HAMBURGISCHE SCHIFFBAU-VERSUCHSANSTALT GMBH

THE HAMBURG SHIP MODEL BASIN

HSVA Report No. 1669

Research for the Parameters of the Damage Stability Rules including the Calculation of Water on Deck of Ro-Ro Passenger Vessels, for the amendment of the Directives 2003/25/EC and 98/18/EC

Final Report Part I

Client:

European Maritime Safety Agency (EMSA)

Hamburg, July 22, 2009

HSVA

Seakeeping & Manoeuvring

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for
The European Maritime Safety Agency (EMSA)

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18. Abstract

Two new RoPax ships were designed to meet the requirements of the new probabilistic SOLAS 2009 damage stability standard. The safety levels attained by the different ship damage stability rules to these two ships were determined with Monte Carlo simulations. For both ship designs the safety level presented by the SOLAS 2009 Reg. B-1 rules clearly drops down to a significantly lower level than that presented by SOLAS 90 Reg. II-1/8 standard together with the Stockholm Agreement. The hydrostatic calculations show that the smaller ship suffers from a general lack of stability, but the designed subdivision is reasonable. The larger ship has a sufficient level of stability, but the ship would capsize or sink rapidly also in calm water, if the lower hold got damaged. In general the numerical simulations give a good picture of the ship heeling and vehicle deck flooding process, but they predict a somewhat too low survivability for these two vessels. Typical damage cases were chosen for the model tests, which gave the following results: The smaller ship capsized already at significant wave height H_s 3.0 m. In some other damage cases ship is expected to capsize in much lower waves, also when there is no water on the vehicle deck. Excluding the lower hold damage the larger ship would probably survive some likely damage cases in a sea state of H_s 4.0 m. Altogether the present investigation of the two RoPax vessels shows that in the framework of the new probabilistic damage stability rules (SOLAS 2009) for passenger ships built from January 1, 2009, it is possible to create ship designs with significant deficits with regard to safety. In view of this it is difficult to come into any other conclusion that the ship stability required by the SOLAS 2009 rules is not likely to be sufficient in all cases. Corrective action should be taken to amend the SOLAS 2009 rules. A suggestion for the direction of future work is given.

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Preface

The findings described in this Final Report are a result of the efforts of the HSVA Consortium consisting of the Hamburg Ship Model Basin, HSVA (coordinator), the Institute of Ship Design and Ship Safety of the Hamburg University of Technology TUHH, the Flensburger Schiffbau-Gesellschaft (FSG) –Shipyard in Flensburg, and the Ship Design and Consult (SDC) GmbH in Hamburg.

The new two RoPax ship designs investigated in this study were developed by the FSG team, the responsible project manager being Rolf Nagel. A description of this development is given in the FSG-Report by Nagel (2009).

The analysis of the safety levels of these two designs attained by different damage stability rules was carried out by Prof. Stefan Krüger of TUHH. Further preliminary hydrostatic analysis and a pre-selection of the damage cases were carried out by TUHH before the actual HSVA simulations. Also this work was led by Stefan Krüger in TUHH. The Chapters 2, 3, 7 and 12 of the Final Report Part I are directly based on the TUHH report by Krüger (2009).

The actual numerical simulations of the ship behavior until capsize or sinking and the analysis of the amount and motions of water on the vehicle deck measured in the model tests were carried out by Petri Valanto of HSVA, manager of the project. Into the numerical simulations with the software program HSVA ROLLS flowed all the preparatory hydrostatic calculations by Michael Wächter of the SDC GmbH. All this analysis above together with the Executive Summary form Part I of the Final Report.

The planning of the two physical ship models and the model tests were carried out by Arndt Schumacher and Norman Ludwig in the HSVA. The results related to the survivability of these two RoPax vessels are reported detailed in the two HSVA reports by Ludwig (2009a, 2009b), which form the Part IIa and Part IIb of the Final Report, respectively. The analysis of the amount and motions of water on the vehicle deck by the present author is reported only in Chapter 11 of the Part I of the Final Report.

The financial support due to the award decision of the European Maritime Safety Agency EMSA under the contract number 08-EMSA/OP/09/2008 is gratefully acknowledged. Special tanks are extended to Mikael Vartio at EMSA for editorial work on the correct reference to the various stability rules.

Executive Summary

The purpose of this project was to evaluate the level of ship safety provided by the new probabilistic ship damage stability rules SOLAS 2009. Two new RoPax ships were designed to meet the requirements of the new SOLAS 2009 damage stability standard.

The smaller vessel is 80 m long, having a RoRo-cargo space on the main deck with stern access and a passenger capacity of 300 persons. Typically, RoPax vessels of this size are operated on very short distance routes, like on island connections. The second design is a 200 m long RoPax vessel with a passenger capacity of 600 persons, designed for short international voyages. The ship has a stern access and a bow access for the wheeled cargo and a long lower hold. The ship is able to carry wheeled cargo in different cargo compartments on four decks.

The safety levels attained by the different ship damage stability rules to these two ships were determined with Monte Carlo simulations. For both ship designs the safety level presented by the SOLAS 2009 Reg. B-1 rules clearly drops down to a significantly lower level than that presented by SOLAS 90 Reg. II-1/8 standard in conjunction with the Stockholm Agreement. The hydrostatic calculations show that the smaller ship suffers from a general lack of stability, but the designed subdivision is reasonable. The larger ship has a sufficient level of stability, but the ship capsizes or sinks rapidly also in calm water, if the lower hold gets damaged.

The most important ones of the generated damage cases were chosen and the behavior of the two ship designs in these damage cases were numerically simulated: In general the simulations give a good picture of the ship heeling and vehicle deck flooding process, but they predict a somewhat too low survivability for these two vessels: Based on the numerical simulations neither vessel would survive in 4.0 m waves in typical damage cases.

Four typical damage cases were chosen for the model tests, which gave the following results: The smaller ship capsized already at significant wave height of 3.0 m. In some other damage cases not tested the ship is expected to capsize in much lower waves, also when there is no water on the vehicle deck. The larger ship would probably survive likely damage cases in a sea state having a significant wave height of 4.0 m, as long as the lower hold is not damaged. With the long lower hold having the length of 39 percent of the ship length the probability that a collision damage at the ship side would extend to the lower hold, however, is considerable. A modified version of the larger ship exceeding the requirements by SOLAS 2009 was made: This version survived the long lower hold damage up to wave height of 3.8 m. This design may turn out to the trend-setting for RoPax ships with a large lower hold. In all model tests the behavior and accumulation of water on the vehicle deck were measured, as this is crucial for the capsizing process of this ship type in case of damage.

Altogether the present investigation of the two RoPax vessel designs shows that in the framework of the new probabilistic damage stability rules (SOLAS 2009), it is possible to create ship designs with significant deficits in safety. In view of this it is difficult to come into any other conclusion that the ship stability required by the SOLAS 2009 rules is not likely to be sufficient in all cases. Corrective action should be taken to amend the SOLAS 2009 rules. In order to reliably make the right changes, some more new RoPax designs according to the probabilistic SOLAS 2009 rules should be investigated.

In view of the present results the HSVA Consortium found the idea to leave the damage stability rules in SOLAS 2009 in the present form and to develop an additional, separate Water-on-Deck (WoD) -criterion for RoPax ships based on first principles for the amendment of the SOLAS 2009 rules as best.

List of Project Reports

Krüger, S. (2009) Determination of the Safety Levels of the Ship Designs EMSA1 and EMSA2 based on a Monte Carlo Approach, Bericht Nr. 09-625015HSVA, Technische Universität Hamburg-Harburg, Institut für Entwerfen von Schiffen und Schiffssicherheit.

Ludwig, N. (2009a) Damage Stability Tests with the Model of an 80 m RoPax Vessel, HSVA Report No. S590a/09, Hamburg. Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA), Hamburg.

Ludwig, N. (2009b) Damage Stability Tests with the Model of a 200 m RoPax Vessel, HSVA Report No. S590b/09, Hamburg. Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA), Hamburg.

Nagel, R., (2009) Research for the Parameters of the Damage Stability Rules including the Calculation of Water on Deck of Ro-Ro Passenger Vessels, for the amendment of the Directives 2003/25/EC and 98/18/EC – FSG Report, Flensburger Schiffbau-Gesellschaft, Flensburg.

Valanto, P. (2009) Research for the Parameters of the Damage Stability Rules including the Calculation of Water on Deck of Ro-Ro Passenger Vessels, for the amendment of the Directives 2003/25/EC and 98/18/EC – Final Report, HSVA Report No. 1669, Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA), Hamburg.

Abbreviations

B	Breadth of ship
EMSA1	Name for the design of the 80 m RoPax ship in this project
EMSA2	Name for the design of the 200 m RoPax ship in this project
E4	Ship Design Software
FSG	Flensburger Schiffbau-Gesellschaft - Shipyard, Flensburg.
GM	Metacentric Height
GZ	Righting Lever
HARDER	EU- Research Project
HSVA	Hamburg Ship Model Basin
H_s	Significant wave height
IMO	International Maritime Organisation
KG	Height of the Center of Gravity above keel
L	Length of ship
LLH	Long Lower Hold
NAPA	Ship Design Software
Pax.	Passenger
PS	Port side
SA	Stockholm Agreement (Directive 2003/25/EC, as amended)
SDC	Ship Design and Consult
s_i	survival probability of a damaged compartment or group of compartments
p_i	damage probability of a damaged compartment or group of compartments
SOLAS	Safety of Life at Sea
SOLAS 90	SOLAS74, as amended up to SOLAS 96/98 Amendments (Dir. 98/18/EC, as am.)
SOLAS 2009	IMO Res.MSC.216(82)
STB	Starboard side
TGZ	Coefficient
TRange	Coefficient
TUHH	Hamburg University of Technology
VCG	Vertical Center of Gravity
T_p	Peak period of the wave spectrum

Table of Contents of Part I

(Part II contains the reports of the HSVA model test, which were reported separately.)

1 Introduction

This report contains a description of the work carried out by the HSVA Consortium in the framework of the project ''Research for the Parameters of the Damage Stability Rules including the Calculation of Water on Deck of Ro-Ro Passenger Vessels, for the amendment of the Directives 2003/25/EC and 98/18/EC".

Directive 98/18/EC, as amended, on the safety rules and standards for passenger ships seeks to introduce a uniform level of safety of life and property on new and existing passenger ships when engaged on domestic voyages inside EU waters, and to enable the harmonisation of the rules for their international voyages outside EU waters. This Directive is in a phase of revision which takes into account the new stability calculation regulation for passenger vessels that are built after the entry into force of SOLAS 2009.

Directive 2003/25/EC, as amended, concerns the regional IMO requirement for the calculation of water on deck relating to damage stability of ro-ro passenger vessels. The Directive makes reference to Directive 98/18/EC and applies not only to new ships, but also to existing ships in EU waters.

The Ro-Ro passenger vessel is a significant means for the transfer of passengers and goods between member states, and forms an essential part of the EU transport network. Bearing in mind that there have been several major disasters involving this type of ship in recent decades, this matter is considered to be of fundamental importance and worthy of significant further research. This is the motivation for the present investigation.

The purpose of this project is to evaluate the ship safety provided by the new probabilistic ship damage stability rules SOLAS 2009. For this purpose two new RoPax ship designs were created by FSG to meet the requirements of the new probabilistic SOLAS 2009 damage stability standard.

The smaller vessel is 80 m long, having a RoRo-cargo space on the main deck with stern access and a passenger capacity of 300 persons. In this report this vessel is called EMSA1. Typically, RoPax vessels of this size are operated on very short distance routes, like on island connections. Based on the nature of such routes the ship has no overnight accommodation for passengers, only for the crew of 22 (Nagel, 2009).

The second design, called EMSA2, is a 200 m long RoPax vessel with a passenger capacity of 600 persons, designed for short international voyages. The ship has a stern access and a bow access for the wheeled cargo and a long lower hold (LLH). The ship is able to carry wheeled cargo in different cargo compartments on four decks (Nagel, 2009).

The safety level of these two designs provided by different ship damage stability rules were evaluated by TUHH using a Monte Carlo approach. The most relevant of the generated damage cases were chosen and the behavior of these two ship designs were numerically simulated for the chosen damage cases and seaways. A few most interesting damage cases of these were further investigated with model tests. As the behavior of water on the vehicle deck of a damaged RoPax ship plays a very significant role in the survivability of the vessel, also this issue was investigated in the model tests. Different ways to move forward in the development of the SOLAS 2009 rules are briefly discussed and some initial suggestions are given.

The four partners of the HSVA Consortium are the Hamburg Ship Model Basin HSVA (coordinator), the Institute of Ship Design and Ship Safety of the Hamburg University of Technology TUHH, the Flensburger Schiffbau-Gesellschaft (FSG) –Shipyard in Flensburg, and the Ship Design and Consult (SDC) GmbH in Hamburg.

2 Monte-Carlo Simulation for Damage Stability Problems

2.1 Simulation Principle

Each statistical process can be described by a distribution function, also called the Cumulative Density Function (CDF). In this case these distributions are based on known damage statistics. Examples for such distributions can be found below in Figure 1.

The Monte-Carlo simulation is a method for iteratively evaluating a deterministic model using sets of random numbers as inputs. By using a generator for uniformly distributed random numbers, a value between zero and one is chosen. This random number is considered as a probability and the corresponding event is selected from the distribution. If this is repeated with a sufficient number of samples, these events will converge to the original underlying distribution. The number of events in discrete intervals are counted by a simple yes/no selection. Integrating the resulting data leads to an approximation of the underlying distribution, except for the tail sections, which will be discussed later. In addition a confidence interval can be computed, which shows the statistical accuracy depending on the number of samples.

Using this approach the generation of damage cases simplifies to the generation of a sufficient amount of uniformly distributed random numbers and to the selection of the corresponding damage extends and their locations from the known distribution models. Such a damage cube breaches a certain combination of ship compartments. Counting the number of hits for each combination and dividing it by the total number leads to the encountered frequency of damage to this combination.

This generation can be summarized as follows:

- Draw the damage cube from the damage distributions
- Find the corresponding compartment combination
- Integrate the hits for each combination

After a sufficient number of hits, the frequency for each combination is simply the fraction of hits to the total number of samples. This method has the following advantages compared to a manual method to calculate the attained indices:

The hit frequency can be directly computed even for a very complicated combination of compartments. There is no need to look at any subcases and their probabilities. This clarifies the presentation of the damage cases.

- Because the counting of hits is simply a binary event (yes/no), also very complicated geometries can easily be handled.

- Sorting the damage cases according to the frequency gives direct access to the cases of highest importance for the subdivision design. This shows the designer, which combinations of compartments influence the subdivision index the most.

- Since the simulation is completely automatic, more combinations can be found compared to the manual method. In extreme, all possible combinations are found. This is very important for validation purposes.

After the generation of the damage cases, the survivability for each case can be computed according to the different regulations in the rules. The only requirements for this method are the damage distributions and a reliable method to retrieve the combinations of the damaged compartments.

Figure 1 shows some of the damage distributions for the damage location, length, penetration and upper vertical extent according to the different rules. These distributions result from the analysis of so-called “damage cards” of real accidents. The interpretation in each rule differs significantly from what we call the real statistics labelled HARDER in the plots. We have obtained these distributions called HARDER by a numerical integration of the damage distributions as given by the original HARDER data, without excluding damages or without assuming any analytical distribution. Therefore, if we generate a sufficiently large population of damages, we can assume that these damages represent all damages that have been actually measured or recorded. We assume further that all these damages are actually possible. Therefore, the HARDER distribution is assumed as a population which represents all possible damages.

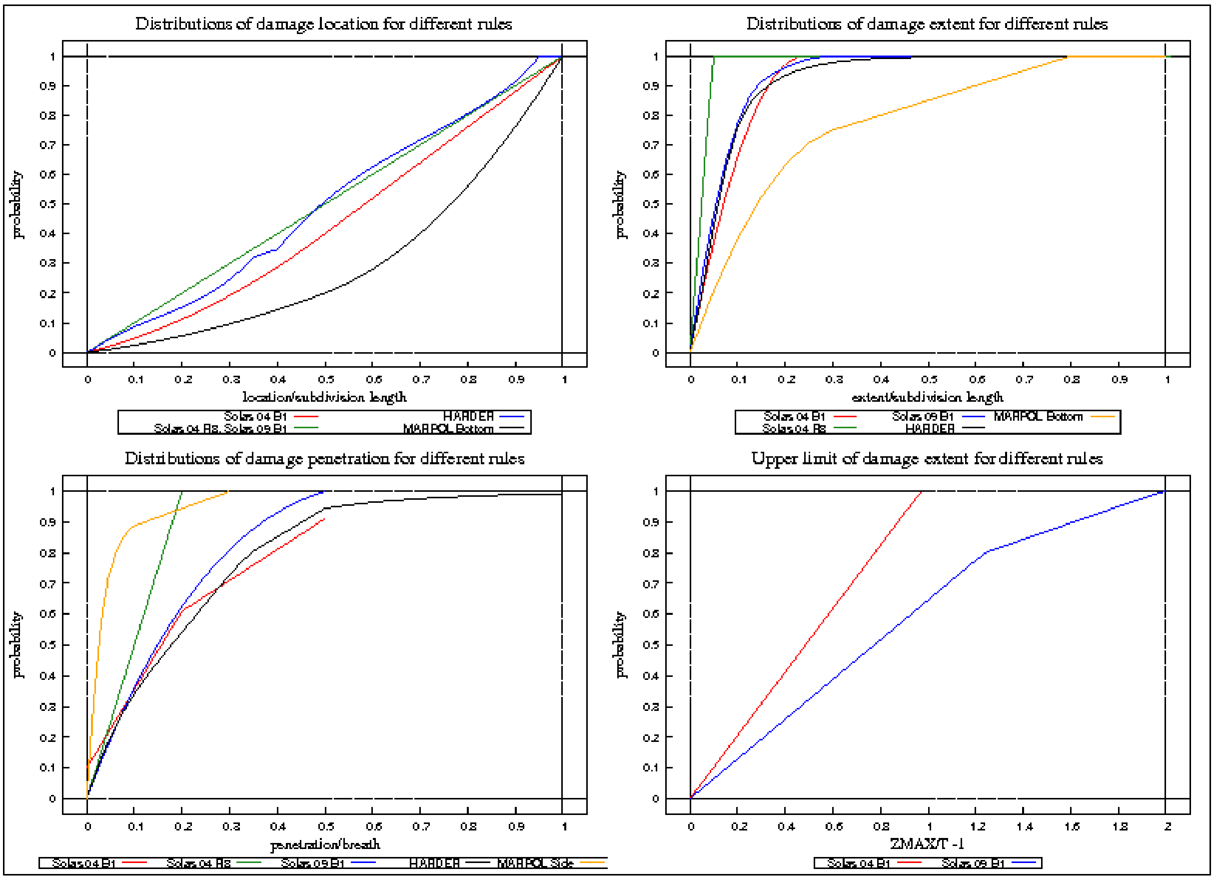

Fig. 1 Different damage distributions according to different damage stability standards. Top left: Longitudinal location, top right: Longitudinal extent, bottom left: Penetration, bottom right: Upper limit.

When the sketched concept was implemented, some practical problems occurred in the correct rule based treatment of the damage generation process. These problems result mainly from the inconsistent analysis of the statistical material used in the development of the rules. The main difficulties together with their numerical healing are explained by Krüger (2009). This also leads to the need to be able to generate real and rule based damages.

Figure 1 depicts the distribution functions of the damage size and location known from the damage cards. These data sets are compiled by the classification societies at the inspection of damages due to accidents. An in-depth overview can be found in the reports of the EU research project HARDER (IMO 2002). The following data have been recorded for each damage:

- Damage location
- Damage length (in longitudinal ship direction)
- Damage penetration depth (from the outer shell)
- Height of upper damage limit above baseline

For the formulation of the regulations, these basic data sets are converted to an aft and fore limit of the damage in order to make it possible to define the (longitudinal) damage probability p_i for a certain compartment group. According to the rules, factors for different penetrations r_i and vertical extents v_i are taken into account at the computation of the damage survivability s_i, even though these are probabilities for the damage definition as well. In the following the damage probability refers to the product of p_i v_i r_i. The damage survivability means only the probability to survive this damage.

2.2 Safety Level Analysis of Damage Stability Rules

2.2.1 General aspects

In the present context the simulation computes the safety index obtained by a certain damage stability rule, when applied to a specific ship design. This index can be used to determine the level of safety attained to the ship design by any chosen damage stability rule. In the framework of one specific damage stability standard, an increase in the computed safety index represents also an increase in the safety level. When two different damage stability standards are compared with respect to the safety level they represent, the one with the lower computed safety index is stricter, sets higher requirements, and represents thus a higher safety level. This allows us to compare the safety levels given by different rules by comparing their computed safety indices. Whether a passenger ship design gets a higher or lower safety index according to the new SOLAS 2009 Reg. B-1 rules compared to the deterministic SOLAS 90 Reg. II-1/8 rule, and which influence is given by the water on deck requirement according to the Stockholm Agreement Requirements, will be discussed in detail. The Monte Carlo based damage simulation is a very useful tool to answer exactly such type of questions.

2.2.2 Comparison of the damage sets

The key parameters of the different damage stability rules are compared in Table 1.

Table 1 Key parameters of the different damage stability rules.

Criteria	SOLAS 90 Reg. II-1/8	SOLAS 2009 Reg. B1
Max. damage length	11m or 3m+0.03L	0.303L for L<200 m
	One or two compartment status	
Max. damage penetration	0.2B	0.5B
Lever range	15°	16°
Lever area	0.015mrad	Omitted
Max GZ	From heeling moments	0.12m or from heeling moments
Freeboard	MARGIN LINE not submerged	Escape Routes not submerged

Since the deterministic SOLAS 90 Reg. II-1/8 is based on a deterministic concept, mainly a few limiting damage cases influence the subdivision design and the related stability. For comparison of the different rules under these circumstances, the safety levels defined by each rule have to be determined. This is impeded by the fact that all mentioned inconsistencies in the rules are also included in the defined safety levels, represented by the computed safety indices. In order to quantify the different safety indices, it must first be determined, which damages of all possible damages are actually included in each damage stability standard or rule. ***The statistical material defined by the HARDER project is here considered as the total set of all possible real damages***. In addition, the resulting distributions have to be applied thoroughly and the inconsistencies described in the previous sections have to be avoided. ***Since every known damage***

rule has defined limits for the damage size, each rule assembles only a subset of all damages. This is illustrated in Figure 2. It does not matter whether the rule is deterministic (e.g. SOLAS 90 Reg. II-1/8) or probabilistic based.

The damage distributions for each rule can be computed by simply choosing damages based on the HARDER statistics and disregarding all damages not included in the specified rule. This way it is also possible to retrieve the size of the subsets, that is, the portion, e.g. in percent, of the total HARDER population included in each rule. The results of this simulation is shown in Figure 2, right. The percentage of damages included in the new (SOLAS 2009 Reg. B-1) and old probabilistic damage rules (SOLAS 90 Reg. B-1, SOLAS 04 B1 in Fig.2) and the deterministic rules (SOLAS 90 Reg. II-1/8, SOLAS 04 R8 in Fig. 2) are plotted over the ship's subdivision length. Because an upper limit for the damage length is defined for both new and old rules, the number of damages included in the rules starts to decrease for ships with a length greater than approx. 200m.

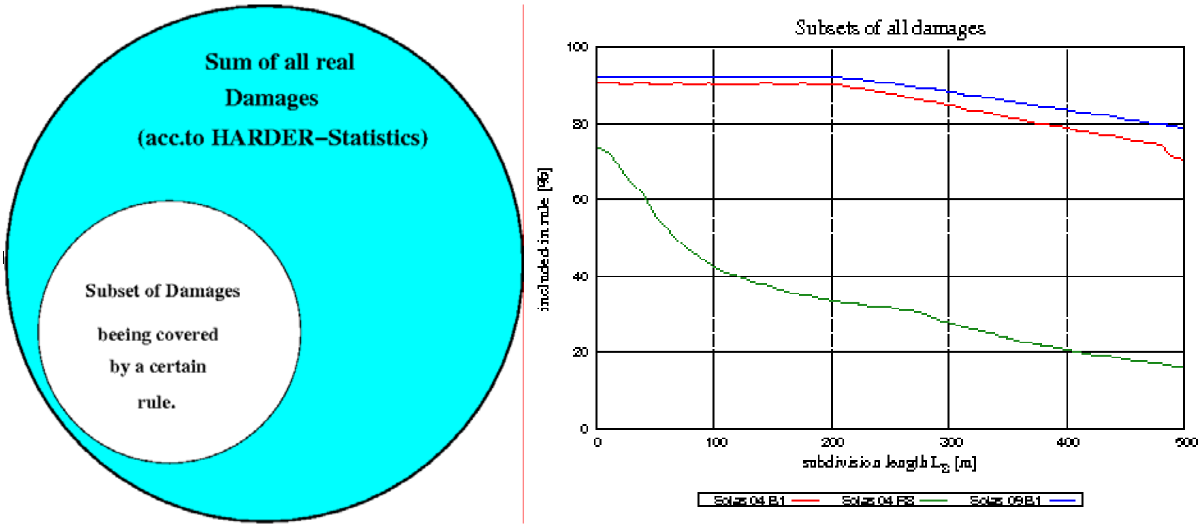

Fig. 2 Principle of the determination of damage subsets from the HARDER population for different damage stability regulations.

In general the subset of covered damages increases for the new rules, but the influence is marginal: The old SOLAS 90 Reg. B-1 rule covers about 90 percent of all damages, the new SOLAS 2009 Reg. B-1 about 94 percent. The increase is due to the increase of the maximum assumed damage length from 0.24L up to 0.303L. The influence of this increase in maximum damage length on the safety level is only marginal, since the probability for the occurrence of damages with a large extent is very low as well. This also means that the artificial limitation of the damage length in the former implementation of the SOLAS 90 Reg. B-1 rule does not have much influence on the overall index.

On the other hand in the old deterministic SOLAS 90 Reg. II-1/8 rules, only a relatively small number of damages is actually included in this standard. In addition the curve declines strongly with the ship length. For example for a short ship of only 100m in length, only 42 percent of all damages are covered by SOLAS 90 Reg. II-1/8. This drops down to only approximately 20 percent for a very large ship of 400m in length. This appears to suggest that the safety level of this damage stability standard is low, as only a small part of all possible damages is addressed and needs to be survived. But it is equally possible that damages, which are not addressed by this standard, are survived. Because of this, when applying the SOLAS 90 Reg. II-1/8 to a ship, it is important to determine also the contribution of all damages ***not*** included in the subset of the rule, as these can represent an important contribution to the safety level. The influence of such aspects can only be computed for real ships, which will be examined in more detail in the following sections.

2.3 Determination of the Safety Levels of Ship Designs

2.3.1 Principal definitions

The aim of the present analysis is to determine the safety levels attained to the ship designs EMSA1 and EMSA2 according to different damage stability standards. These safety levels determined based on the safety indices computed with the Monte Carlo simulation as explained above. This simulation method results at first in a distribution of assumed damages. These damages then lead to combinations of compartments, which are assumed to be flooded. These are called damage cases. For each individual damage case, the probability of survival is then computed. This probability of survival depends on the calculation method as well as on the survival criteria. During the present analysis, hydrostatical calculations are used to determine the equilibrium floating condition and the resulting righting levers. The computations follow the prescribed procedure for all damage stability calculations according to statutory requirements. Any specific damage stability standard influences the calculation procedure in the following way:

- The standard prescribes the damage distributions.
- The standard prescribes the survivability criteria.

As the aim of the present analysis is to compare different damage stability standards with respect to the safety indices they attain to a particular ship design, the essentials of these standards are briefly explained in the following.

2.3.2 SOLAS 90 Reg. II-1/8 damage stability standard

This damage stability standard is subject to evaluation during this analysis. The standard is of deterministic type and may be applied either as one (1) or two (2) compartment status. The assumed damage length is 0.03L+3m, the maximum damage penetration is B/5. For the two-compartment status, the assumed damage may occur at any position of the ship. For the one-compartment status, the damage is located only at such positions that a transversal bulkhead is not penetrated. Any damage of lesser extent resulting in more severe requirements will overrule the maximum damage extent. Cross- or down-flooding as well as intermediate stages of flooding have additionally to be computed, if applicable. The survivability criteria prescribe a maximum heel for the equilibrium floating condition. Further, the Margin Line must not become submerged for that equilibrium floating condition, and no progressive flooding through any opening must take place. The standard prescribes minimum values for the maximum righting lever, the range of positive righting levers and the area under the righting lever curve. Due to the deterministic nature of this standard, the attained probability of survival can always be either 1 (survived) or 0 (not survived). This standard has to be fulfilled on all possible drafts of the ship.

2.3.3 SOLAS 90 Reg. II-1/8 + Stockholm Agreement damage stability standard

This damage stability standard is actually an addendum to SOLAS 90 Reg. II-1/8 according to the Stockholm Agreement. This addendum specifies an additional amount of water on the freeboard deck, which has to be considered during the calculation of the righting levers of the ship. This assumed amount of water on the freeboard deck depends on the residual freeboard to this deck in the equilibrium floating condition without water on deck. As the Stockholm Agreement specifies the amount of water on deck by assuming a certain filling height, this amount of water on deck varies for the different heeling angles of the righting lever curve. Both the damage assumptions and survivability criteria are the same as for the SOLAS 90 Reg. II-1/8 standard, except for the fact that the Margin Line criterion does not apply to the equilibrium floating condition including the additional amount of water on deck. It should be noted that if the residual freeboard during the equilibrium is more than 2 m, the additional amount of water on deck becomes zero, in which case there is no difference to the SOLAS 90 Reg. II-1/8 standard.

2.3.4 SOLAS 2009 Reg. B-1 probabilistic damage stability standard

This standard uses a maximum damage length of 0.303 L, however not more than 60 m. The damage penetration depends on the damage length: The maximum amounts to B/2. The probability distributions of these assumed damages are prescribed in the SOLAS 2009 Reg. B-1. The survivability of the ship is computed as the sum of three individual attained indices attained for three drafts, where each of these three indices must not be lower than 0.9 of the so called required index. The latter depends on the ship length and the number of passengers. The survivability criteria attained to an individual damage case prescribe a permissible maximum heel for the equilibrium floating condition. There is no Margin Line Criterion in this standard. Instead the standard requires that the escape ways must not be submerged. The survivability criteria prescribe further the minimum righting lever, as well as the minimum range of positive righting levers. The survivability criteria yields a probability of survival, which may take any value between 0 and 1, where 1 is attained in case all survivability criteria are met.

2.3.5 SOLAS 2009 Reg. B-1/8 deterministic damage stability standard

Besides the probabilistic component, the new SOLAS 2009 Reg. B-1 also contains a deterministic component. The idea behind this deterministic component is that a minor damage shall not result in a major consequence. This component is based on the same assumptions as the SOLAS 90 Reg. II-1/8 except for the following differences:

- The assumed penetration depth is B/10 instead of B/5
- The probability of survival must not meet 1, but 0.9

These requirements must be fulfilled for the three drafts at the prescribed stability values. These deterministic requirements may partly overrule the probabilistic part of SOLAS 2009 Reg. B-1. The SOLAS 2009 Reg. B-1 also contains a deterministic component regarding bottom damages.

2.3.6 HARDER damage distributions

An essential part of the present analysis is the generation of damage distributions. Each damage stability standard has its individual damage assumptions, which result in the fact that some damages, which have actually taken place and been recorded, are not included in the standard in question. For the determination of the total safety index attained to the ship, in principle all possible damages must be included in the analysis. As most damage stability standards focus on side damages only, we follow this assumption in the present analysis and exclude bottom damages. This may be justified by previous investigations carried out by TUHH, where it could be demonstrated that the survivability of a modern ship after a bottom damage is by far higher compared to a side damage. With respect to the remaining side damages, it is assumed throughout in this analysis that the damage distributions collected by the HARDER project represent a damage distribution, which includes the total amount of possible damages. The related cumulative probability functions have been derived from the original HARDER probability density functions without excluding any of the recorded damages. These are used in the following analysis to define a population of all possible damages and their related probability distributions. For such a population of all possible damages, each individual damage can be covered by a specific damage stability standard, or it can be outside of that damage stability standard (e.g. if it exceeds the maximum damage extent of that particular damage stability code).

3 The Safety Index of the Ship Design EMSA1 based on a Monte Carlo Approach

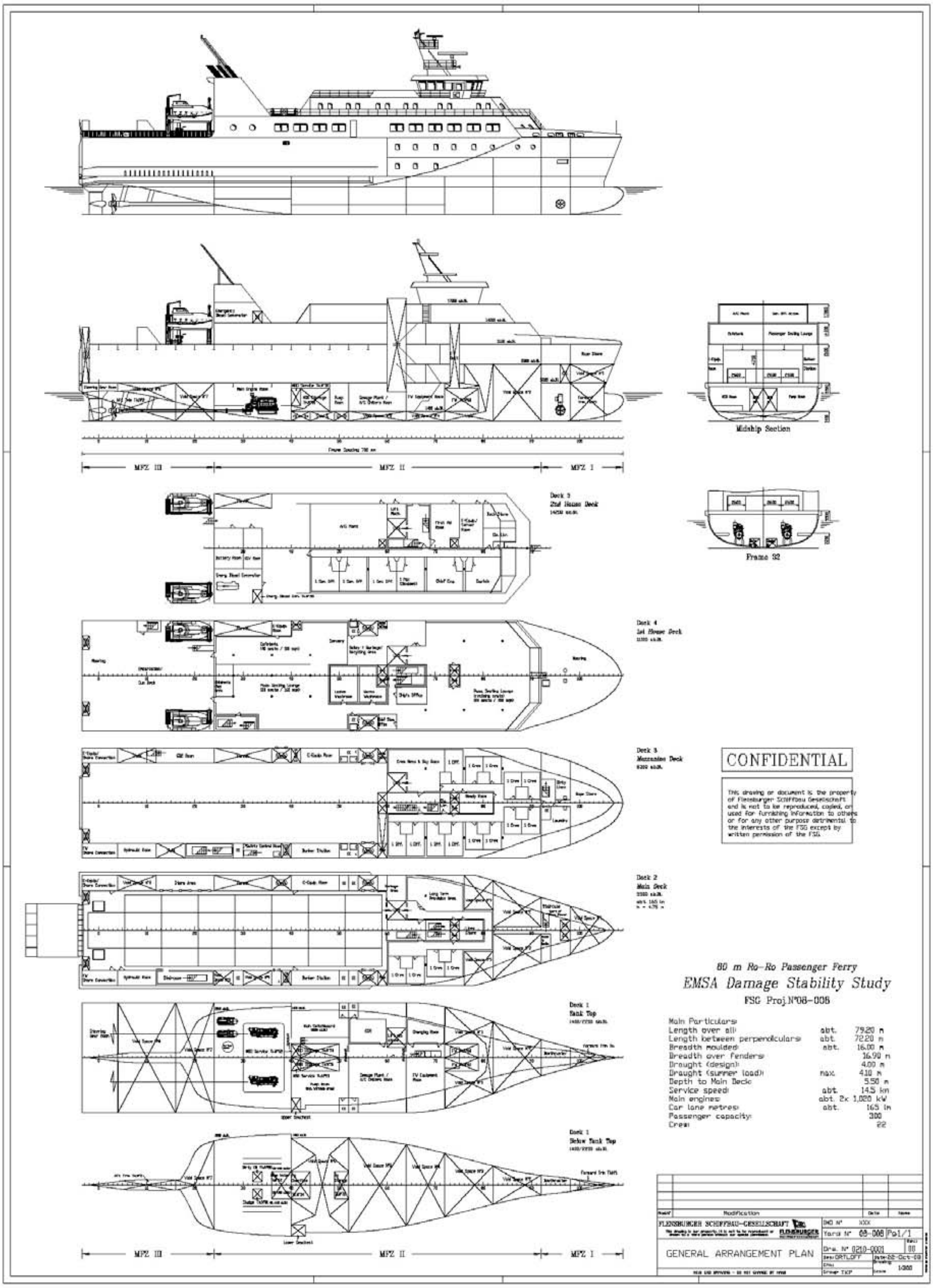

Fig. 3 General arrangement of the ship design EMSA1.

3.1 Initial Safety Considerations

The ship EMSA1 was designed by the FSG as a reference vessel for the new damage stability regulation SOLAS 2009 Reg. B-1. Care was taken during the design to barely fulfill the minimum requirements of this damage stability standard. The curves of required GM were computed, at first for the relevant intact criteria only. The governing intact stability limit was the weather criterion according to the IMO Res. A. 749 intact stability standard. According to the internal FSG standards, all righting levers are always computed on a ***free trimming basis***, which is physically realistic. The thus obtained curve of required GM is shown by the higher blue curve in Figure 4 (see also Figure 12 for the righting lever curves at the deepest draft). The uppermost green curve shows the level of stability according to the FSG internal stability standard based on the requirement that the ship has a sufficient stability to prevent capsizing events caused by heavy weather.

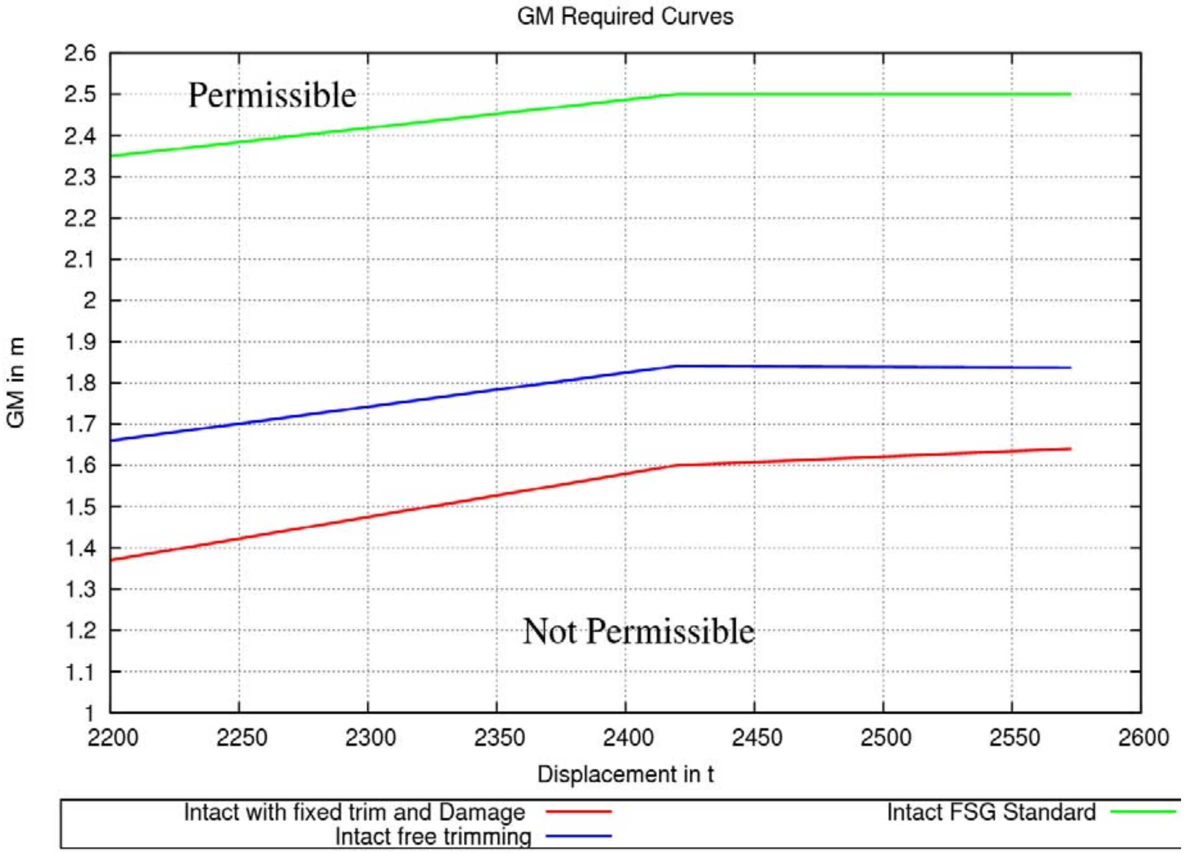

Fig. 4 Required *GM*-curves of the ship for the intact criteria, here weather criterion according to IMO Res. A. 749. The intact limit was calculated for both fixed and free trim basis as well as according to the internal FSG intact stability standard. The red curve is at the same time the limit for the damage stability.

The first evaluation of the damage stability standard according to the new SOLAS 2009 Reg. B-1 showed that it was relatively easy to reach the required index for the *GM*-values according to the intact stability limit obtained on a free trimming basis. Indeed, a significant surplus of attained index was computed. The required index value amounts to 0.700, and the computed attained index was beyond 0.75. As the task was to barely fulfill the requirements, it was decided to compute the intact stability curve on the basis of a fixed trim. According to most administrations, this is allowed. This curve is also shown in Figure 4 as the lower red curve. The difference between the required GM values obtained with the different calculation methods is significant. The attained index was then recalculated based on the *GM*-values with the fixed trim, and it was again found that the attained index was still larger than the required index. It is important to note that for this ship, the limiting stability standard is therefore the intact limit. The calculations resulted in an attained index of 0.713, which is still above the required index of 0.700.

But the damage stability is also governed by the deterministic component of SOLAS 2009 Reg. B-1/8, which means B/10 penetration and one-compartment status damages for the selected number of passengers. These requirements were also satisfied with the selected *GM*-values.

As the damage stability standard was more than fulfilled even with the lower *GM*-values, a further reduction of the stability level would have been possible. However, the *GM* values could not be lowered further due to the prescribed intact stability criteria, and it made from ship design aspects no sense to modify the internal subdivision. Consequently, there would have been the option to increase the number of persons on board, until the attained index would have met the required index. This would be a reasonable design option. However, it was found that the required and the attained indices intersected somewhere beyond 400 persons, which would have been possible from the probabilistic part of the new SOLAS 2009 Reg. B-1. But in this case, the prescribed deterministic B/10 damages of the SOLAS 2009 Reg. B-1 would have needed to be fulfilled for a two-compartment status, which was clearly not possible.

Already on the basis of these findings it can be initially concluded that the safety level of the probabilistic part of the SOLAS 2009 Reg. B-1 for this particular ship is lower than that of its deterministic part. As this deterministic component covers only B/10 side damages, the safety level achieved with this damage assumption ***must*** be smaller compared to the SOLAS 90 Reg. II-1/8 B/5 side damages. It should be also noted that a significant increase in the number of persons on board results only in a small additional required index to be achieved, but shifts the design in fact from a one- to a two-compartment status for the deterministic part of SOLAS 2009 Reg. B-1. The ship will not survive most of these two-compartment damage cases.

3.2 Attained Index according to the SOLAS 2009 Reg. B-1 Probabilistic Standard

The shipyard results for the attained index were recomputed with the Monte Carlo simulation method, in which all mathematical inconsistencies of the probability distributions were removed. The results obtained by the simulation based on 20000 samples are shown in the following Table 2.

