floating positions and the righting lever curves of the ships after damage for the current SOLAS 2009 incl. the Stockholm Agreement (water assumed on bulkhead deck where applicable) and for SOLAS 2009 are listed.

6.2.3.1 Nils Holgersson

a) Critical damage at partial draught d_p:

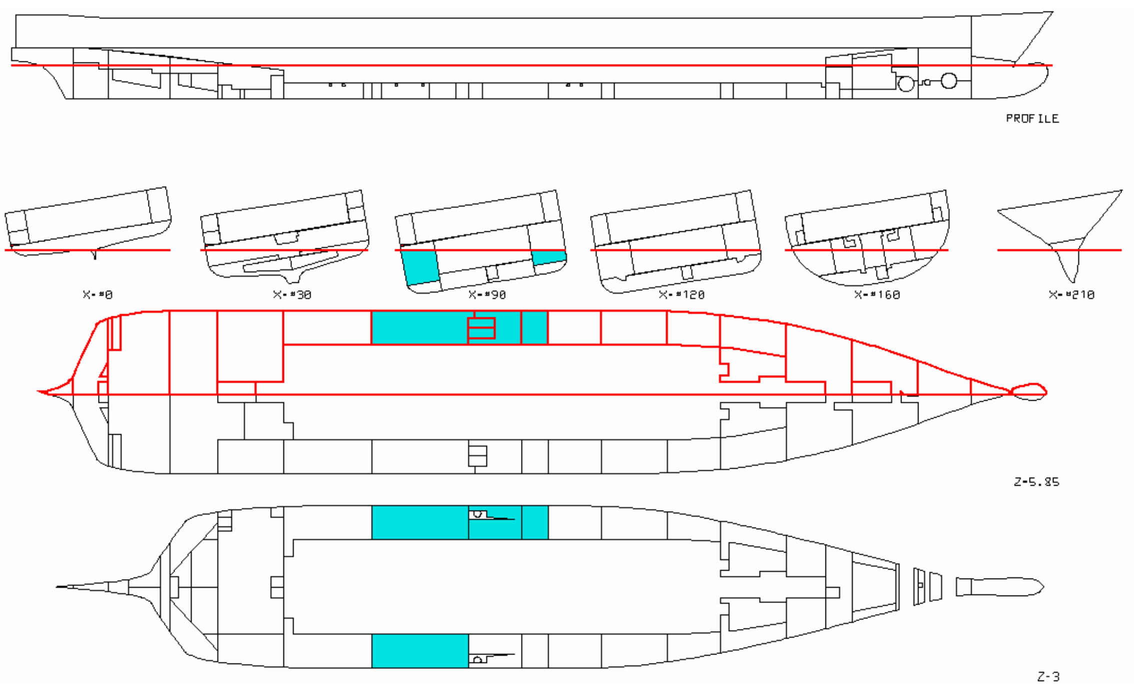

Figure 6-4: Critical damage of Nils Holgersson at draught d_p

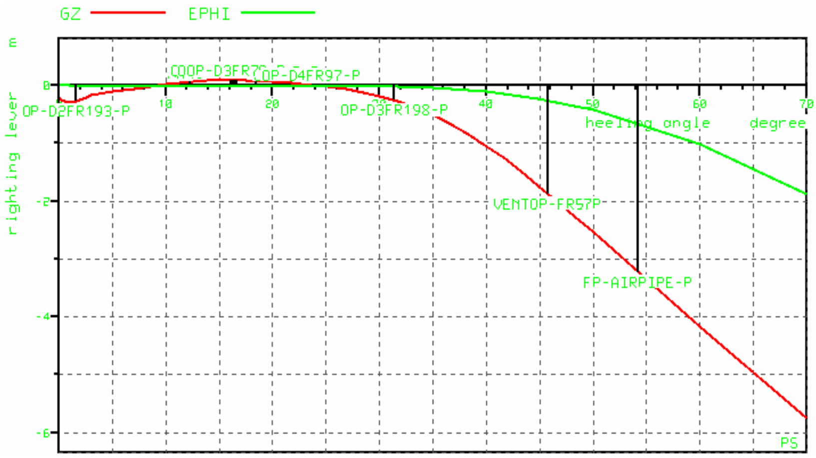

Figure 6-5: Righting lever curve with WOD acc. to IMO/Circ.1891

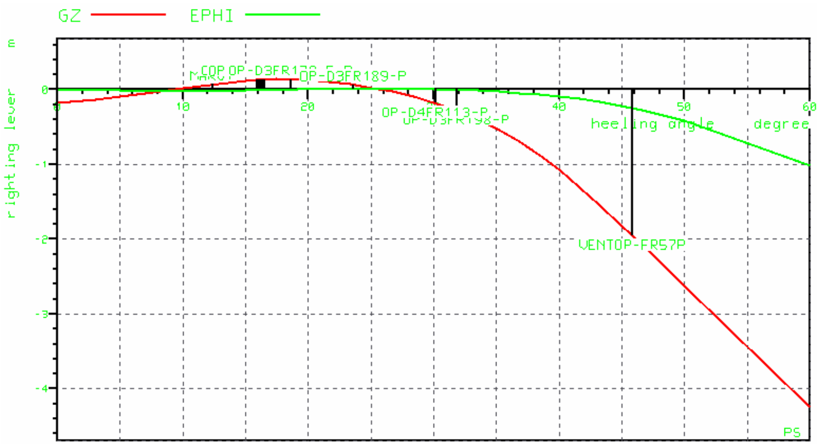

Figure 6-6: Righting lever curve acc. to SOLAS 2009

Initial Draught d_p = 5.716m	Draught after damage [m]	Heel [°]	GZ_{max} [m]	area [mrad]	Range [°]	Determ. criterion	s_i
Stockholm	5.86	9.3	0.10	0.0152	14.7	min. area	1
SOLAS 2009	5.86	9.0	0.14	---	16.8	---	0.864