Table 2 Results of the damages stability assessment with the Monte Carlo approach. Damage assumptions and survivability criteria according to SOLAS 2009 Reg. B-1 probabilistic part.

Draft	**Displacement [t]**	**Index PS**	**Index STB**	**Index Mean**
Light	2200	0.822	0.817	0.820
Partial	2420	0.715	0.725	0.720
Deepest	2573	0.653	0.637	0.645

According to the prescribed index contribution of 20, 40 and 40 percent, the total index amounts to 0.710. The index on the deepest draft is still slightly larger than 90 percent of the required index. The computed value of 0.710 is in good agreement with the value obtained by the classical manual computation by the shipyard.

3.3 Determination of the Total Safety Index according to the Probabilistic SOLAS 2009 Reg. B-1 Standard

3.3.1 Damages included in the probabilistic SOLAS 2009 Reg. B-1 standard

If a Monte Carlo simulation of damage stability is performed using the original damage distributions developed by the HARDER project, the simulation also includes damages, which are ***not*** covered by the probabilistic SOLAS 2009 Reg. B-1 standard. These are very long damages and those having a very large penetration. For this particular ship EMSA1, it was found that the damage assumptions of the SOLAS 2009 Reg. B-1 standard represent 91.875 percent of all damages, which are actually in the HARDER damage distributions. At first, only the contribution of these 91.875 percent of damages was computed. The index values given in Table 3 below are based on the number of these damages, whereas the last column gives the index values based on the total number of damages. So if the ship would survive all these damages, the PS and STB indices would amount to 1.000 and the contribution to the total safety index would then amount to 0.91875. It must be further noted that the index values computed in this section may differ from those computed before due to the following reasons:

- In the simulations the incorrect probabilities given by the rules for the aft and forward terminals of the ship are corrected.
- In the simulations the correct dependency of the damage penetration with respect to the damage length is used.
- In the simulations the correct longitudinal distribution of the damages is used, whereas in the rules all possible longitudinal locations have the same probability.

The probability of survival was computed according to the SOLAS 2009 Reg. B-1 standard and may take any value between 0 and 1.This results in the following safety contributions from all damages covered by the SOLAS 2009 Reg. B-1 standard:

Table 3 Indices of all damages represented by the SOLAS 2009 Reg. B-1 damage stability standard. Damage distributions according to HARDER.

Draft	Displacement	SOLAS 2009 Damages = 91.875 percent of all HARDER damages			HARDER Damages
		Index	Index	Index	Index Contribution
	[t]	PS	STB	Mean	Mean
Light	2200	0.804	0.785	0.795	0.730
Partial	2420	0.715	0.724	0.720	0.662
Deepest	2573	0.674	0.683	0.679	0.624

3.3.2 Damages not included in the probabilistic SOLAS 2009 Reg. B-1 standard

As mentioned above, there remains an amount of 8.125 percent of all damages represented by the HARDER distribution, which are ***not*** included in the probabilistic SOLAS 2009 Reg. B-1 standard. But it is of course possible that the ship can survive such a damage, which would result in a positive contribution of that damage to the overall safety index of the ship. Therefore, as a next step, only those HARDER damages, which are not covered by the probabilistic SOLAS 2009 Reg. B-1 standard, are considered and their contribution to the overall safety index is computed. As before, the different indices are based on the total number of these damages, which is 8.125 percent. Further, the total contribution to the overall safety index is given, which would amount to 0.08125 in case all these damages would be survived. As before, the probability of survival is computed according to the SOLAS 2009 Reg. B-1 standard. The following results were obtained:

Table 4 Indices of all HARDER damages **not** included in the SOLAS 2009 Reg. B-1 damage distributions.

Draft	Displacement	HARDER Dam. - SOLAS 2009 Damages = 8.125 percent of all HARDER damages			HARDER Damages
		Index	Index	Index	Index Contribution
	[t]	PS	STB	Mean	Mean
Light	2200	0.636	0.634	0.635	0.052
Partial	2420	0.542	0.556	0.549	0.045
Deepest	2573	0.523	0.526	0.524	0.043

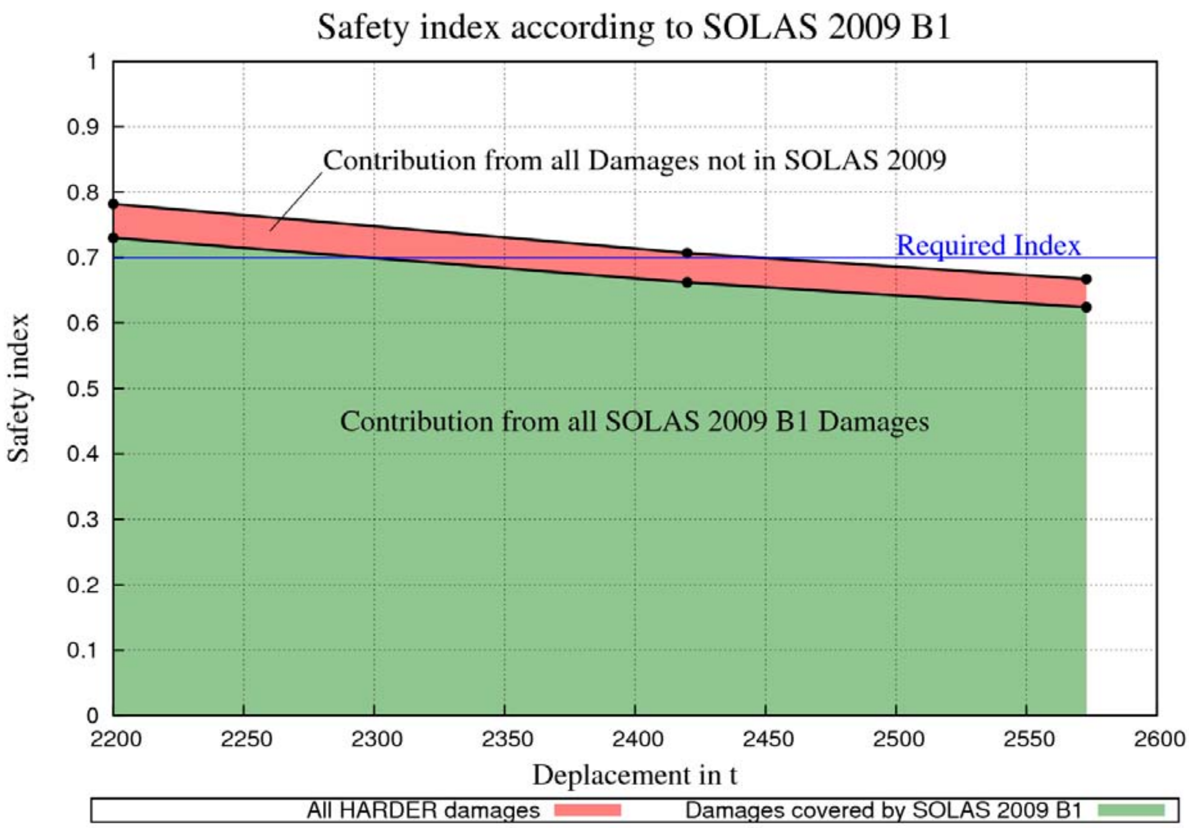

Fig. 5 Visualization of the overall safety index and the different damage contributions for the SOLAS 2009 Reg. B-1 probabilistic standard. The horizontal axis shows the displacement ranging from the value at the light draft (2200 t) to the one at the deepest draft (2573t).

3.3.3 Interpretation of the results

About 50 to 60 percent of all damages, which are not covered by the SOLAS 2009 Reg. B-1 standard, are survived. As their total number is quite small with about 8 percent, this results only in about 4 percent contribution to the overall safety index. There are some discrepancies between the indices computed here for all damages covered by the probabilistic SOLAS 2009 Reg. B-1 standard and those values computed earlier so that now the attained indices are slightly smaller. This is due to the above mentioned mathematical problems in the SOLAS 2009 Reg. B-1 standard. As the ship design EMSA1 has no double hull below the vehicle deck, this results in the situation that the ship does not benefit from the correct selection of the penetration. This explains the slightly smaller indices. The following total safety index values based on the total number of damages are computed: **Light *Draft: 0.782, Partial Draft: 0.707, Deepest Draft: 0.667.*** The values are the sums of the last column in Tables 3 and 4. In this context it should also be mentioned that the ***overall*** safety index, and also the related safety level, ***decreases with increasing draft***, whereas a deterministic standard requires (at least within the assumptions of such standard) ***the same safety level on all drafts.***

3.4 Determination of the Total Safety Index of SOLAS 90 Reg. II-1/8 One-Compartment Status without the Stockholm Agreement

3.4.1 Damages included in the SOLAS 90 Reg. II-1/8 one-compartment standard

As a next step, the total safety index of the ship according to the SOLAS 90 Reg. II-1/8 standard for a one-compartment status is determined. This resulted in a total amount of 15.4 percent of all possible damages, which are covered by a SOLAS 90 Reg. II-1/8 one-compartment status for this design. Consequently, all these damages have to be survived, which must result in an overall contribution to the total safety index value of 0.154. As this ship has no lower hold and consequently no longitudinal bulkheads below the freeboard deck, the B/5 damage assumption of SOLAS 90 Reg. II-1/8 leads to the same damage cases as the deterministic SOLAS 2009 Reg. B-1 standard, which were all survived on the basis of the selected minimum *GM*-values. But the survivability criteria of Reg. 8 are a little more demanding due to the Margin Line criterion as well as due to the fact that SOLAS 2009 Reg. B-1 requires only 0.9 as survivability criterion, whereas SOLAS 90 Reg. II-1/8 attains only fulfilled (1) or not fulfilled (0). Nevertheless, we have recomputed these cases using the Monte Carlo method. It was found that all cases were survived having $s_i=1$ according to the SOLAS Reg. II-1/8 criteria. It should be kept in mind that according to this standard, only 15.4 percent of all possible damages have to be survived. For all computations, the permeability of the RoRo-cargo hold was set to 0.9 or to 0.95 for the light draft, respectively.

3.4.2 Damages not included in the SOLAS 90 Reg. II-1/8 one-compartment standard

Like before, all damages which are not covered by the standard under consideration are investigated. For SOLAS 90 Reg. II-1/8 one-compartment standard this results in 84.6 percent of all HARDER damages not being covered. The contribution of these damages to the overall safety index is computed in the same way as was done before for the probabilistic SOLAS 2009 Reg. B-1 standard. The results are the following:

Table 5 Indices of all damages not represented by the SOLAS Reg. II-1/8 One-Compartment status damage assumptions.

Draft	**Displace-ment**	**HARDER – SOLAS 90 Reg. 8 One-Comp. Damage = 84.6 percent of HARDER damages**			**HARDER Damages**
		Index	**Index**	**Index**	**Index Contribution**
	[t]	**PS**	**STB**	**Mean**	**Mean**
Light	2200	0.645	0.642	0.644	0.544
Partial	2420	0.480	0.480	0.480	0.405
Deepest	2573	0.469	0.469	0.469	0.396

The results show that a significant amount of damages, which is not explicitly covered by the standard is actually survived according to the SOLAS 90 Reg. II-1/8 criteria.

3.4.3 Interpretation of the results

All one-compartment cases are actually survived according to the SOLAS 90 Reg. II-1/8 criteria. This is due to the fact that the B/5 damage assumption does not lead to more severe cases compared to the B/10 penetration depth for this particular ship. Only 15.4 percent of all possible HARDER damages are actually addressed by the one-compartment status. A significant number of damages outside of the SOLAS 90 Reg. II-1/8 standard is also survived, which results then in the final safety index values: ***Light Draft: 0.698, Partial Draft: 0.559, Deepest Draft : 0.550.*** The values are the sums of the values of the last column in Table 5 and the contribution of 0.154 by all survived SOLAS 90 Reg. II-1/8 damages. The comparison to the total safety indices obtained by the evaluation according to the SOLAS 2009 Reg. B-1 standard shows that the ***SOLAS 90 Reg. II-1/8 standard attains a lower*** **safety index value** to the ship as the new SOLAS 2009 Reg. B-1 standard. This is due to the following reasons:

- According to SOLAS 90 Reg. II-1/8, the probability of survival s_i can only be 1 or 0, but it cannot take any intermediate values. As the new standard uses the power of 1/4 to determine the probability from the maximum righting lever h_{max} and its range of positive values in each damage case, this result in very small values of h_{max} and range still leading to significant values of s_i.

- According to SOLAS 90 Reg. II-1/8, the probability of survival s_i is automatically set to zero in case the margin line becomes submerged. The SOLAS 2009 Reg. B-1 does not have this criterion.

Concluded, it was found for this particular ship that ***the SOLAS 90 Reg. II-1/8 damage stability standard attains a lower*** safety index ***to this design compared to the new SOLAS 2009 Reg. B-1 standard***. Therefore, this analysis can thus quantify the effect of the revised criteria for the survivability of the ship, especially the Margin Line criterion. The results are also shown in Figure 6.

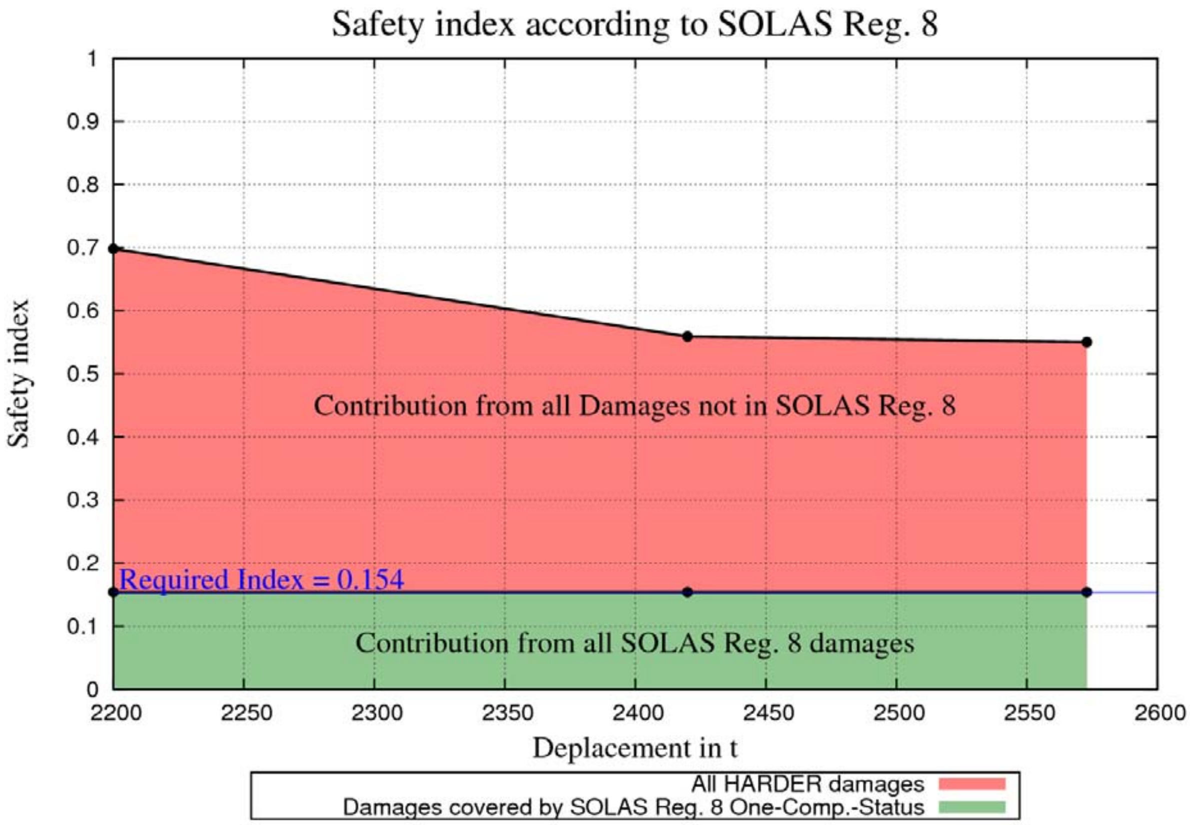

Fig. 6 Visualization of the overall safety index and the different damage contributions for the SOLAS 90 Reg. II-1/8 standard without Stockholm agreement. The horizontal axis shows the displacement ranging from the value at the light draft (2200t) to the one at the deepest draft (2573 t).

3.5 Determination of the Total Safety Index of SOLAS 90 Reg. II-1/8 One-Compartment Status including the Stockholm Agreement

3.5.1 Damages included in the standard

The same procedure for the evaluation of the safety index, now with consideration of the Stockholm Agreement requirement, is repeated. Now, the probability of survival s_i takes into account the additional amount of water on the freeboard deck, as defined by the Stockholm Agreement. As before, the total amount of damages included by the standard amounts to 15.4 percent. If the ship had to fulfill SOLAS Reg. II-1/8 with water on deck according to the Stockholm Agreement, all damage cases must be survived, which should result in an index value contribution of 0.154 on all three drafts. ***In fact, this ship does not fulfill the Stockholm Agreement requirement, as some cases are definitively not survived. This clearly shows that a ship designed according to the new standard SOLAS 2009 will not necessarily fulfill the Stockholm Agreement.***

Especially for the deepest draft, the loss in the safety index is about 23 percent, as many damage cases including those with a high probability of occurrence are not survived. This investigation quantifies how large the loss of safety within those damages covered by SOLAS 90 Reg. II-1/8 is. But it must be taken into account that this standard only covers an amount of 15.4 percent of all possible damages.

Table 6 Indices of all damages represented by the SOLAS 90 Reg. II-1/8 one-compartment damage assumptions.

Draft	Displace-ment	SOLAS90 - Reg. 8 One-Comp. Damages = 15.4 percent of HARDER Damages			HARDER Damages
		Index	Index	Index	Index Contribution
	[t]	PS	STB	Mean	Mean
Light	2200	0.938	1.000	0.969	0.149
Partial	2420	0.938	0.938	0.938	0.144
Deepest	2573	0.802	0.725	0.764	0.118

3.5.2 Damages not included in the standard

All damages not included in the SOLAS 90 Reg. II-1/8 standard amount to 84.6 percent of all possible HARDER damages. The contribution of those damages to the total safety index of the ship including the effect of the Stockholm Agreement is shown in the following Table 7.

Table 7 Indices of all damages **not** represented by the SOLAS 90 Reg. II-1/8 one-compartment damage assumptions.

Draft	Displa-cement	HARDER Dam. - SOLAS90 Reg. 8 One-Comp. – Dam-ages = 84.6 percent of HARDER Damages			HARDER Damages
		Index	Index	Index	Index Contribution
	[t]	PS	STB	Mean	Mean
Light	2200	0.472	0.534	0.503	0.425
Partial	2420	0.364	0.480	0.396	0.356
Deepest	2573	0.226	0.225	0.226	0.191

It can be seen in Table 7 that when the Stockholm Agreement is considered additionally to the SOLAS 90 Reg. II-1/8 requirements, the safety index attained to the ship is further drastically reduced compared to the situation of SOLAS 90 Reg. II-1/8 without the Stockholm Agreement, which already attains a lower safety index to the ship compared to the SOLAS 2009 Reg. B-1 standard.

3.5.3 Interpretation of the results

The ship design EMSA1 does not fulfill the Stockholm Agreement requirement for a one-compartment status. Not all of these damage cases are survived. This does especially hold for any combination of Engine Room and RoRo-Compartment. These damage cases have by far the highest probability of occurrence and they are not survived only on the light draft, STB side, but on no other draft or side. This results in the fact that the safety **index** contribution from the cases covered by the standard does not reach the required value of 0.154. In total, the following safety **index values** are achieved: ***Light Draft: 0.574, Partial Draft: 0.500, Deepest Draft: 0.309.*** The values are the sums of the last column in Tables 6 and 7. These results show that on the deepest draft which is the most probable draft for the ship, the total survivability amounts only to 0.309, ***which means that the ship is not going to survive approx. 70 percent of all damages represented by the HARDER distributions*** according to the survivability criteria prescribed by the SOLAS 90 Reg. II-1/8. For comparison purposes it should be mentioned that the new SOLAS 2009 Reg. B-1 standard stated that the ship will not survive about 33 percent of all possible HARDER damages, based on the survivability criteria of SOLAS 2009 Reg. B-1.

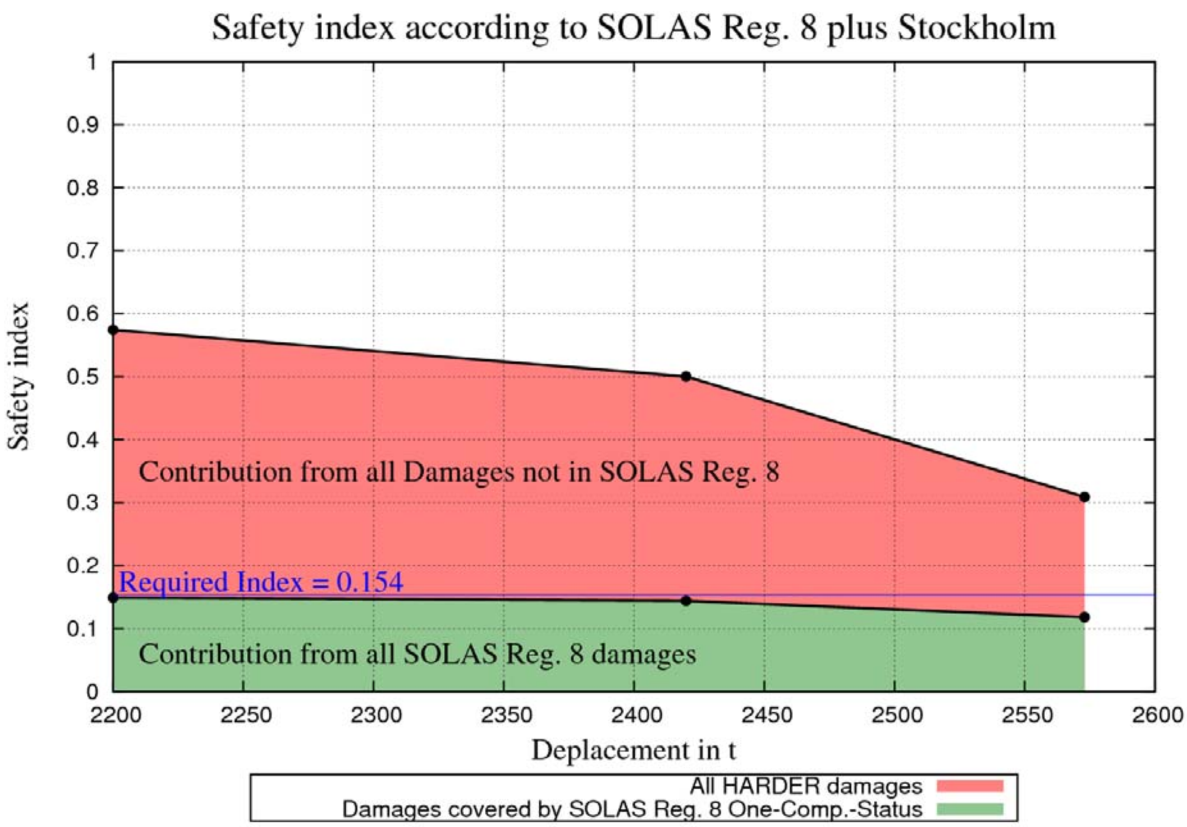

Fig. 7 Visualization of the overall safety index and the different damage contributions for the SOLAS 90 Reg. II-1/8 standard including Stockholm Agreement. The horizontal axis shows the displacement ranging from the value at the light draft (2200t) to the one at the deepest draft (2573 t).

Further it should be kept in mind that the ship still fulfills the SOLAS 2009 Reg. B-1 requirements on the deepest draft with a clear margin, that is, it does not represent the absolute minimum according to the probabilistic SOLAS 2009 Reg. B-1 standard. Therefore there can be little doubt about the fact that for the ship design EMSA1, the requirements of the new damage stability standard are less stringent compared to the SOLAS 90 Reg. II-1/8 standard, and they are drastically lower in comparison with the situation in which the requirements of the SOLAS 90 Reg. II-1/8 in conjunction with the Stockholm Agreement have to be satisfied. The question remains whether the safety level achieved by the new standard is still sufficient for this ship**.** The results are also shown in Figure 7.

3.6 Comparison of the Results obtained for the Different Standards

The overall safety indices of all three standards investigated is summarized in the following Table 8.

Table 8 Comparison of the different safety indices attained to the ship by the investigated standards for the three drafts. Note the strong dependence of the safety indices on the draft. Ideally the level should be the same on all drafts.

Draft	**Safety Index**	**Safety Index**	**Safety Index**
	SOLAS 2009 B-1	SOLAS 90 Reg. 8	SOLAS 90 Reg. 8 + SA
Light	0.782	0.698	0.574
Partial	0.707	0.559	0.500
Deepest	0.667	0.550	0.309
Status	Fulfilled	Fulfilled	Not fulfilled

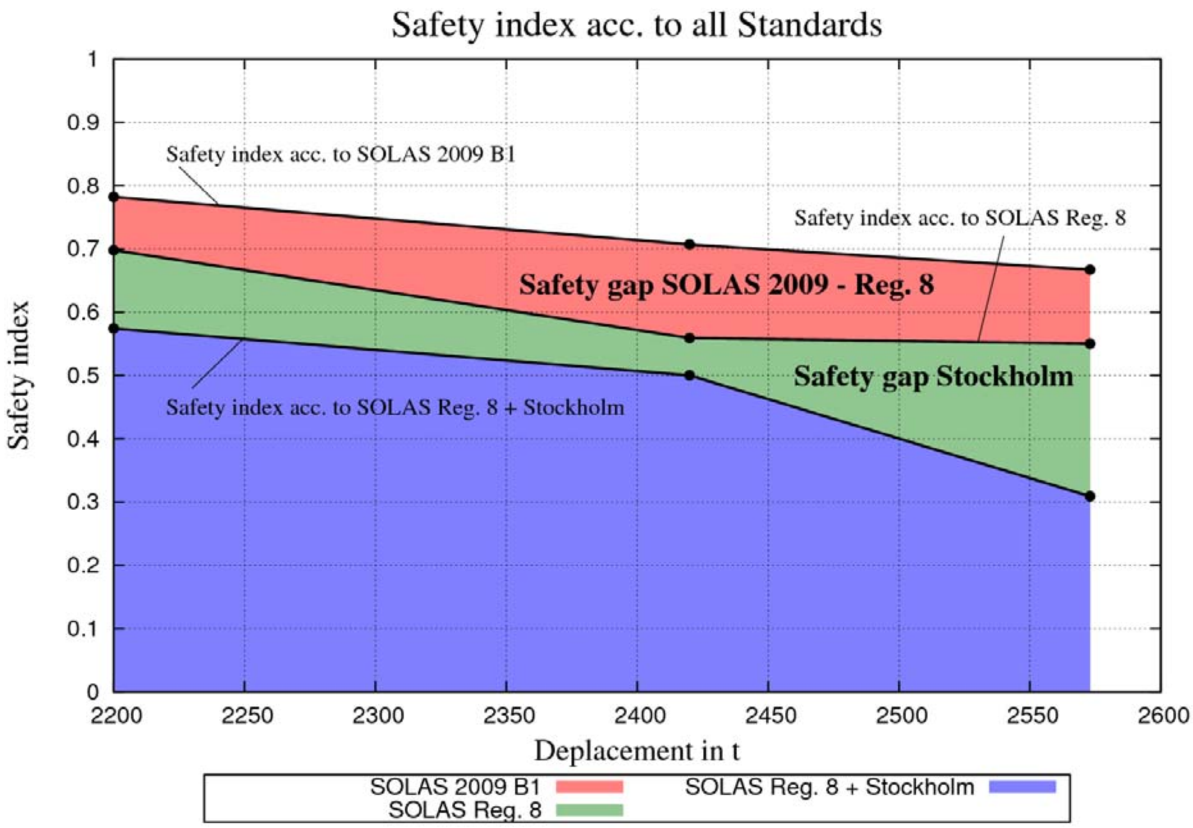

Fig. 8 Comparison of the different safety indices attained for the ship by the investigated damage stability standards. The horizontal axis shows the displacement ranging from the value at the light draft (2200t) to the one at the deepest draft (2573 t).

With respect to the ***formal*** fulfillment of the damage stability standards investigated, the following situation has occurred:

- The ship clearly fulfills the probabilistic SOLAS 2009 Reg. B-1 damage stability standard as well as the SOLAS 2009 Reg. B-1 deterministic standard for the one-compartment status.

- The ship fulfills the SOLAS 90 Reg. II-1/8 damage stability standard for the one-compartment status.

- The ship does ***not*** fulfill the requirements of the Stockholm Agreement for the one-compartment status.

A reasonable design option of increasing the number of persons beyond 400 was theoretically considered. This would have the following impact on the damage stability:

- The ship would with minor alterations fulfill the probabilistic part of SOLAS 2009 Reg. B-1. This design option would result in a two-compartment status for the deterministic part of SOLAS 2009 Reg. B-1. These damage cases would not be survived. The *GM*-required curve for the total SOLAS 2009 Reg. B-1 standard would then only be on the basis of its deterministic part.

- The SOLAS 90 Reg. II-1/8 two-compartment status would then clearly ***not*** be achieved, as the deterministic standard requires $s_i=1$ for all cases, where SOLAS 2009 Reg. B-1 requires $s_i=0.9$.

- The requirements of the Stockholm Agreement would in that case never be met, as most of the two-compartment flooding cases would not have any chance to survive with additional water on the freeboard deck.

These investigations carried out by the TUHH clearly lead to the following conclusions on the ship design EMSA1:

- ***The requirements of the probabilistic part of SOLAS 2009 Reg. B-1 are for this particular ship less stringent compared to the deterministic standard SOLAS 90 Reg. II-1/8.*** This is shown by the fact that SOLAS 2009 Reg. B-1 attains by far the highest total safety index to the ship.

- As the deterministic part of SOLAS 2009 Reg. B-1 is per definition less stringent than the deterministic standard according to SOLAS 90 Reg. II-1/8, it clearly represents a generally lower safety level. So whenever this deterministic part of SOLAS 2009 Reg. B-1 becomes the governing damage stability requirement for a specific ship design, it is obvious that the overall safety level is lower than according to SOLAS 90 Reg. II-1/8.

- If the calculation of water on deck, as required by the Stockholm Agreement requirement, is regarded as a useful contribution to the safety of RoRo passenger ships, it was found for this particular ship that the safety standard represented by the SOLAS 2009 Reg. B-1 lies significantly below the requirements of the SOLAS 90 Reg. II-1/8 in conjunction with the Stockholm Agreement. Even for the one-compartment flooding, the difference in the loss of the safety index, and of the related safety level, is tremendous.

Concluded, for the ship design EMSA1 the TUHH has not found any reason to assume that the safety level represented by the new SOLAS 2009 Reg. B-1 standard would be equivalent to or higher than the SOLAS 90 Reg. II-1/8 standard in conjunction with the Stockholm Agreement requirements. On the contrary, all calculations show that the safety clearly drops down to a significantly lower level. The remaining open question is of course whether this safety level is still sufficient.

As all these computations have quantified the ***difference*** in the safety indices attained to the ship, we will in the following section discuss the absolute safety level achieved for this ship.

3.7 The Effect of Additional Water on the Freeboard Deck

The results of the damage stability calculations according to the Stockholm Agreement for all relevant one-compartment cases on the deepest draft, starboard side, are summarized in the following Table 9. Figures 9 and 10 show the results in a graphical way.

Table 9 Brief summary of damage stability results according to the Stockholm Agreement, one-compartment flooding, deepest draft, starboard side.

Deepest XB   Tap= 4.089 m, Tfp= 4.089 m, KG= 7.780 Stockholm

Nr	Damage case	T ap m	Trim m	Heel Deg.	Range Deg.	hmax m	FBmin m	Note HRALFST	si	pi
1	68.6: 76.4	3.964	0.379	-0.267	20.526	0.222	1.301		1.0000	0.1994
2	57.4: 64.4	3.712	1.243	-0.556	17.784	0.172	1.016		1.0000	0.1431
3	-2.4: 2.8	4.115	-0.047	0.419	21.353	0.191	1.383		1.0000	0.1191
4	2.8: 11.2	4.448	-0.587	1.456	13.859	0.113	1.075	R	0.0000	0.0790
5	28.0: 36.4	4.289	0.156	-3.222	11.776	0.109	1.043	RA	0.0000	0.0635
6	11.2: 16.8	4.583	-0.706	1.830	14.832	0.177	1.026		1.0000	0.0469
7	44.8: 50.4	3.927	0.866	-0.680	15.964	0.143	1.035		1.0000	0.0431
8	36.4: 44.8	4.083	0.867	-0.644	14.888	0.115	0.856		1.0000	0.0337
9	68.6: 76.4	3.964	0.379	0.000	30.000	0.267	0.120		1.0000	0.0320
10	50.4: 57.4	3.745	1.310	-0.768	15.523	0.136	0.941		1.0000	0.0278
11	16.8: 19.6	4.973	-0.799	3.386	3.366	0.046	0.712	RAL S	0.0000	0.0227
12	21.0: 25.2	4.973	-0.799	3.384	3.361	0.046	0.712	RAL S	0.0000	0.0204
13	42.0: 44.8	4.083	0.867	-0.645	12.271	0.109	0.855	RA	0.0000	0.0197
14	57.4: 64.4	3.712	1.243	0.000	30.000	0.259	0.000		1.0000	0.0168
15	2.8: 11.2	4.448	-0.587	1.456	13.859	0.113	1.075	R	0.0000	0.0126
16	28.0: 36.4	4.289	0.156	-3.222	11.779	0.109	1.042	RA	0.0000	0.0120
17	28.0: 36.4	4.289	0.156	-3.222	11.776	0.109	1.043	RA	0.0000	0.0120
18	16.8: 28.0	4.973	-0.799	3.397	3.487	0.047	0.712	RAL S	0.0000	0.0113
19	64.4: 68.6	3.973	0.370	-0.253	20.511	0.223	1.298		1.0000	0.0104
20	-2.4: 2.8	4.115	-0.047	0.419	21.358	0.191	1.383		1.0000	0.0100
21	11.2: 16.8	4.583	-0.706	1.830	14.832	0.177	1.026		1.0000	0.0081
22	8.4: 11.2	4.448	-0.587	1.456	13.859	0.113	1.075	R	0.0000	0.0078
23	36.4: 44.8	4.083	0.867	-0.644	14.887	0.115	0.856		1.0000	0.0074
24	16.8: 28.0	4.973	-0.799	3.397	3.487	0.047	0.712	RAL S	0.0000	0.0071
25	36.4: 44.8	4.083	0.867	-0.644	14.888	0.115	0.856		1.0000	0.0058
26	42.0: 44.8	4.083	0.867	-0.645	12.271	0.109	0.855	RA	0.0000	0.0049
27	67.2: 68.6	3.973	0.370	-0.253	20.511	0.223	1.298		1.0000	0.0049
28	44.8: 50.4	3.927	0.866	-0.680	15.964	0.143	1.035		1.0000	0.0039
29	50.4: 57.4	3.745	1.310	0.000	30.000	0.226	0.234		1.0000	0.0036
30	44.8: 50.4	3.927	0.866	0.000	30.000	0.215	1.035		1.0000	0.0032
31	28.0: 35.0	4.289	0.156	-3.222	11.779	0.109	1.042	RA	0.0000	0.0023
32	44.8: 50.4	3.927	0.866	0.000	30.000	0.215	1.035		1.0000	0.0013
33	64.4: 68.6	3.973	0.370	0.000	30.000	0.269	1.402		1.0000	0.0010
34	36.4: 44.8	4.083	0.867	-0.644	14.887	0.115	0.856		1.0000	0.0010
35	22.4: 25.2	4.089	-1.0E-5	0.451	23.207	0.237	1.411		1.0000	0.0006
36	16.8: 19.6	4.089	-1.0E-5	0.406	23.660	0.237	1.411		1.0000	0.0006
37	11.2: 12.6	4.583	-0.706	1.386	15.121	0.175	0.999		1.0000	0.0006
38	8.4: 11.2	4.089	-1.0E-5	0.335	24.580	0.237	1.411		1.0000	0.0003

The Table 9 lists all relevant damage cases by their forward and aftward x- coordinates. The results of the equilibrium floating condition and the characteristics of the righting levers are given. The last two columns show the s_i- and the p_i- values attained for the damage case according to SOLAS 90 Reg. II-1/8. The former must always be 1 for the Stockholm Agreement requirements to be fulfilled. The p_i–value denotes the total probability of the group of compartments being damaged, which includes the r_i and v_i

probabilities. The column denoted by “Note” gives a remark why the particular case fails to meet the requirements, where R means insufficient Range, L means insufficient righting lever, H means excessive Heel, S means that the required passenger or life boat moments are not achieved. F would mean that a non watertight opening will be submerged.

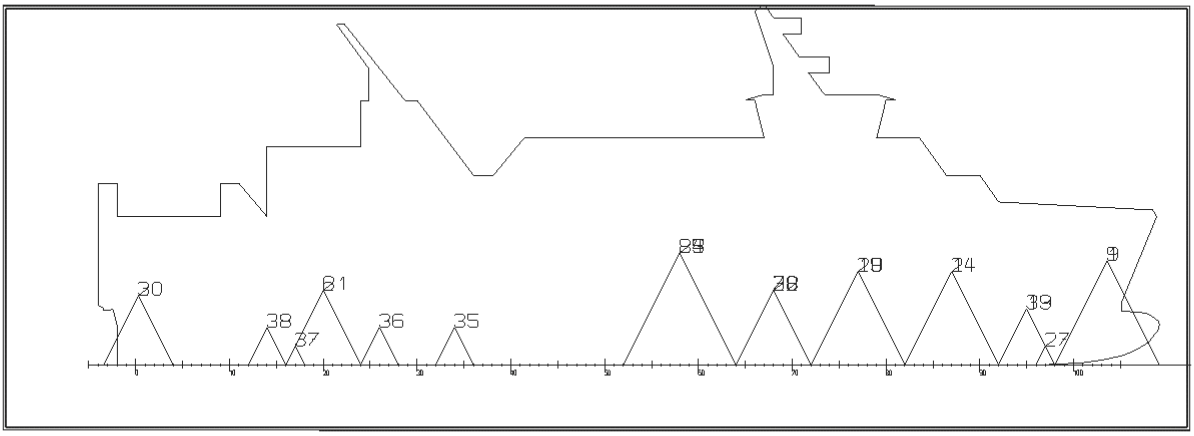

Fig. 9 Illustration of all one-compartment damages that are survived according to the Stockholm Agreement requirements. Deepest draft, starboard side.

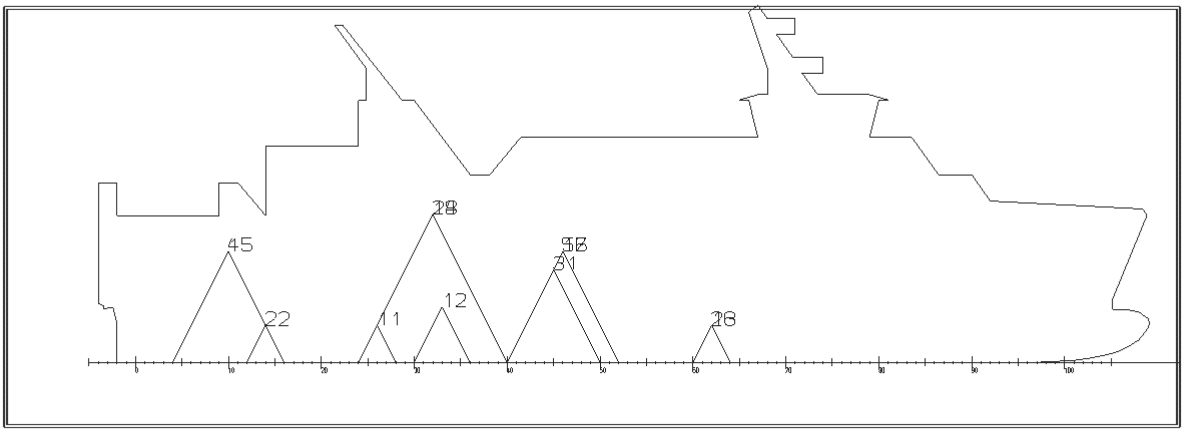

Fig. 10 Illustration of all one-compartment damages that are not survived according to the Stockholm Agreement requirements. Deepest draft, starboard side.

As all cases have been generated on the basis of a Monte Carlo approach using the damage definitions of SOLAS 90 Reg. II-1/8, it is now possible to associate damage probabilities to all cases. All damage cases have been sorted with descending probability of occurrence, and therefore, those cases on top of the list are the most interesting ones. As mentioned before, all cases computed here are ***survived without water on deck***. So, if the Water-on-Deck -assumption shall be analyzed with respect to whether it represents a useful safety element, then those cases, which have the largest difference between the computations with and without water on deck, are the most interesting ones.

The most interesting damage case in this context is Case no. 11. This case includes the Engine Room, RoRo Cargo Hold and Void Space 11. This case was survived on all drafts, and some other combinations of the flooded Main Engine Room together with the RoRo-

Compartment were also not survived. The equilibrium floating condition and the righting levers of that case are shown in the following figure:

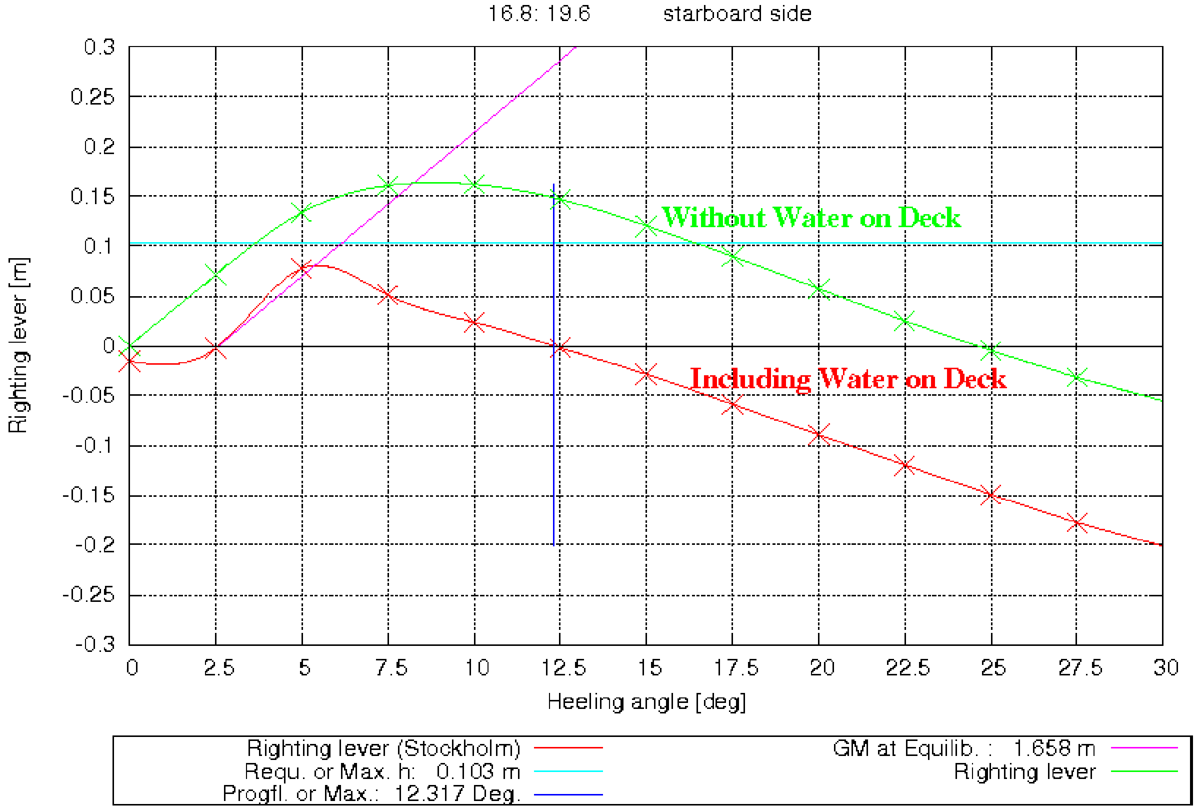

Fig. 11 Righting levers of Damage Case No.11 with and without water on deck according to the computational standard of the Stockholm Agreement.

The comparison of the righting levers computed with and without water on deck shows the significant impact of the water on deck requirement on the survivability of the ship: Without water on deck, the damage case fulfills the prescribed minimum requirements of SOLAS 90 Reg. II-1/8. However, if water on deck is to be considered, the righting levers are significantly reduced, and none of the SOLAS 90 Reg. II-1/8 criteria is fulfilled. The maximum righting lever is about 0.081 m, and the range of positive righting levers is 9.725 degrees. As the residual freeboard in the equilibrium floating condition amounts to 0.712 m, 0.379 m of additional water on deck have to be considered for the computations according to the Stockholm Agreement. This results in the following additional masses of water on deck which are to be assumed according to the calculation procedure prescribed by the Stockholm Agreement:

Table 10 Amounts of additional floodwater on the vehicle deck according to the Stockholm Agreement standard.

Heel [Deg]	0	2.5	5	7.5	10	12.5
Water on Deck [t]	152.6	49.12	25.38	67.19	116.56	168.51

The reference deck edge for the measurement of the additional water on deck becomes submerged at about 4.9 degrees. Already quite small additional amounts of water on the freeboard deck lead to a significant reduction of the righting levers, which then leads to the consequence that this damage case would probably ***not*** survive according to the

Stockholm Agreement standard. This is likely, because the resulting righting levers including water on deck are of small magnitude only. This may be seen as a hint that the ship cannot survive even quite small additional heeling moments. Further calculations have shown that if the ship shall survive this damage case, the *KG* needs to be lowered by about 0.35m. ***As this case is the worst one, this would imply that the whole limit of stability on the deepest draft must be increased by about 0.35 m to make this ship compliant with the requirements of the Stockholm Agreement.***

It is interesting to note that according to the new SOLAS 2009 stability standard, this case would get an attained basic probability of survival of s_i **= 0.8003,** and including the s_{mom} reduction, s_i would still amount to **0.398,** whereas the deterministic standard clearly attains s_i**=0.** This may also serve as a reason why the probabilistic SOLAS 2009 Reg. B-1 is found to be less stringent for this ship EMSA1.

As a conclusion, we can summarize the findings on this damage case as follows:

- Without any consideration of additional water on deck, this case is survived according to both the SOLAS 2009 Reg. B-1 and the SOLAS 90 Reg. II-1/8.

- Including water on deck, this case is not survived according to the SOLAS 90 Reg. II-1/8 criteria. The SOLAS 2009 Reg. B-1 would attain a probability of survival of about 0.4 to that damage case.

- The analysis has shown that the ship cannot survive even a quite small amount of water on deck, which represents quite a small additional heeling moment.

TUHH recommends this case for a further study by more sophisticated methods compared to the simple hydrostatical analysis. It should be mentioned that the following situations may occur after a more detailed study:

- The detailed analysis may show that in fact this damage case is survived.

- The detailed study may show that this case is not survived. In this case, it is throughout possible that ***the detailed investigations show that the water ingress on the freeboard deck is even higher than according to the assumptions of the Stockholm Agreement. In this case, further investigations might be considered.***

Besides this damage case which according to analysis presented is the most important one, TUHH have also suggested other cases to HSVA for further investigation. These cases are less severe compared to Case No. 11, but they include damages concentrated at the ship forward and aftward terminal, which might later give a hint about the reliability of such kind of hydrostatical calculations. But in principle, all other cases selected have in common that they are seen as survived without water on deck and they do ***not survive even with quite small additional volumes of water on the freeboard deck.*** The mentioned Case No. 11 is the Damage Case 1 of the ship design EMSA1 in the HSVA analysis following.

3.8 Remarks on the Overall Safety Level of the Ship Design EMSA1

The above mentioned investigations clearly show that the new damage stability regulations can lead to a reduction of the overall safety level of the particular ship analyzed. As soon as water on deck is to be considered as an additional requirement, the safety level of the ship falls down to a level, which the TUHH regards as clearly not acceptable. ***The determination of the absolute safety indices including water on deck by TUHH has shown that the ship will on the deepest draft sink or capsize***

in about 70 percent of all possible HARDER damages according to the damage stability standard survival criteria. This is certainly sufficient to raise a serious concern, as calculations of existing RoRo- passenger ships fulfilling the SOLAS 90 Reg. II-1/8 standard have shown significantly higher safety indices. In the present situation it may be useful to give an explanation for the large fall in the total safety index attained to the ship design EMSA1.

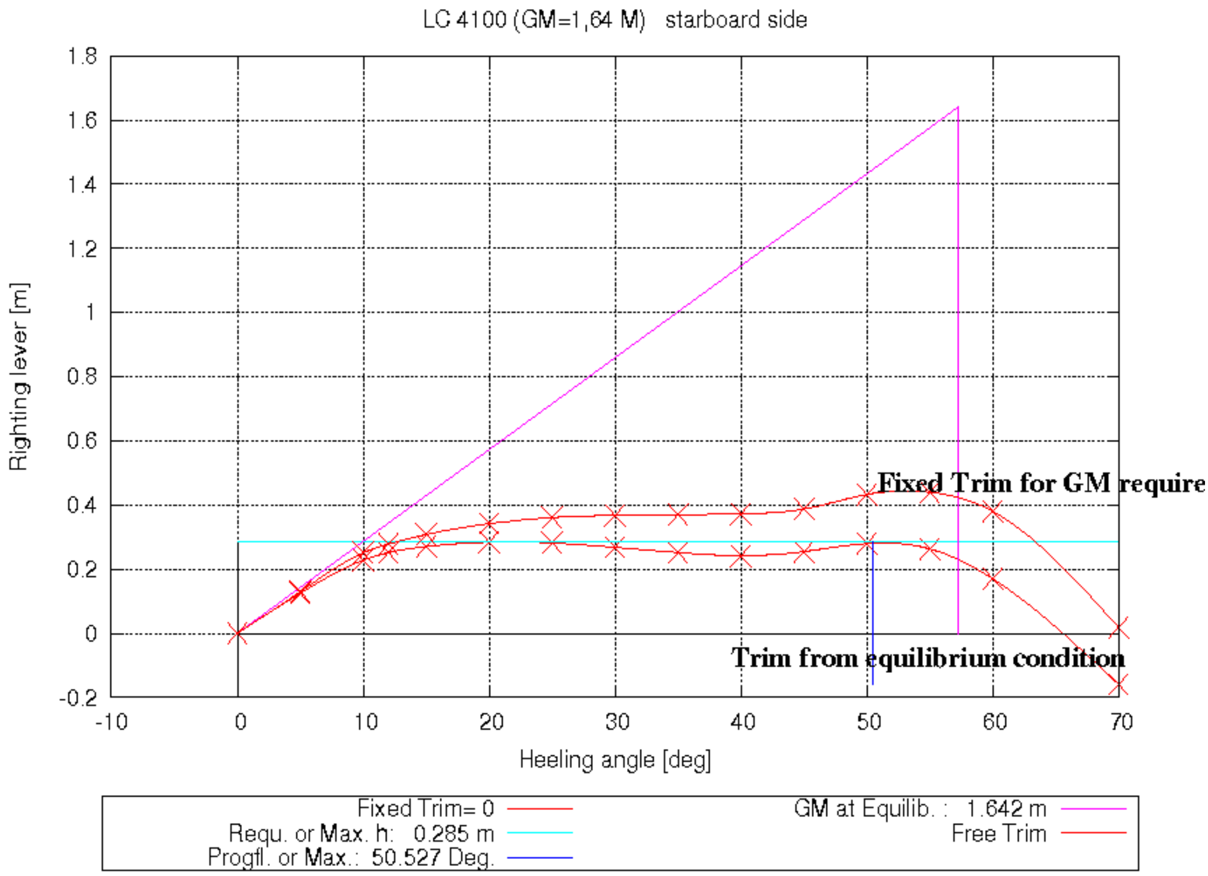

Fig. 12 Righting levers for the intact condition according to the intact stability standard compared to the righting levers based on the trim chosen from equilibrium condition.

The basic reason behind all the problems related to the survivability in damaged condition is that this ship suffers from an insufficient level of stability in general. The stability level of this ship design is governed by the ***intact stability criteria***. This is in fact a ***new*** situation: It used to be a well known rule for RoPax-designers that the limiting stability, at least for the deeper drafts, was always governed by the ***damage stability requirements***. But as shown in the previous sections, the damage stability criteria according to SOLAS 2009 Reg. B-1 are less stringent for this particular ship compared to SOLAS 90 Reg. II-1/8. Therefore, it has now become possible to reduce the limiting stability to the level required by the intact criteria. Further, the absolute fall in the safety level of the new criteria is so large that for this particular ship it has now become possible to fulfill the damage stability requirements with *GM*-values obtained on the basis of intact stability calculations with ***fixed trim***. The righting lever curve on the deepest draft, which belongs to this fixed trim *GM*-required curve, is shown in Figure 12. together with the free trimming righting levers, which represent the real (hydrostatic) physics.

Figure 12 illustrates the main problem of this particular ship design: It is possible to fulfill the existing intact stability criteria with the righting lever curve obtained for the fixed trim. But the other righting lever curve, computed correctly with the trim that has been chosen for the equilibrium floating condition, shows that the actual righting levers are of a very small magnitude only. Even worse, beyond approx. 20 degrees, the values of the righting levers decrease steadily, which means that any permanent heeling moment, which would heel the ship beyond the angle of 20 degrees, would ***automatically lead to the capsize of the ship even in intact condition****.* The absolute value of the maximum righting lever, which occurs at the angle of 20 degrees, represents a small tolerable heeling moment. This clearly explains the reason, why this ship cannot survive any substantial heeling moment in damaged condition. Further, it is quite clear that the additional water on deck requirement according to the Stockholm Agreement represents such an additional heeling moment. If the Stockholm Agreement requirements were applied to the ship, this would require an increase of the initial metacentric height of approx. **0.35m** in order to fulfill this more stringent stability requirement. In this case, the limiting stability curve would then not be governed by the intact criteria, but by that damage stability requirement.

In this context, it is important to notice that the safety gap between SOLAS 90 Reg. II-1/8 plus Stockholm Agreement compared to the probabilistic part of SOLAS 2009 Reg.B-1 would for this particular ship be drastically larger in case the number of passengers would have been increased, requesting the ship to fulfill the two-compartment status.

The main reason for the problem of the application of the new damage stability regulations for this ship can be described with the fact that it is possible to fulfill those requirements with stability values taken from the intact stability curve, provided that the subdivision is reasonable. It has been put forward by several authors in the past (including TUHH and FSG), that the actual limit for the intact stability is too low for the ships types, which are characterized by flared hull forms. This observation made the development of additional criteria for dynamic stability necessary. However, this was not regarded as a serious problem in the past, because the ***minimum stability requirement*** was anyway ***determined by the prescribed damage stability codes***, which were SOLAS 90 Reg.II-1/8 one- or two-compartment status plus Stockholm Agreement requirements for RoRo-Passenger ships. Now, the analysis for this particular ship shows that the SOLAS 90 Reg. II-1/8 even without the Stockholm Agreement requirements would attain a lower safety index to this design. The additional water on deck requirement results clearly in the lowest safety index attained to the ship. Therefore, the following arguments connected to the total safety regime can be forwarded to explain the drastic reduction in the safety level of the ship EMSA1:

- ***The new damage stability regulations lead into the situation, in which there is no need to increase the stability beyond the values determined by the intact criteria.***

- ***The level of stability is exactly reduced to that one which is represented by the intact stability criteria, which appears to be too low for this particular ship.***

Based on the findings of the investigation of the ship design EMSA1, the TUHH suggests the following actions to be considered:

- ***First, a water on deck requirement (equivalent to SA) shall be worked into the stability regulations to ensure that this condition is represented correctly.***

- ***Second, an equivalent level of safety as with SOLAS 90 Reg.II-1/8 without water on deck shall be achieved for a RoRo- Passenger ship on all drafts.***
- ***Third, a sufficient level of safety represented by the intact stability criteria shall be achieved in such a way that the stability values attained to the ship are large enough as such, without improvements by the secondary means of damage stability requirements.***

3.9 Stability Assessment according to the Internal Standard of FSG

For this particular project, FSG had the task to design a ship which fulfills the new damage stability requirements of SOLAS 2009 Reg. B-1 at the lowest possible level. The purpose here was to exploit the design options in the framework of the new stability requirements. It was found that this particular ship design complies with the rules at a generally low level of stability. It should be noticed that this ship does not comply with the internal stability standard of FSG, which would have led to better stability of the designed vessel. Thus, the ship design EMSA1 is not a typical vessel designed by FSG, but a design complying with the new stability requirements SOLAS 2009 Reg. B1 at its minimum.

FSG uses an internal stability standard of higher level compared to the IMO stability regulations, which can overrule the IMO requirements in case they are found too low.

The minimum stability of the ship according to the internal FSG standard is obtained for a specific hull form from the requirement that the ship shall have sufficient stability to prevent capsizing events in heavy weather. This procedure is based on the evaluation of the righting levers in the conditions wave crest and trough, or, alternatively, by numerical simulations.

According to that internal standard, the minimum stability attained to the ship design of EMSA1 should be elevated by approx. 0.7 m by a reduction of *KG* (see Figure 4). As this is technically not possible, the internal stability requirement of FSG would result in alternative design measures, which would lead to better stability characteristics in comparison with the present design. Regardless of how the increase in safety level with respect to the stability would be achieved, the internal stability standard of FSG would result in the situation that the ship would fulfill the Stockholm Agreement requirements and the new SOLAS 2009 Reg. B-1 stability standards without problems, as its nominal stability would be sufficient. This is because the ship design EMSA1 does not suffer from a poor subdivision, but from a lack of stability in general.

4 Numerical Simulation of the Behavior of the Damaged Ship EMSA1 in Seaway

4.1 Introduction

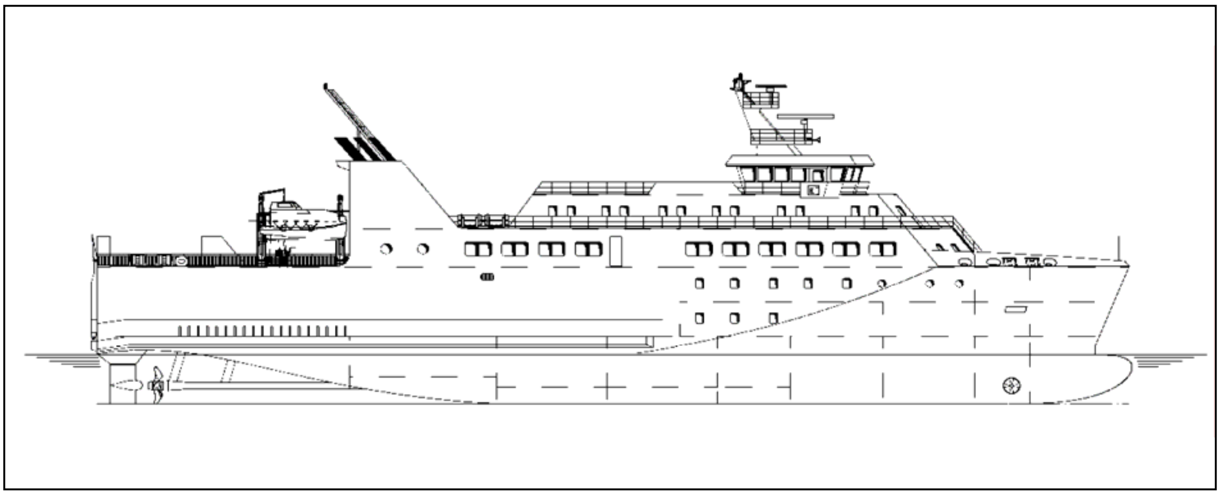

Fig. 13 First investigated ship EMSA1, a 80 m Ro-Ro Passenger Ferry.

The first ship to be investigated in seaway with the numerical simulation with the HSVA ROLLS is the small Ro-Ro Passenger Ferry EMSA1. The design of the vessel satisfies the requirement of the SOLAS 2009 rules, but not those of SOLAS 90 in conjunction with the Stockholm Agreement. The main particulars of the ship are shown in Table 11.

Table 11

Main Particulars of the Vessel: 80 m Ro-Ro Passenger Ferry: FSG Project No. 08-008	
Length over all, LOA	79.20 m
Length between perpendiculars, Lbp	73.60 m
Breadth moulded	16.00 m
Breadth over fenders	16.90 m
Draught (design)	4.00 m
Draught (summer loadline)	4.10 m
Depth to main deck	5.50 m
Displacement	2512 m^3
Waterplane area at draught 4.1 m	916.5 m^2
Vehicle Deck area	~ 640 m^2
Service speed	14.5 kn
Main Engines	2 x 1020 kW
Car lane meters	165 m
Passenger capacity	300
Crew	22

The water flooding on the vehicle deck of the vessel is an important detail to be modeled in the numerical simulations with the HSVA ROLLS. A watertight bulkhead at the front end on frame number 60 of the vessel was introduced for a somewhat easier modeling of the flooding of the vehicle deck. This bulkhead closes out a possible flow of water from the vehicle deck to the bow compartments, which would be quite complicated to model properly, but which are not really relevant for the damage cases to be studied.

On the vehicle deck there are compartments on both sides forming the side casings. Some of these compartments are watertight and totally separate. Thus they can be excluded from the vehicle deck model. The other compartments are non-watertight and are modeled. There are basically three alternative ways to model these small compartments: (1) The non-watertight walls are ignored, and the water can flow freely through; (2) The walls with closed doors are modeled as non-watertight elements. This is very difficult to do properly and reliably; (3) The non-watertight walls are modeled as watertight, but all doors and openings to these spaces are modeled as completely open. Thus the water can flow into these compartments, but it cannot slosh freely through the walls. This last alternative (3) is considered to be the best choice for modeling these compartments.

Figure 14 shows the modeled compartments on the vehicle deck. The shallow-water equations used for modeling the fluid flow are solved with a random choice method on 111 x 40 grid covering the deck area 44.4 m x 16 m. The grid spacing is 0.4 m in both directions. The damage opening in each damage case modifies the numerical grid on the vehicle deck only locally. The width of the side compartments is about 2.6 m, that is, 0.1625 B.

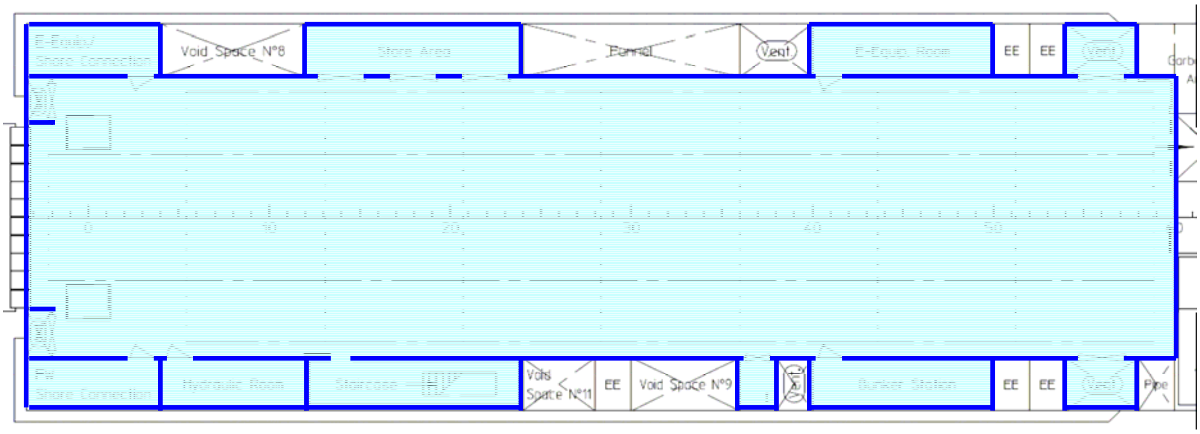

Fig. 14 The vehicle deck as modeled in the simulations with the HSVA ROLLS.

In the following chapters the survivability of the vessel in a few chosen damage cases will be investigated with numerical simulations in irregular long–crested seas. Some selected damage cases will also be further investigated with seakeeping model tests in the HSVA.

4.2 Damage Cases

Four damage cases were suggested by the TUHH for further investigation. The vessel survives these chosen damage cases according to the SOLAS 2009 rules only barely, but does not survive them according to SOLAS 90 in conjunction with the Stockholm Agreement. The Table 12 below gives the extent of these damage cases.

Table 12

DAMAGE CASE	DAMAGED COMPARTMENTS
Damage Case 1	RoRo Cargo Hold Void Space 11 Engine Room
Damage Case 2	RoRo Cargo Hold Pump/ Switchboard Room
Damage Case 3	RoRo Cargo Hold Void Space 08 Steering Gear Room
Damage Case 4	RoRo Cargo Hold Pump/ Switchboard Room ECR/Sewage/A.C. Room Void Space 05 Void Space 06
Damage Case 4LE	RoRo Cargo Hold Pump/ Switchboard Room ECR/Sewage/A.C. Room

The damage cases are further illustrated in Figures 15-19 below.

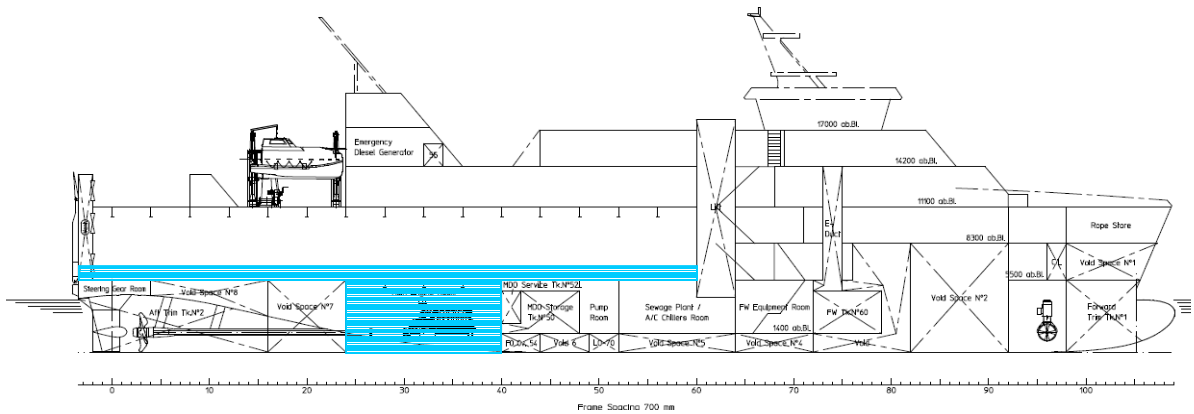

Fig. 15 Damage Case 1.

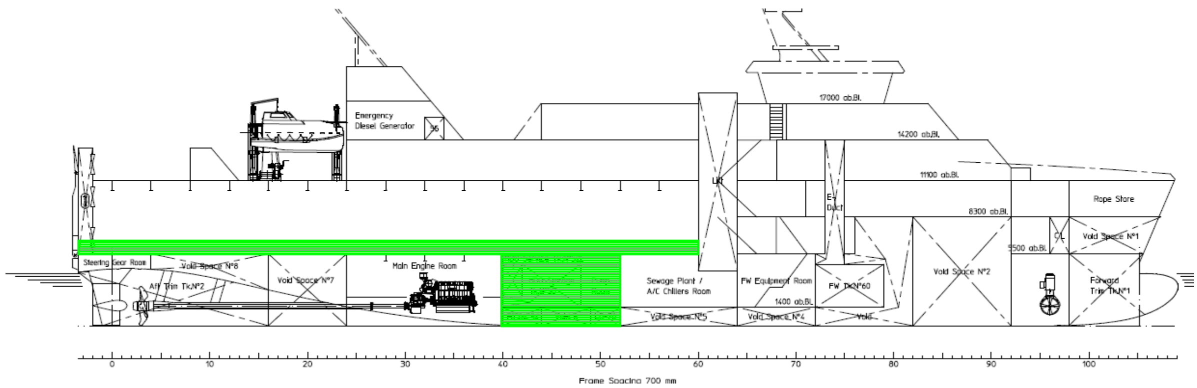

Fig. 16 Damage Case 2.

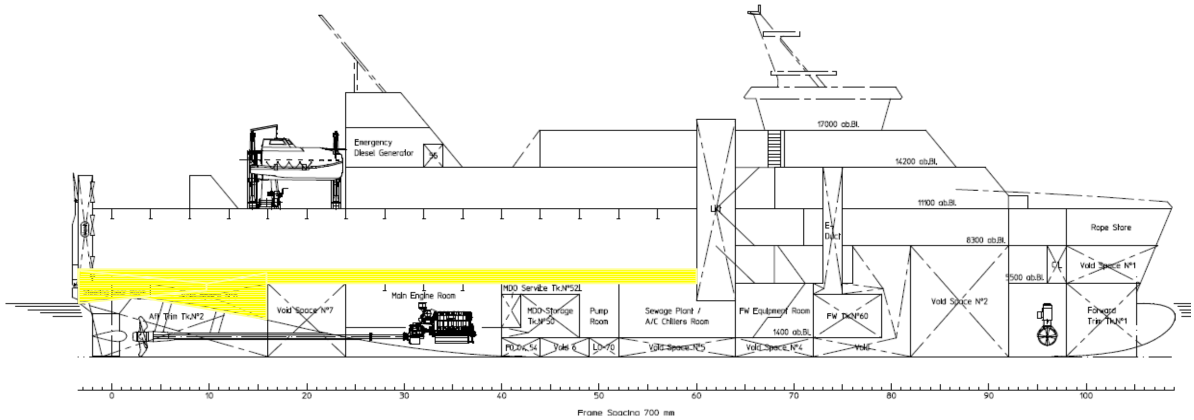

Fig. 17 Damage Case 3.

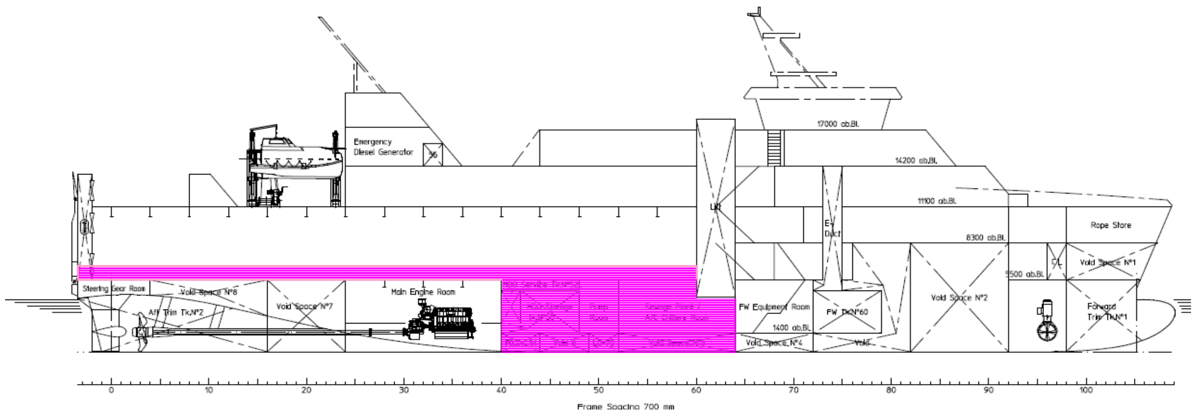

Fig. 18 Damage Case 4.

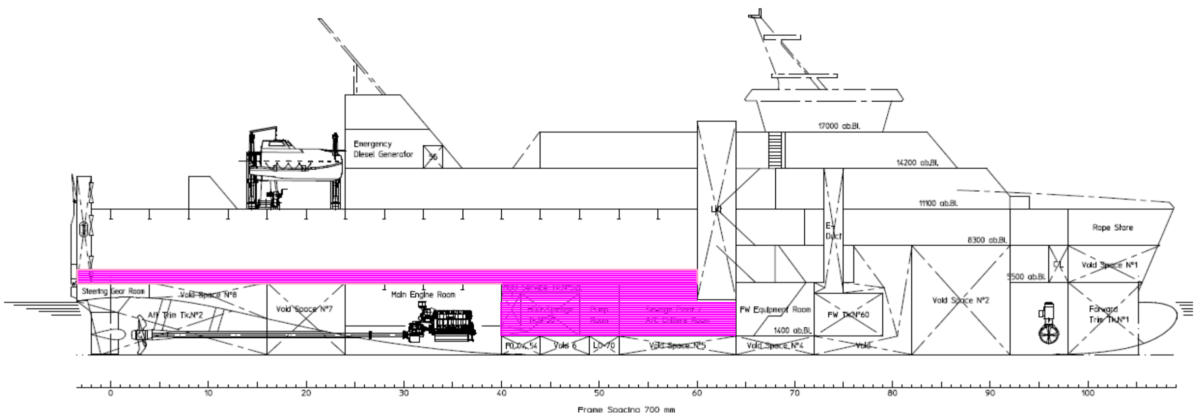

Fig. 19 Damage Case 4LE.

4.3 Initial Simulations

The damage cases were investigated with the program HSVA ROLLS. The significant wave height value (H_s) of 4.0 m was used. The natural rolling period of the damaged ship was determined to be 11.8 s with a numerical roll decay test with the ship having water on the vehicle deck and in the damaged compartments. In all simulations the mentioned natural rolling period of the damaged ship (11.8 s) was used as the modal wave period in the JONSWAP-spectrum together with the peak parameter value γ of 3.3 for the wave generation. Thus in the numerical simulations the modal wave period of the generated wave spectrum is the (numerically determined) natural rolling period of the vessel.

The damage opening on the starboard side was chosen to be always 2.208 m wide, which is 3 percent of the L_{bp}. Also the opening to the vehicle deck had always this width. It should be noticed that the damage width is smaller than that defined in the Annex of the Stockholm Agreement. The damage opening height was limited to the height of the compartment in question.

First it was investigated how long the vessel would survive in practically beam seas coming from the side of the damage, with the wave direction 85°, in a sea state having a significant wave height 4.0 m. The capsize events were taken as roll angle of more than 30° against the vertical axis, occurring more frequently than in 20 percent of the rolling cycles, or steady heel greater than 20°. The vessel survives, when the capsize criteria is not met in 30 minutes and a stationary state is reached. This criteria follows from the Stockholm Agreement.

The first simulations were performed in each damage case with only one random seed for the wave realization of the irregular seas: ***In none of the investigated damage cases the vessel designed to fulfill SOLAS 2009 could survive the sea state with the significant wave height of 4.0 m.*** As the first results turned out to be very significant, the simulations were repeated with 10 different random seeds for the wave realization. These results are shown in Table 13.

Table 13 The simulation results of the Ship EMSA1, a 80 m RoRo Passenger Ferry, in beam seas with the original *KG* of 7.78 m and with a significant wave height H_s of 4.0 m. Ten different random seeds were used for the wave realization in the simulations.

KG = 7.78 m, as designed. Significant wave height H_s = 4.0 m				
Damage Case	Final Condition after 30 min.		Max. time to Capsize [min]	Survival Criteria satisfied
	Steady Heel no. [-]	Capsize no. [-]		
DACA 1	1/10	9/10	2.5	No, Capsize (9) or List > 35° (1)
DACA 2	0	10/10	2.3	No, Capsize
DACA 3	0	10/10	1.0	No, Capsize
DACA 4	2/10	8/10	7.5	No, Capsize (8) or List > 22° (2)
DACA 4 LE	0	10/10	5.8	No, Capsize
SUM	3	47	Av. 3.7	No

According to these results the vessel would capsize in less than 7.5 minutes in 47 cases out of 50, which amounts to 94 percent. In 3 cases (6 percent) a steady list was reached, which was high enough to make evacuation of the passengers and crew on the ship either impossible or very difficult and slow. As the simulation was ceased after 30 minutes, a later capsize also in these cases cannot be ruled out. On the contrary, the possibility of later capsizing can be regarded as considerable due to the statistical distribution of the capsize times, which can be quite wide in relatively low sea states.

The use of a wider damage opening would further shorten the survival times. After these first important results it was studied: (1) At which significant wave height the vessel survives; (2) at which *KG* or *GM* -values the vessel survives in a sea state of H_s 4.0 m. The results are shown in Table 14.

Table 14 The simulation results of the EMSA Ship 1 in beam seas with a *KG* of 7.78 m, and with a significant wave height H_s of 4.0 m. Only one random seed for the wave realization was used in the simulations.

KG = 7.78 m, as designed. Survival H_s				Sea state H_s = 4.0 m, Survival *KG*			
Damage Case	H_s [m]	Water Vol on V-Deck [m³]	Water Vol in Comp. [m³]	*KG* [m]	*GM* [m]	Water Vol. on V-Deck [m³]	Water Vol. In Comp. [m³]
INTACT	> 4.00	0	0	≤ 7.78	≥ 1.64	0	0
DACA 1	≤ 1.15	~ 138	~ 700	≤ 5.55	≥ 3.87	~ 1300	~ 750
DACA 2	≤ 1.70	~ 42	~ 180	≤ 5.70	≥ 3.72	~ 500	~ 140
DACA 3	< 0.80	0	~ 200-250	≤ 5.10	≥ 4.32	~ 1350	~ 410
DACA 4	≤ 2.40	~ 80	~ 600	≤ 6.50	≥ 2.92	~ 950	~ 1200
DACA 4 LE	< 0.80	0	~ 300	≤ 5.90	≥ 3.52	~ 1250	~ 970

The second column from left shows the significant wave height H_s, at which the vessel having a *KG* of 7.78 m survives. This limiting significant wave height was obtained by lowering the wave heights starting from 4.0 m until the state of survival was reached. Notice that the freeboard is less than 1.5 m to the damaged vehicle deck and that the low waves bring only little water onto the vehicle deck. In Damage Cases 3 and 4LE no state of survival could be reached with the lowest applied wave height of 0.8 m: The simulations resulted in a steady heeling angle of more than 20° at all significant wave heights tested, even if no water entered onto the vehicle deck in these two damage cases, as shown in Table 14.

The 5th column shows the *KG*-values, at which the vessel survives in a sea state of H_s 4.0 m. The limiting values of *KG* or metacentric height *GM* were obtained by lowering the *KG* until the vessel survives in the almost beam seas (dir. 85°) in the sea state of H_s 4.0 m. Due to the significant wave height 4.0 m, to the low freeboard to the damaged vehicle deck (< 1.5 m) and due to the high *GM,* a large amount of water can accumulate onto this deck without the vessel capsizing. The vehicle deck has a surface area of ca. 640 m². The simulations with the HSVA ROLLS show that in some damage cases there can be about 2 m of water on the vehicle deck. This is much more than the maximum water height (0.5 m) assumed in the Stockholm Agreement. *It should be kept in mind that we have not checked here, whether the obtained KG- values sufficient for survival would be realistic from the point of view of the ship design.*

As well it is important to notice that ***the derivation of the Stockholm Agreement calculation procedure is implicitly bound with the SOLAS 90 rules***. If the SOLAS 2009 rules allow for a ship design a lower freeboard to vehicle deck or different (initial) stability than the SOLAS 90 rules, also the most likely height of water on the vehicle deck to be applied in a calculation procedure like the Stockholm Agreement can change. This is not insignificant, as the water ingress on the vehicle deck in a damage case is sensitive to the wave height and the actual freeboard depending also on the ship motions. Thus if the Stockholm Agreement provides a sufficient level of safety in conjunction with the SOLAS 90 rules, it does not mean that this is the case, when the Stockholm Agreement requirements are used in conjunction with the SOLAS 2009.

The ship EMSA1 does not fulfill the Stockholm Agreement with the *KG* 7.78 m. According to the TUHH in order of the requirements of the Stockholm Agreement to be filled the *KG* has to be reduced to 7.30 m. With this value of *KG* the ship, however, does not according to the HSVA simulations survive any of the Damage Cases 1- 4/4LE in a sea state of significant wave height 4.0 m. See Table 15. This example shows that the Stockholm Agreement calculation procedure is not always suitable for a direct application on a ship designed according to SOLAS 2009 requirements.

Table 15 The simulation results of the ship EMSA1 with a *KG* of 7.3 m in beam seas of H_s 4.0 m. Only one wave realization was used in the simulations.

	H_s [m]	*KG* [m]	*GM* [m]	Water Vol. on V-Deck [m³]	Water Height on V-Deck [m]	Water Vol. In damaged Comp. [m³]	Final Condition after 30 min.	
							Time to Capsize [min]	Steady Heel [°]
DACA 1	4.0	7.30	2.12	~ 235	0.37	400- 240	-	32
DACA 2	4.0	7.30	2.12	~ 200	0.31	180- 240	~ 6	-
DACA 3	4.0	7.30	2.12	160 - 230	0.25 -0.36	300- 400	~ 2	-
DACA 4	4.0	7.30	2.12	~ 500	0.78	500 -700	~ 6	-
DACA 4LE	4.0	7.30	2.12	1270-1450	1.98 -2.26	~980	~ 2	-

As the vessel does not survive, but capsizes in most cases relatively rapidly, no significant conclusions can be drawn on the amount of water on the vehicle deck, except that the lower *KG* or higher *GM* -values on the r.h.s. of Table 14 provide more stability resulting in more water entering the vehicle deck than in the cases of Table 15, in which the vessel capsizes already at smaller amounts of water on the vehicle deck. This is not unexpected.

4.4 Further Simulations with Different Realizations of the Sea State

4.4.1 Introduction

The Damage Cases 1 and 4 were considered most interesting for further investigations. The damage openings are located in the midship area of the ship and they represent potentially likely damage locations. In the Damage Case 2 the damage opening is located just beside that of the Damage Case 1. Therefore the Damage Case 2 was not preferred. The survivability of the vessel in the Damage Case 3 is so low that the need for further investigations is not very high. After the initial simulations the Damage Cases 1 and 4 were investigated with 10 random seeds for the sea state realizations with the survival wave heights 1.15m, and 2.40 m, respectively.

4.4.2 Damage Case 1 with *KG* 7.78 m and H_s 1.15 m

The Damage Case 1 on the original design of the ship EMSA1 with *KG* 7.78 m was investigated in a sea state having a significant wave height of 1.15 m using random seeds 1-10 for the sea state generation in the simulations. This is an extension of the first results shown in Table 14:

The ship survives this damage case in 7 simulations out of 10. Therefore it can be concluded that the H_s 1.15 m is quite a good limit value. With some simplifications we can assume that in general the ship survives the Damage Case 1 in sea states with H_s somewhat lower than 1.15 m. In those 3 cases the ship does not survive, it would capsize. Thus these cases would lead into a catastrophe, not into a stable state with a high heeling angle. The vessel heels first slightly to the damaged starboard side, but capsizes later to the port side. Figures 20 and 21 illustrate the behavior of the vessel and flooding of the vehicle deck in one of the simulations.

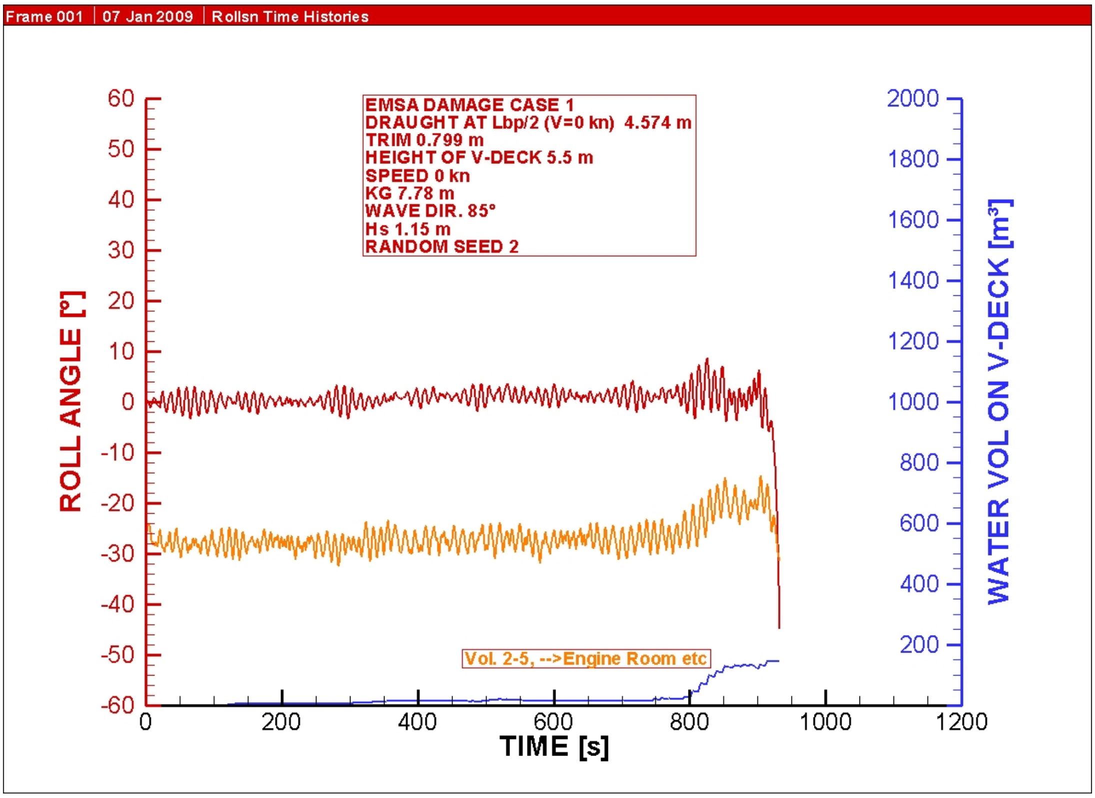

Fig. 20 The heeling angle and the water volumes on the vehicle deck and in the engine room as a function of time.