Table 15: Floating position and righting lever curve properties at after damage at d_p

The determining criterion for the shown damage case in the deterministic damage stability calculation according to the current SOLAS incl. the Stockholm Agreement is the minimum area criterion, which, depending on the range of the positive righting lever, requires an area of

0.015 to 0.0225mrad under the righting lever curve [1]. This area constitutes 0.0152mrad for this damage case.

In the damage stability calculation according to SOLAS 2009 this damage case attains s_i = 0.864 according to formula

$$s_i = \text{minimum}\ \{s_{intermediate,i} \text{ or } s_{final,i} * s_{mom,i}\}.$$

Factor $s_{final,i}$ equals 0.864 when calculated according to formula

$$s_{final,i} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16}\right]^{\frac{1}{4}} = 1$$

where

GZ_{max} is not to be taken as more than 0.12m,

Range is not to be taken as more than 16°,

$K = 1$ if $\theta_e \leq \theta_{min}$,

$K = 0$ if $\theta_e \geq \theta_{max}$ and

$K = \sqrt{\dfrac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}$ otherwise,

where

θ_{min} is 7° for passenger ships and 25° for cargo ships and

θ_{max} is 15° for passenger ships and 30° for cargo ships,

as K = 0.864 for heel θ_e = 9.02°.

Factor $s_{mom,i}$ is also equal to 1 when calculated according to formula

$$s_{mom,i} = \frac{(GZ_{max} - 0.04) \cdot \Delta}{M_{heel}} = 1$$

where:

M_{heel}: greatest of the heeling moments, in this case M_{wind} = 895tm,

Displacement: intact displacement of the draught under consideration = 19435t.

This damage case is an example for the cases attaining a lesser s_i according to SOLAS 2009 than according to SOLAS 2009 incl. the Stockholm Agreement.

b) Critical damage at deepest subdivision draught d_s:

The damage case determining the minimum GM for Nils Holgersson at deepest subdivision draught d_s is shown in the following graphic:

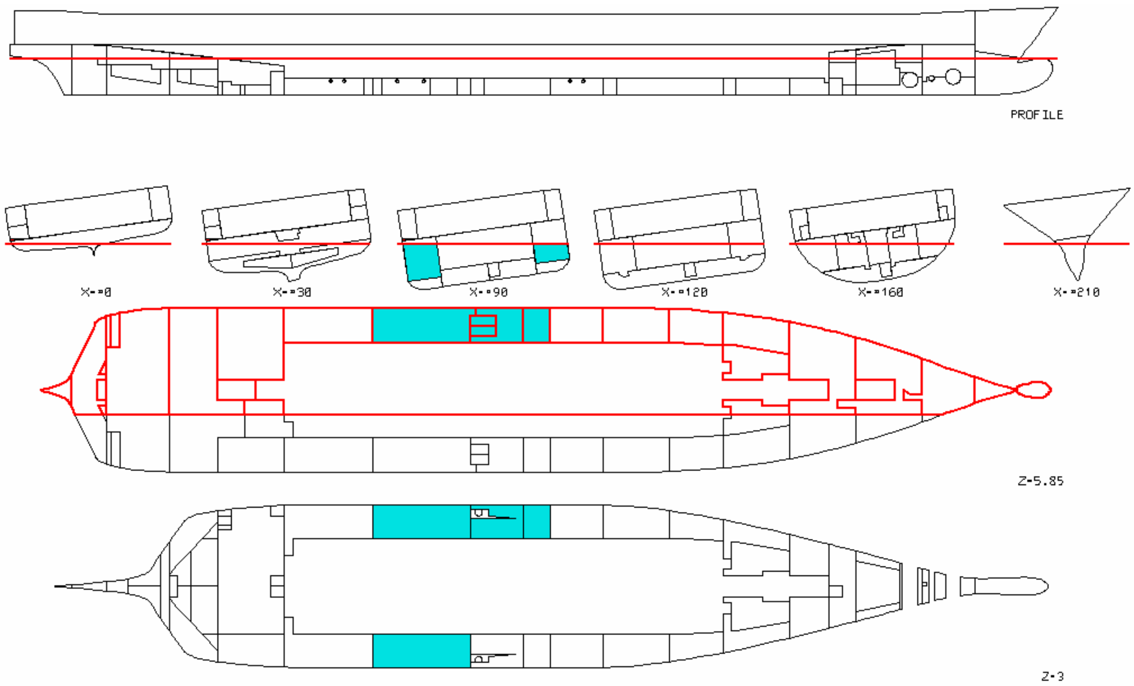

Figure 6-7: Critical damage case of Nils Holgersson at draught d_s

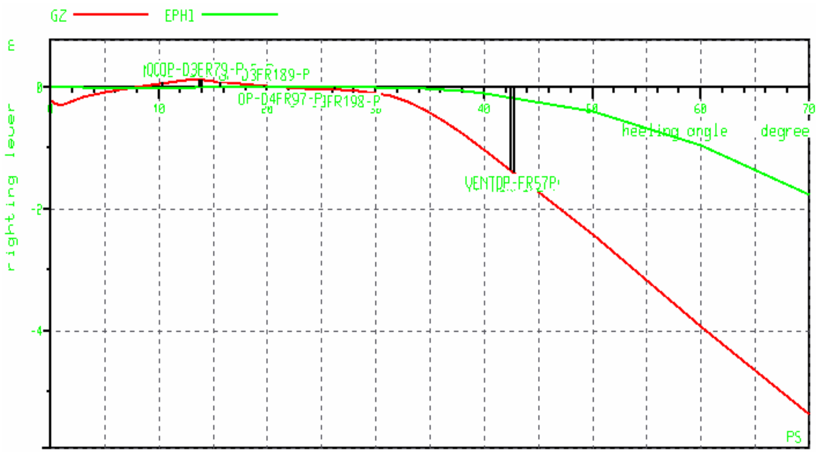

Figure 6-8: Righting lever curve with WOD acc. to IMO/Circ.1891

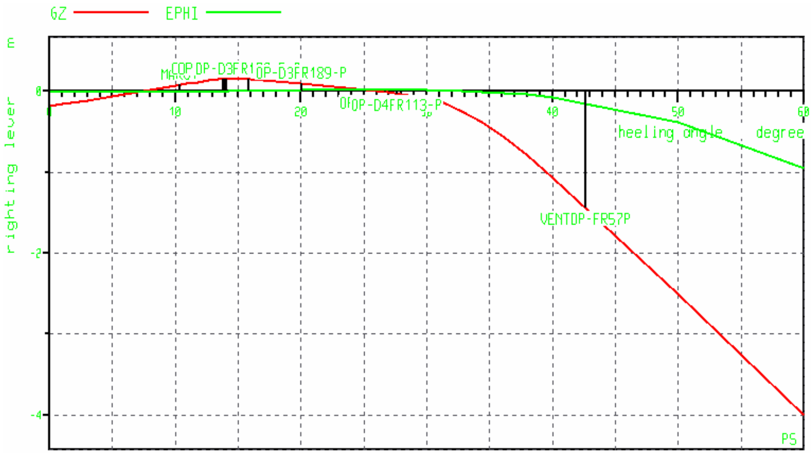

Figure 6-9: Righting lever curve acc. to SOLAS 2009

Initial Draught $d_s = 6.200$m	Draught after damage [m]	Heel [°]	GZ_{max} [m]	area [mrad]	Range [°]	DCRI	s_i
Stockholm	6.40	7.8	0.11	0.015	13.3	min. area	1
SOLAS 2009	6.40	7.5	0.16	---	18.5	---	0.967

Table 16: Floating position and righting lever curve properties at after damage at d_s

The determining criterion for the shown damage case in the deterministic damage stability calculation according to the current SOLAS incl. the Stockholm Agreement is the minimum area criterion, which, depending on the range of the positive righting lever, requires an area of 0.015mrad under the righting lever curve [1]. This area constitutes 0.015mrad for this damage case.

In the damage stability calculation according to SOLAS 2009 this damage case attains s_i = 0.967 according to formula

$$s_i = \text{minimum}\,\{s_{intermediate,i} \text{ or } s_{final,i} \cdot s_{mom,i}\}.$$

Factor $s_{final,i}$ equals 0.967 when calculated according to formula

$$s_{final,i} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16}\right]^{\frac{1}{4}} = 1$$

where

GZ_{max} is not to be taken as more than 0.12m,

Range is not to be taken as more than 16°,

$K = 1$ if $\theta_e \leq \theta_{min}$,

$K = 0$ if $\theta_e \geq \theta_{max}$,

$K = \sqrt{\frac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}$ otherwise,

where

θ_{min} is 7° for passenger ships and 25° for cargo ships and

θ_{max} is 15° for passenger ships and 30° for cargo ships,

because K = 0.96723 for heel θ_e = 7.518°.

Factor $s_{mom,i}$ is also equal to 1 when calculated according to formula

$$s_{mom,i} = \frac{(GZ_{max} - 0.04) \cdot \Delta}{M_{heel}} = 1$$

where:

M_{heel}: greatest of the heeling moments, in this case M_{wind} = 878tm,

Displacement: intact displacement of the draught under consideration = 21541t.

This damage case is another example for the cases attaining a lesser s_i according to SOLAS 2009 than according to SOLAS 2009 incl. the Stockholm Agreement. This occurs in this case because of heel constituting θ_e = 7.518° what according to SOLAS 2009 reduces s_i by reducing K in the above mentioned formula whereas it does not affect the results of the damage stability calculation according to the current SOLAS incl. the Stockholm Agreement.