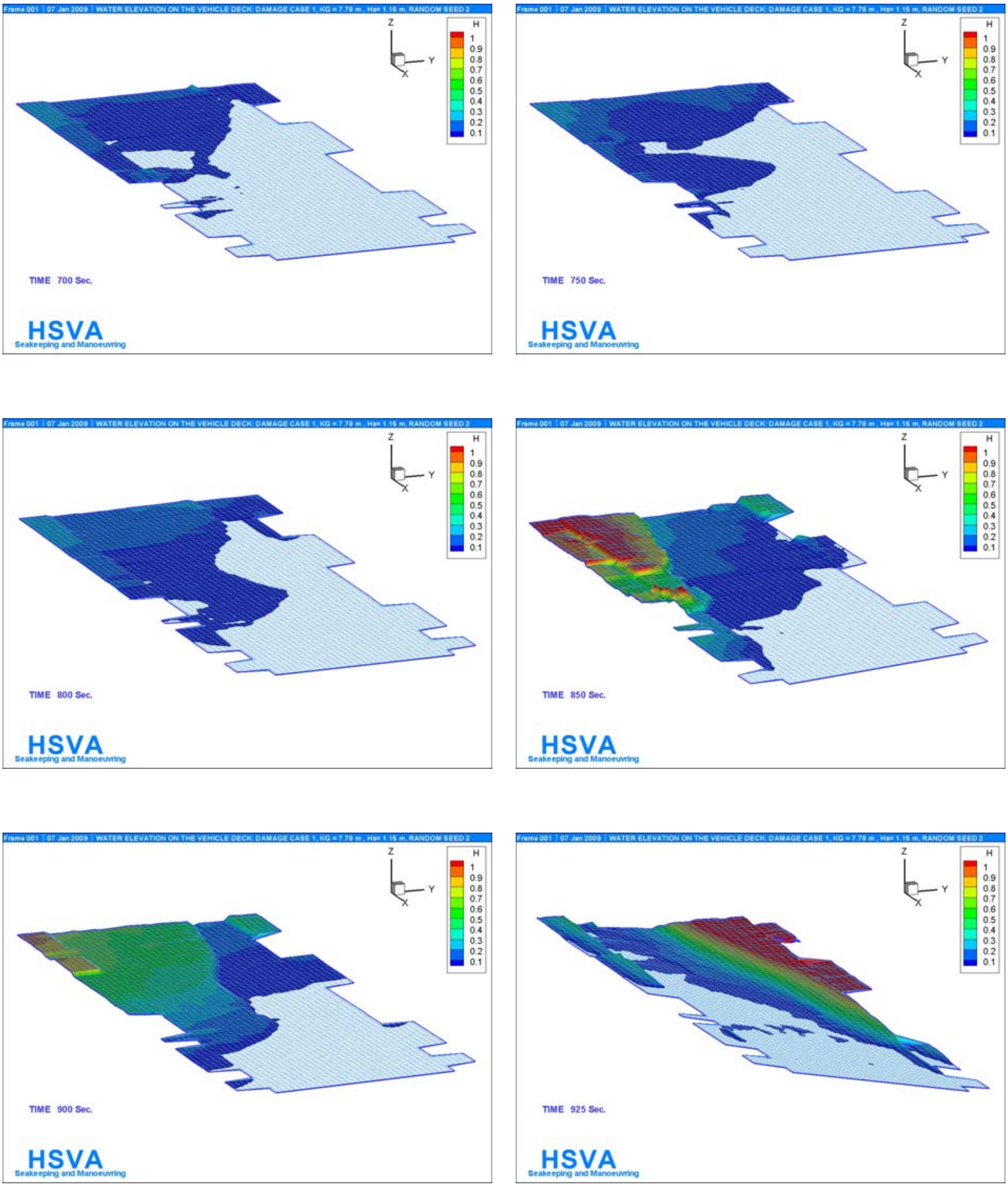

Fig. 21 Screenshots of the vehicle deck flooding according to the simulation with the HSVA Rolls at times 700, 750, 800, 850, 900, 925 s. The coloring expresses the water height on the deck perpendicular to the deck. Damage Case 1, *KG* = 7.78 m, H_s = 1.15 m, random seed 2. The stern of the vessel is located in the left upper corner, the bow in the lower right corner in each figure.

Notice that the vessel having the damage on the starboard side heels first slightly towards the damaged starboard side, but capsizes at the end on the undamaged port side.

4.4.3 Damage Case 1 with H_s 4.0 m and *KG* 5.55 m

The Damage Case 1 on the original design of the ship EMSA1, however with *KG* 5.55 m, was investigated in a sea state having a significant wave height H_s of 4.0 m using random seeds 1-10 in the simulations. This is an extension of the first results shown in Table 14:

The ship survives this damage case in 6 simulations out of 10. In all cases a stable state was reached, but in the 4 cases of failed survival criterion the average heeling angle exceeds 20°. Based on the results it can be concluded that the *KG* -value 5.55 m is quite a good limit value for survival in the sea state with the H_s of 4.0 m. With some simplifications we can assume that in general the ship survives the Damage Case 1 the sea state H_s 4.0 m with the *KG*-value lower than 5.55 m. This means that the ship survives the damage case with a *GM*-value 3.87 m, instead of the original 1.64 m. In all simulations the ship heels to the undamaged port side.

4.4.4 Damage Case 4 with *KG* 7.78 m and H_s 2.4 m

The Damage Case 4 on the original design of the ship EMSA1 with *KG* 7.78 m was investigated in a sea state having a significant wave height of 2.40 m using random seeds 1-10 for the wave generation in the simulations. This is an extension of the first results shown in Table 14:

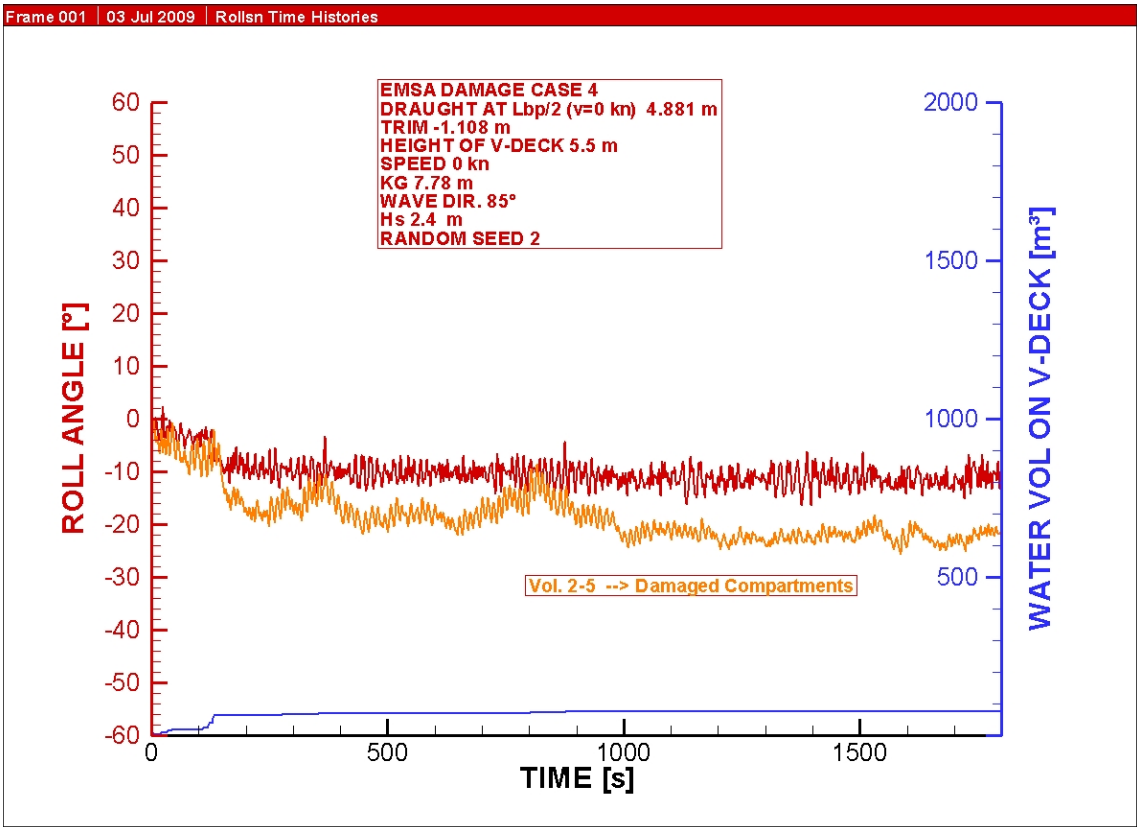

Fig. 22 The heeling angle and the water volumes on the vehicle deck and in the damaged compartments as a function of time.

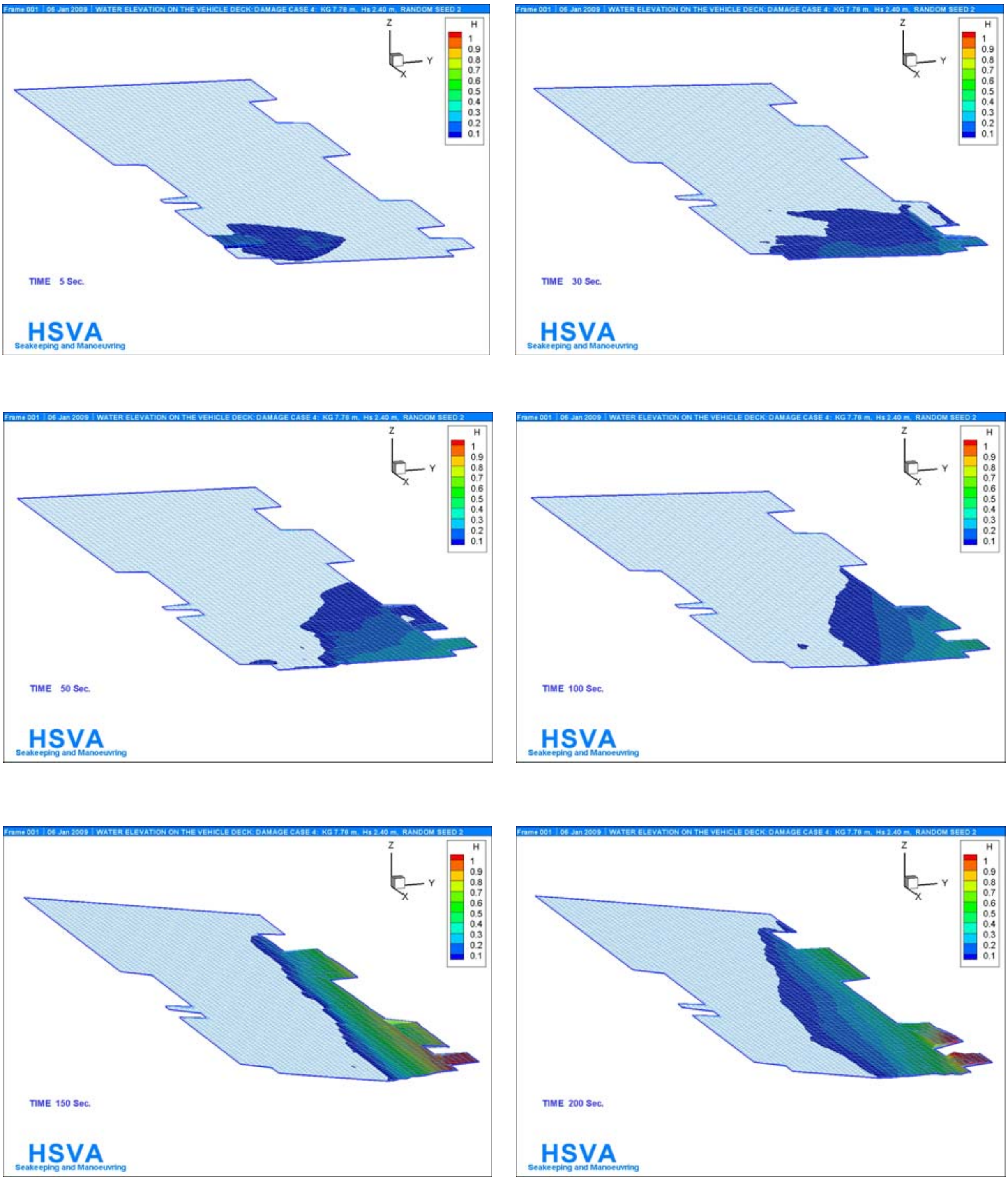

Fig. 23 Screenshots of the vehicle deck flooding according to the simulation with the HSVA Rolls at times 5, 30, 50, 100, 150, 200 s. The coloring expresses the water height on the deck perpendicular to the deck. Damage Case 4, *KG* = 7.78 m, H_s = 2.4 m, random seed 2. The stern of the vessel is located in the left upper corner, the bow in the lower right corner in each figure.

The ship survives this damage case in 7 simulations out of 10. Therefore it can be concluded that the H_s 2.40 m is quite a good limit value. With some simplifications we can assume that in general the ship survives the Damage Case 1 in sea states with H_s

somewhat lower than 2.40 m. In the three simulations out of ten the ship does not survive, it would probably capsize in two cases. Thus in these two cases the damage would lead into a catastrophe, not into a stable state with a high heeling angle. In all simulations the ship having the damage on the starboard side heels towards the undamaged port side. Figures 22 and 23 illustrate the behavior of the vessel and flooding of the vehicle deck in one of the simulations.

4.4.5 Damage Case 4 with H_s 4.0 m and *KG* 6.50 m

The Damage Case 4 on the original design of the ship EMSA1, however with *KG* 6.50 m, was investigated in a sea state having a significant wave height H_s of 4.0 m using random seeds 1-10 for the wave generation in the simulations. This is an extension of the first results shown in Table 14:

The ship survives this damage case in 5 simulations out of 10. In all cases a stable state was reached, but in the 5 simulations of the failed survival criterion the average heeling angle slightly exceeds 20°. Based on the results it can be concluded that the *KG* value 6.50 m is a suitable limit value for survival according to the survival criterion in the sea state with the H_s of 4.0 m. With some simplifications we can assume that in general the ship survives the Damage Case 4 in the sea state H_s 4.0 m with the *KG* somewhat lower than 6.50 m. This means that the ship would need a *GM* value of at least 2.92 m, instead of the original 1.64 m in order to survive in the sea state with the H_s of 4.0 m. In 9 simulations out of 10 the ship heels to the undamaged side.

4.4.6 Heeling moment due to wind and Pax -moments

All damage cases investigated above were simulated without the heeling moment due to wind and due to crowding of passengers on the ship side.

A few simulation runs with Damage Case 1 showed the following:

- A heeling moment due to wind from the damaged side and a moment due to passengers crowding on the undamaged side tend to lift the damaged opening higher up, which leads to longer survival times.

- A heeling moment due wind to from the undamaged side and a moment due to passenger crowding on the damaged side tend to lower the damaged opening further down, which leads to very short survival times.

As the waves come from the damaged side, the wind should do this, too. The situation, in which the waves and the wind come from opposite directions, is here considered unlikely. For this reason the perhaps second worst situation is the one, in which the waves and the wind come from the side of the damage opening and the passengers gather on the damaged side, causing a larger opposite moment tending to lower the damage opening. This produces a realistic model of the damage scenario. The total moment is in this case M_{pax}-M_{wind}.

The worst situation is likely to be the one, in which the waves, but temporarily no wind, come from the side of the damage opening and the passengers gather on the damaged side, causing a large moment tending to lower the damage opening. This produces a realistic worst damage scenario. The total moment is in this case M_{pax}. The two Damage Cases 1 and 4 were investigated with the additional total heeling moment M_{pax}-M_{wind} towards the damaged starboard side.

4.4.7 Damage Case 1 with *KG* 7.78 m , H_s 1.15 m and M_{pax}-M_{wind}

The Damage Case 1 on the original design of the ship EMSA1 with *KG* 7.78 m was investigated in a sea state having of a significant wave height of 1.15 m using random seeds 1-10 in the simulations. The ship survives this damage case in one simulation out of 10 under the influence of the heeling moment M_{pax}-M_{wind}. In the other 9 simulations the ship capsizes to the undamaged side in less than 11 minutes. Therefore it can be concluded that in general the ship would not survive the sea state H_s 1.15 m under the influence of the heeling moment M_{pax}-M_{wind}. The failed test runs would lead into a catastrophe, not into a stable state with a high heeling angle.

4.4.8 Damage Case 4 with *KG* 7.78 m , H_s 2.4 m and M_{pax}-M_{wind}

The Damage Case 4 on the original design of the ship EMSA1 with *KG* 7.78 m was investigated in a sea state having of a significant wave height of 2.40 m using random seeds 1-10 in the simulations.

The ship does not fulfill the survive criterion of a steady heeling angle of 20° or less in any of the simulated 10 sea state realizations under the influence of the heeling moment M_{pax}-M_{wind}. However, in all 10 cases the steady ship heel is about 23° and momentary values do never exceed 30°. Thus the ship does not fulfill the survival criterion, but it appears to survive in all 10 wave realizations with a somewhat higher angle of list.

4.4.9 Damage Case 1 with *KG* 7.78 m , damage opening on the port side

The Damage Cases 1 and 4 can be considered to be the most suitable for model testing. For technical reasons these damages should be modeled on different sides of the ship model. A suitable solution to this requirement is to have the opening of the Damage Case 1 on the port side of the vessel and the opening of the Damage Case 4 on the starboard side. For this reason the Damage Case 1 with the opening on the port side (PS) was also simulated with the HSVA ROLLS. The Tables 16 and 17 list the simulated results.

Table 16 The simulation results of the Ship EMSA1, a 80 m RoRo Passenger Ferry, in beam seas with the original *KG* of 7.78 m and with a significant wave height H_s of 4.0 m. Ten different random seeds for the wave realization were used in the simulations.

KG = 7.78 m, as designed. Significant wave height H_s = 4.0 m				
Damage Case	Final Condition after 30 min.		Max. time to Capsize [min]	Survival Criteria satisfied
	Steady Heel no. [-]	Capsize no. [-]		
DACA 1	1/10	9/10	2.5	No, Capsize (9) or List > 35° (1)
DACA 1 PS	0	10/10	13.5	No, Capsize

Table 17 The simulation results of the EMSA Ship 1 in beam seas with a *KG* of 7.78 m, and with a significant wave height H_s of 4.0 m. Only one random seed for the wave realization was used in the simulations.

KG = 7.78 m, as designed. Survival H_s				Sea state H_s = 4.0 m, Survival *KG*			
Damage Case	H_s [m]	Water Vol. on V-Deck [m³]	Water Vol. in Comp. [m³]	*KG* [m]	*GM* [m]	Water Vol. on V-Deck [m³]	Water Vol. In Comp. [m³]
DACA 1	≤ 1.15	~ 138	~ 700	≤ 5.55	≥ 3.87	~ 1300	~ 750
DACA 1 PS	≤ 0.80	~ 18	~ 540	≤ 5.55	≥ 3.87	~ 1300	~ 800

Based on the simulation results on Damage Case 1 there appears to be no great differences in the ship behavior between a damage opening on the left or damage opening on the right side. Therefore nothing speaks against modeling the Damage Case 1 having the damage opening on the port side.

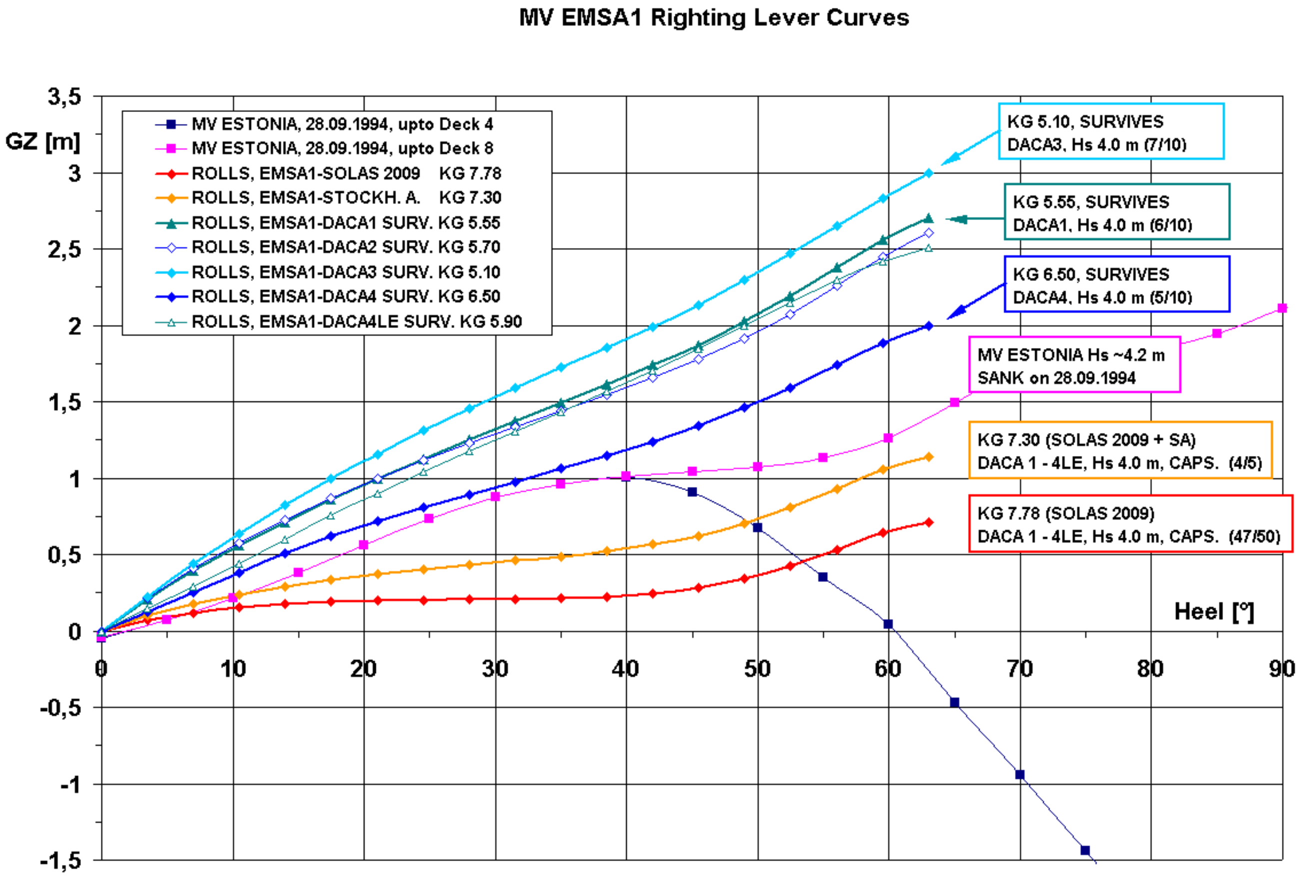

Fig. 24 Righting lever curves of the intact vessel with various values of *KG*. The draught and trim of the vessel are always those of the damage case investigated.

4.5 Survivability of the Ship EMSA1

Figure 24 shows the righting lever curves used in the program HSVA ROLLS. The vessel is assumed to be watertight up to higher decks (above the bulkhead deck) during the dynamic rolling motions. The damage opening and its influence is modeled elsewhere in the program. The two curves in the middle are plotted for comparison only and they show the righting lever curves of the *MV Estonia* up to the Bulkhead Deck (4) and up to the Deck 8. All other curves show the righting lever of the ship EMSA1 with different values of *KG*. These are plotted up to the heeling angle 63°. ***Notice that the applied survival criterion limits the relevant part of the righting lever curves to that below 30°***. The two lowest curves show the vessel as designed (SOLAS 2009) and when it satisfies Stockholm Agreement with SOLAS 2009 (SOLAS 2009 + SA). In both cases the righting levers are low and the vessel capsizes in the investigated damage cases in the sea state of H_s 4.0 m with a high probability. These righting lever curves are located below that of the *MV Estonia*.

The righting lever curves, at which the vessel survives in the majority of the simulations in the sea state of H_s 4.0 m, are all located considerably higher above the righting lever curve of the original design and also higher than the corresponding curve of the *MV Estonia*. This appears plausible.

From the point of view of ship design it is, however, not possible to reduce the *KG* without a limit. Therefore the survivability of the vessel may need to be improved by other means, for example by increasing the freeboard to the damaged vehicle deck. In the simulations this would results in decreased water ingress on the vehicle deck, and thus to better survivability.

4.6 Conclusions on EMSA1 based on the Numerical Simulations

- The ship EMSA1, a 80 m Ro-Ro Passenger Ferry was designed by the FSG to satisfy the requirements of SOLAS 2009.

- The vessel does not satisfy the requirements of the SOLAS 90 and the Stockholm Agreement.

- The TUHH suggested four damage cases to be investigated with the numerical simulation of the motions of the damaged ship in beam seas together with the modeling of the flooding of the vehicle deck.

- The numerical simulations were carried out with the program HSVA ROLLS. The damage openings onto the vehicle deck were chosen relatively narrow (2.208 m, i.e. 3 percent of L_{bp}) in order to facilitate a gradual flooding.

- ***In none of the investigated Damage Cases 1-4/4LE the vessel designed to fulfill SOLAS 2009 could satisfy the survive criteria in the sea state with the significant wave height of 4.0 m.*** In 47 cases out of 50, that is, in 94 percent of the cases, the vessel capsized in less than 7.5 minutes. The use of a wider damage opening would further shorten the survival times. These results are rather clear, even in view of possible numerical modeling errors.

- In order for the vessel to survive the chosen damage in a sea state with a H_s of 4.0 m, the *KG*-values of the ship should be reduced from the original 7.78 m to about 5.1-6.5 m depending on the damage case. The corresponding increase in the *GM*-value would be from the original 1.64 m to about 2.92 - 4.32 m. In this connection it should be kept in mind that the *KG* cannot be reduced endlessly.

The simulations with the elevated *GM*-values show that in some damage cases there can be about 2 m of water on the vehicle deck. This is much more than the maximum water height (0.5 m) assumed in the Stockholm Agreement.

It is important to notice that ***the derivation of the Stockholm Agreement calculation procedure is implicitly bound with the SOLAS 90 rules.*** If the SOLAS 2009 rules allow for a ship design a lower freeboard to vehicle deck or different (initial) stability than the SOLAS 90 rules, also the most likely height of water on the vehicle deck to be applied in a calculation procedure like the Stockholm Agreement can change.

- The ship EMSA1 does not fulfill the Stockholm Agreement with the *KG* 7.78 m. According to the TUHH in order of the requirements of the Stockholm Agreement to be filled the *KG* has to be reduced to 7.30 m. With this value of *KG* the ship, however, did not survive in the HSVA simulations any of the Damage Cases 1-4/4LE in a sea state with significant wave height 4.0 m with one random seed for the wave generation. This example shows that the Stockholm Agreement calculation procedure is not always suitable for a direct application on a ship designed according to SOLAS 2009 requirements.

- The Damage Cases 1 and 4 were further analyzed using 10 sea state realizations for each case under the influence of the heeling moment due to passenger crowding on the damaged side of the ship, but opposed by the wind heeling moment. The original *KG*-value of 7.78 m was used together with the significant wave heights of 2.4 m and 1.15 m, respectively.

  In Damage Case 1 the situation deteriorates to the extent that in 9 simulations out of 10 the ship capsizes in less than 11 minutes.

  In Damage Case 4 the situation deteriorates to the extent that in all 10 simulations the ship does not satisfy the survival criterion of steady heel equal to or lower than 20°, but reaches a steady state with a list of about 23° in all cases.

Taking this all into account the following conclusion can be drawn:

> The ship EMSA1, a 80 m RoRo Passenger Ferry, designed by a well-known European shipyard to fulfill the requirements of the SOLAS 2009, has according to the numerical simulations a rather limited capacity to survive a narrow collision damage at the midship area in sea states having a significant wave height of more than 2.4 m. In some damage cases this limiting wave height is still much lower.
>
> In view of this it is difficult to come into any other conclusion that the ship stability required by the SOLAS 2009 rules is not likely to be sufficient in all cases. If these numerical results are confirmed in the model tests, corrective action should be taken to amend the SOLAS 2009 rules.

5 Damage Stability Tests with the Ship EMSA1 in Seaway

5.1 Introduction

This chapter gives a short review of the model tests carried out with the HSVA model No. 4614 of the ship design EMSA1. The model and the damage opening of the Damage Case 1 are illustrated in Figures 25 and 26. The tests are reported in detail separately in the HSVA Report No. S590a/09 “Damage Stability Tests with the Model of an 80 m RoPax Vessel” by Ludwig (2009a).

Fig. 25 The model HSVA No. 4614 of the ship EMSA1 with the opening of the Damage Case 1.

The main purpose of the tests was to find out whether the ship designed according to SOLAS 2009 would survive in model tests carried out according to the guidelines in the Annex of the Stockholm Agreement or according to the Directive 2003/25/EC, as amended. The width of the damage openings to the vehicle deck was always 2.208 m (i.e. 3 percent of the L_{bp}) and on the ship side 5.2 m (i.e. ~ 3 percent of the L_{bp} + 3m). In addition to the issue of survival, information on the behavior of water on the vehicle deck of the damaged vessel was gathered with video cameras viewing vehicle deck and with 14 wave sensors measuring the water elevation on various locations on the vehicle deck during each test. These recordings give important information on the capsize mechanism of the RoPax vessel with water on deck, and were carried out particularly in view of the further development of the stability rules, which may turn out to be necessary.

Fig. 26 The damage opening of the Damage Case 1.

The tests were carried out in the HSVA’s large towing tank on 23-24 of February 2009. The scale of the model was chosen to be 16. Thus a 5 m long model was used in the 18 m wide test basin, leaving sufficient space in front of the bow and behind the stern of the vessel in beam seas. The 300 m long test basin provided a sufficiently long measurement period practically free of wave reflection. The irregular beam seas were generated with the JONSWAP- spectrum. Figures 27-30 illustrate the tests with the model of the EMSA 1.

5.2 Test Results on the Ship EMSA1 in Damage Cases 1 and 4

Tables 18 and 19 below show the main results of the model tests with the ship design EMSA1 in Damage Cases 1 and 4. The tables list the test runs giving the measured wave height H_S and peak period of the wave spectrum T_P in each test together with the information, whether the ship survived according to the survival criteria or not. The cases in which the ship survived according to the criteria, but capsized shortly afterwards, are also identified in Table 18. The cases of non-survival are marked with red color. In Damage Case 4 the lowest and highest wave heights tested are marked with blue color.

Fig. 27 Model and the towing carriage.

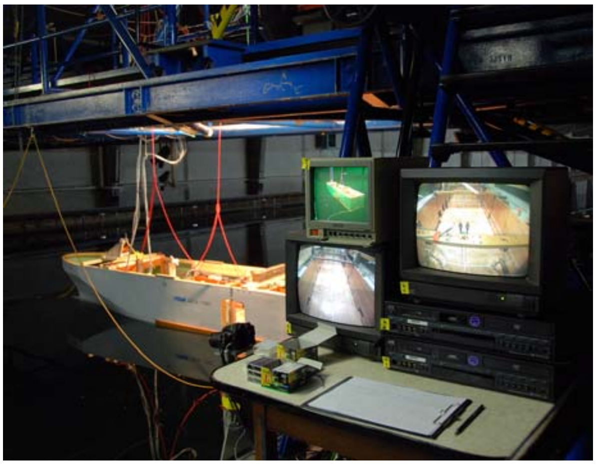

Fig. 28 In each test one video camera was viewing the model in seaway and two cameras the motion of water on the vehicle deck.

Fig. 29 The model was kept in beam seas with occasional control by two lines connected to the bow and stern of the model, if necessary.

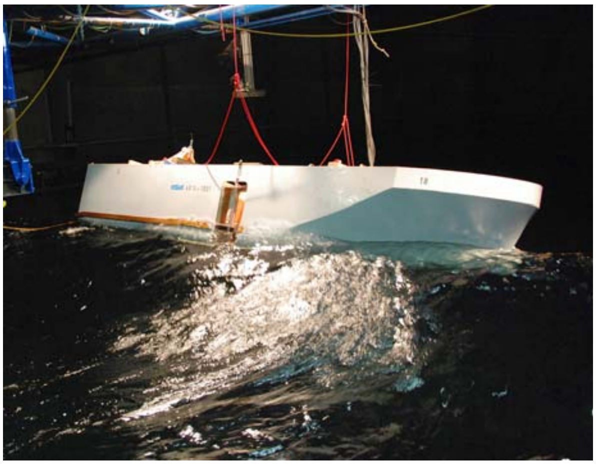

Fig. 30 The model on a wave crest in beam seas during a test.

The critical significant wave heights leading to capsize according to the Stockholm Agreement survival criteria are summarized in Table 20. Beside the critical H_S also the maximum value of the *GZ* and the range of the positive values of *GZ* in the damage cases are given. The measured data shows an obvious correlation between survivability and maximum value and range of the positive values of the righting lever *GZ*.

Table 18 Survival of the damaged ship EMSA1 in the model tests: Damage Case 1.

EMSA1: Damage Case 1						
Test Run No	GZ_{MAX} [m]	Range [°]	H_S [m]	T_P [s]	Survived[1]	Capsize after 30 min
1	0.113	15.0	4.21	12.3	YES	
2	0.113	15.0	4.33	12.5	YES	X
3	0.113	15.0	4.36	12.5	YES	X
4	0.113	15.0	4.23	12.3	YES	
5	0.113	15.0	4.19	12.3	NO	
6	0.113	15.0	3.24	7.7	NO	
7	0.113	15.0	3.36	7.5	NO	
8	0.113	15.0	3.20	7.2	NO	
9	0.113	15.0	3.23	7.3	NO	
10	0.113	15.0	3.63	7.8	NO	
11	0.113	15.0	2.63	6.8	YES	
12	0.113	15.0	3.01	7.7	YES	X
13	0.113	15.0	2.99	6.9	NO	
14	0.113	15.0	2.92	6.8	YES	X
15	0.113	15.0	2.97	6.9	NO	

1) According to the survival criterion of the Directive 2003/25/EC used in this study: The ship should be considered surviving, if a stationary state is reached for the successive test runs, provided that the angles of roll of more than 30° against the vertical axis, occurring more frequently than in 20 percent of the rolling cycles or steady heel greater than 20° should be taken as capsizing events, even if a stationary state is reached.

Table 19 Survival of the damaged ship EMSA1 in the model tests: Damage Case 4.

EMSA1: Damage Case 4					
Test Run No	GZ_{MAX} [m]	Range [°]	H_S [m]	T_P [s]	Survived[1]
16	0.136	24.0	4.16	12.2	YES
17	0.136	24.0	4.15	12.2	YES
18	0.136	24.0	4.20	12.3	YES
19	0.136	24.0	4.18	12.3	YES
20	0.136	24.0	4.10	12.2	YES
21	0.136	24.0	4.35	8.3	YES
22	0.136	24.0	4.36	8.4	YES
23	0.136	24.0	4.38	8.4	YES
24	0.136	24.0	4.38	8.4	YES
25	0.136	24.0	4.35	8.3	YES
26	0.136	24.0	4.35	8.3	YES
27	0.136	24.0	4.38	8.4	YES
28	0.136	24.0	4.47	8.5	YES
29	0.136	24.0	4.35	8.3	YES
30	0.136	24.0	4.36	8.3	YES
31	0.136	24.0	4.34	8.3	YES
32	0.136	24.0	4.40	8.4	YES

The significant wave heights H_S and peak periods of the wave spectrum T_P in Tables 18 and 19 are values actually realized in the model tests. The peak periods were chosen according to the Directive 2003/25/EC: Thus the two periods were used: (1) $T_P = 4\sqrt{H_S}$, and (2) T_P = rolling period of the damaged ship, but not greater than $6\sqrt{H_S}$.

Table 20 Significant wave heights critical for survival of the damaged vessel EMSA1.

Ship Design EMSA1: Model Test Results			
Damage Case	GZ_{max} [m]	Pos. range of GZ [°]	$Hs_{critical}$ [m]
EMSA1: 1	0.113	15.0	3.0
EMSA1: 4	0.134	24.0	> 4.4

6 Numerical Simulation vs Model Tests on the Ship EMSA1

6.1 Comparison of Computed and Model Test Results

The numerical simulations and the model tests do not give identical results. A short comparison of these two methods is given below. This should help in interpreting the results.

- The cost of numerical simulation is only a small fraction of that related to carrying out survival tests in the seakeeping basin.
- The numerical simulations underestimate the critical H_S, that is, in model tests and in reality the ship can survive in somewhat higher waves than in those predicted by the numerical simulation.
- The simulations underestimate the time (duration) to capsize.
- The development of the ship list in the simulations is very similar to that in model tests, but faster.
- The accumulation of water in the simulations very similar is to that in model tests, but faster.
- The flow patterns of the flooding water on the vehicle deck are very similar to those in the model tests.
- The critical amount of water on the vehicle deck just before capsize shows very similar values in the computations and in the model tests, whereas the Static Equivalent Method (SEM) appears to show considerably lower values.
- The roll amplitude of the vessel in beam seas is higher in the simulations than in the model tests.
- The natural periods of roll in the numerical model and in model tests are very close: With the ship design EMSA1 in Damage Case 1 the HSVA ROLLS gave 11.8 s and the model test 12.2 s.

The critical significant wave heights obtained with numerical simulations and with model tests are given together in Table 21.

Table 21 Critical significant wave heights based on numerical simulations and model tests.

Ship Design EMSA1: Numerical Simulations and Model Tests							
DAMAGE CASE	GZ_{MAX} [m]	Pos. range of GZ [°]	Computation		Model Test		SURVIVES ?
			$Hs_{critical}$ [m]	T_P [s]	$Hs_{critical}$ [m]	T_P [s]	
EMSA1: 1	0.113	14.4	1.15 1.50	11.8 8.4	4.1 3.0	12.3 6.9	NO
EMSA1: 2	0.097	17.8	1.70	11.8			NO(?)
EMSA1: 3	0.034	13.3	~0.2	4.2	-	-	NO(?)
EMSA1: 4	0.134	25.1	2.40 2.90	11.8 9.4	> 4.1 > 4.4	12.2 8.4	YES
EMSA1: 4LE	0.074	13.8	< 0.8				NO(?)

The numerical simulations and model tests with the ship design EMSA1 showed the following:

Damage Case 1:	The ship capsized in model tests with H_S 3.0 m and 4.2 m with peak periods 6.9 s and 12.3 s of the wave spectra, respectively.
Damage Case 2:	In view of model test results of the very similar Damage Case 1 and the numerical simulations with Damage Case 2 it can be expected that the ship capsizes also in the latter case in lower significant wave heights than 4.0 m.
Damage Case 3:	The ship capsizes in the numerical simulations also without water on the vehicle deck in all wave heights above 0.2 m.
Damage Case 4:	The ship survived in model tests with H_S lower than 4.4 m.
Damage Case 4LE:	The ship is not expected to survive in wave heights exceeding about 1 m.

6.2 Conclusions on the Safety of the Ship Design EMSA1

The following conclusions can be drawn based on the TUHH calculations, and on the numerical simulations and model tests by the HSVA:

- The results of the TUHH estimations of the total safety level of the ship design EMSA1 are certainly sufficient to raise a serious concern on the minimum stability level required by the SOLAS 2009 rules. The new SOLAS2009 rules can lead to a significant reduction in the safety level of the ship in comparison with older rules in force until January 2009.

- The HSVA model tests showed that the ship EMSA1 would survive Damage Case 4 in waves lower than 4.4 m, but not survive Damage Case 1 in 3.0 m high waves.

- The GZ-values, the range of their positive values and the numerical simulations with the HSVA ROLLS indicate that the ship would probably not survive Damage Cases 1, 2, 3, or 4LE in seaway of 4.0 m significant wave height.

- The TUHH analysis of the safety level of the ship design EMSA1, the numerical simulations with the HSVA ROLLS, and the HSVA model tests do not provide identical results. This was to be expected. These analyses, computations and model tests, however, all lead only to one conclusion: ***The ship EMSA1 designed in accordance with the new probabilistic damage stability rules (SOLAS 2009) cannot be regarded as a safe design in a likely damage case.***

7 The Safety Index of the Ship Design EMSA2 based on a Monte Carlo Approach

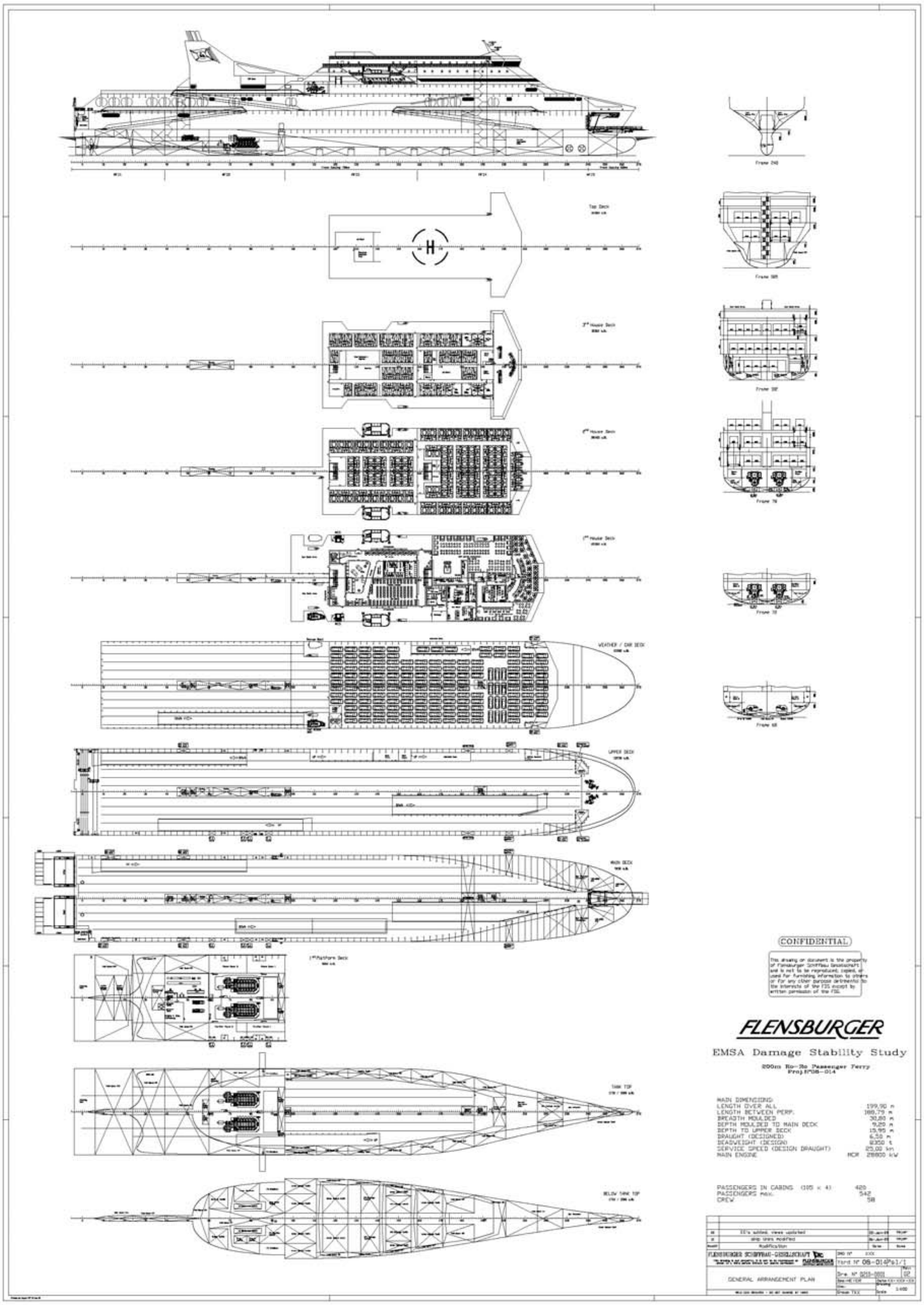

Fig. 31 General arrangement of the ship designs EMSA 2 (modified as EMSA2MOD.)

7.1 Initial Safety Considerations

The ship EMSA2 was designed by the FSG as a second reference vessel with respect to the new damage stability regulation SOLAS 2009 Reg. B-1. The ship should have a lower hold in the maximum extensions possible and should at the same time have a two-compartment status. This resulted in a lower hold, which is bounded by a B/10 double skin below the main vehicle deck. Based on the damage assumptions of the deterministic addendum of SOLAS 2009 Reg. B-1 this resulted in the situation that such a lower hold would not be penetrated due to the assumed damage extensions. The ship could fulfill the index of the probabilistic part of SOLAS 2009 Reg. B-1 easily with the *GM*-values shown in Figure 32, which were all below the requirements of the intact stability code. The combination of the weather criterion and the requirement that the maximum *GZ* should occur at an angle beyond 25 degrees were in this case the governing criteria.

With these *GM*-values, the ship did not pass the deterministic addendum of SOLAS 2009 Reg. B-1/8 at the maximum draft, where two compartment cases with a B/10 penetration depth needed to be considered. This resulted in an increase in the required *GM*-values at the maximum draft to a level above the prescribed intact stability criteria. It is important to note that this increase was necessary due to the deterministic addendum of SOLAS 2009 Reg. B-1/8. In general, the stability level required by the probabilistic part of SOLAS 2009 Reg. B-1 is lower than the prescribed intact criteria for the ship design EMSA2. The limiting stability curves are shown in Figure 32. The required index amounts to 0.722, which is equal to the attained index according to the shipyard calculations.

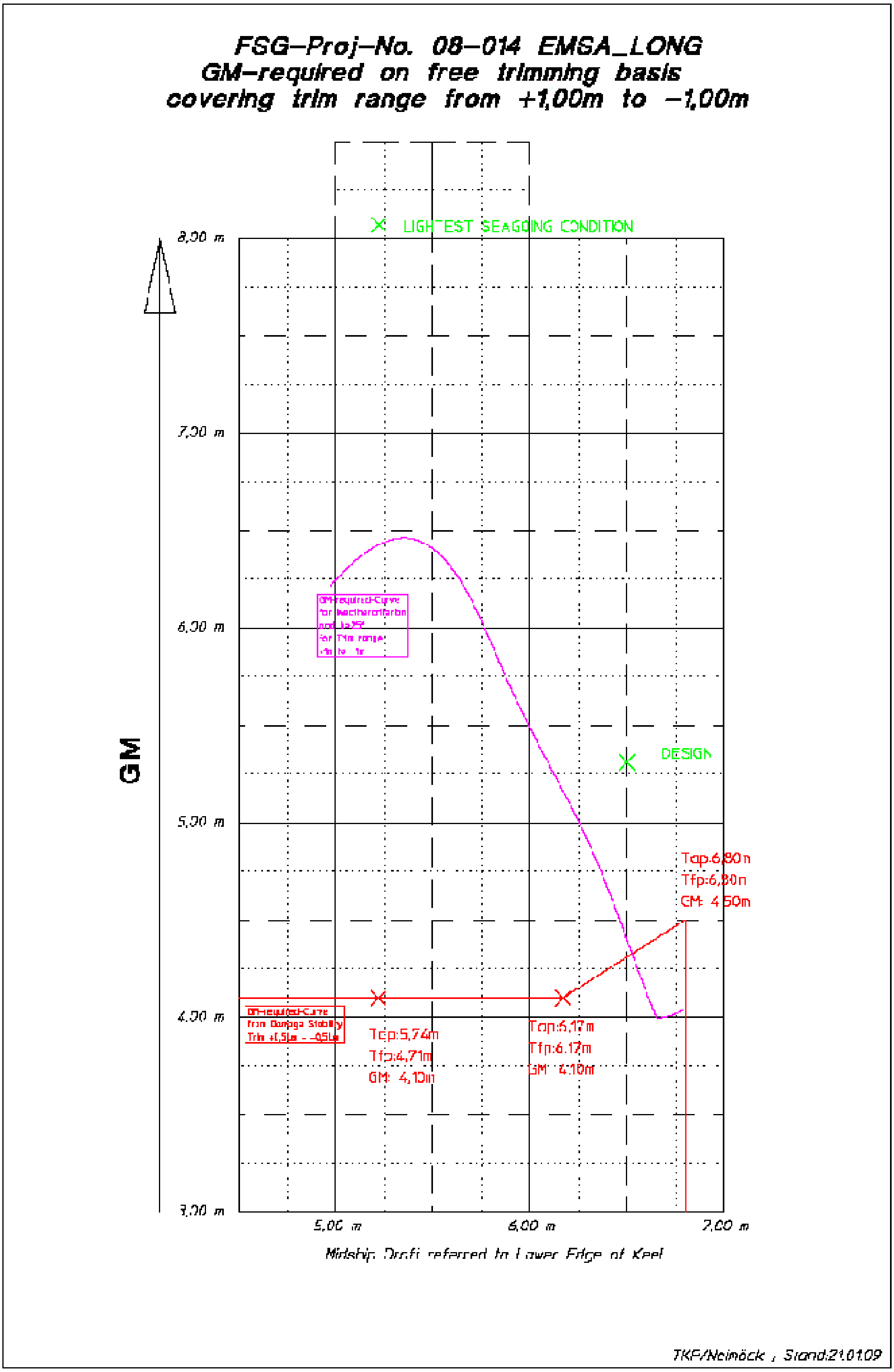

Fig. 32 Curve of *GM*-required for the Ship Design EMSA 2 for the intact criteria as well as according to SOLAS 2009 Reg. B-1.

7.2 Attained Index according to the SOLAS 2009 Reg. B-1 Probabilistic Standard

The shipyard results for the attained index were recomputed on the basis of a Monte Carlo simulation method. The results obtained by the simulation, which were based on 20000 samples are shown in Table 22.

Table 22 Results of the damages stability assessment with the Monte Carlo approach. Damage assumptions and survivability criteria according to SOLAS 2009 Reg. B-1 probabilistic part.

Draft	Displacement	Index	Index	Index
	[t]	PS	STB	Mean
Light	16081	0.724	0.680	0.702
Partial	19933	0.761	0.725	0.743
Deepest	22875	0.735	0.700	0.718

According to the prescribed index contribution of 20, 40 and 40 percent, the total index amounts to 0.725. The index on the deepest draft is still slightly larger than 90 percent of the required index. The computed value of 0.725 is in good agreement with the value obtained by the classical manual computation by the shipyard, which computed an index value of 0.722.

7.3 Determination of the Total Safety Index according to the Probabilistic SOLAS 2009 Reg. B-1 Standard

7.3.1 Damages included in the probabilistic SOLAS 2009 Reg. B-1 standard

If a Monte Carlo simulation of damage stability is performed using the original damage distributions developed by the HARDER project, the simulation also includes damages, which are ***not*** covered by the probabilistic SOLAS 2009 Reg. B-1 standard. These are very long damages and those having a very large penetration. For this particular ship EMSA2, it was found that the damage assumptions of the SOLAS 2009 Reg. B-1 standard represent 92.5 percent of all damages, which are actually in the HARDER damage distributions. At first, only the contribution of these 92.5 percent of damages were computed. The index values given in Table 23 are based on the number of these damages, whereas the last column gives the index values based on the total number of damages. So if the ship would survive all these damages, the PS and STB indices would amount to 1.000 and the contribution to the total safety index would then amount to 0.925. It must be further noted that the index values computed in this section may differ from those computed before due to the reasons explained by the evaluation of the ship design EMSA1 in Chapter 3.3.

The probability of survival has been computed according to the SOLAS 2009 Reg. B-1 standard and may take any value between 0 and 1. This results in the following safety contributions from all damages covered by the SOLAS 2009 Reg. B-1 standard:

Table 23 Indices of all damages represented by the SOLAS 2009 Reg. B-1 damage stability standard. Damage distributions according to HARDER.

Draft	Displacement	SOLAS 2009 Damages = 92.5 percent of all HARDER damages			HARDER Damages
		Index	Index	Index	Index Contribution
	[t]	PS	STB	Mean	Mean
Light	16081	0.746	0.706	0.726	0.665
Partial	19933	0.786	0.756	0.771	0.715
Deepest	22875	0.769	0.740	0.755	0.703

7.3.2 Damages not included in the probabilistic SOLAS 2009 Reg. B-1 standard

As mentioned above, there remains the amount of 7.5 percent of all damages represented by the HARDER distribution, which are ***not*** included in the probabilistic SOLAS 2009 Reg. B-1 standard. But it is of course possible that the ship can survive such a damage, which would result in a positive contribution of that damage to the overall safety index of the ship. Therefore, as a next step, only those HARDER damages, which are not covered by the probabilistic SOLAS 2009 Reg. B-1 standard are regarded and their contribution to the overall safety index is computed. As before, the different indices are based on the total number of these damages, which is 7.5 percent. Further, the total contribution to the overall safety index is given, which would amount to 0.075 in case all these damages would be survived. As before, the probability of survival s_i is computed according to the SOLAS 2009 Reg. B-1 standard. The following results were obtained:

Table 24 Indices of all HARDER damages not included in the SOLAS 2009 Reg. B-1 damage distributions.

Draft	**Displacement**	**HARDER Damages - SOLAS 2009 Damages = 7.5 percent of all HARDER damages**			**HARDER Damages**
		Index	**Index**	**Index**	**Index Contribution**
	[t]	**PS**	**STB**	**Mean**	**Mean**
Light	16081	0.464	0.414	0.439	0.029
Partial	19933	0.502	0.468	0.485	0.032
Deepest	22875	0.468	0.441	0.455	0.030

7.3.3 Interpretation of the results

About 40 to 50 percent of all damages, which are not covered by the SOLAS 2009 Reg. B-1 standard, are survived. As their total number is quite small with about 8 percent, this results only in about 3 percent contribution to the overall safety index. There are some discrepancies between the indices computed here for all damages covered by the probabilistic SOLAS 2009 Reg. B-1 standard to those values computed earlier so that now, the attained indices are remarkably larger, if based on the 92.5 percent of all harder damages. The reason for this is that the ship benefits from the correct selection of the penetration depth from the assumed damage length.

The following total safety index values based on the total number of damages are computed: ***Light Draft 0.695, Partial Draft: 0.748, Deepest Draft: 0.733.*** The values are the sums of the last column in Tables 23 and 24. In this context it should also be mentioned that the overall safety index is the lowest for the lowest draft. This is due to the fact that the ***ship does not survive many cases, where the lower hold is flooded in an intermediate stage of flooding condition at the lowest draft.*** These intermediate stages are the most unfavourable at that respective draft.

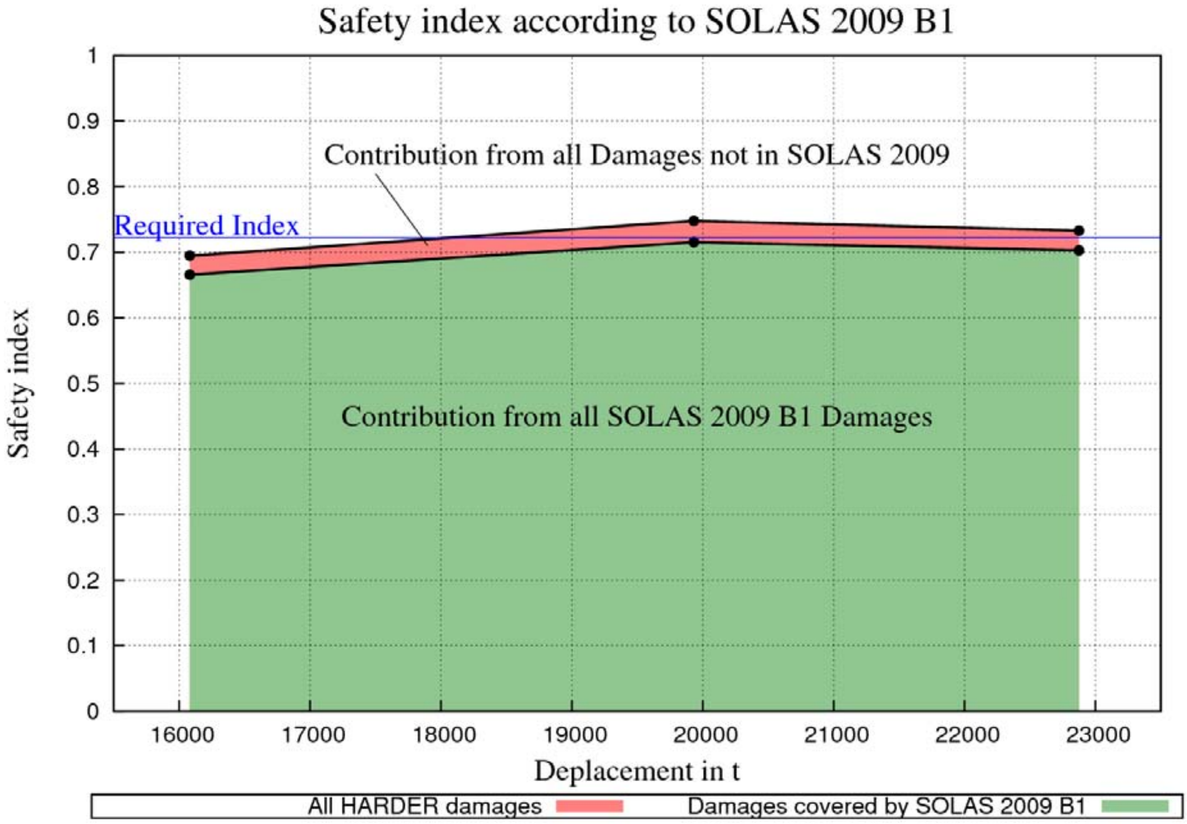

Fig. 33 Visualization of the overall safety index and the different damage contributions for the SOLAS 2009 Reg. B-1 probabilistic standard. The horizontal axis shows the displacement ranging from the value at the light draft (16081t) to the one at the deepest draft (22875t).

7.4 Determination of the Total Safety Index of SOLAS 90 Reg. II-1/8 without the Stockholm Agreement

7.4.1 Damages included in the SOLAS 90 Reg. II-1/8 standard

As a next step, the total safety index of the ship according to the SOLAS 90 Reg. II-1/8 standard is determined. This resulted in a total amount of approximately 36 percent of all possible damages, which are covered by a SOLAS 90 Reg. II-1/8 ***two-***compartment status for this design. Consequently, all these damages have to be survived, which must result in an overall contribution to the total safety index of 0.36. This ship has now a B/10 double bottom and B/10 longitudinal bulkheads in way of the lower hold below the freeboard deck. The B/5 damage assumption of SOLAS 90 Reg. II-1/8 leads therefore to a flooded lower hold, whenever the longitudinal damage extent will be within the range of the lower hold. Therefore, the B/5 damage assumption leads to a more unfavourable flooding extent compared to the deterministic addendum of SOLAS 2009 Reg. B-1/8. Therefore, it is to expected that some damage cases will not be survived. For all computations, the permeability of the RoRo-cargo hold was set to 0.9 or to 0.95 for the light draft, respectively.

The results are the following:

Table 25 Indices of all damages represented by the SOLAS 90 Reg. II-1/8 two-compartment status damage assumptions.

Draft	Displace-ment	SOLAS 90 Reg. II-1/8 Damages = 36 percent of all HARDER damages			HARDER Damages
		Index	**Index**	**Index**	**Index Contribution**
	[t]	**PS**	**STB**	**Mean**	**Mean**
Light	16081	0.911	0.901	0.906	0.318
Partial	19933	0.898	0.887	0.893	0.323
Deepest	22875	0.900	0.887	0.893	0.325

7.4.2 Damages not included in the SOLAS Reg. II-1/8 standard

Like before, all damages which are not covered by the standard under consideration are investigated. For SOLAS 90 Reg. II-1/8 standard this results in 64 percent of all HARDER damages not being covered. The contribution of these damages to the overall safety index is computed in the same way as done before for the probabilistic SOLAS 2009 Reg. B-1 standard. The results are the following:

Table 26 Indices of all damages not represented by the SOLAS 90 Reg. II-1/8 two-compartment status damage assumptions.

Draft	Displace-ment	HARDER Damages - SOLAS 90 Reg. II-1/8 Dam. = 64 percent of all HARDER damages			HARDER Damages
		Index	**Index**	**Index**	**Index Contribution**
	[t]	PS	STB	Mean	Mean
Light	16081	0.653	0.496	0.575	0.363
Partial	19933	0.535	0.470	0.502	0.319
Deepest	22875	0.484	0.452	0.468	0.296

The results show that still a significant amount of damages, which is not explicitly covered by the standard is actually survived according to the SOLAS 90 Reg. II-1/8 criteria.

7.4.3 Interpretation of the results

As expected, the ship design EMSA2 cannot fulfill the SOLAS 90 Reg. II-1/8 two-compartment status. This is a result of the B/10 design of the lower hold. According to the deterministic addendum of SOLAS 2009 Reg. B-1, all two compartment damages with a B/10 penetration depth must be survived at least with an attained s_i value of 0.9. The increased penetration depth of B/5 instead of B/10 leads now to a number of damage cases, which do actually penetrate the B/10 longitudinal bulkhead and damage also the lower hold. As the penetration depth probability has now been chosen correctly, this leads to slightly lower probabilities that the lower hold will actually be damaged compared to the damage assumptions of SOLAS 2009 Reg. B-1. Therefore, the loss of safety index is perhaps less severe than expected, but nevertheless remarkable. The flooded lower hold leads to a deep submergence of the hull with bow trim, so that the Margin Line becomes submerged in these cases. Additionally, there are some cases at the lighter draft, in which the ship survives in the final equilibrium condition, but where an intermediate stage of flooding leads to the situation that the final equilibrium will not be reached. For this reason the safety regime of SOLAS 90 Reg. II-1/8 attains a lower safety index to the design compared to that of SOLAS 2009 Reg. B-1. The results are also shown in Figure 34.

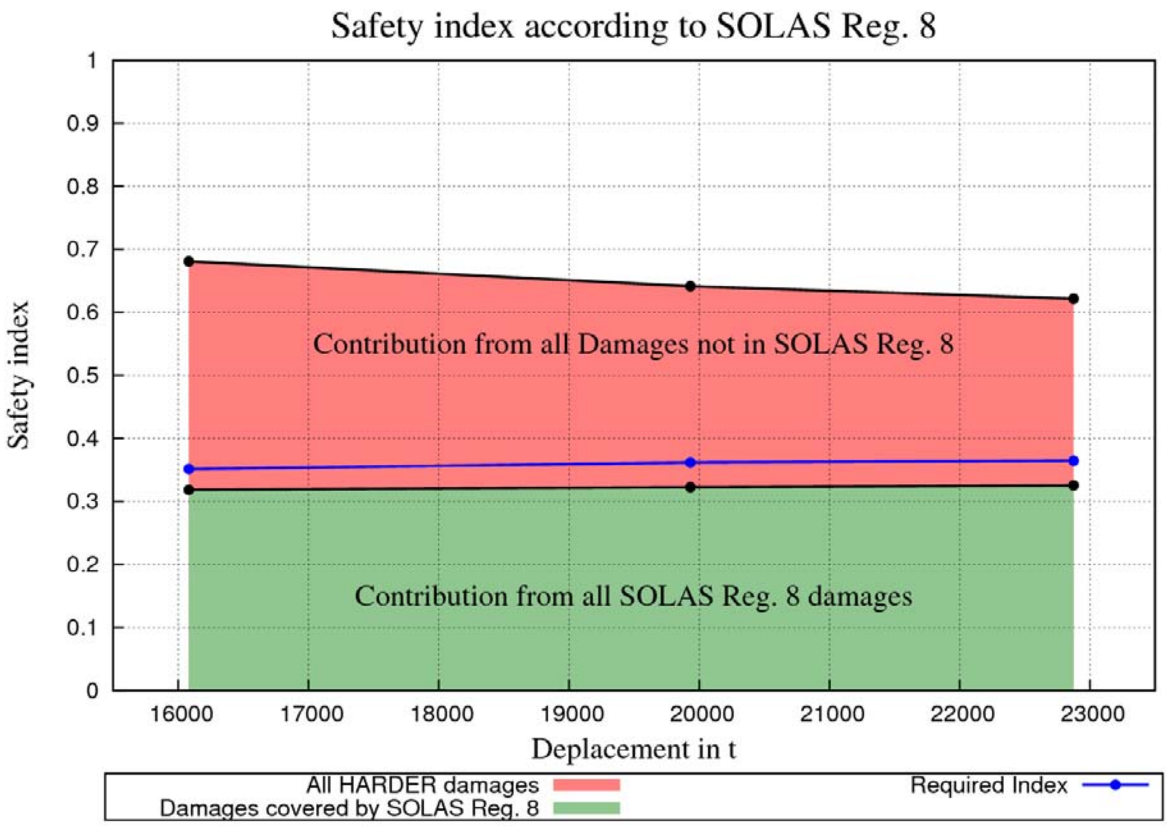

Fig. 34 Visualization of the overall safety index and the different damage contributions for the SOLAS 90 Reg. II-1/8 standard without Stockholm Agreement. The horizontal axis shows the displacement ranging from the value at the light draft (16081t) to the one at the deepest draft (22875t).

7.5 Determination of the Total Safety Index of SOLAS 90 Reg. II-1/8 including the Stockholm Agreement

7.5.1 Damages included in the standard

The same procedure for the evaluation of the safety index, now with consideration of the Stockholm Agreement requirement, is repeated. Now, the probability of survival s_i takes into account the additional amount of water on the freeboard deck, as defined by the Stockholm Agreement. As before, the total amount of damages included by the standard amounts to 36 percent. If the ship had to fulfill SOLAS 90 Reg. II-1/8 with water on deck according to the Stockholm Agreement, all damage cases must be survived, which should result in an index contribution of 0.36 on all three drafts. As the ship does not comply with SOLAS 90 Reg. II-1/8 even without additional water on deck, it is obvious that the ship cannot comply with the Stockholm Agreement. But as the latter is more stringent, it is of course to be expected that the safety index attained to the ship by the Stockholm Agreement is lower. It must be taken into account that this standard only covers an amount of 36 percent of all possible damages.

Table 27 Indices of all damages represented by the SOLAS 90 Reg. II-1/8 two-compartment damage assumptions.

Draft	Displace-ment	SOLAS 90 Reg. II-1/8 Damages = 36 percent of all HARDER damages			HARDER Damages
		Index	Index	Index	Index Contribution
	[t]	PS	STB	Mean	Mean
Light	16081	0.896	0.886	0.891	0.313
Partial	19933	0.898	0.886	0.892	0.322
Deepest	22875	0.899	0.863	0.881	0.321

7.5.2 Damages not included in the standard

All damages not included in the SOLAS 90 Reg. II-1/8 standard amount to 64 percent of all possible HARDER damages. The contribution of those damages to the total safety index of the ship including the effect of the Stockholm Agreement is shown in Table 28.

Table 28 Indices of all damages not represented by the SOLAS 90 Reg. II-1/8 damage assumptions.

Draft	Displace-ment	HARDER Damages - SOLAS 90 Reg. II-1/8 Damages = 64 percent of all HARDER dam.			HARDER Damages
		Index	Index	Index	Index Contribution
	[t]	PS	STB	Mean	Mean
Light	16081	0.538	0.485	0.512	0.323
Partial	19933	0.493	0.454	0.473	0.300
Deepest	22875	0.438	0.389	0.414	0.262

It can be seen in Table 28 that when the Stockholm Agreement is considered additionally to the SOLAS 90 Reg. II-1/8 requirements, the safety index attained to the ship is further reduced compared to the situation of SOLAS 90 Reg. II-1/8 without the Stockholm Agreement, which already attains a lower safety index to the ship compared to the SOLAS 2009 Reg. B-1 standard. But this reduction on EMSA2 is smaller than with the ship design EMSA1. This follows from the fact that the Ship design EMSA1 does not even comply with the SOLAS 90 Reg. II-1/8 standard without water on deck. Most of the B/10 damage cases on EMSA2 are also survived with water on deck, and those cases which did not fulfill SOLAS 90 Reg. II-1/8 will of course also not fulfill SOLAS 90 Reg. II-1/8 including the Stockholm Agreement.

7.5.3 Interpretation of the results

The application of the Stockholm Agreement to the ship design EMSA2 shows a significant fall in the attained safety index. But different to the ship design EMSA1, this fall in the safety index takes now place in two steps: Due to the larger penetration depth of SOLAS 90 Reg. II-1/8 compared to SOLAS 2009 Reg. B-1, the lower hold is flooded in some damage cases, which are not survived. Additionally, the water on deck requirement leads to a further reduction of the safety index simply because the SOLAS 90 Reg. II-1/8 standard is more stringent. So we have again identified a case where a ship designed according to the new damage stability standard SOLAS 2009 Reg. B-1 has a lower safety level compared to the deterministic standard of SOLAS 90 Reg. II-1/8 with and without water on deck. However, it must also be taken into account that the required index of the ship design EMSA2 is quite low, as the ship carries a relatively small number of passengers.

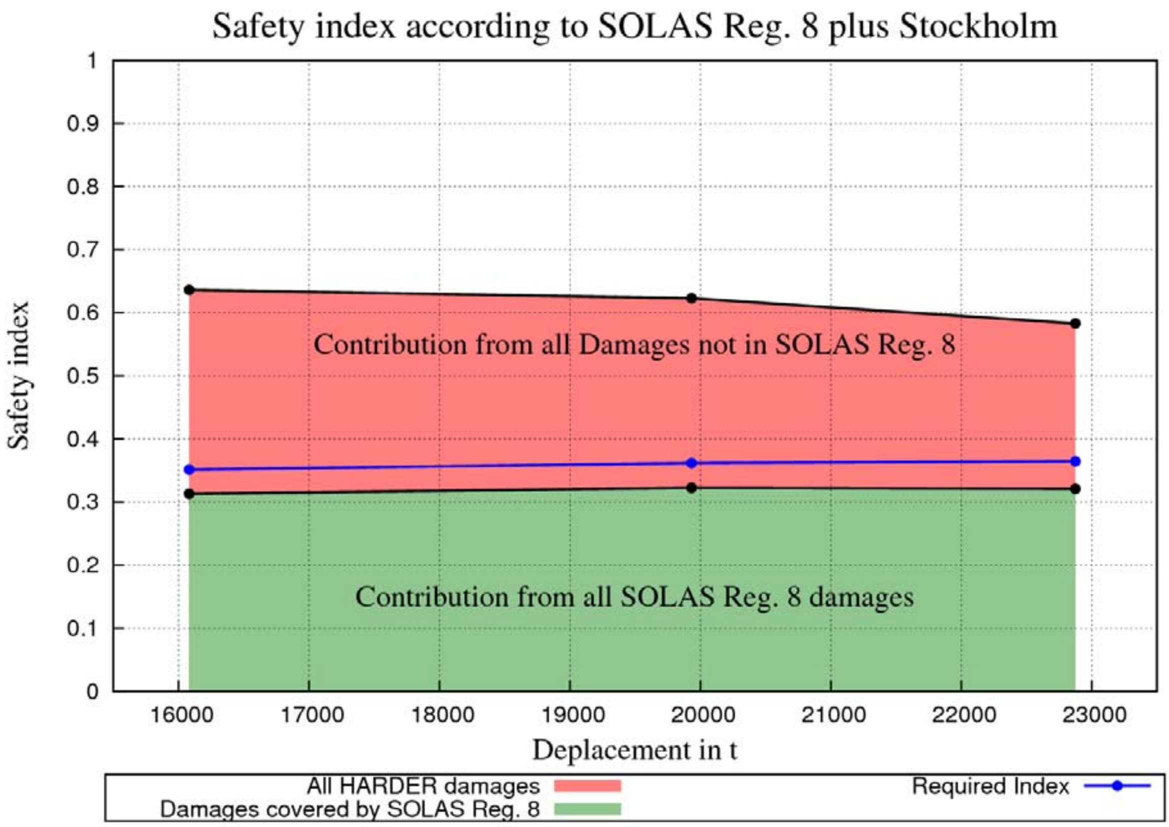

Fig. 35 Visualization of the overall safety index and the different damage contributions for the SOLAS 90 Reg. II-1/8 standard including Stockholm Agreement. The horizontal axis shows the displacement ranging from the value at the light draft (16081t) to the one at the deepest draft (22875t).

7.6 Comparison of the Results obtained for the Different Standards

The overall safety indices of all three standards investigated is summarized in Table 29.

Table 29 Comparison of the different safety indices attained to the ship by the investigated standards for the three drafts. Note the strong dependency of the safety index on the draft, which should ideally be the same on all drafts.

Draft	**Safety Index**	**Safety Index**	**Safety Index**
	SOLAS 2009 Reg. B-1	SOLAS 90 Reg. 8	SOLAS 90 Reg. 8 + SA
Light	0.695	0.681	0.636
Partial	0.748	0.641	0.623
Deepest	0.733	0.621	0.583
Status	Fulfilled	Not fulfilled	Not fulfilled

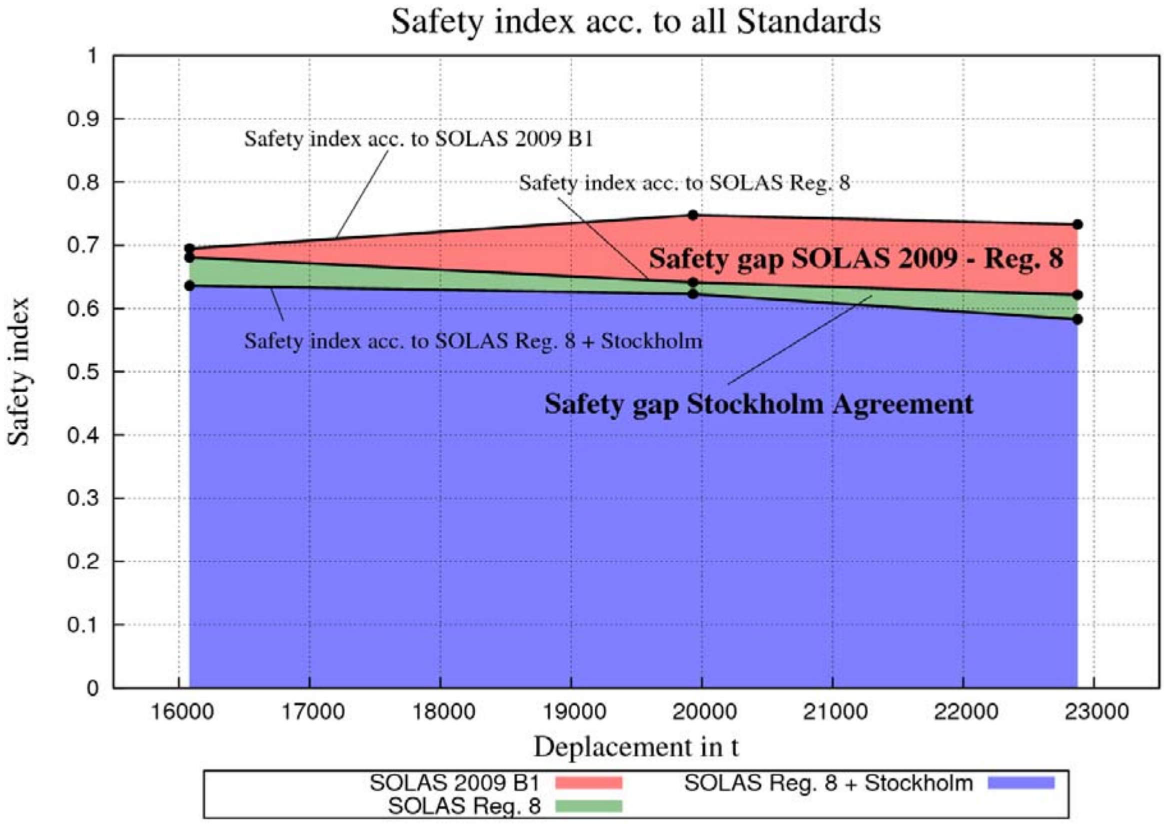

Fig. 36 Comparison of the different safety indices attained for the ship by the investigated damage stability standards. The horizontal axis shows the displacement ranging from the value at the light draft (16081t) to the one at the deepest draft (22875t).

With respect to the formal fulfillment of the damage stability standards investigated, the following situation has occurred:

- The ship clearly fulfills the probabilistic SOLAS 2009 Reg. B-1 damage stability standard as well as the SOLAS 2009 Reg. B-1/8 deterministic addendum for a two-compartment status.
- At the deepest draft, the limiting stability curve was governed by the deterministic addendum of SOLAS 2009 Reg. B-1/8.
- The ship does not fulfill the SOLAS 90 Reg. II-1/8 two-compartment damage stability standard.
- The ship does not fulfill the requirements of the Stockholm Agreement.

It must be noted in this context that, except for the deepest draft, the limiting stability requirements are not governed by the damage stability requirements, but by the intact criteria. For the deepest draft, the limiting stability curve is not governed by the probabilistic part of SOLAS 2009 Reg. B-1, but by the deterministic addendum. Consequently, as the ship has a lower hold, the safety level of the ship at the deepest draft must be lower for SOLAS 2009 Reg. B-1 as the damage assumptions of the deterministic addendum are less severe (B/10 instead of B/5).

These investigations carried out by the TUHH lead to the following conclusions on the ship design EMSA2:

- ***The requirements of the probabilistic part of SOLAS 2009 Reg. B-1 are for this particular ship less stringent compared to the deterministic standard SOLAS 90 Reg. II-1/8***. This is shown by the fact that SOLAS 2009 Reg. B-1 attains by far the highest total safety index to the ship. Following the revelation that the deterministic addendum of SOLAS 2009 Reg.B-1/8 was the governing criterion at least for the deepest draft, this was confirmed.

- If the water on deck requirement as required by the Stockholm Agreement is regarded as a useful contribution to the safety of RoRo passenger ships, it was for this particular ship found that the safety level represented by the SOLAS 2009 Reg. B-1 is significantly below the level of the SOLAS 90 Reg. II-1/8 together with the Stockholm Agreement.

- For this particular design, the effect of the Stockholm Agreement is less severe compared to the ship design EMSA1, as most of the safety index reduction is associated to the difference in damage assumptions of SOLAS 90 Reg. II-1/8 and SOLAS 2009 Reg. B-1.

Concluded, for the ship design EMSA2 the TUHH has not found any reason to assume that the safety level represented by the new SOLAS 2009 Reg. B-1 standard would be equivalent or higher than the SOLAS 90 Reg. II-1/8 standard together with the Stockholm Agreement requirements. On the contrary, all calculations show that the safety clearly falls down to a significantly lower level. The remaining open question is of course whether this safety level is still sufficient.

7.7 Discussion of the Results

The above mentioned investigations clearly show that the new damage stability regulations lead to a reduction of the safety level of the ship design EMSA2 analyzed here. This was found also to be the case with the ship design EMSA1, too. In comparison with the ship design EMSA1, the situation with the ship design EMSA2 is more complex: EMSA1 simply suffered from a general lack of stability, but the designed subdivision was reasonable. All problems associated with the ship design EMSA1 could simply be healed by a reasonable increase in ship stability, if any of the regulations would have demanded such an increase.

With the ship design EMSA2, the situation is more complex, as the stability of the ship is found to be of a sufficient level also according to the internal stability standard of FSG. The problem of the ship design EMSA2 has its origin in the situation that whenever the lower hold is flooded, the ship has ***insufficient amount of reserve buoyancy***, especially if the upper hold is damaged, too. It is obviously possible according to the new damage stability standard SOLAS 2009 Reg. B-1 to design internal subdivisions that do formally comply with the damage stability standard, but do not lead to a sufficient safety level. In this context, it is of utmost importance to remember that at least a part of the limiting stability curve was actually governed by the deterministic addendum of SOLAS 2009 Reg. B-1/8, namely the B/10 two-compartment status flooding. This addendum was introduced into the probabilistic damage stability standard for the following reason: It should prevent ship designs, where ***a minor damage leads to a major consequence***. This is a practical necessity. But for the ship design EMSA2 the situation has occurred that this addendum, which should only prevent major consequences resulting from minor damages, has now become the governing safety criterion for the limiting stability curve at the deepest draft, which is at the same time the most important draft, as the ship will operate most of the time on a draft close to this one. Especially for this particular draft, the requirements from SOLAS 2009 Reg. B-1 are weakest. This investigation leads therefore lead to the conclusion:

For the ship design EMSA2 it is by far too easy to gain a sufficient attained index, which fulfills the requirement against the required index. Thus ***for the ship design EMSA2, the required index is probably too low***. This correlates directly with the establishment of the formulae of the required index in general: The demand that the safety level should generally increase with the ship size and especially with the number of passengers, has led to a situation where typically for ship designs like EMSA2, only a small required index (in this case abt. 0.725) need to be achieved. On the deepest draft, this results in a maximum attained index value to be achieved of only 0.653, ***which means in practice that the ship is allowed to sink or capsize in about 35 percent of all damage cases, which are included in the SOLAS 2009 Reg. B-1 standard*** (92.5 percent of all HARDER damages).

On the other hand, there are indications that this particular problem identified for the ship design EMSA2 does not occur for all types of RoPax ferries: If, due to a higher number of passengers, the required index would be significantly higher, the identified stability problems of the ship design EMSA2 would not have occurred in that severity: A higher required index would demand also for the probabilistic part of SOLAS 2009 Reg. B-1 that design features would need to be introduced into the ship design EMSA2, which would enable the ship to survive also the long lower hold damages.

It must be pointed out in this context that a lower hold, even a B/10 lower hold, does not necessarily lead to an unsafe ship design in general. There are many possible design options, which will lead to a safe ship, even if the ship has a large B/10 lower hold.

The new damage stability standard SOLAS 2009 Reg. B-1 allows now for submerging the Margin Line. This results in a situation, where it is very attractive to fit a double hull between freeboard deck and upper deck. Earlier such a double hull was of limited value only, when the margin line was not allowed to submerge, because that reserve buoyancy became only efficient at larger heeling angles. Now, new concepts are possible where reserve buoyancy “is shifted” from the lower hold double hull to a freeboard deck double hull in case of a damage: This new double hull can be submerged in the final equilibrium floating condition, providing stability.

It is likely that such designs would lead to a much higher safety level compared to designs without such a double hull, and they might be much more attractive from an economic point of view at the same time. Therefore, the TUHH and FSG have considered an additional double hull on the freeboard deck, which is of the same transversal extent as the conventional web frames. ***Such double hulls have already been introduced by the FSG into the design of RoRo-cargo vessels, whenever it was found necessary from the point of view of damage stability*****.** The effect of such a double hull on the safety level, and on the computed safety index, of the ship design EMSA2 will be studied in detail in the sections below. This design modification has also been chosen to study the effect of a submerged vehicle deck and a possible water on deck requirement for such a design in a damaged condition: It is unclear, how additional water on deck shall be treated in case the residual freeboard to the vehicle deck is clearly below zero.

7.8 The Effect of Additional Water on the Freeboard Deck

For the ship design EMSA2, a certain dilemma existed for the further investigation of the effect of additional water on deck: Originally, it was the scope of this investigation of the ship design EMSA2 to consider a damage case, where the lower hold is flooded for further investigations concerning additional floodwater on the freeboard deck.

It was considered to be most useful, if such damage cases could be identified, which were seen as survived by the hydrostatic analysis without additional water on deck and which did at the same time not survive according to the hydrostatic analysis, if additional water on the freeboard deck was taken into account. However, it turned out that all damage cases where the lower hold was actually flooded, did clearly not survive in the hydrostatic analysis, even if no additional water on deck was considered. Preliminary dynamic simulations, which were carried out by HSVA confirmed this situation. It was then found useless to test a damage case in the model basin, in which the ship would have immediately capsized or sunk also in calm water.

On the other hand, nearly all damage cases, where the lower hold was not flooded clearly survived according to the TUHH analysis, even when additional water on deck was considered. In this situation it seemed not to be a good option to test a damage case, which would most probably not take any relevant amount of flood water on the vehicle deck.

Therefore, a decision was made to split the further analysis in two parts: In the first part, in order to investigate the effect of water on deck for the ship design EMSA2, only two damage cases for further consideration were selected: These cases have both a transversal extent of the damage aft of the lower hold and do therefore not penetrate it. Both damage cases are selected for the deepest draft, as the water- on-deck influence on that draft is the largest. These two cases, HSVA EMSA2 Damage Cases 1 and 2, were further analyzed with numerical simulation in Chapter 8.

In the second part, the influence of water on the vehicle deck in case the lower hold would be flooded was considered to be of special interest. In order to be able to investigate damage cases involving also the Long Lower Hold, it was decided to modify the ship design EMSA2 for further studies of the water on deck problem. This modification should also show a direction into which a future RoPax design might develop. As the new damage stability regulations SOLAS 2009 Reg. B-1 allow for the submersion of the Margin Line, it has turned out that under this situation, an additional double hull on the freeboard deck becomes attractive, as it can contribute to reserve buoyancy and stability in the equilibrium floating condition. Therefore, it was decided that the design EMSA2 should be fitted with an additional double hull on the freeboard deck. Following the standards that have already been introduced in the design of cargo RoRo-Ships, the conventional web frame steel structure was simply replaced by a double hull of the same size. This results in additional buoyancy, where at the same time no cargo space is lost. For this modified ship design EMSA2MOD, the effect of the double hull was investigated by the Monte-Carlo-Simulation of the attained indices according to the probabilistic part of SOLAS 2009 Reg. B-1. The results are shown in the following Table 31. For purposes of comparison, the comparable values for the original design EMSA2 are given in Table 30.

Table 30 Results of the damages stability assessment with the Monte Carlo approach. Damage assumptions and survivability criteria according to SOLAS 2009 Reg. B-1 probabilistic part for the ***original ship design EMSA2***. See also Table 22.

Draft	Displacement [t]	Index PS	Index STB	Index Mean
Light	16081	0.724	0.680	0.702
Partial	19933	0.761	0.725	0.743
Deepest	22875	0.735	0.700	0.718

Table 31 Results of the damages stability assessment with the Monte Carlo approach. Damage assumptions and survivability criteria according to SOLAS 2009 Reg. B-1 probabilistic part for the ***modified design EMSA2MOD***.