6.2.3.2 Safedor project ship

a) Critical damage at partial draught d_p:

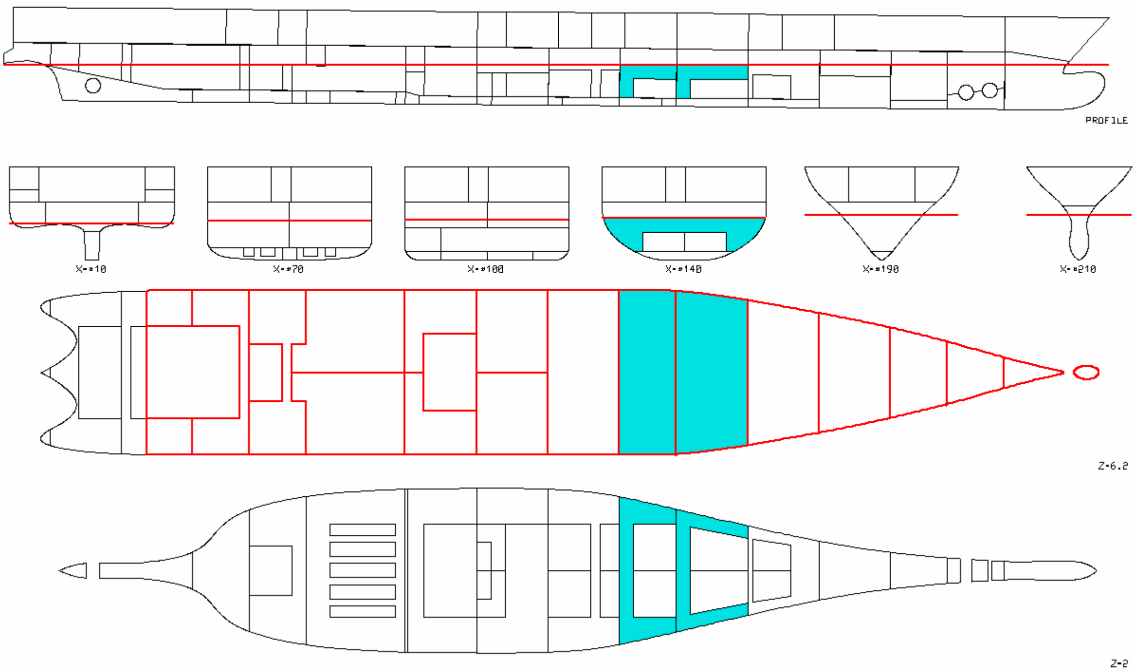

Figure 6-10: Critical damage of the Safedor project ship at draught d_p

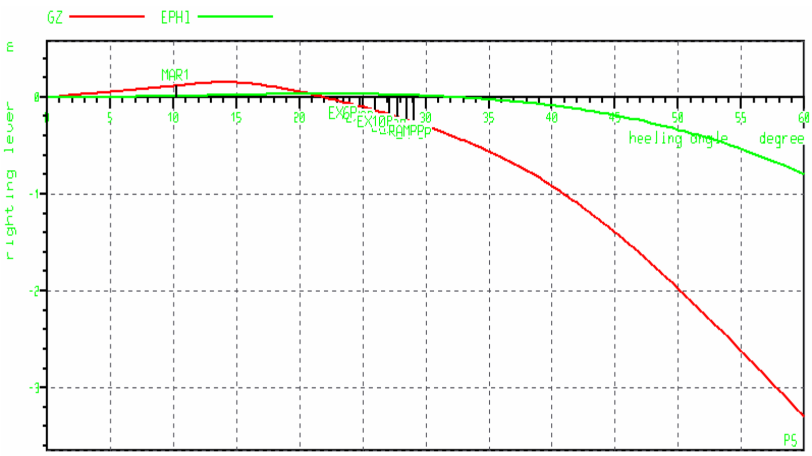

Figure 6-11: Righting lever curve with WOD acc. to IMO/Circ.1891

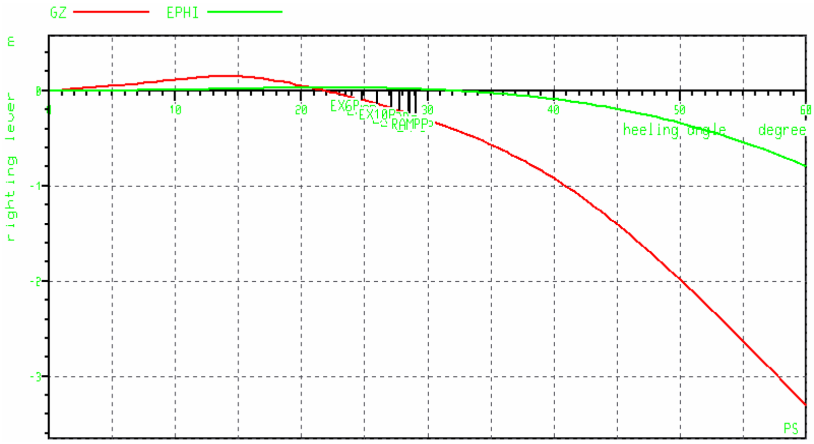

Figure 6-12: Righting lever curve acc. to SOLAS 2009

Initial Draught d_s = 6.121m	Draught after damage [m]	Heel [°]	GZ_{max} [m]	area [mrad]	Range [°]	DCRI	s_i
Stockholm	6.83	0.0	0.15	0.0327	22.0	GZ pass	1
SOLAS 2009	6.83	0.0	0.15	---	22.0	---	1

Table 17: Floating position and righting lever curve properties at after damage at d_p

The determining criterion for the shown damage case in the deterministic damage stability calculation according to the current SOLAS incl. the Stockholm Agreement is the residual righting lever criterion under the influence of the passenger heeling moment $M_{passenger}$:

$$GZ = \frac{M_{heel}}{\text{Displacement}} + 0.04\,[\text{m}],$$

where:

M_{heel}: greatest of the heeling moments, in this case $M_{passenger}$ = 2064tm,

Displacement: intact displacement of the draught under consideration = 18845t.