Draft	Displacement [t]	Index PS	Index STB	Index Mean
Light	16081	0.801	0.758	0.780
Partial	19933	0.817	0.776	0.797
Deepest	22875	0.827	0.783	0.805

The results show a significant increase of the attained index, which is the largest on the deepest draft. The attained index is 0.797 for the modification EMSA2MOD, whereas it is 0.722 for EMSA2. This shows that it is in fact possible to increase the safety of the design at a relatively low additional cost.

Most important for our investigation is now that many damage cases, where the lower hold is actually flooded, are now survived according to the standards of SOLAS 2009 Reg. B-1: When the lower hold is flooded, the ship sinks down to an equilibrium floating condition, where the double hull on the main deck provides sufficient stability. In practically all of these cases, the freeboard deck becomes submerged. The hydrostatic analysis of such damage cases show that the ship survives these cases from stability point of view. Now the formal situation has arrived that this floating condition would not fulfil the requirements of SOLAS 90 Reg. II-1/8, while the Margin Line becomes submerged. But the hydrostatic analysis shows that the ship would clearly survive such damage.

As a consequence of this, we are running into ***problems with the formal fulfillment of the Stockholm Agreement for such a damage case.*** The Stockholm Agreement is an addendum to SOLAS 90 Reg. II-1/8. It was made as an additional water-on-deck requirement for a damaged main vehicle deck that did not have any floodwater in it in the equilibrium floating condition, simply due to the fact the "Margin Line"- criterion required explicitly that this line shall never submerge. Now, we face the problem that if the Stockholm Agreement requirement would be applied in a damage case, where the freeboard deck is already flooded, formally the water level in that compartment would have to be increased by 0.5m as the residual freeboard is below zero. It is not quite clear whether this is in line with the physics of the problem. With such a damage case, we have identified the limitations of the Stockholm Agreement requirements in case it shall be applied within the framework of SOLAS 2009 Reg. B-1. Such a damage case, HSVA EMSA2MOD Damage Case 4, was further analyzed with numerical simulation in Chapter 8.

8 Numerical Simulation of the Behavior of the Damaged Ship EMSA2 in Seaway

8.1 Introduction

The second ship to be investigated is a large Ro-Ro Passenger Ferry. The design of the vessel satisfies the requirement of the SOLAS 2009 rules, but not those of SOLAS 90 in conjunction with the Stockholm Agreement.

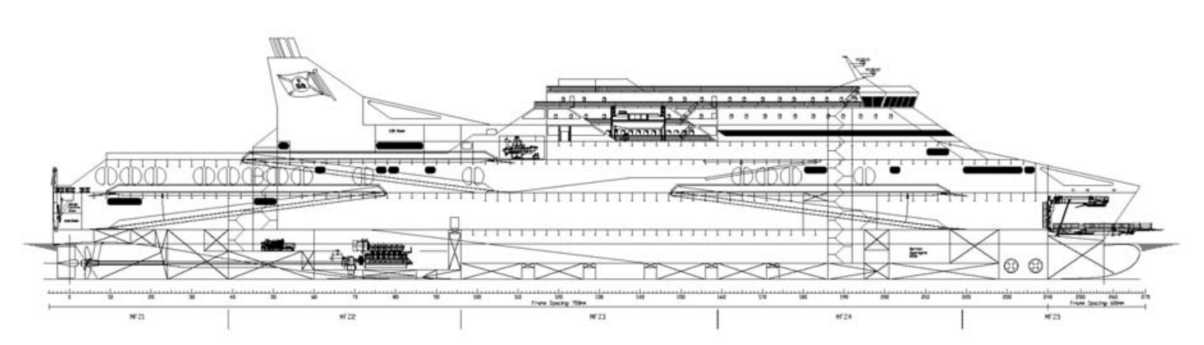

Fig. 37 Second investigated ship EMSA2, a 200 m Ro-Ro Passenger Ferry.

The main particulars of the ship are shown in Table 32.

Table 32 Main Particulars of the Ship Design EMSA2/EMSA2MOD.

EMSA2: 200 m Ro-Ro Passenger Ferry: FSG Project No 08-014	
Length over all, LOA	199.90 m
Length between perpendiculars, Lbp	189.67 m
Breadth moulded	30.80 m
Draught (design)	6.50 m
Draught (summer loadl.)	6.80 m
Depth to main deck	9.20 m
Depth to upper deck	15.95 m
Displacement at draught 6.8 m	22875 m^3
Waterplane area at draught 6.8 m	4731 m^2
Vehicle Deck area (original)	~ 4747 m^2
Vehicle Deck area (version 1)	~ 4488 m^2
Roro cargo Hold volume (original)	33109 m^3
Roro cargo Hold volume (version 1)	30114 m^3
Long Lower Hold Volume	9907 m^3
Service speed	25.0 kn
Main Engine	28800 kW
Passenger capacity (max.)	542
Crew	58

The water flooding on the vehicle deck of the vessel is an important detail to be modeled in the numerical simulations with the HSVA ROLLS. Figure 38 shows the modeled compartments on the vehicle deck. Some small watertight compartments at the sides are not shown in the figure, but are modeled accurately in the simulations. There are two types of compartments at the centerline of the vehicle deck: (1) watertight compartments, which are excluded from the model; (2) non-watertight compartments, which are modeled with watertight walls, but with doors open. Thus the water can flow into these compartments, but it cannot slosh freely through the walls.

The shallow-water-equations used for modeling the fluid flow are solved with a random choice method on 164 x 28 grid covering the vehicle deck area 183 m x 30.8 m. The grid spacing is about 1.1 m in both directions. The damage opening in each damage case modifies the numerical grid on the vehicle deck only locally.

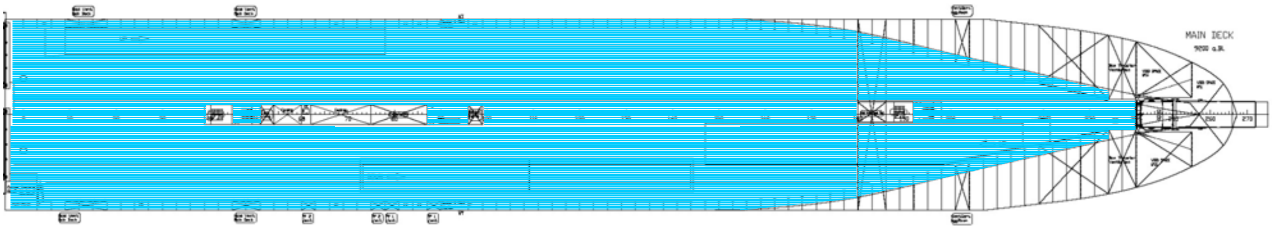

Fig. 38 The original vehicle deck of the ship design EMSA2

The original design EMSA2 has a large "Long Lower Hold" (LLH) below the main vehicle deck. If this 74 m long compartment becomes exposed to sea, the vessel sinks also in calm water. For example a narrow side damage in the middle of the ship with a B/9 penetration is sufficient to cause this. For this reason the FSG made an alternative design EMSA2MOD, which has sufficient buoyancy added to the vehicle deck providing also stability in case the LLH is punctured. This allows us to study the stability of the vessel with a damaged LLH.

On the modified vehicle deck there are compartments on both sides forming side casings. These compartments are watertight and totally separate. Thus they are excluded from the vehicle deck model. The width of the side compartments is only about 1.4 m, that is, 0.045B, and they do not cover the whole length of the vehicle deck. These compartments are not wider than the web frames, thus no car lane space is lost in this modification.

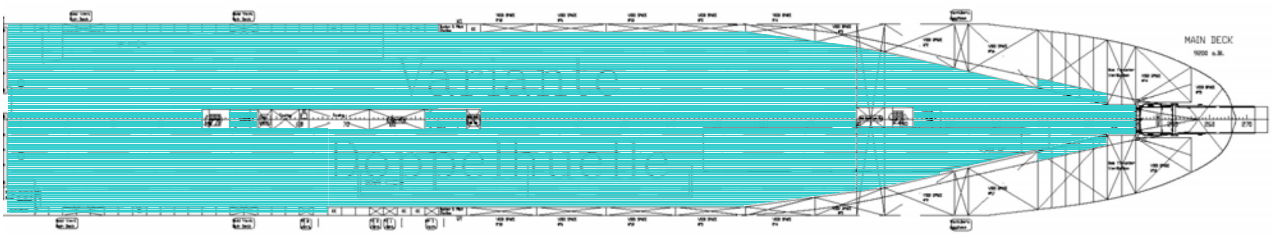

Fig. 39 The modified vehicle deck of the ship design version EMSA2MOD.

In the following chapters the survivability of the vessel in a few chosen damage cases will be investigated with numerical simulations in irregular long–crested seas. Some selected damage cases will also be further investigated with seakeeping model tests in the HSVA.

8.2 Damage Cases

The following five damage cases were considered most relevant for further investigation. The Table 33 below gives the extent of these damage cases.

Table 33

DAMAGE CASE	DAMAGED COMPARTMENTS
EMSA2: Damage Case 1	RoRo Cargo Hold Void Space 07 Void Space 08 Purifier Plant 2 SB
EMSA2: Damage Case 2	RoRo Cargo Hold Water Ballast Tank 14 HFO Storage 36 Void Space 12 EE LH PS Fin Stabilizer PS Store 01 PS
EMSA2: Damage Case 3 (Vessel sinks/capsizes in calm water)	RoRo Cargo Hold Long Lower Hold Void Space 03
EMSA2MOD: Damage Case 4 (Modified vehicle deck)	RoRo Cargo Hold Long Lower Hold Void Space 03
EMSA2MOD: Damage Case 5 (Modified vehicle deck)	RoRo Cargo Hold Long Lower Hold Void Space 13

The damage cases are further illustrated in Figures 40-43 below.

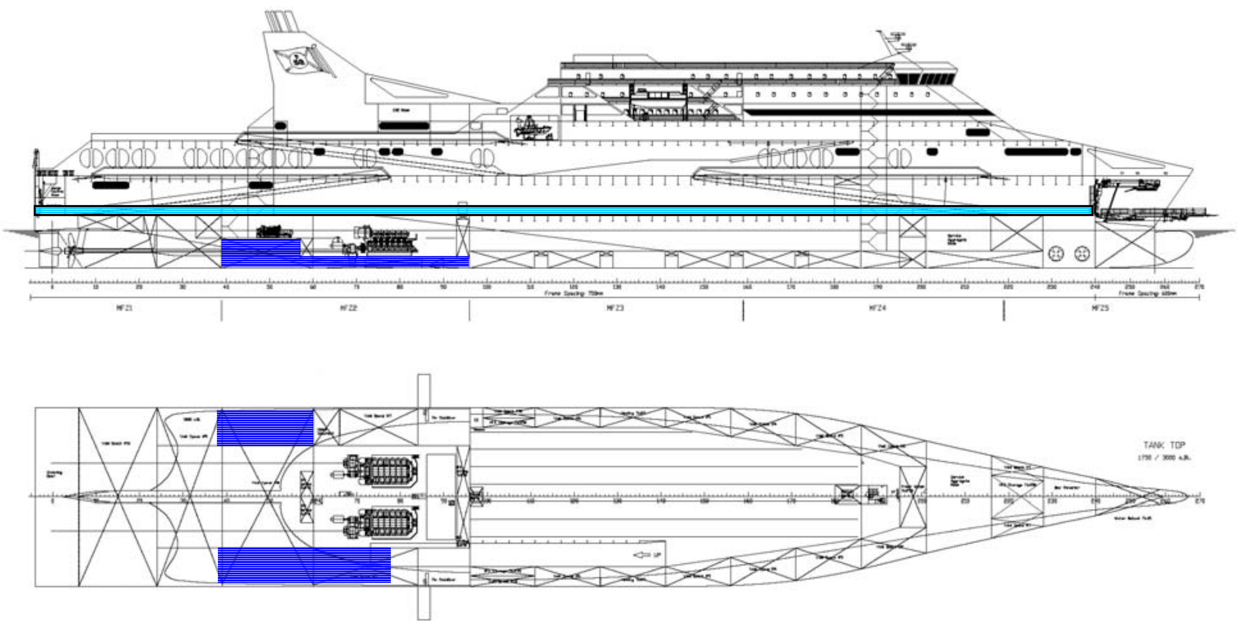

Fig. 40 EMSA2: Damage Case 1.

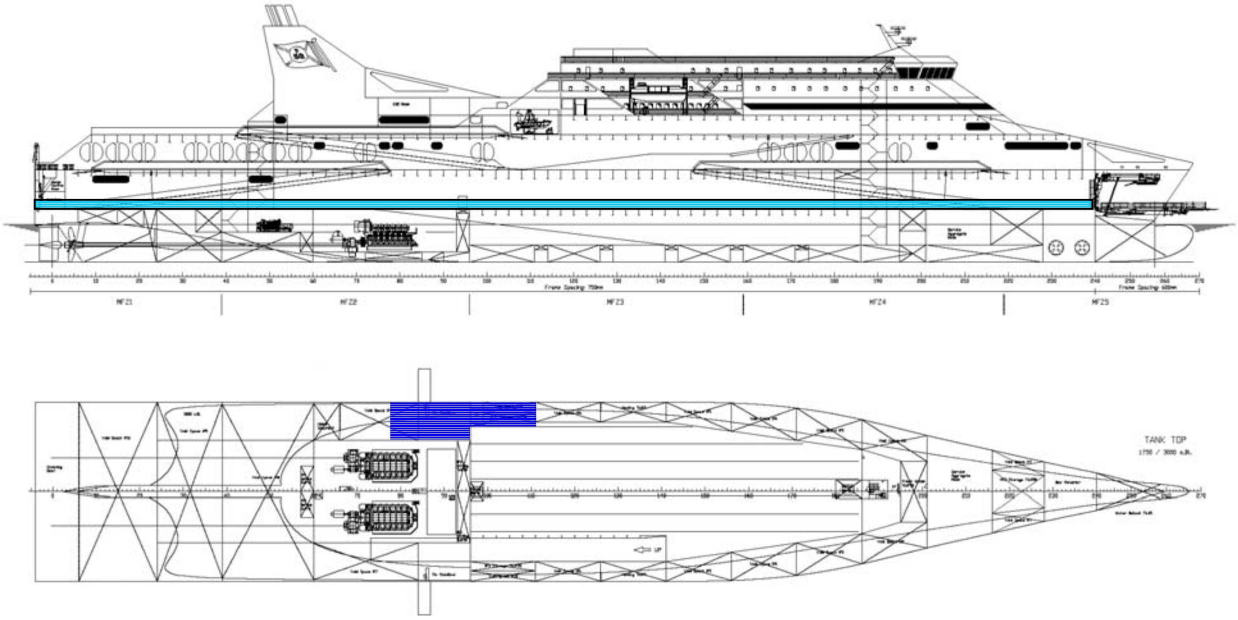

Fig. 41 EMSA2: Damage Case 2.

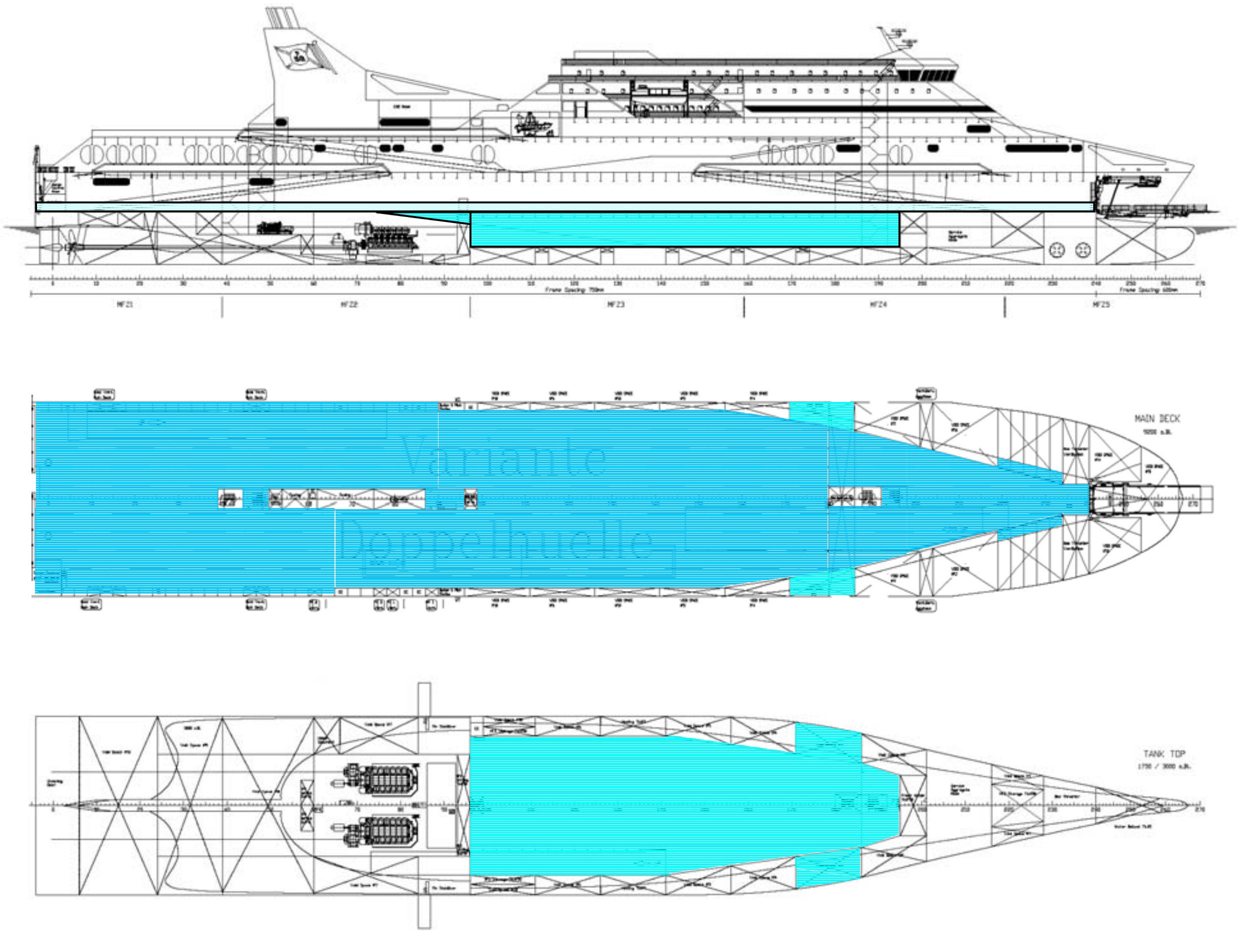

Fig. 42 EMSA2MOD: Damage Case 4.

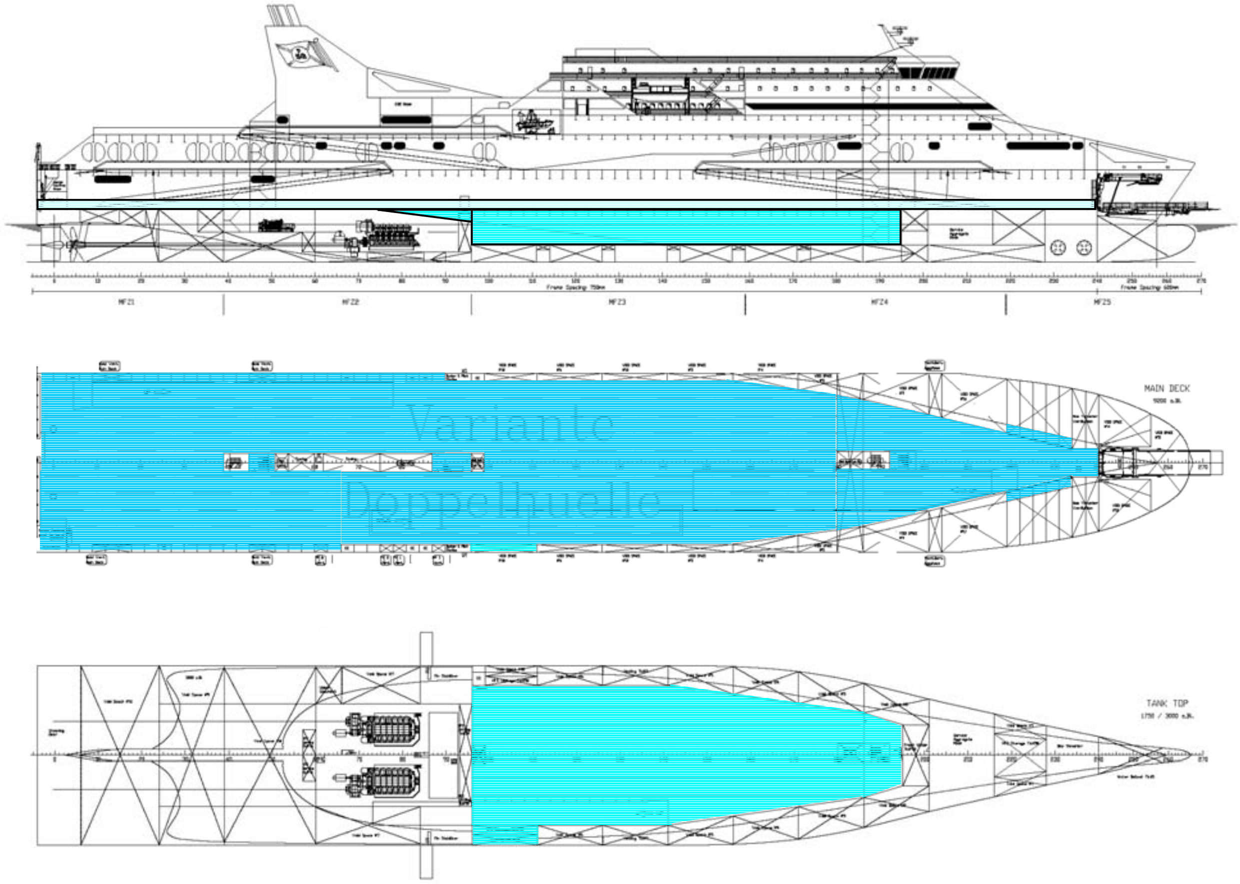

Fig. 43 EMSA2MOD: Damage Case 5.

8.3 Initial Simulations

The damage cases were investigated with the program HSVA ROLLS. The significant wave height value (H_s) of 4.0 m was used. The natural rolling period of the damaged ship was determined to be 13.3 s with a numerical roll decay test. In the simulations the mentioned natural rolling period of the damaged ship (13.3 s) was used as the modal wave period in the JONSWAP-spectrum together with the peak parameter value γ of 3.3 for the wave generation. Thus in the numerical simulations the modal wave period of the generated wave spectrum is the (numerically determined) natural rolling period of the vessel.

The damage opening on the ship side was chosen to be always 8.690 m wide, which is 3 percent of the L_{bp} + 3 m. A triangle of B/5 in height was in general used to describe the damage penetration. In the original ship version without side compartments on the vehicle deck the opening to the vehicle deck had always the mentioned width. In the version with side compartments on the vehicle deck the opening to the vehicle deck was determined based on the mentioned triangle. The damage width is as defined in the Annex of the Stockholm Agreement. The damage opening height was limited to the height of the compartment in question.

The compartments beside the Long Lower Hold have a width varying from just above B/10 to more than B/4. In Damage Case 4 a larger penetration depth 0.3B, that is, the height of the mentioned triangle, was used for the damage to penetrate the LLH in the chosen location. The width of the damage is not changed, only the depth.

First it was investigated how long the vessel would survive in practically beam seas coming from the side of the damage, with the wave direction 85°, in a sea state having a significant wave height 4.0 m. The capsize events were taken as roll angle of more than 30° against the vertical axis, occurring more frequently than in 20 percent of the rolling cycles, or steady heel greater than 20°. The vessel survives, when the capsize criteria is not met in 30 minutes and a stationary state is reached, as described by the Stockholm Agreement.

The numerical simulations shoved the following behavior:

EMSA2: Damage Case 1

The vessel behaves in a very straightforward manner: Either both the water volume on the vehicle deck and the heeling angle remain low, other grow monotonously, in the beginning very slowly, later moderately and at the end very rapidly ending into a capsize.

EMSA2: Damage Case 2

The behavior is very similar to that in Damage Case 1

EMSA2: Damage Case 3

The vessel sinks in calm water according to the TUHH hydrostatic calculations with the system E4. Calculations with NAPA by SDC give the same result. A trial simulation with the HSVA ROLLS, starting with a vehicle deck free of water leads to the same result. The vehicle deck does not need to be damaged, the gaps around the bow ramp let water slowly in, as the lower edge of the bow ramp submerges below still water level. As the initial condition of the vessel, which hydrostatically sinks, is for the numerical simulations of the ship motions not properly defined, the case is not further simulated with the HSVA ROLLS.

EMSA2MOD: Damage Case 4 with modified vehicle deck

The vessel survives up to significant wave height of 6.0 m, if the vehicle deck is initially flooded. All non-survival cases ended up in a steady heel over 20°. If not, the ship survives up to significant wave height of 3.0 m.

EMSA2MOD: Damage Case 5 with modified vehicle deck

The vessel did not survive in any simulated case. The one sided damage causes a sufficient heeling angle for the water to flow onto the vehicle deck on the damage side. This process does not end and no steady state was reached.

8.4 Survival Times

The first simulations were performed in each damage case with ten random seeds for the wave realization of the irregular seas: *In none of the three investigated damage cases the original vessel designed to fulfill SOLAS 2009 could survive the sea state with the significant wave height of 4.0 m.* These results are shown in Table 34.

Table 34 The simulation results of the Ship EMSA2/EMSA2MOD, a 200 m RoRo Passenger Ferry, in beam seas with the original *KG* of 14.20 m and with a significant wave height H_S of 4.0 m. Ten different random seeds were used for the wave realization in the simulations.

KG = 14.20 m, as designed. Significant wave height H_s = 4.0 m					
Damage Case	*Final Condition after 30 min.*			Maximum. time to Capsize [min]	Survival Criteria satisfied
	Steady Heel no. [-]	*Capsize no.* [-]	*Survived no.* [-]		
EMSA2: 1	0	10/10	0	9.1	No, Capsize
EMSA2: 2	0	10/10	0	6.5	No, Capsize
EMSA2: 3	0	10/10	0	-	No, Capsizes/sinks already in calm water
SUM	0	30	0	9.1	No
EMSA2MOD: 4a	0	8/10	2	26	No, max. heel > 30°
EMSA2MOD: 5	0	10/10	0	< 4.2	No, Capsize
SUM	0	18	2		

According to these results the original ship design EMSA2 would capsize in Damage Cases 1-3 in less than 9.1 minutes in all 30 cases computed with the HSVA ROLLS. In Damage Case 4 the modified ship design EMSA2MOD would survive in 2 out of 10 cases. In Damage Case 5 the modified ship design EMSA2MOD did not survive in any of the 10 cases. It should be kept in mind that in the studied cases the large LLH is damaged, in which case the original vessel would have sank. The design modification certainly is a step into right direction, providing the vessel a greatly improved survivability. According to the simulations of the Damage Cases 4 and 5 the modification was, however, not a sufficient one.

After these first results it was studied: (1) At which significant wave height the vessel survives; (2) at which *KG* or *GM* -values the vessel survives in a sea state of H_s 4.0 m. The results are shown in Table 35. The Damage Case 4a was started without any water on the vehicle deck. The Damage Case 4b was started with the initial amount of water on deck given by the hydrostatic calculations. In this latter case the vessel survives in 4.0 m high waves.

Table 35 The simulation results of the ship EMSA2/EMSA2MOD in beam seas with a *KG* of 14.20 m, and with a significant wave height H_S of 4.0 m. Only one random seed for the wave realization was used in the simulations.

KG = 14.20 m, as designed. Survival H_s				Sea state H_s = 4.0 m, Survival *KG*			
Damage Case	H_s [m]	Water Vol on V-Deck [m³]	Water Vol in Comp. [m³]	*KG* [m]	*GM* [m]	Water Vol. on V-Deck [m³]	Water Vol. In Comp. [m³]
INTACT	> ?	0	0	≤ 14.20	≥ 4.50	0	0
EMSA2: 1	≤ 2.4	~ 7	~ 2500	≤ 12.00	≥ 6.70	~ 3446	~ 2952
EMSA2: 2	≤ 2.5	~ 425	~ 505	≤ 11.72	≥ 6.98	~ 2836	~ 511
EMSA2: 3	0.0	-	-	-	-	-	-
E2MOD: 4a	≤ 3.1	~ 600	~ 1800	-	-	-	-
E2MOD: 4b	≤ 6.1	~ 300	~ 3000	-	-	-	-
E2MOD: 5	< 0.2	-	-	≤ 8.50	≥ 10.2	~ 21500	~ 9250

The second column from left shows the significant wave height H_s, at which the vessel having a *KG* of 14.20 m survives. This limiting significant wave height was obtained by lowering the wave heights usually starting from 4.0 m until the state of survival was reached. Notice that in Damage Cases 1-3 the freeboard is less than 2.2 m to the damaged vehicle deck and that the low waves bring only little water onto the vehicle deck.

The Damage Cases 4 and 5 were investigated with the modified vehicle deck of the vessel EMSA2MOD to avoid an instant sinking in calm water. In Damage Case 4 the damaged compartments are symmetric, the vessel gets a heavy bow trim, and it survives up to the significant wave height of 6.1 m or 3.1 m depending on the initial condition. The Case 4a, that is, without water on the vehicle deck in the start, has the lower survivability, which indicates that the vessel may be more vulnerable during the initial transient phase of the vehicle deck flooding with water than later, when the final hydrostatic floating position has been reached.

In Damage Case 5 no state of survival could be reached even with the lowest applied wave height of 0.2 m: The damaged compartments at the ship side cause a sufficient list to lower the damage opening to the vehicle deck into water. As the vehicle deck is partly submerged, practically any wave height is sufficient to bring water onto vehicle deck through the damage opening. As a consequence the ship heels, which moves more water to the damaged side and the ship heels continuously over. This damage case has a lower trim than the Damage Case 4, which has an adverse effect on the survival.

The 5th column shows the *KG*-values, at which the vessel survives in a sea state of H_s 4.0 m. The limiting values of *KG* or metacentric height *GM* were obtained by lowering the *KG* until the vessel survives in the almost beam seas (dir. 85°) in the sea state of H_s 4.0 m. Due to the significant wave height 4.0 m, to the low freeboard to the damaged vehicle deck (< 2.2 m) in Damage Cases 1-3 and due to the high *GM,* a large amount of water can accumulate onto this deck without the vessel capsizing. The vehicle deck has a surface area of ca. 4747 m². The simulations with the HSVA ROLLS show that in some damage cases there can be about 0.7 m of water on the vehicle deck. This is more than the maximum water height (0.5 m) assumed in the Stockholm Agreement. In Damage Cases 4-5 the vessel EMSA2MOD gets an enormous amount of water onto the vehicle deck, due to increased draught as a result of the damage in the large LLH. In general it should be kept in mind that we have not checked here, whether the obtained *KG*- values sufficient for survival would be realistic from the point of view of the ship design.

As well it is important to notice that ***the derivation of the Stockholm Agreement calculation procedure is implicitly bound with the SOLAS 90 rules***. The Damage Cases 4-5 of the ship EMSA2MOD lead into a situation, namely the partial submergence of the vehicle deck, which is not defined in the Stockholm Agreement.

8.5 Further Simulations with Different Realizations of the Sea State

The Damage Cases 1 and 4 were considered most interesting for further investigations: The damage openings are located in the midship - afterbody area just behind the LLH, and in the front part of the LLH, respectively. Damages in front of the LLH should not be critical due to the relatively small compartment size there and the narrowness of the ship forebody.

8.5.1 Damage Case 1 with *KG* 14.20 m and H_s 4.0 m

The Damage Case 1 on the original design of the ship EMSA2 with *KG* 14.20 m was investigated in a sea state having a significant wave height of 4.0 m using random seeds 1-10 for the sea state generation in the simulations, as shown in Table 36.

Table 36 The simulation results of the ship EMSA2 with a *KG* of 14.20 m in beam seas of H_S 4.0 m. Ten wave realizations were used in the simulations.

	H_s [m]	T_P [s]	Final Condition after 30 min.	
			Capsize no. [-]	Time to Capsize [av.] [min]
DACA 1	2.4	13.3	1/10	~ 18
DACA 1	2.5	13.3	2/10	~ 16.2
DACA 1	2.8	13.3	8/10	~ 13.3
DACA 1	4.0	13.3	10/10	~ 7.1

The ship survives this damage case in a seaway having a significant wave height of 2.4 m, but not anymore in all cases. With the significant wave height 2.5 m the ship survives in 8 cases out of 10. With the significant wave height of 2.8 m the ship capsized in 8 cases out of 10. With some simplifications we can assume that in general the ship survives the Damage Case 1 in sea states with H_s somewhat lower than 2.5 m. In all computed cases, in which the ship did not survive, it always capsized to the damaged starboard side. Thus the ship never reached a stable position with a large heeling angle. Figures 44 and 45 illustrate the behavior of the vessel and flooding of the vehicle deck in one typical simulation.

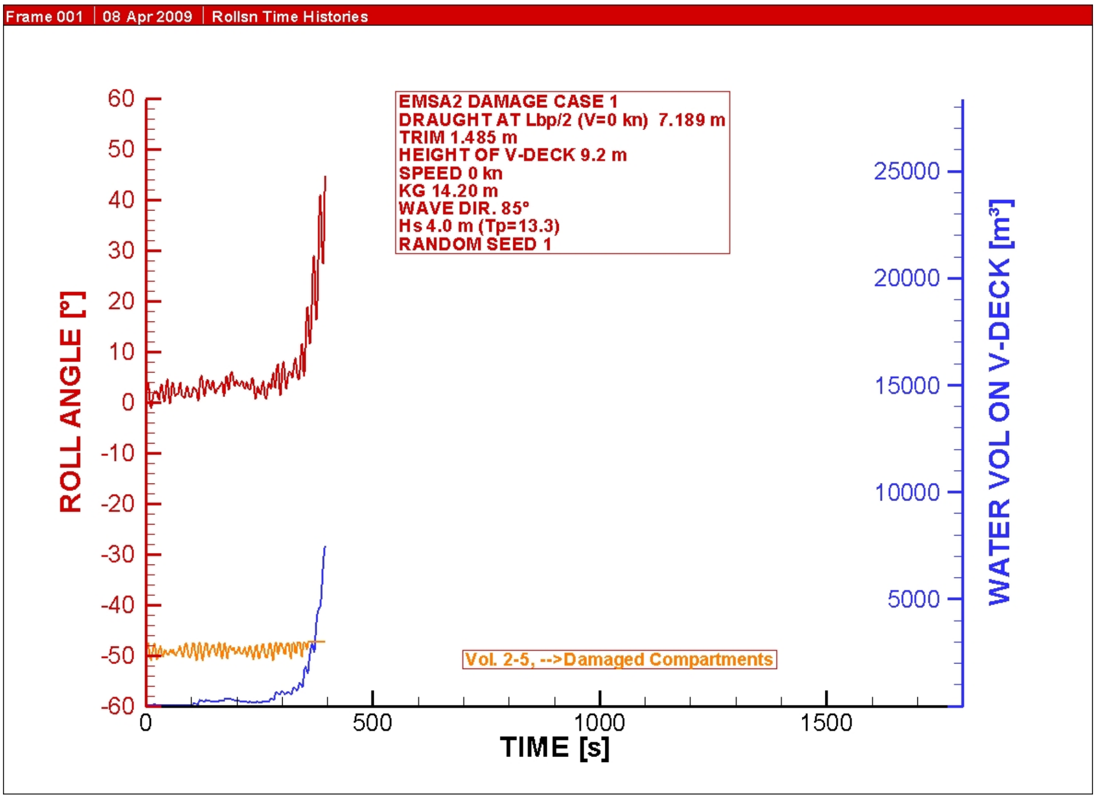

Fig. 44 The heeling angle and the water volumes on the vehicle deck and in the damaged compartments of the ship design EMSA2 in Damage Case 1 as a function of time.

The short center casing happens to cover the damaged ship length, which to certain extent prevents the flood water from sloshing on to the port side of the vehicle. This probably contributes to the fact that the vessel heels in all simulations to the damaged side. The initial heel to the damaged side is about 1.5°.

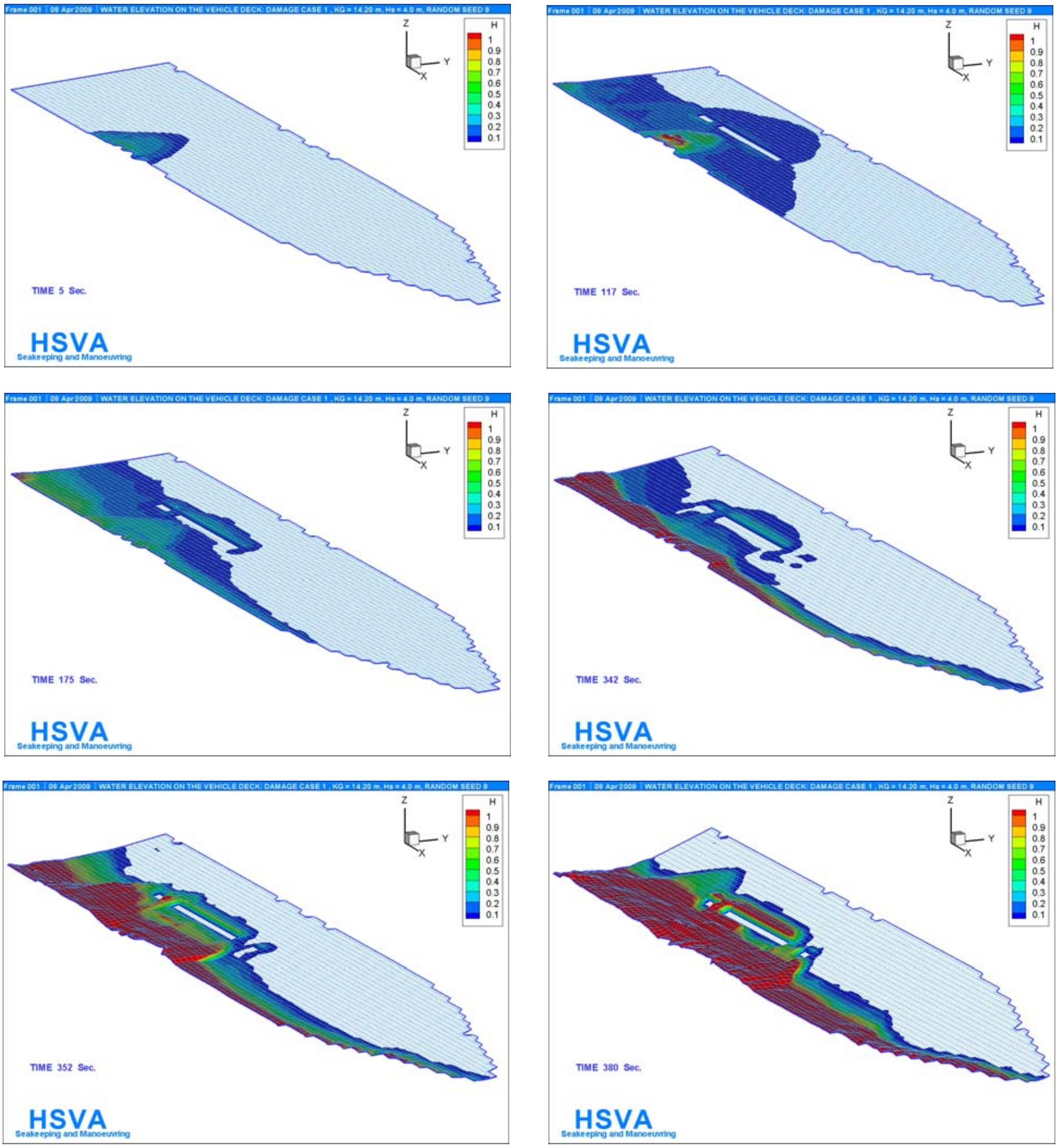

Fig. 45 Screenshots of the vehicle deck flooding according to the simulation with the HSVA Rolls at times 5, 117, 175, 343, 352, 380 s. The coloring expresses the water height on the deck perpendicular to the deck. EMSA2: Damage Case 1, *KG* = 14.20 m, H_s = 4.0 m, random seed 1.

8.5.2 Damage Case 4 with *KG* 14.20 m and H_s 3.2 m

The Damage Case 4 on the modified design of the ship EMSA2MOD with *KG* 14.20 m was investigated in a sea state having a significant wave height of 4.0 m using random seeds 1-10 for the sea state generation in the simulations, as shown in Table 34.

Figures 46 and 47 illustrate the behavior of the vessel and flooding of the vehicle deck with the lowest significant wave height leading to capsize (H_s 3.20 m).

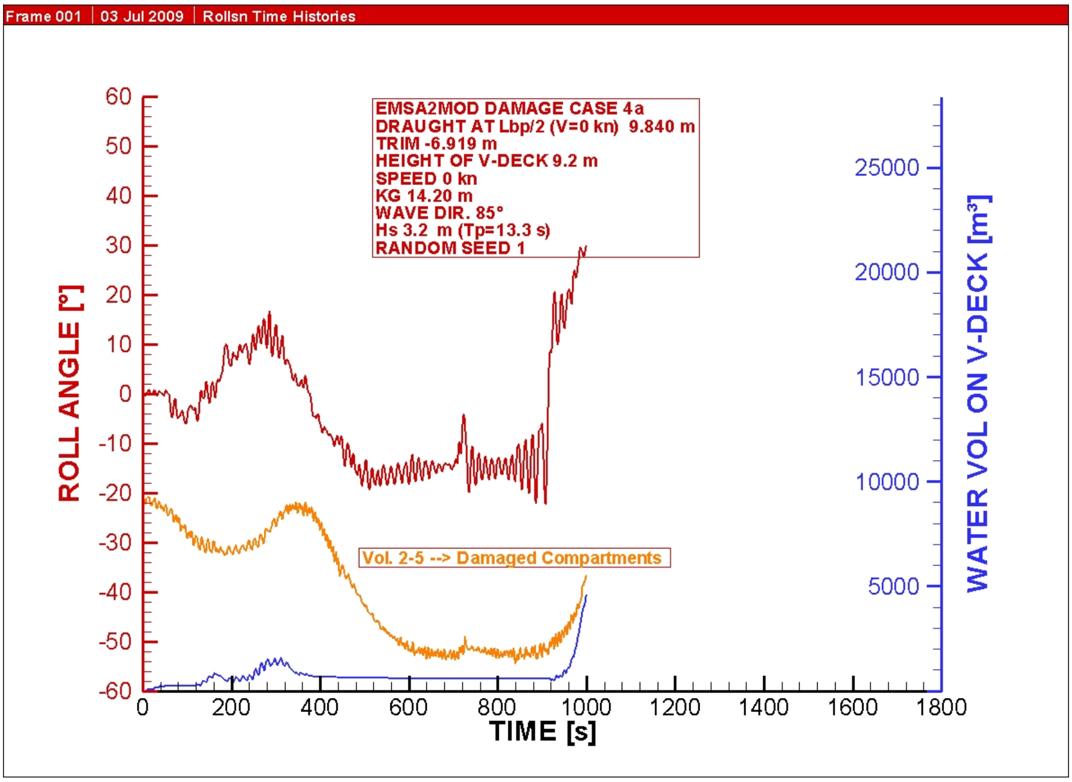

Fig. 46 The heeling angle and the water volumes on the vehicle deck and in the damaged compartments of the ship design EMSA2MOD in Damage Case 4a as a function of time.

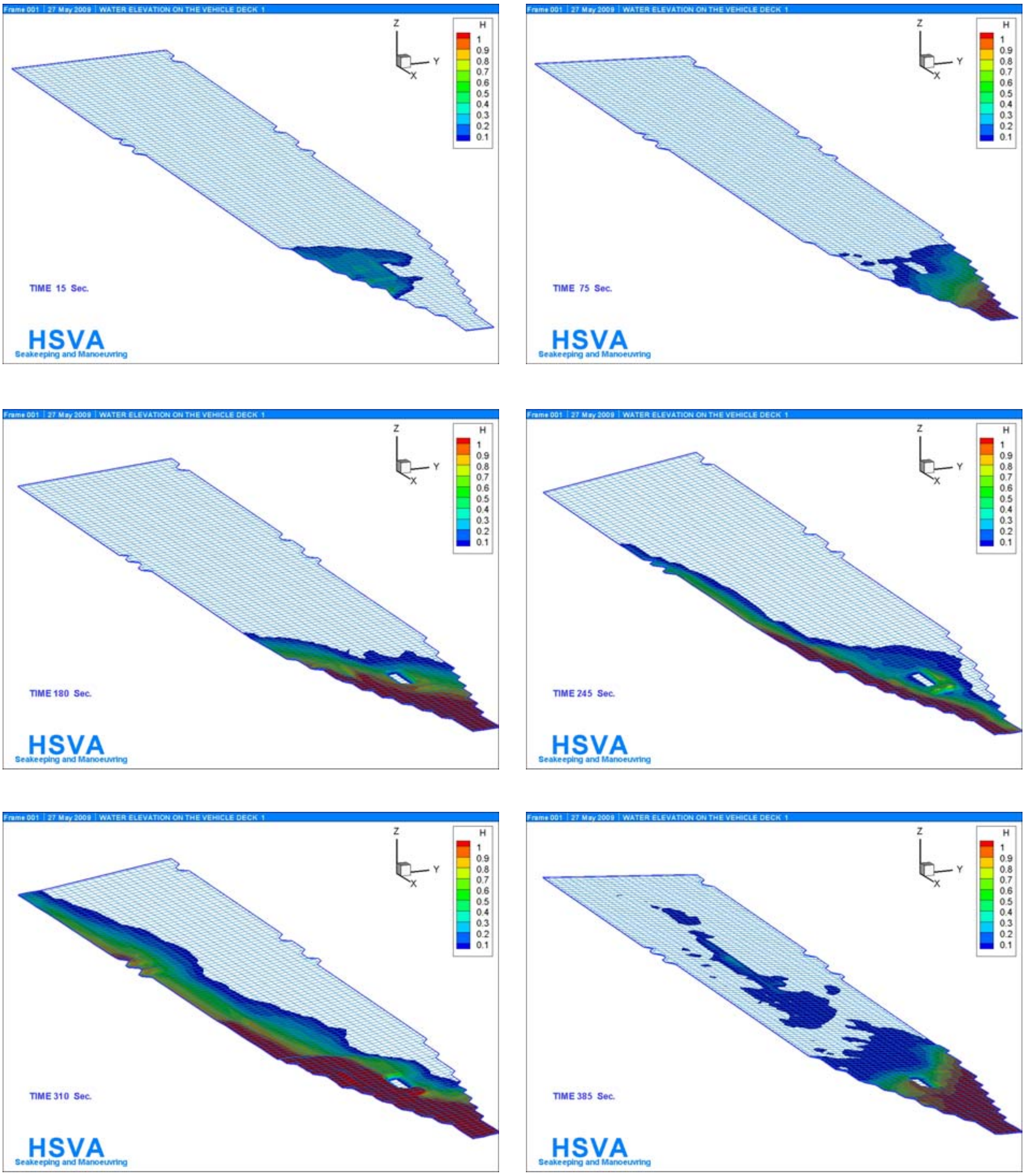

Fig. 47 Screenshots of the vehicle deck flooding according to the simulation with the HSVA Rolls at times 15, 75, 60, 180, 245, 310, and 385 s. The coloring expresses the water height on the deck perpendicular to the deck. EMSA2MOD: Damage Case 4a, *KG* = 14.20 m, H_s = 3.2 m, random seed 1.

8.6 Righting Levers of the Ship EMSA2

Figure 48 shows the righting lever curves used in the program HSVA ROLLS. The vessel is assumed to be watertight up to higher decks (above the bulkhead deck) during the dynamic rolling motions. The damage opening and its influence is modeled elsewhere in the program. The two curves in the middle are plotted for comparison only and they show the righting lever curves of the *MV Estonia* up to the Bulkhead Deck (no. 4) and up to the Deck 8. All other curves show the righting lever of the ship EMSA2/EMSA2MOD. These are plotted up to the heeling angle 63°.

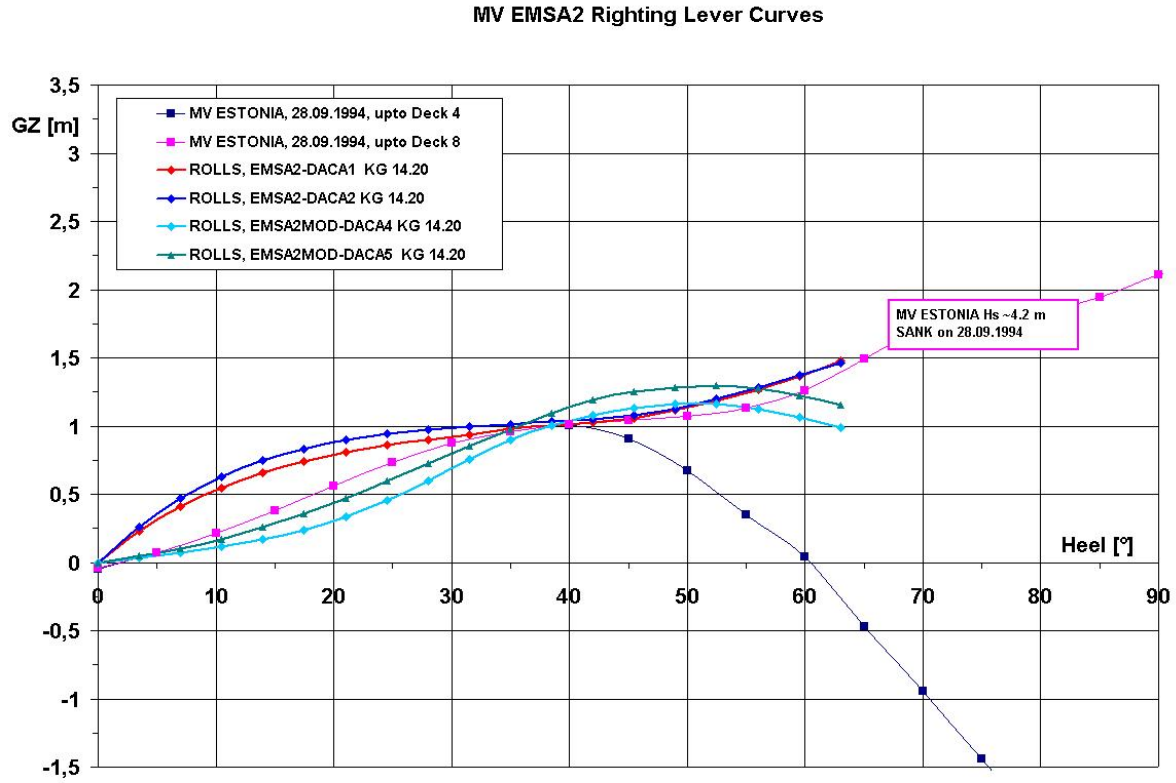

Fig. 48 Righting lever curves of the intact vessel. The draught and trim of the vessel are always those of the damage case investigated.

Note that the applied survival criterion limits the relevant part of the righting lever curves to that below 30°. None of the righting lever curves deviates radically from those of the *MV Estonia*. In this respect the situation with the design EMSA2 is considerably better than with the design EMSA1, which has considerably lower righting lever values. Notice also that these righting lever curves of the intact ship are related to the initial floating position of the vessel in each damage case and they differ significantly due to different trim and draught values.

8.7 Conclusions

- The ship EMSA2, a 200 m Ro-Ro Passenger Ferry was designed by the FSG to satisfy the requirements of SOLAS 2009.

- The design of the vessel does not satisfy the requirements of the SOLAS 90 and the Stockholm Agreement.

- The TUHH suggested four damage cases to be investigated with the numerical simulation of the motions of the damaged ship in beam seas together with the modeling of the flooding of the vehicle deck.

- The numerical simulations were carried out with the HSVA ROLLS. The width of the damage openings were chosen as recommended in the Stockholm Agreement, that is, they amount to 8.690 m, i.e. 3 percent of L_{bp} + 3 m.

- *In none of the investigated Damage Cases 1-3 the original vessel EMSA2 designed to fulfill SOLAS 2009 could satisfy the survive criteria in the sea state with the significant wave height of 4.0 m.* In all cases out of 30, the vessel have would have capsized in less than 9.1 minutes. If the long lower hold becomes exposed to sea the vessel sinks. These numerical predictions are rather clear, even in view of possible numerical modeling errors.

- In order for the original vessel EMSA2 to survive the chosen damage in a sea state with a H_s of 4.0 m, the *KG*-values of the ship should be reduced from the original 14.20 m to about 11.7-12.0 m depending on the damage case. The corresponding increase in the *GM*-value would be from the original 4.5 m to about 6.7 – 7.0 m. In this connection it should be kept in mind that the *KG* cannot be reduced endlessly.

- In the investigated Damage Cases 4-5 the modified vessel EMSA2MOD exceeding the requirements of SOLAS 2009 shows a behavior leading to following conclusions: In Damage Case 4 the damaged compartments are symmetric, the vessel gets a heavy bow trim, and the vessel survives up to the significant wave height of 6.1 m or 3.1 m depending on the initial condition. This indicates that the vessel may be more vulnerable during the initial transient phase of the vehicle deck flooding with water than later, when the final hydrostatic floating position has been reached. In Damage Case 5 no state of survival could be reached even with the lowest applied wave height of 0.2 m. The modification to add watertight compartment on the vehicle deck is certainly a good, recommendable solution, but it is at this moment not quite clear, whether this particular design modification is large enough to provide a sufficient safety level in all damage cases involving the LLH.

- As well it is important to notice that ***the derivation of the Stockholm Agreement calculation procedure is implicitly bound with the SOLAS 90 rules.*** The Damage Cases 4-5 of the ship EMSA2MOD lead into a situation, namely the partial submergence of the vehicle deck, which is not defined in the Stockholm Agreement.

Taking this all into account the following conclusion can be drawn:

The original ship EMSA2, a 200 m RoRo Passenger Ferry, designed by a well-known European shipyard to fulfill the requirements of the SOLAS 2009, has according to the numerical simulations a limited capacity to survive a collision damage at the midship area in sea states having a significant wave height of more than 2.5 m. In addition any damage deeper than B/10 in the midship area can penetrate the Long Lower Hold having a length of 39 percent of the L_{bp}. In such a case the ship sinks/capsizes rapidly also in calm water.

In view of this it is difficult to come into any other conclusion that the ship stability required by the SOLAS 2009 rules is not likely to be sufficient in all cases. If these numerical results are confirmed in the model tests, corrective action should be taken to amend the SOLAS 2009 rules.

9 Damage Stability Tests with the Ship EMSA2 in Seaway

9.1 Introduction

Fig. 49 The model HSVA No. 4615 of the ship EMSA2/EMSA2MOD with the opening of the Damage Case 4 at the ship side. The closed opening for the Damage Case 1 can also be seen between the stations 4 and 6.

This chapter gives a short review of the model tests carried out with the HSVA model No. 4615 of the ship design EMSA2. The model and the damage opening of the Damage Case 4 are illustrated in Figures 49 and 50. The tests are reported in detail separately in the HSVA Report No. S590b/09 "Damage Stability Tests with the Model of a 200 m RoPax Vessel" by Ludwig (2009b).

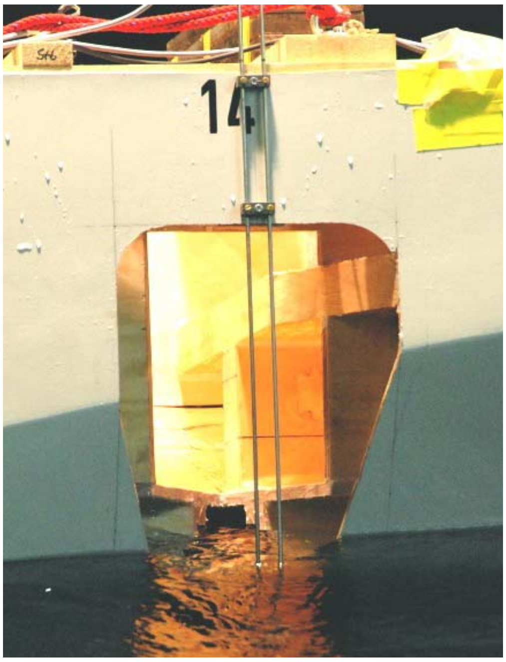

Fig. 50 The damage opening of the Damage Case 4.

The main purpose of the tests was to find out whether the ship designed to meet the SOLAS 2009 requirements would survive in model tests carried out according to the guidelines in the Annex of the Stockholm Agreement or according to the Directive 2003/25/EC, as amended. The width of the damage openings at the ship side was always 8.690 m (i.e. 3 percent of the L_{bp} + 3 m). In addition to the issue of survival, information on the behavior of water on the vehicle deck of the damaged vessel was gathered with video cameras viewing the vehicle deck and with 14 wave sensors measuring the water elevation on various locations on the vehicle deck during each test. These recordings give important information on the capsize mechanism of the RoPax vessel with water on deck, and were carried out particularly in view of the further development of the stability rules, which may turn out to be necessary.

The tests were carried out in the HSVA's large towing tank on 4-6 of May 2009. The scale of the model was chosen to be 34. Thus a 5.9 m long model was used in the 18 m wide test basin, leaving sufficient space in front of the bow and behind the stern of the vessel in beam seas. The 300 m long test basin provided a sufficiently long measurement period practically free of wave reflection. The irregular beam seas were generated with the JONSWAP- spectrum. Figures 51-54 give a sequence of typical behavior of the model of the EMSA 2 in Damage Case 1 in the model tests. See also Figures 44 and 45.

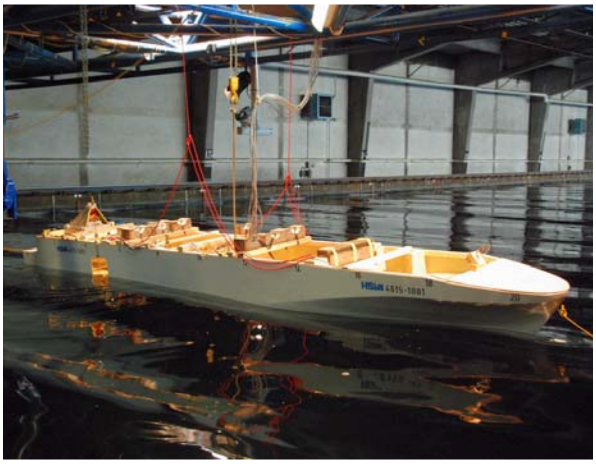

Fig. 51 The model of the ship design EMSA2 floats in Damage Case 1 with a small list to the damaged side.

Fig. 52 The list increases gradually.

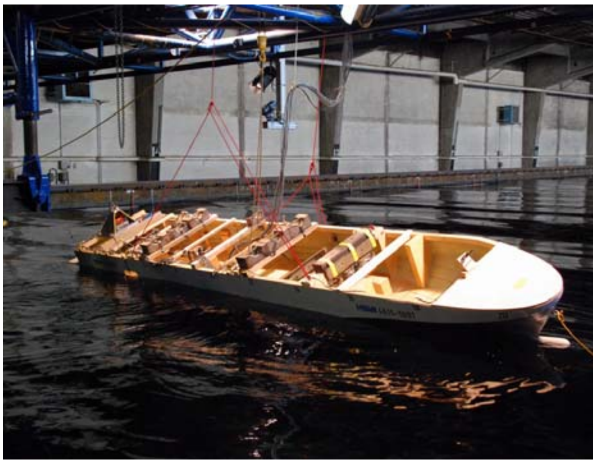

Fig. 53 The list exceeds 20°.

Fig. 54 The list grows further and a full capsize of the model is avoided only with the help of the red “preventer” lines.

9.2 Test Results on the Ship EMSA2 / EMSA2MOD in Damage Cases 1 and 4

Tables 37 and 38 below show the main results of the model tests with the ship design EMSA2, EMSA2MOD in Damage Cases 1 and 4, respectively. The tables list the test runs giving the measured wave height H_S and peak period of the wave spectrum T_P in each test together with the information, whether the ship survived according to the survival criteria or not. The cases of non-survival are marked with red color. Beside the critical H_S leading to capsize also the maximum value of the *GZ* and the range of the positive values of *GZ* in the damage cases are given.

Table 37 Survival of the ship EMSA2 with Damage Case 1 in the model tests.

EMSA2: Damage Case 1					
Test Run-No. No.	GZ_{MAX} [m]	Range [deg]	H_S [m]	T_P [s]	Survived[1]
1	0.248	14.5	3.97	12.0	YES
2	0.248	14.5	4.01	12.0	YES
3	0.248	14.5	4.02	12.0	YES
4	0.248	14.5	4.03	12.0	YES
5	0.248	14.5	4.46	12.0	NO
6	0.248	14.5	4.87	12.2	NO
7	0.248	14.5	4.32	11.6	NO
8	0.248	14.5	3.81	8.4	YES
9	0.248	14.5	3.73	8.4	YES
10	0.248	14.5	4.51	8.6	YES
11	0.248	14.5	4.77	8.7	NO
12	0.248	14.5	4.99	8.9	NO
13	0.248	14.5	4.58	8.6	NO
14	0.248	14.5	4.65	8.6	YES
15	0.248	14.5	4.65	8.6	NO

1) According to the survival criterion used in this study: The ship should be considered surviving, if a stationary state is reached for the successive test runs, provided that the angles of roll of more than 30° against the vertical axis, occurring more frequently than in 20 percent of the rolling cycles or steady heel greater than 20° should be taken as capsizing events, even if a stationary state is reached.

Table 38 Survival of the ship EMSA2MOD with Damage Case 4 in the model tests.

EMSA2MOD: Damage Case 4					
Test Run No.	GZ_{MAX} [m]	Range [deg]	H_S [m]	T_P [s]	Survived[1]
16	0.162	17.9	3.90	11.8	YES
17	0.162	17.9	3.75	11.6	YES
18	0.162	17.9	4.64	12.3	YES
19	0.162	17.9	4.62	12.2	YES
20	0.162	17.9	4.64	12.3	YES
21	0.162	17.9	3.73	8.3	YES
22	0.162	17.9	4.35	8.4	YES
23	0.162	17.9	4.31	8.4	YES
24	0.162	17.9	4.30	8.4	YES
25	0.162	17.9	4.38	8.4	YES
26	0.162	17.9	6.50	10.2	YES
27	0.162	17.9	6.69	11.1	YES
28	0.162	17.9	4.39	8.5	YES
29	0.162	17.9	5.60	10.3	YES
30	0.162	17.9	6.64	11.1	YES
31	0.162	17.9	4.21	8.3	NO
32	0.162	17.9	3.91	8.3	NO
33	0.162	17.9	3.70	8.3	NO
34	0.162	17.9	3.68	8.3	NO
35	0.162	17.9	3.78	8.3	NO

The significant wave heights H_S and peak periods of the wave spectrum T_P in Tables 37 and 38 are values actually realized in the model tests. The peak periods were chosen according to the Directive 2003/25/EC: Thus the two periods were used: (1) $T_P = 4\sqrt{H_S}$, and (2) T_P = rolling period of the damaged ship, but not greater than $6\sqrt{H_S}$.

Table 39 Critical significant wave heights based on numerical simulations and model tests.

Ship Design EMSA2: Numerical Simulations and Model Tests							
DAMAGE CASE	GZ_{MAX} [m]	Pos. range of GZ [°]	Computation		Model Test		SURVIVES?
			$Hs_{critical}$ [m]	T_P [s]	$Hs_{critical}$ [m]	T_P [s]	
EMSA2: 1	0.250	14.6	2.4 … 2.8	13.3	4.3 4.6	11.6 8.6	YES
EMSA2: 2	0.231	14.3	2.5	13.3			
EMSA2: 3			0		-	-	NO
EMSA2MOD: 4	0.175	18.1	6.1[1] 3.1[1]		> 6.7 3.8[2]	11.1 8.3	~YES
EMSA2MOD: 5			< 0.2				

1) Depends whether the vehicle deck is flooded initially or not:.
2) Trim before damage +2.8 m (stern trim), => trim after damage -4.6 m (bow trim) + 4 ° list to undamaged side.

The critical significant wave heights obtained with numerical simulations and with model tests are given together in Table 39. The following conclusions can be drawn:

- The model tests showed that the ship EMSA 2 would survive Damage Case 1 in 4.0 m waves.

- Hydrostatic calculations and the numerical simulations indicate that the ship EMSA2 would not survive Damage Case 3 in calm water or in waves: The ship capsizes/sinks also in calm water.

- The ship design EMSA2MOD survives the Damage Case 4 (identical to Damage Case 3) in 6.7 m waves, when there is no initial heel towards the undamaged ship side. In this case the net water ingress on the vehicle deck goes gradually to zero. The amount of water on the vehicle deck is considerable: There is 3.7 m water at the very end of the vehicle deck at the bow.

- With a 4° list after the damage the ship EMSA2MOD with Damage Case 4 capsizes in 3.8 m waves.

  The 4° list does not follow from any specific rule, but from an easy possibility to cause a list to the undamaged side by moving a weight in the ship model during the tests. The purpose was to find out whether the relatively high survivability of the vessel EMSA2MOD would be sensitive to reasonable changes in the initial trim and list.

The numerical simulations and the model tests with the ship design EMSA2 showed the following:

Damage Case 1: The ship capsizes with H_s 4.3 m and 4.6 m with peak periods 11.6 s and 8.6 s of the wave spectra, respectively. Thus the ship is expected to survive in 4.0 m waves.

Damage Case 2: In view of model test results with the very similar Damage Case 1 and the numerical simulations with Damage Case 2 it can be expected that the ship would survive the Damage Case 2 in 4.0 m waves.

Damage Case 3: The ship sinks also in calm water.

In view of the numerical simulations and hydrostatic calculations showing that the ship EMSA2 can sink/capsize in calm water in Damage Case 3, the original design cannot be regarded as a safe design in a likely damage case.

Damage Case 4: The modified ship EMSA2MOD did not capsize with H_s 6.7 m with the peak period of 11.1 s. After change of trim and initial heeling the ship capsized with H_s 3.8 m.

The modified version EMSA2MOD provides sufficient buoyancy for the vessel also in the case the Long Lower Hold (LLH) is damaged. Whether this design is safe in all phases of flooding, particularly in the initial transient phase, in all initial floating conditions (heeling, trim) is not yet established. This first modification to enable for the ship to have the attractive design feature LLH and survive in case of LLH damage in 4.0 m waves is certainly a step in the right direction. There is no doubt that the suggested modification can be extended, if needed, to provide a safe ship also in case of a LLH-Damage.

10 Behavior of Water on the Vehicle Deck of a Damaged RoPax Ship in Seaway

10.1 Water on Deck of the Ship Design EMSA1

The motion and amount of water on the vehicle deck were investigated based on the water heights measured on the vehicle deck in the model tests. The height of water on the vehicle deck was recorded with 14 wave probes in the model tests with the ship EMSA1. The exact position of these probes on the vehicle deck is given in Figure 9 of the HSVA model test report S590a/09 and is also shown without dimensioning below in Figure 55. The sensors were arranged in rows and columns based on the numerical simulations of the water motion and accumulation on the vehicle deck, in order to put the few sensors in the most relevant locations.

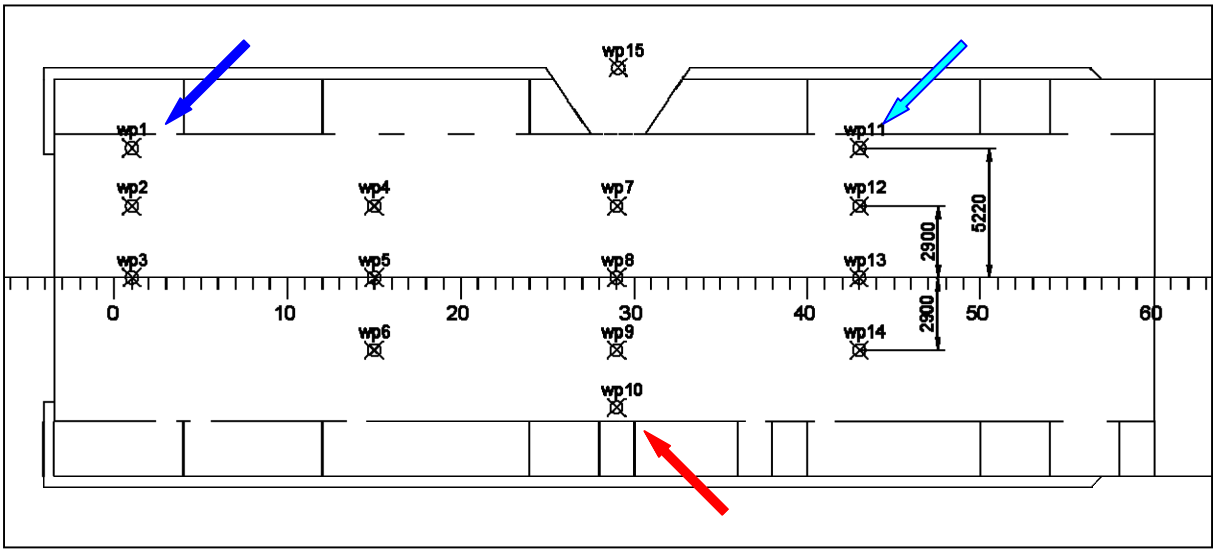

Fig. 55 The positions of the wave probes on the vehicle deck of the ship model EMSA1 in Damage Case 1. The arrows indicate the positions of the sensors wp1, wp10, and wp11.

The total water volume on the vehicle deck was calculated based on interpolation between the sensors and extrapolation towards the vehicle deck walls in transverse and longitudinal directions. In the extrapolation the momentary heel and trim angles of the vessel were used. The results are illustrated in Figures 56, 57, and 59 and are given also in the Table 40 as full scale values.

The uppermost red curve in Figure 56 shows the roll angle as a function of time from the beginning of the measurement. The light blue curve in the middle shows the total amount of water on the vehicle deck and in the side compartments. The lowest dark blue curve shows the amount of water on the vehicle deck only, without the side compartments.

The total amount of water on vehicle deck and in the side compartments just before the capsizing starts can be called the critical amount. If more water accumulates on the vehicle deck than this amount, the vessel can be expected to capsize. The critical amount was evaluated as follows: The heeling (roll) angle –curve changes its slope just before the capsizing starts. This point was identified and the average amount of water at this moment of time was read from the scale.

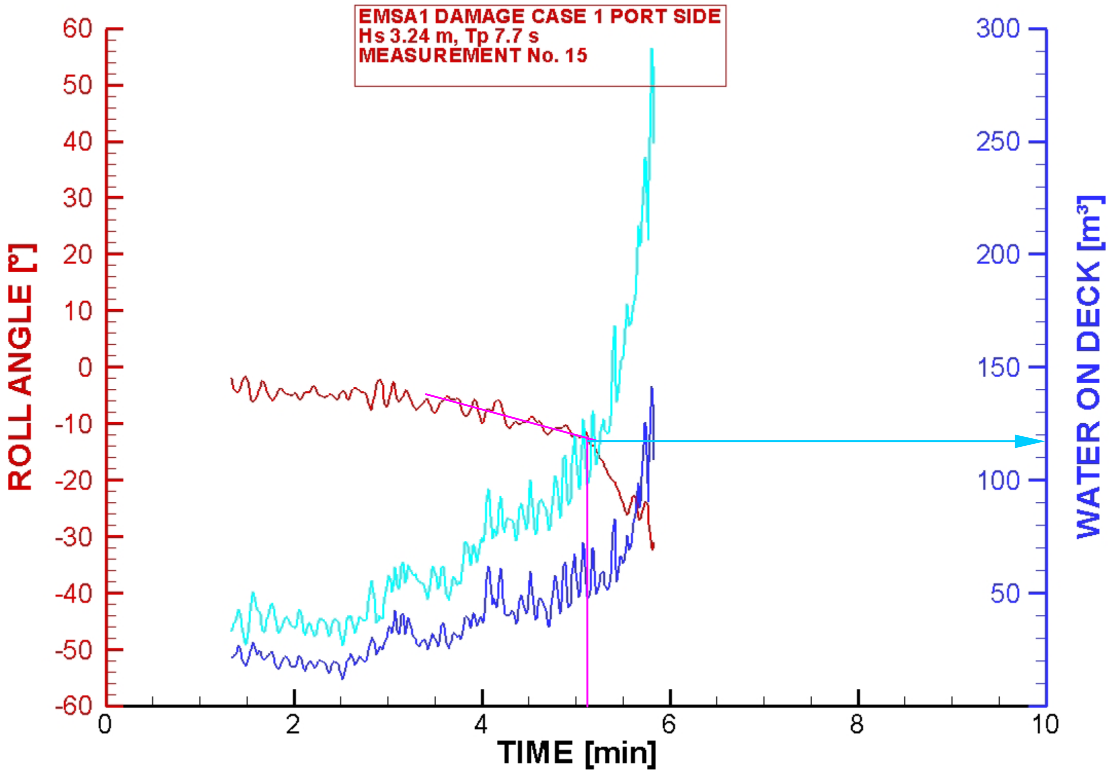

Fig. 56 Water on deck in the measurement no. 15 in the model tests. The extra lines and the arrow show how the amount of water on the vehicle deck just before capsize is evaluated.

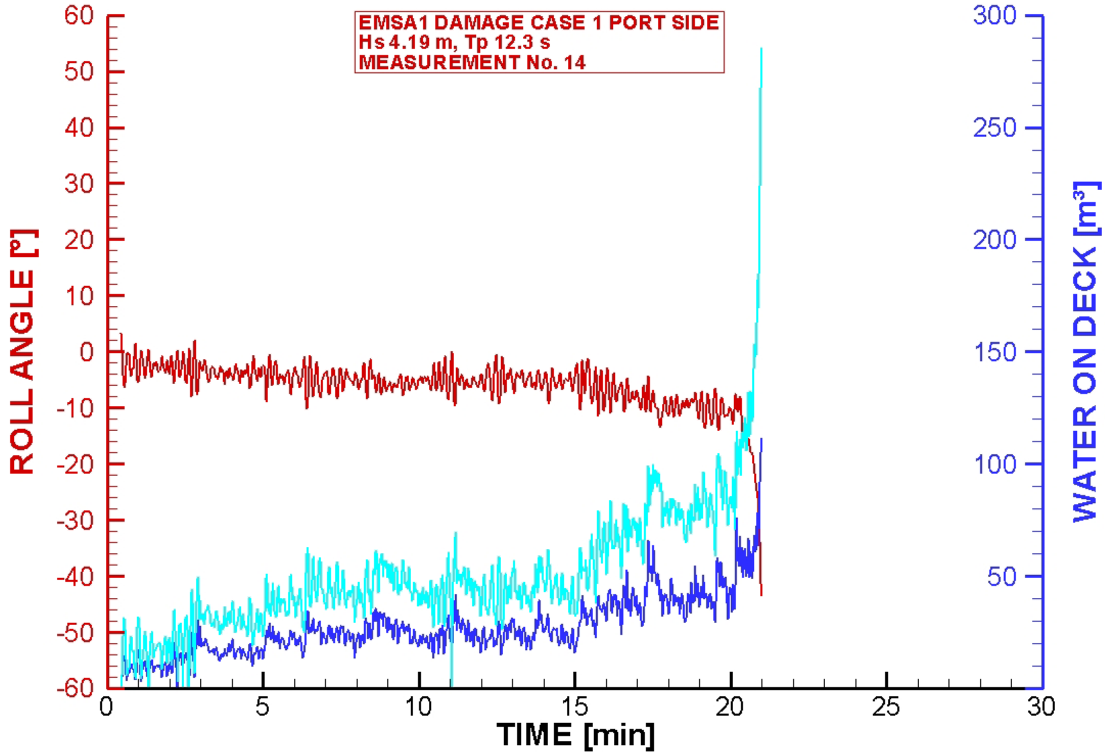

Fig. 57 Water on deck in the measurement no. 14 in the model tests.

The critical amount of water on the vehicle deck was evaluated for 14 cases. In those 9 cases, in which the ship with the Damage Case 1 capsized, the average critical amount of water on the vehicle deck area (640 m^2) corresponds to water height of 0.17 m. The variation in the results is small, as shown in Table 40. In those test cases, in which the ship survived, there were in general less than 0.15 m water on the vehicle deck.

Table 40 Evaluated amount of water on the vehicle deck based on the HSVA measurements.

EMSA 1 Damage Case 1: Selected Measurements				
Meas. (Run) No	Hs [m]	Tp [s]	Time to Capsize [min]	Water height on Deck [m]
4 (-)	3.85	13.3	survived	< 0.08
9 (-)	4.13	12.3	survived	< 0.09
10 (1)	4.21	12.3	survived	< 0.11
11 (2)	4.33	12.5	> 30 min	0.16 - 0.18
12 (3)	4.36	12.5	> 30 min	0.17 - 0.18
13 (4)	4.23	12.3	survived	< 0.14
14 (5)	4.19	12.3	21	0.177
15 (6)	3.24	7.7	6	0.178
16 (7)	3.36	7.5	7	0.177
17 (8)	3.20	7.2	6	0.175
18 (9)	3.23	7.3	6	0.163
19 (10)	3.63	7.8	6	0.180
22 (13)	2.99	6.9	28	0.144
24 (15)	2.97	6.9	survived	0.150

Notice that the probability to capsize and the time to capsize depend on the wave period: In the measurements 4, and 9-14 the significant wave height was 3.85-4.36 m (av. 4.19 m) and the peak period of the wave spectrum 12.3-13.3 s resulting in capsize rate of 3/7, that is, 43 percent. In two of these cases the ship capsized only after 30 minutes.

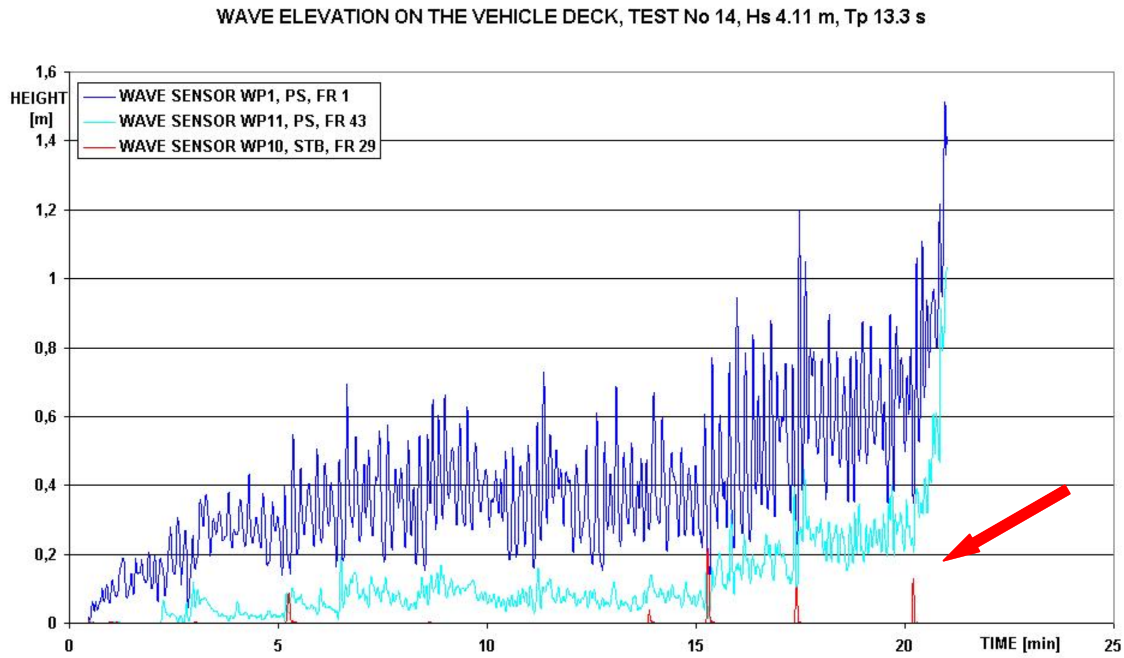

Fig. 58 Water elevation on the vehicle deck in measurement no. 14 near the side wall on the port side at the stern (wp1), and at the front part of the vehicle deck (wp11); and in the middle of the other side at the starboard side wall (wp10).

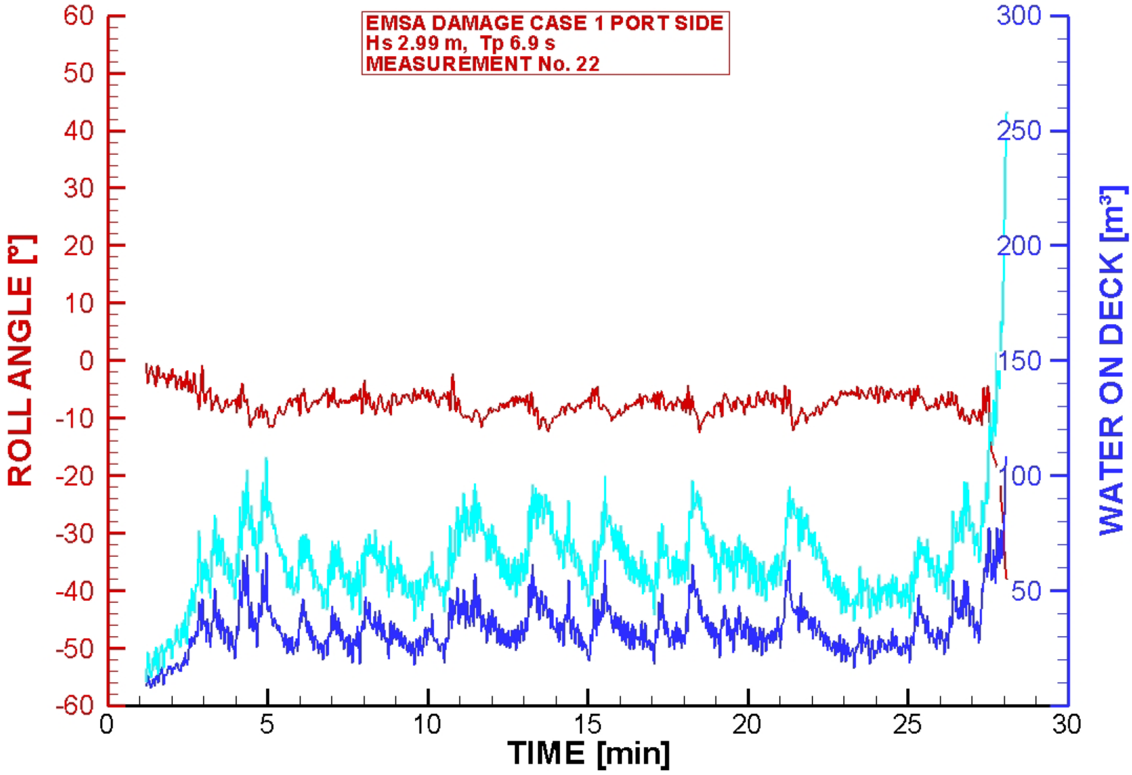

Fig. 59 Water on deck in the measurement no. 22 in the model tests.

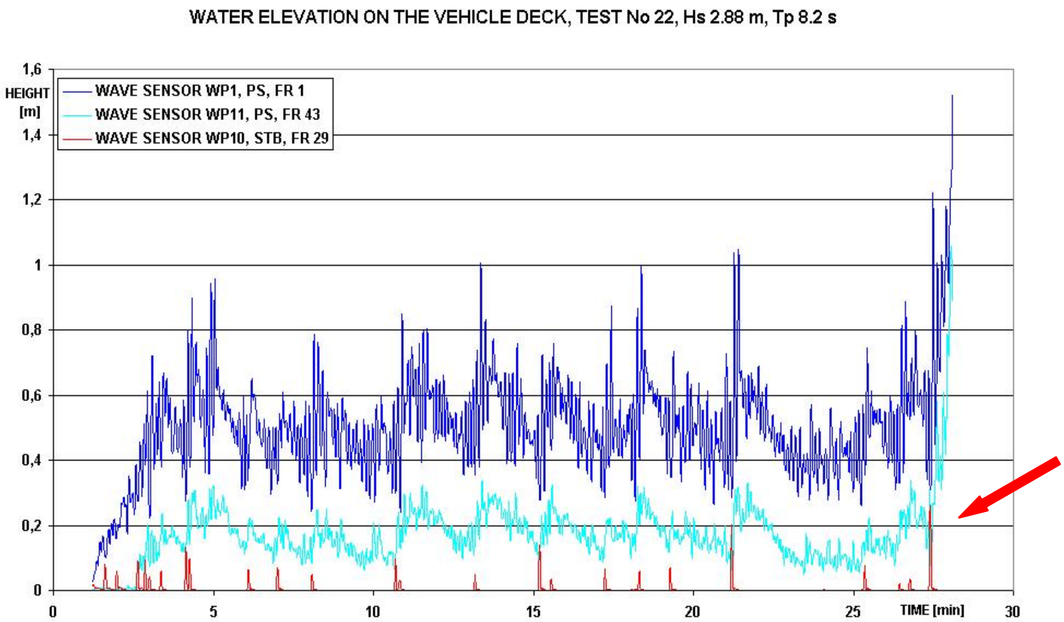

Fig. 60 Water elevation on the vehicle deck in measurement no. 22 at the stern (wp1), and at the front part of the vehicle deck (wp11), near the side wall on the port side, and in the middle of the deck at the starboard side wall (wp10). Notice how the sloshing motions coincident with the changes in water volume shown in Figure 59.