This results in a minimum GZ of 0.15m.

The same damage case attains s_i = 1 in the probabilistic damage stability calculation according to SOLAS 2009:

$$s_i = \text{minimum}\,\{s_{intermediate,i} \text{ or } s_{final,i} * s_{mom,i}\}$$

Factor $s_{final,i}$ equals 1 when calculated according to formula

$$s_{final,i} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}} = 1.$$

Factor $s_{mom,i}$ is also equal to 1 when calculated according to formula

$$s_{mom,i} = \frac{(GZ_{max} - 0.04) \cdot \Delta}{M_{heel}} = 1.$$

The intermediate stages and phases do not result in a factor $s_{intermediate,i}$ less than the $s_{final,i}$ from the final equilibrium. For this damage case the differences in the survivability factor s_i between the two regulations do not cause a difference in the results obtained by the damage stability calculations according to the current SOLAS incl. the Stockholm Agreement and SOLAS 2009.

b) Critical damage at deepest subdivision draught d_s:

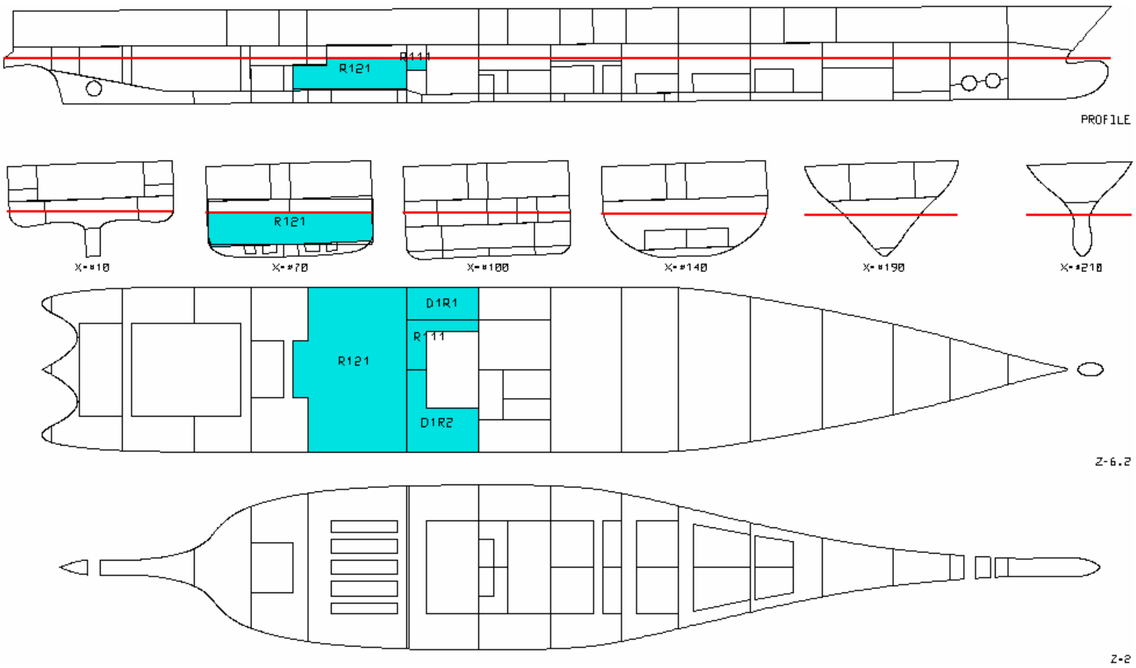

Figure 6-13: Critical damage of the Safedor project ship at draught d_s

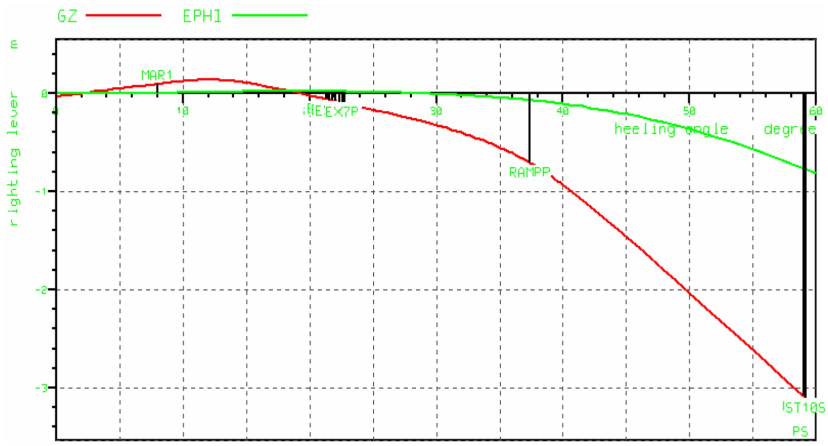

Figure 6-14: Righting lever curve with WOD acc. to IMO/Circ.1891

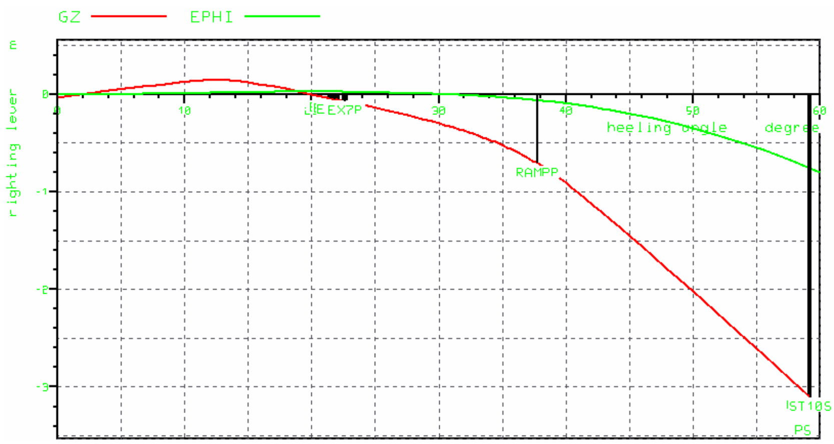

Figure 6-15: Righting lever curve acc. to SOLAS 2009

Initial Draught d_s = 6.733m	Draught after damage [m]	Heel [°]	GZ_{max} [m]	area [mrad]	Range [°]	DCRI	s_i
Stockholm	7.239	2.1	0.139	0.0250	17.3	GZ (pass)	1
SOLAS 2009	7.242	1.8	0.144	---	18.2	---	0

Table 18: Floating position and righting lever curve properties at after damage at d_s

Heel to portside despite of symmetrical flooding occurs as room D1R2 has a lesser permeability (0.60 for stores) than the other rooms (0.85 or 0.95 for machinery spaces or workshops). The determining criterion for this damage case in the deterministic damage stability calculation is the residual righting lever criterion under the influence of the passenger heeling moment

$M_{passenger}$. This damage case is not survived in the probabilistic damage stability calculation according to SOLAS 2009, as flooding stages had to be considered due to the assumed “A”-class rated fire walls at centre line within room R121 and between R111 and D1R2. At equilibrium at the end of the first stage of flooding before collapsing of the fire walls, the ship is lost because of negative righting levers. If the final equilibrium could have been reached it would have the floating properties stated in the table and would attain $s_i = 1$.
For the Safedor project ship no deterministic damage case could be found attaining $s_i < 1$ in the probabilistic damage stability calculation according to SOLAS 2009 and not containing rooms separated by fire walls. The reason for this is that for this ship at d_s and d_p the determining criterion for the deterministic damage stability calculation is the mentioned residual righting lever criterion under the influence of the passenger heeling moment. This has the effect, that $s_{mom,i}$ equals 1 for all deterministic damage cases when assessed according to SOLAS 2009 because this criterion is equivalent in both regulations. The deterministic damage cases can only obtain s_i less than 1 for this ship when assessed according to SOLAS 2009, if the floating condition following that damage resulted in a heel greater than 10° or 15° as the case may be according to the area-criterion and at the same time less than 16°. Such damage could not be found for this ship.
It could be seen from the above discussion of the critical damage cases that the factor K from the formula for $s_{final,i}$ is an element of SOLAS 2009 that deals stringently with heeling angles greater than 7°. Ship designs having heeling angles greater than 7° for many damage cases due to asymmetrical flooding will lose some contribution of these damage cases to the attained index A. Designs with predominantly symmetrical flooding are favoured by SOLAS 2009.

6.2.4 On the development of the required subdivision index R

The intersessional correspondence group on subdivision and damage stability (SDS) of the SLF originally aimed for SOLAS 2009 to provide the same level of safety [7] as the current SOLAS. It was assumed that the current regulations corresponded to a satisfactory level of safety. The average equivalence of safety was expressed by the formula

$$\frac{A_{new}}{R_{new}} \approx \frac{A_{existing}}{R_{existing}} \text{ giving } R_{new} = A_{new} \cdot \frac{R_{existing}}{A_{existing}} \text{ [7].}$$

The procedure to establish the R level was based on the mean level of a regression of the collected and newly calculated A values of the sample of data, corresponding to ships and loading conditions marginally meeting existing SOLAS criteria as collated by the HARDER project. For passenger ships constructed under deterministic rules, the ratio $R_{existing}$ / $A_{existing}$ was assumed to constitute 1 taking into account the minimum GMs to comply with the damage stability regulations.
First, for cargo ships it was found [7] that dry cargo RoRo ships (DCRR) and car carriers (CC) attained in average considerably lower A values than conventional dry cargo (DC) ships. The reason for this behaviour of DCRR's and CC's is mainly the low assumed permeability of 0.60 for their cargo spaces according to the current SOLAS whereas SOLAS 2009 considers permeabilities of 0.90 to 0.95 depending on the draught under consideration. Although this is not directly relevant to the passenger vessels, there is a similar effect as the low assumed permeability of 0.60 for their cargo spaces according to the current SOLAS whereas SOLAS 2009 considers permeabilities of 0.90 to 0.95 depending on the draught under consideration. This consideration of a extensively higher permeability results in a level of safety for RoRo passenger vessels which is significantly increased.
Second, when building the regression curve for passenger ships, a downward trend of the survivability level for larger existing passenger vessels was found [7]. This trend was observed considering only the subdivision length L_s of the ship and also if the length together with the number N of passengers carried was considered.

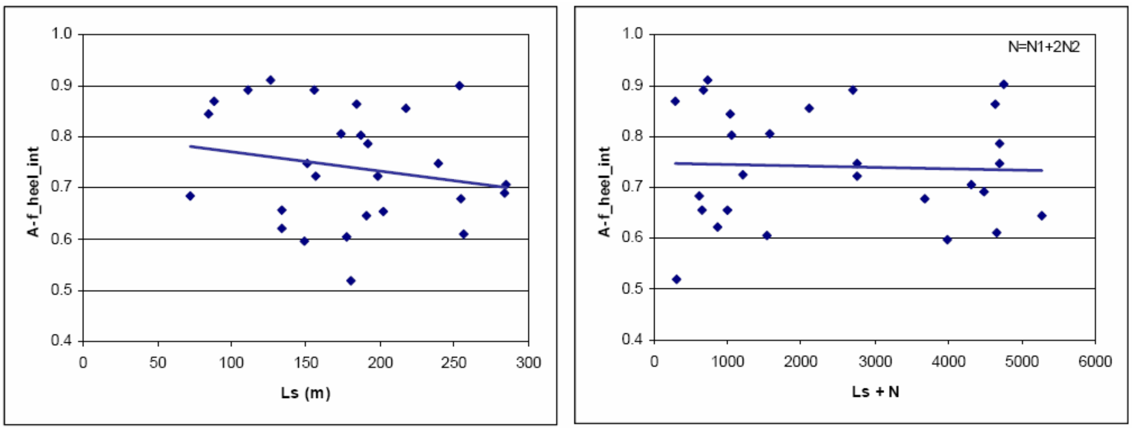

Figure 6-16: Downward trend of survivability according to the current SOLAS [10]

This downward trend results mainly from the ratio “damage length / ship length”. Due to the maximum damage length of 11m according to the current SOLAS comparably shorter damages are considered for larger ships. This reduces their survivability when damages of up to 60m of length are considered according to SOLAS 2009.

The majority of the Sub-Committee agreed that this downward trend was unacceptable [7] as it was contrary to the intent of SOLAS II-1/Reg.6 that the level of safety shall be greatest for the ships with the greatest length and primarily engaged with the carriage of passengers. As deciding about this meant to exceed the mandate given to the Sub-Committee by the MSC, i.e. to maintain an equivalent level of safety, the Sub-Committee agreed to let the MSC decide about that matter.

In its 78th session the MSC decided [8], that the standard of survivability of passenger ships should increase with ship size and number of persons on board, although this might also mean, that the current SOLAS standard would be exceeded by SOLAS 2009.

The trend line for the survivability was altered to achieve an upward trend by employing the ALARP (As Low As Reasonably Possible) risk assessment concept. The effect was that sample ships being too safe or not satisfactorily save according to the ALARP concept were extracted from the database on which was based the required subdivision index R.

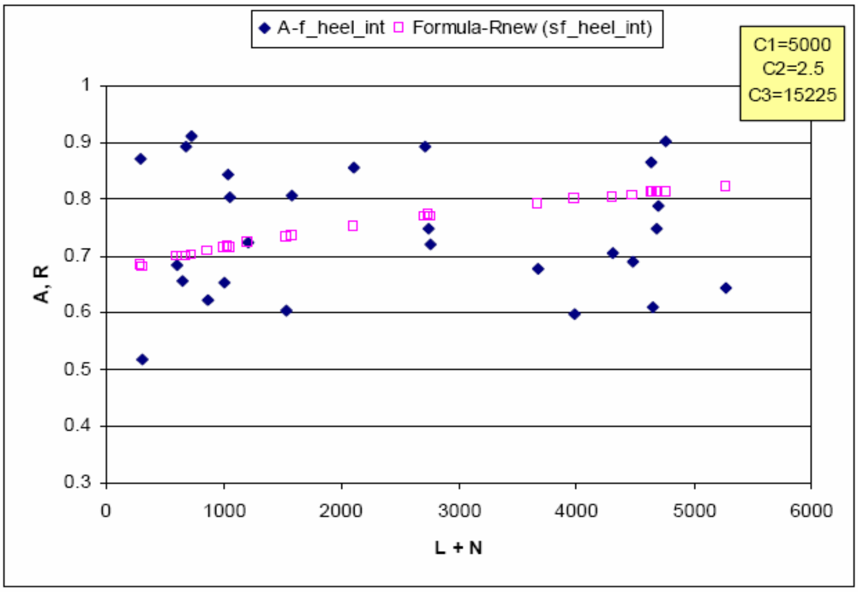

Figure 6-17: Altered trend line [10]

The risk of the low permeability of the RoRo spaces has been accounted for by considering permeabilities of 0.90 to 0.95 for RoRo spaces, also for RoRo passenger vessels. This and the mentioned decision of the MSC to raise the level of safety as for large passenger ships results in an increased level of safety for RoRo passenger ships built according to SOLAS 2009 as compared to RoRo passenger ships built according to the current SOLAS.

7 Summary

By listing the decisions of the MSC on the development of the required subdivision index R and the survivability factor s_i and by re-drawing the line of arguments leading to these decisions, it was shown that SOLAS 2009 has been developed to provide a higher level of safety than the current SOLAS. This was achieved despite of the initial intent to obtain the same level of safety for the harmonized SOLAS 2009 compared to the current SOLAS.
The trend line from which the required subdivision index R of passenger ships was developed for SOLAS 2009, had been altered to comply with the intent of SOLAS II-1/Reg.6, i.e. that the level of safety shall be greatest for the ships with the greatest length and primarily engaged with the carriage of passengers (6.2.4). The formula for the required index R therefore considers increased requirements for the survivability of larger passenger ships.
Other aspects also increase the level of safety for RoRo passenger vessels. Such are raising the considered permeabilities for RoRo cargo spaces significantly from 0.60 to 0.90 or 0.95 depending on the draught under consideration or dealing stringently with asymmetrical flooding by having damage cases with greater heel contribute less to the attained index A (6.2.3).
The WoD effect is accounted for by the GZ approach for the survivability factor s_i (6.2.1). The Stockholm Agreement, which had been adopted to account for the WoD effect for RoRo passenger ships designed to comply with the current, deterministic SOLAS, might therefore be dispensable for the probabilistic SOLAS 2009.
The results from the damage stability calculations performed (chapters 4 and 5) show, that Nils Holgersson and the Safedor Project ship attain 99% of their required indices R according to the regulations of SOLAS 2009.
It has been observed that the results strongly depend on the geometry of the ships and the interpretation of the regulations. The mostly symmetrical arrangement of the rooms of the Safedor project ship helps to attain the required index R. The unsymmetrical flooding following damage which Nils Holgersson often shows reduces the attained index A.
Also the way symmetrical flooding is achieved has impact on the results. Whereas in case of the Safedor project ship large cross section ducts allow equalization within 20-30s and therefore no additional flooding stages needed to be considered, Nils Holgersson is equipped with regular cross flooding pipes, allowing equalization within times of 58 - 1100s depending on the damage extent and location and on the initial conditions involved. Nils Holgersson’s pipes had been designed to allow equalization within 900s according to the current SOLAS, whereas SOLAS

2009 only allows times for equalization of 600s. For Nils Holgersson flooding stages had to be considered for the stages before equalization.

Another factor influencing the results are the flooding stages considered for the calculation according to SOLAS 2009 where “A”-class rated fire walls are present between rooms taking part in the damage. According to the draft for the explanatory notes [4] for the SOLAS 2009, these fire walls are typical structures to significantly slow down equalization.

The effect of the consideration of flooding phases can not be generalized. It also depends on the geometrical properties of the ships. Here, only the results for the Safedor project ship are affected by the chosen number of phases within a flooding stage. Again, geometrical properties of the ships result in differences in the results.

From the results of the calculations performed, the conclusion can be drawn, that SOLAS 2009 for these two ships and for the input data stated provides at least the same level of safety as the current SOLAS incl. the Stockholm Agreement IMO/Circ.1891.

8 List of literature

[1] IMO, "SOLAS", Consolidated Edition 2004
The Bath Press, Bath
2004

[2] MSC 80/24/Add.1, Annex 1, “Amendments to the international convention for the safety of life at sea, 1974, as amended, Chapter II-1, Parts A + B"
May 2004

[3] IMO, Circular Letter No. 1891 (Stockholm Agreement), "Regional agreement concerning specific stability requirements for Ro-Ro passenger ships"
April 1996

[4] SLF 49/3, Annex 1, “Explanatory Notes to the SOLAS Chapter II-1 Subdivision and Damage Stability regulations”
April 2006

[5] HARDER Work Package 3 – Task 3.2, “Generalized S_w Factor”
February 2002

[6] Sigmund Rusaas, "On the Water on Deck Effect (WOD) compared with the GZ approach, used in a probabilistic concept of survival"
December 2003

[7] SLF 46/INF.5, “Evaluation of required subdivision index R for passenger and dry cargo ships, Report from the research project HARDER”
June 2003

[8] SLF 46/16, “Report to the Maritime Safety Committee”
September 2003

[9] MSC 78/26, “ Report of the Maritime Safety Committee on its seventy-eighth session”
May 2004

[10] SLF 47/3/3, “Development of revised SOLAS Chapter II-1 Parts A, B and B-1” (Required subdivision index R)
June 2004

[11] SLF 46/WP.5/Rev.1, “Report of the SDS working group – Part 1”
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[12] Boris Altmayer, "Untersuchung, Bewertung und Modifizierung eines existierenden Passagierschiffsentwurfes hinsichtlich der Erfüllung der Leckstabilitätsforderungen, welche in dem neuen Kapitel ll-1 der SOLAS definiert sind"
October 2005

List of abbreviations

A	attained index
B	breadth moulded
D	depth moulded to freeboard deck
d	draught
d_l	light service draught
d_p	partial subdivision draught
d_s	deepest subdivision draught
dw	deadweight
GL	Germanischer Lloyd
GM	difference between metacentric height and vertical centre of gravity
GZ	righting lever
IMO	International Maritime Organisation
L	length according to the international Loadline Agreement
L_{bp}	length between perpendiculars
l_{max}	maximum damage length
L_{oa}	length over all
L_s	subdivision length
M	heeling Moment
MSC	Maritime Safety Committee
N	number of persons (including officers and crew) the ship is permitted to carry
N_1	number of persons for whom lifeboats are provided
N_2	number of persons in excess of N1
p	probability of occurrence of a damage
R	required index
s	probability of survival
SLF	Sub-Committee for Stability, Loadline and Fishing vessels (SLF)
SOLAS	Safety Of Life At Sea
v_m	factor representing the probability that the spaces above the horizontal subdivision will not be flooded.
θ	angle of heel