In the measurements 15-24 with wave heights between 2.97-3.63 m (av. 3.23 m) and wave periods between 6.9-7.7 s the capsize rate was 8/10, that is, 80 percent. In addition, the time to capsize was rather short in comparison with the measurements in higher waves and with longer wave periods. The critical amount of water as determined in this study did not appear to depend on the wave height or period.

The increase in the heeling angle and in the amount of water on the vehicle deck was in the measurement no. 15 shown in Figure 56 smoother than in the measurement no. 14 in higher waves, which shows phases of ingress and egress of water on the vehicle deck in Figure 57. The video recording of the water motion on the vehicle deck shows also that in the measurement 14 the water sloshes from one side of the vehicle deck to another. A similar behavior was found in measurement no. 22 with a significant wave height of 2.99 m shown in Figure 59.

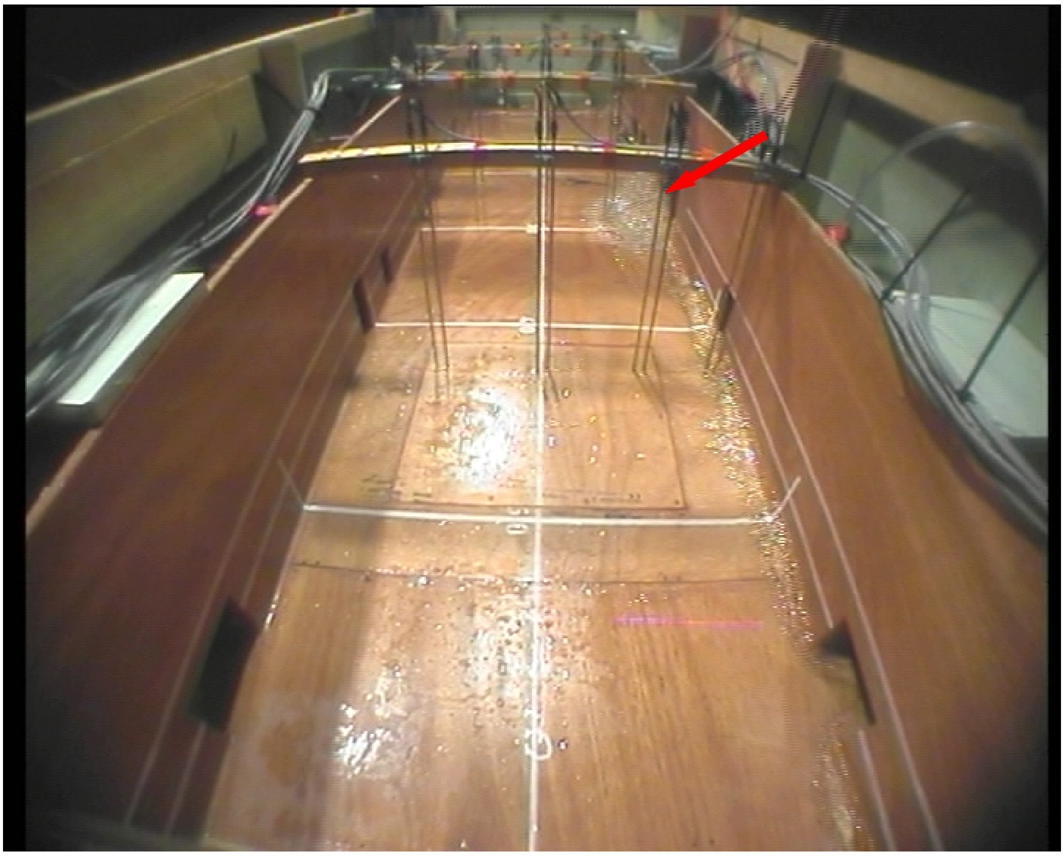

Fig. 61 One of the selected frames from a video recording of the measurement no. 22 related to the last large sloshing motions just before capsize, that is, to the last red peak shown in Figure 60: In this frame the water rushes through the damage opening on to the vehicle deck. As the video camera was fixed onto the model the ship motions do not show in the frames. Figures 8 and 9 show the same view few seconds later.

Figures 58 and 60 show water elevation at selected sensor locations on both sides of the vehicle deck during the measurements no. 14 and 22. In both cases the water does not only accumulate onto one side, but also sloshes over the vehicle deck from one side to another, thus generating a considerable dynamic heeling moment, also just before the vessel finally heels over. This is shown by the recording on the wave sensor wp10 located in the middle of the (higher) starboard side wall of the vehicle deck. Usually its water elevation was zero, but occasionally the sensor wp10 recorded water sloshing over the vehicle deck, sometimes over the whole deck. In Figures 58 and 60 this can be seen as

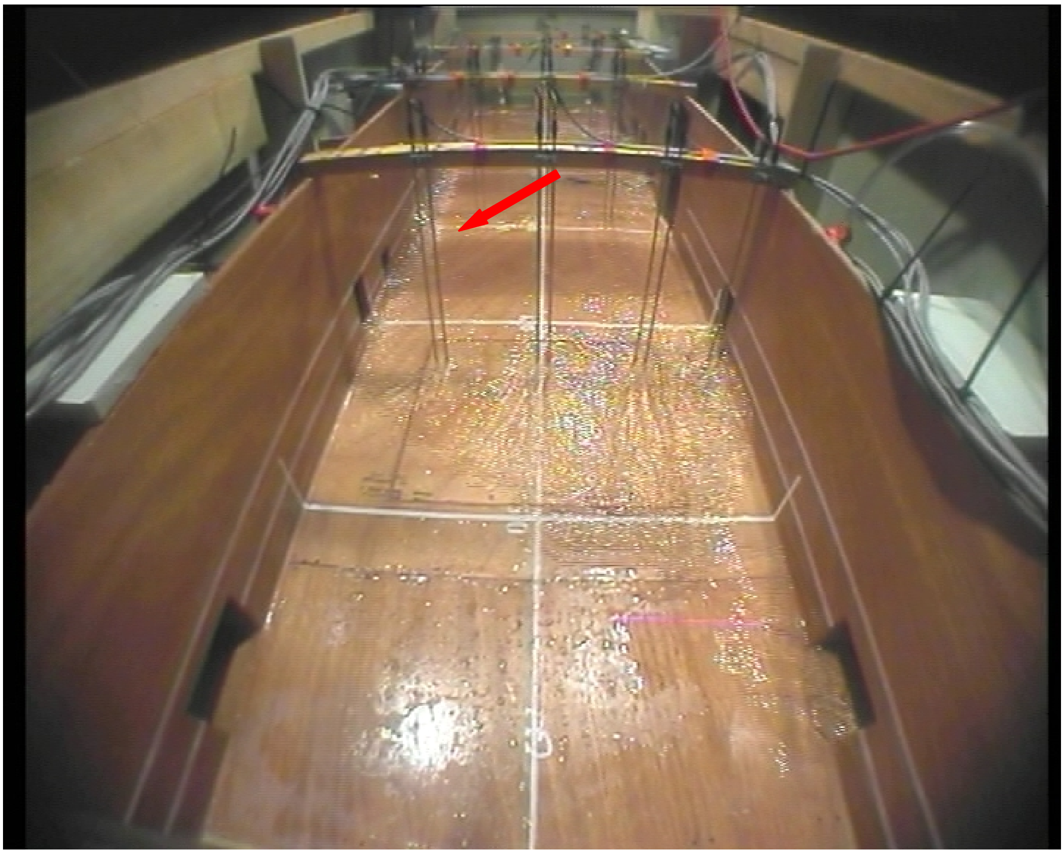

Fig. 62 Water sloshes against the side wall opposing the damaged side.

Fig. 63 Water sloshes against the damaged side wall. The water elevation at the wall exceeds the first white line at 1 m height.

recorded red peaks in the curve representing the sensor wp10. Just after the appearance of such a peak, the water sloshes back to the opposite damaged side, the ship heels and more water flows in. This phenomenon can also be seen in the curves showing the heeling angle in Figures 57 and 59, as little rises or falls. Figures 61-63 show individual frames of the video recording of the water motion on the vehicle deck during the measurement no. 22 close around the moment indicated by the last red peak in Figure 60.

In both measurements 14 and 22 the rapid increase in the water volume and the start of the capsize follow such a sloshing over the whole vehicle deck. In these cases it is difficult to accept the basic assumption behind the Static Equivalent Method (SEM) for prediction of RoPax survivability, namely, that the capsize mechanism almost always appears to be quasi-static in nature (e.g. Tagg & Tuzcu, 2003).

Thus the test results with the ship EMSA1 do not appear to support the assumption of quasi-static capsizing mechanism, like in SEM. This result, however, should not be generalized to hold for other ships for the following reason: The tested Damage Cases 1 and 4 do not have large side compartments in the damaged zones, which would heel the vessel to one side, when flooded. The vessel does not have a center casing, which would contribute to keeping the water flooding onto the vehicle deck only on one side. Further, the ship EMSA1 is a rather small RoPax, which may contribute to the described behavior.

10.2 Water on Deck of the Ship Design EMSA2 in Damage Case 1

The height of water on the vehicle deck was measured with 14 wave probes in the model tests with the ship EMSA2. The exact position of the probes in Damage Case 1 is given in Figure 8 of the HSVA model test report S590b/09 and is also shown without dimensioning below in Figure 64. The sensors were arranged in rows and columns based on the numerical simulations of the water motion and accumulation on the vehicle deck, in order to put the few sensors in the most relevant locations.

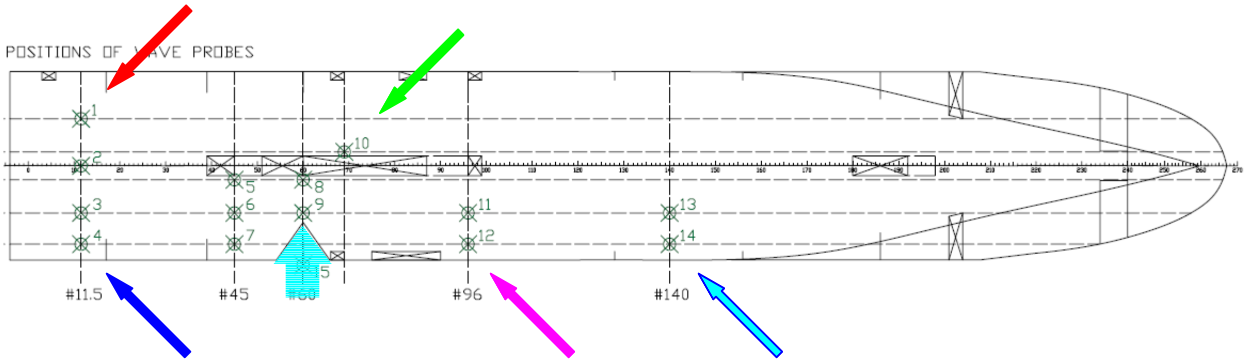

Fig. 64 The positions of the wave probes on the vehicle deck of the ship model EMSA2 in Damage Case 1. The arrows indicate the positions of the sensors wp1, wp4, wp10, wp12 and wp14. The light blue arrow shows the damage location and penetration.

The critical amount of water on the vehicle deck was evaluated for 8 cases. In those 7 cases, in which the ship with the Damage Case 1 capsized, the average critical amount of water on the vehicle deck area (4747 m²) corresponds to water height of 0.39 m. The variation in the results is small, as shown in Table 41. In the test case, in which the ship survived, there was in general less than 0.11 m water on the vehicle deck.

Table 41 Evaluated amount of water on the vehicle deck based on the HSVA measurements.

EMSA 2 Damage Case 1: Selected Measurements				
Meas. (Run) No.	Hs [m]	Tp [s]	Time to Capsize [min]	Water height on Deck [m]
11 (5)	4.46	12.0	14	0.371
12 (6)	4.87	12.2	16	0.363
13 (7)	4.32	11.6	9	0.397
18 (11)	4.77	8.7	23	0.385
19 (12)	4.99	8.9	18	0.337
20 (13)	4.58	8.6	22	0.421
21 (14)	4.65	8.6	survived	< 0.109
22 (15)	4.65	8.6	16	0.451

Notice that the time to capsize depends on the wave period: In the measurements 11-13 the significant wave height was 4.32-4.87 m (av. 4.55 m) and the peak period of the wave spectrum 11.6-12.2 resulting in capsize in 9-16 minutes. In the measurements 18-22 the significant wave height was 4.58-4.99 m (av. 4.73 m) and the peak period of the wave spectrum 8.6-8.9 resulting in capsize in 18-23 minutes.

Also in this case with EMSA2 Damage Case 1 the critical amount of water as determined in this study did not appear to depend on the wave height or period.

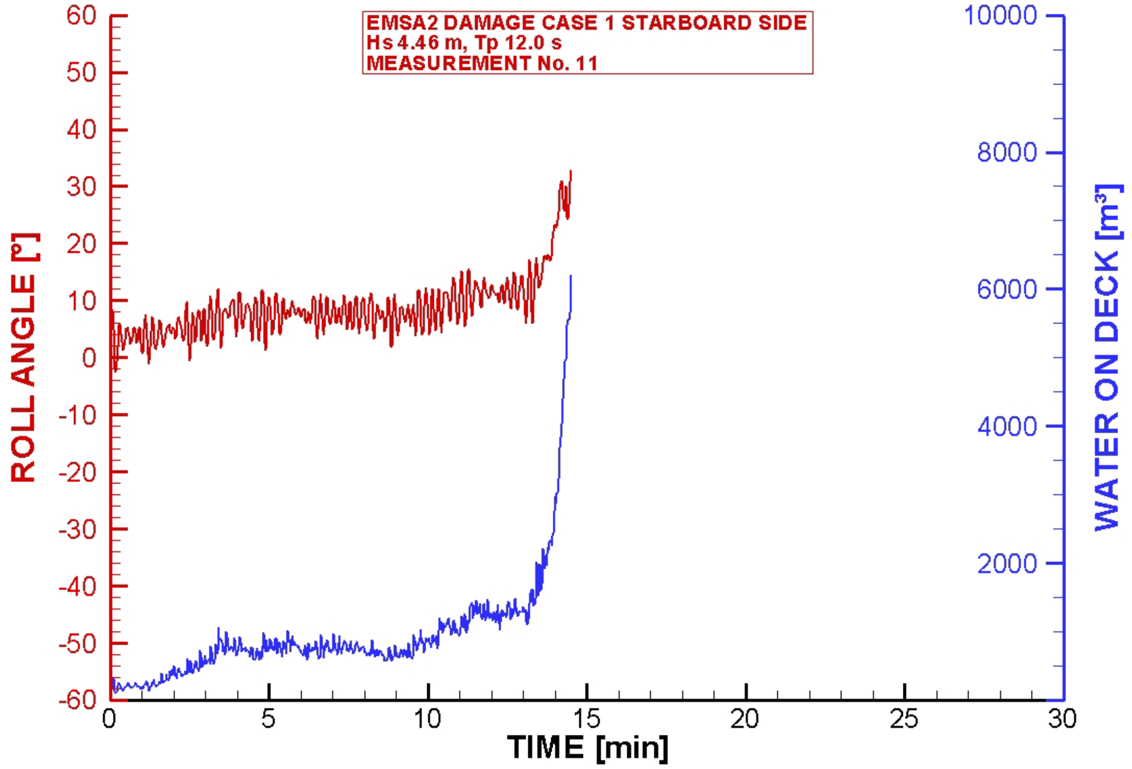

Fig. 65 Water on deck in the measurement no. 11 in the model tests.

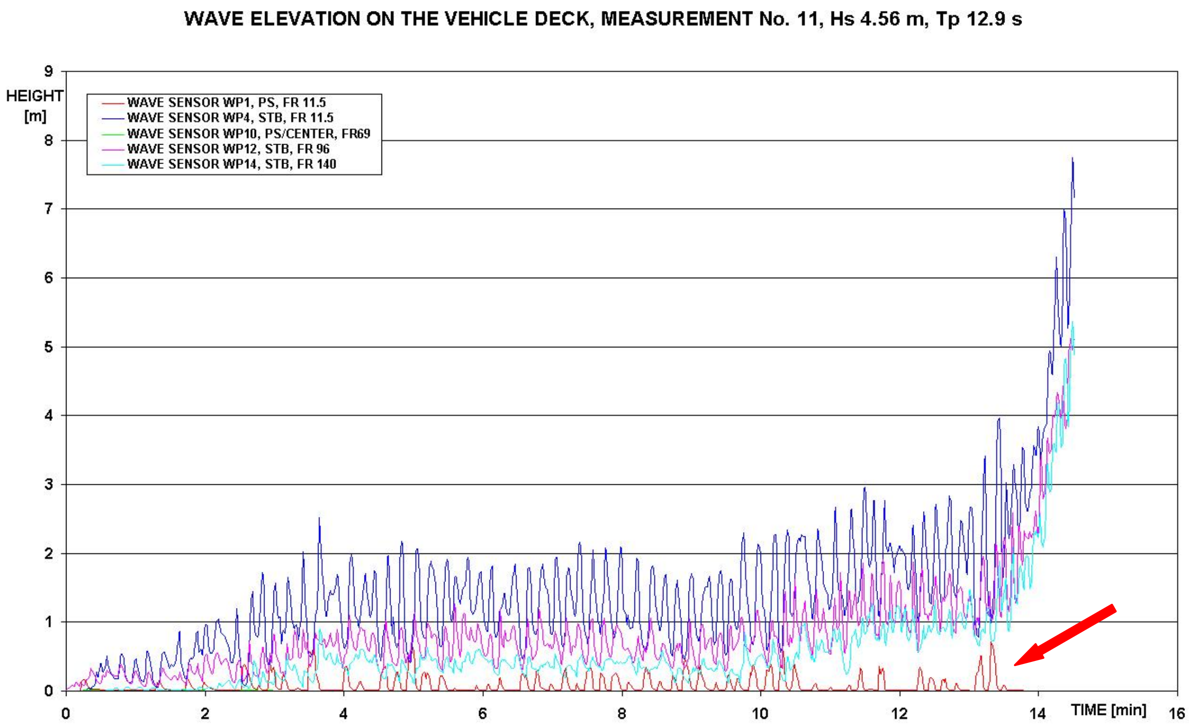

Fig. 66 Water elevation on the vehicle deck in measurement no. 11 at the stern on the higher port side (wp1), on the lower starboard side (wp4) and at the front part of the vehicle deck (wp12 and wp14), and on the port side of the center casing (wp10).

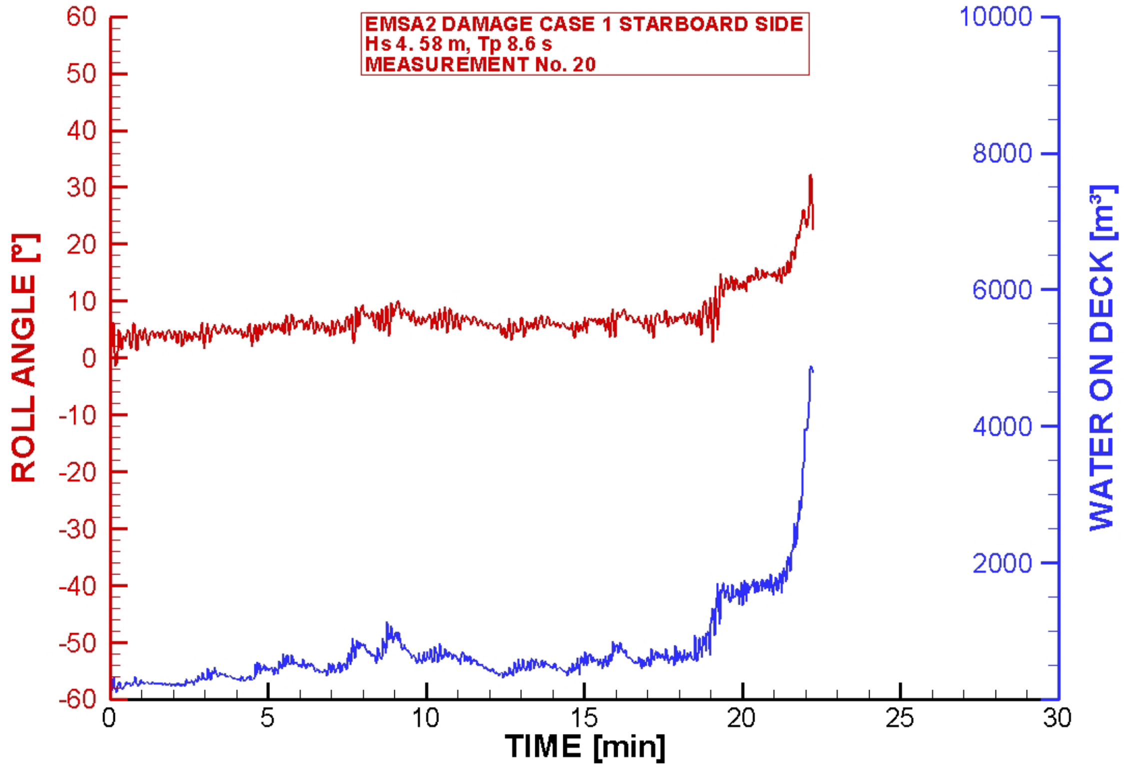

Fig. 67 Water on deck in the measurement no. 20 in the model tests.

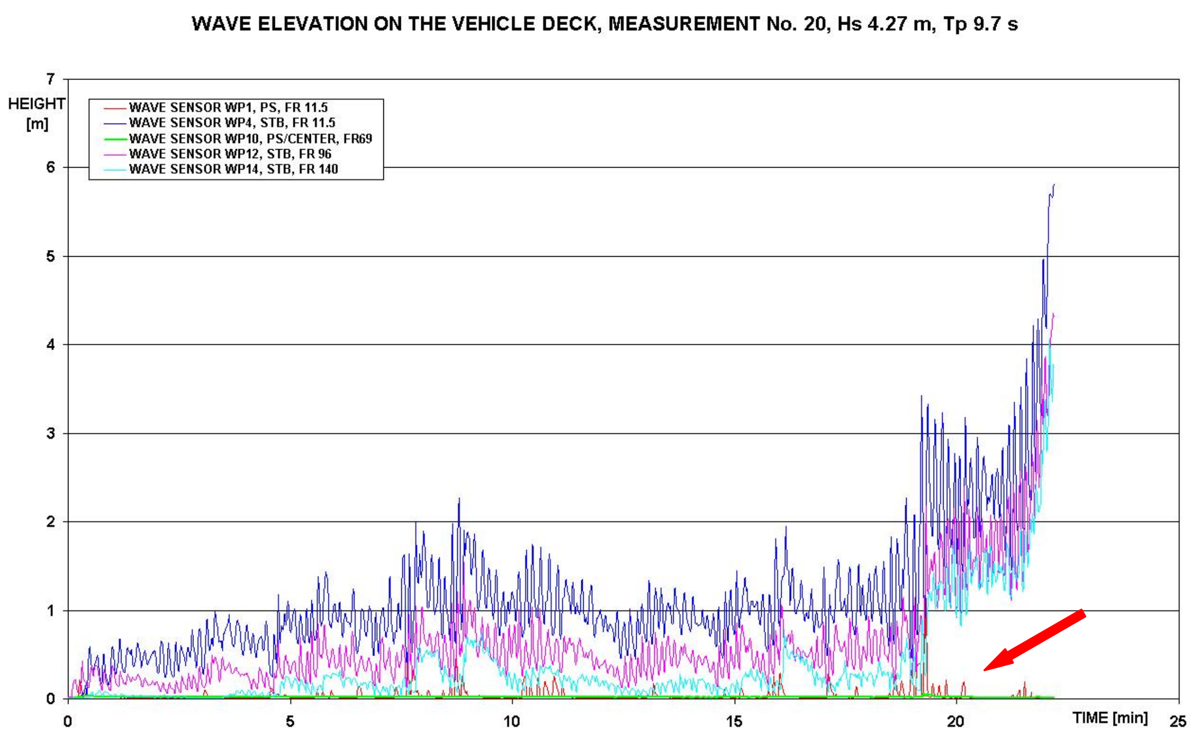

Fig. 68 Water elevation on the vehicle deck in the measurement no. 20.

Figures 65 and 67 show the calculated amount of water on deck in the tests no. 11 and 20. The corresponding water elevations on a few selected sensor locations are shown in Figures 66 and 68. In both cases the sensor wp1 on the higher port side records occasional water elevations, indicating sloshing motion. The sensor wp4 on the lower starboard side shows regular oscillation in the water level higher than 1 m. These oscillations appear to increase towards the end of the curve, as the ship becomes less stable. Thus also in these cases the situation cannot very well be described as quasi-static. In all cases analyzed the wave sensor wp10 on the higher port side in the middle of the center casing recorded practically a zero water height. Thus the water did not reach or flow on to the higher side of the center casing.

10.3 Water on Deck of the Ship Design EMSA2MOD in Damage Case 4

Like in the other damage cases, also in the Damage Case 4 the height of water on the vehicle deck was measured with 14 wave probes in the model tests with the ship EMSA2MOD. The exact position of the probes is given in Figure 8 of the HSVA model test report S590b/09 and is also shown without dimensioning below in Figure 69. The sensors were arranged in rows and columns based on the numerical simulations of the water motion and accumulation on the vehicle deck, in order to put the few sensors in the most relevant locations.

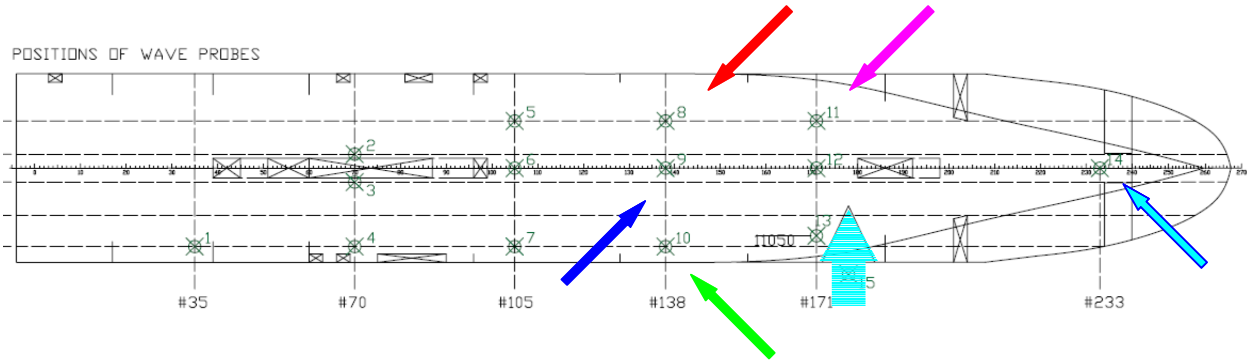

Fig. 69 The positions of the wave probes on the vehicle deck of the ship model EMSA2 in Damage Case 4. The arrows indicate the positions of the sensors wp8, wp9, wp10, wp11 and wp14. The light blue arrow shows the damage location and penetration.

The final amount of water on the vehicle deck was evaluated only for the 5 cases leading to non-survival according to the survival criteria used. In these 5 cases, in which the ship with the Damage Case 4 did not survive, the average final amount of water (~5400 m^3) on the vehicle deck area (4488 m^2) corresponds to water height of about 1.2 m. The variation in the results is small, as shown in Table 42. As no capsize was observed this amount is less than the critical amount needed for the ship to capsize. As there was about 2300 m^3 water on the vehicle deck already in calm water before each test in waves, also the difference in water height between the initial situation and the final situation is shown in Table 42. In average this difference in the water volume is about 3100 m^3.

Table 42 Evaluated amount of water on the vehicle deck based on the HSVA measurements.

EMSA 2MOD Damage Case 4: Selected Measurements						
Measurement (Run) No.	Hs [m]	Tp [s]	Time to Capsize [min]	Initial average water height on Deck [m]	Final average water height on Deck [m]	Increase in the water height on Deck [m]
46 (31)	4.21	8.3	no capsize	0.51	1.203	0.69
47 (32)	3.91	8.3	no capsize	0.51	1.181	0.67
48 (33)	3.70	8.3	no capsize	0.51	1.214	0.70
49 (34)	3.68	8.3	no capsize	0.51	1.214	0.70
50 (35)	3.78	8.3	no capsize	0.51	1.181	0.67

It is emphasized here that, as ship did not capsize, the critical amount of water on the vehicle deck needed for capsize is more than the 5400 m^3 or the water height of 1.2 m on the vehicle deck in the Damage Case 4 measured here.

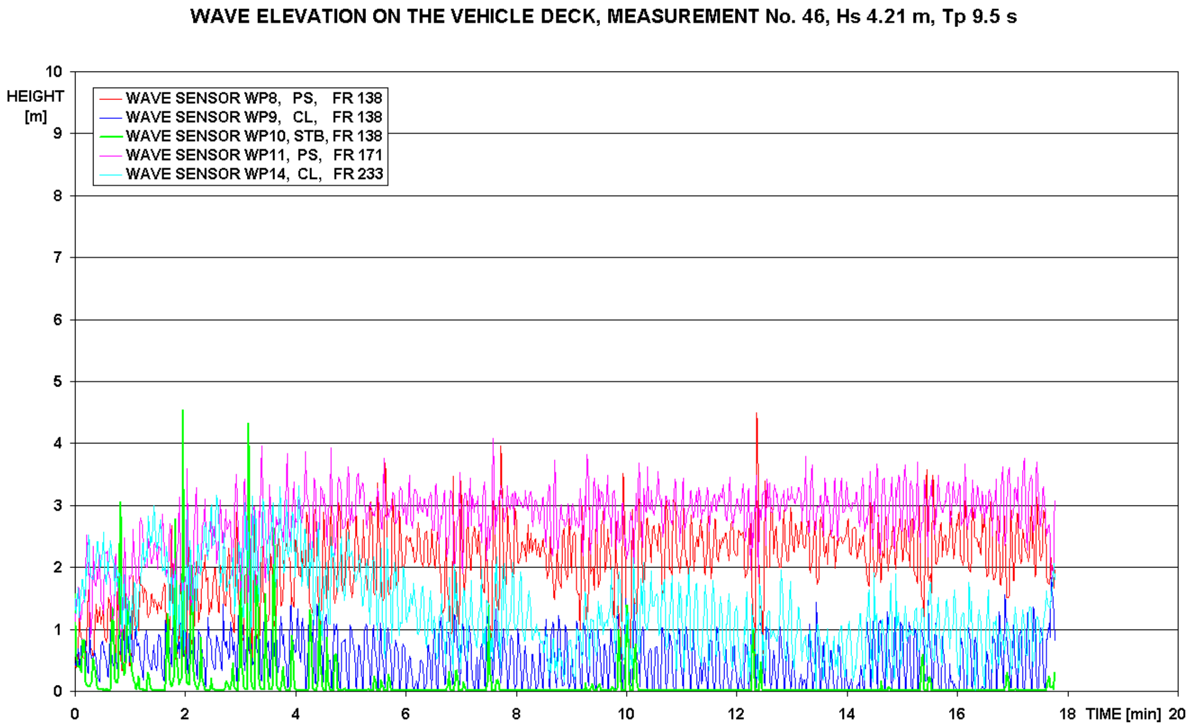

Fig. 70 Water elevation on the vehicle deck in measurement no. 46 (test run no. 31) on the lower port side (wp8, wp11), on the centerline (wp9, wp14) and on the higher, damaged side (wp10).

Figure 70 shows an example of the water elevation on the vehicle deck in test run no. 31 with the significant wave height H_S of 4.21 m and the modal period T_P 8.3 s. The vessel did not survive on the test due to steady heel exceeding 20°. Variations in the water elevation of more than 2 m on the sensor locations can be seen, indicating considerable water motion on the vehicle deck.

Figures 71 and 72 are individual frames from the video recording of the vehicle deck during measurement no. 35 with the significant wave height H_S of 4.3 m. The ship motions together with the large amount of water on the vehicle deck of the ship EMSA2MOD in Damage Case 4 led to rather impressive wave formations on the vehicle deck. Such wave impacts can be expected to be able to move cars. Whether hard objects, cars or other cargo accelerated by sloshing waves, can damage the side walls when *impacting against* them, was not studied here. The issue, however, may be worth some consideration, specially in cases like EMSA2MOD having a large amount of water on the vehicle deck.

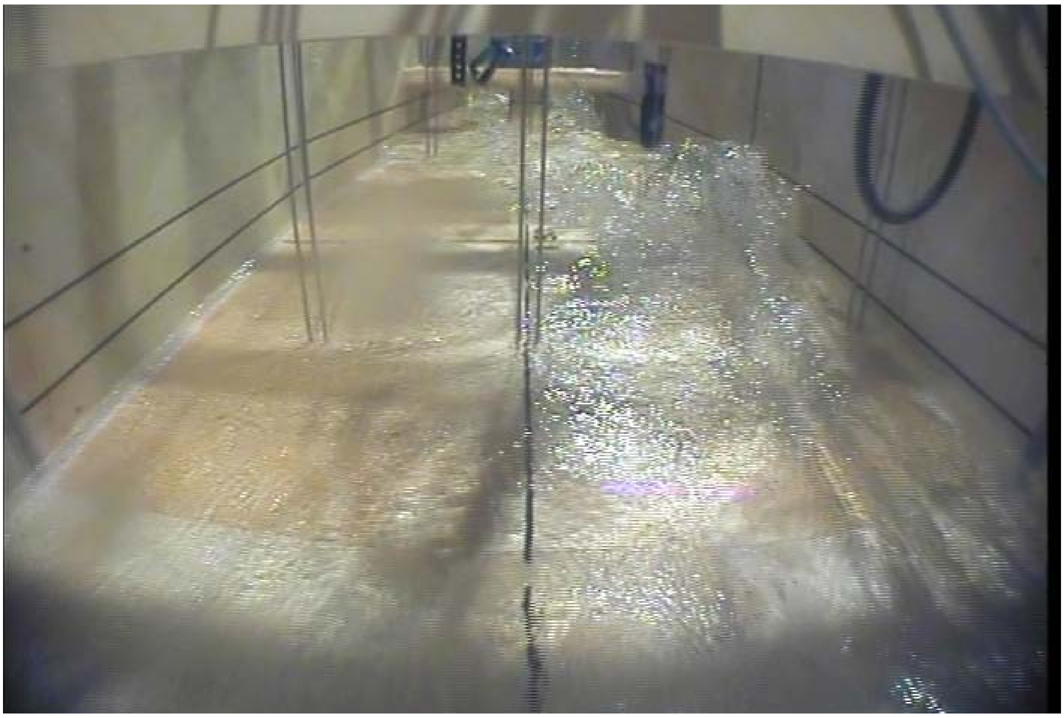

Fig. 71 One of the selected frames from a video recording of the measurement no. 35. The ship EMSA2MOD survived this test run (no. 24) with the significant wave height H_S of 4.3 m and the modal period T_P 8.4 s. Notice how violent the sloshing on the vehicle deck under such circumstances can be. The frame shows two wave fronts colliding: The water "pyramid" exceeds 4 m in height. The black lines on the side wall shows the heights 2 m and 4 m, respectively. Figure 72 shows the same view few seconds later.

Fig. 72 One of the selected frames from a video recording of the measurement no. 35. The frame shows water sloshing over 6 m high against the port side wall.

10.4 Conclusions on the Behavior of Water on the Vehicle Deck

- The investigated vessels do not appear to capsize in the model tests until the amount of water on the vehicle deck has reached a critical value. For the ship EMSA1 with Damage Case 1 this critical amount corresponds to about 0.17 m water on the vehicle deck, and for the ship EMSA2 with Damage Case 1 to about 0.39 m.

- This critical amount of water on the vehicle deck leading to capsize does not appear to depend on the wave height or wave period. This is the case in the model tests results of both vessels.

- If and when the vessel capsizes, depends not only on the wave height, but significantly also on the wave period, as this is relevant for the roll motion of the ship and for the motion and ingress of water on the vehicle deck.

- The final capsizing is often started by a higher wave, which causes a larger roll motion and sloshing of water over the vehicle deck from one side to another. This causes a dynamic heeling moment, which contributes to the capsizing. In the tests with both vessels this was not always the case, but it was often the case. Thus the capsizing mechanism does not appear always to be of quasi-static nature. This is significant for the validity of the assumptions behind the Static Equivalent Method, if such an approach would be used to re-define the s_i-factor in the SOLAS 2009 rules.

- When there appears to be dynamic aspects present in the capsizing mechanism, an appropriate approach in defining the ship survivability, or the s_i-factor in the SOLAS2009 rules, would probably be to relate the ship survivability to the height and range of the righting lever curve of the (damaged) ship.

- The numerical simulations with the HSVA ROLLS predict the critical amount of water on the vehicle deck of the ship EMSA1 and EMSA2 just before capsize relatively well. For the ship EMSA1 Damage Case 1 the computations give about 130 m³ in average, the lowest value leading to capsize being 121 m³. The measured average amounts to about 109 m³.

- For the ship EMSA2 Damage Case 1 the computations give about 1700 m³ in average, the lowest value leading to capsize being 1270 m³ and the highest 2360 m³. The measured average amounts to about 1850 m³.

- As the ship EMSA2MOD in Damage Case 4 did not capsize, but heeled slowly over until the survival criterion of steady heel exceeding 20° was violated, no comparison of the measured and computed amounts of water were carried out.

- In all cases the flow pattern on the vehicle deck was predicted by the HSVA ROLLS very well. These predictions were used to put the wave sensors on most relevant locations on the deck.

- All measured amounts of water given here are based on the 14 values of water height on the vehicle deck actually recorded at each moment of time. The calculation of the total water volume is based on interpolation between the sensors and extrapolation towards the vehicle deck walls using the measured heel and trim angles. The resulting amount is of course an approximation.

- The commercially available ship design software NAPA was used to calculate the amount of water on the vehicle deck needed to reduce the righting lever GZ exactly to zero, as explained by e.g. *Tagg and Tuzcu (2003)* about the SEM-

(Static Equivalent Method) procedure. For the ship EMSA1 Damage Case 1 the result was 46 m^3, for the EMSA2 Damage Case 1 result was 682 m^3. These values are 42 and 37 percent of the values based on the measurements in the HSVA model tests, respectively.

11 On the S_i -Parameter of the Damage Stability Rules

11.1 Attained Subdivision Index A

The SOLAS 2009 Reg.B-1/7/1 defines the attained subdivision index *A* as follows:

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 defined in regulation 2 in accordance with the following formula:

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

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

$$A = \sum p_i s_i \quad , \qquad (1)$$

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, as defined in regulation 7-1,

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, as defined in regulation 7-2.

11.2 The S_i -Factor

The s_i-factor given in SOLAS 2009 Reg. B-1/7-2: Calculation of the factor s_i is defined in subject Ph 3 as follows:

The factor $s_{\text{final,i}}$ shall be obtained from the formula:

$$s_{\text{final,i}} = K \cdot \left[\frac{GZ_{\max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}} \quad , \quad \text{where} \qquad (2)$$

GZ_{max} is not to be taken as more than 0.12 m;
Range is not to be taken as more than 16°;

$$K = 1 \qquad \text{if } \Theta_e \le \Theta_{\min}$$

$$K = 0 \qquad \text{if } \Theta_e \le \Theta_{\max}$$

$$K = \sqrt{\frac{\Theta_{\max} - \Theta_e}{\Theta_{\max} - \Theta_{\min}}} \quad \text{otherwise,}$$

where

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

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.

This definition gives (in principle) the probability of survival in terms of the significant wave height of the critical survivable sea state. In order to produce the probability of survival, the likelihood that the mentioned survivable sea state will be not exceeded at the time of the collision, is required.

The statistical analysis of the observed sea states at the time of casualties was developed in HARDER WP3, "Wave Height Distributions According to Damage Statistics", Report 3-00-W-2001-010-0, November 29, 2001. Plot of this data and a proposed function to fit the data is reproduced according to the Annex of the IMO-document SLF45/3/3 and shown in Figure 73.

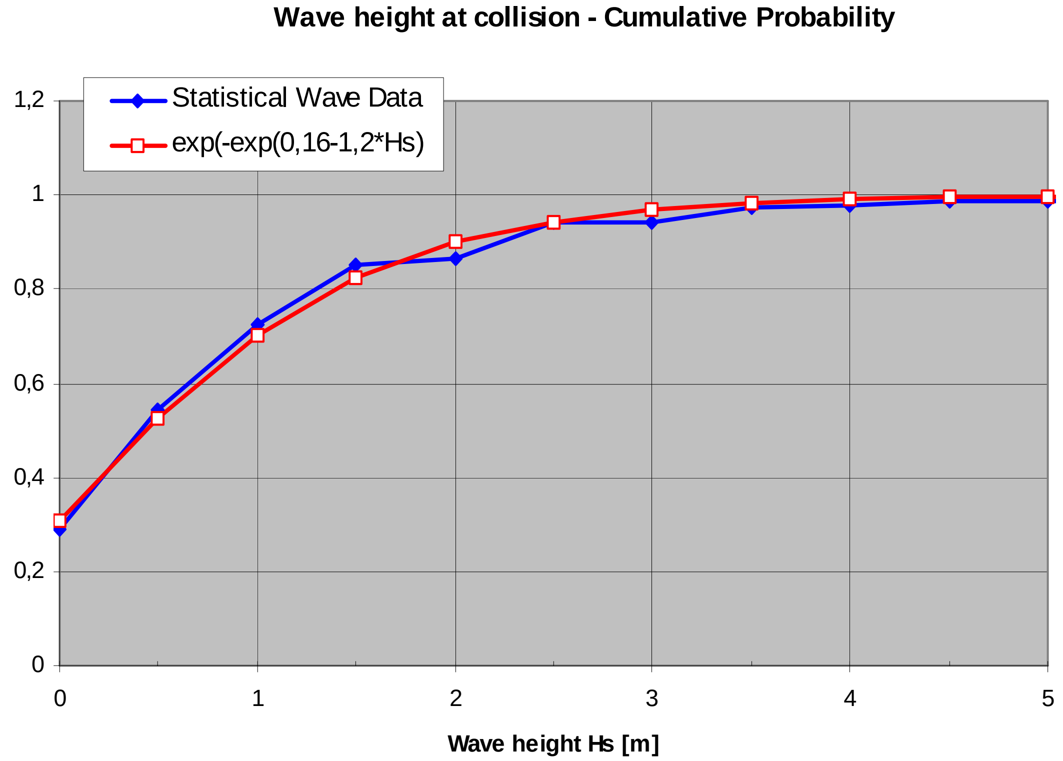

Fig. 73 Cumulative probability of wave height at the time of collision (IMO SLF45/3/3).

After consideration of some alternatives the so called conventional methodology of the *GZ*-curve related criteria was adopted for the development of the SOLAS 2009 damage stability rules (IMO SLF 45/3/3). The mean survival sea states are correlated to the stability parameters, with H_s limited to 4 m, as follows:

$$H_S = 4 \cdot \left[\left(\frac{GZ_{\max}}{TGZ_{\max}} \right) \cdot \left(\frac{Range}{TRange} \right) \right] \qquad (3)$$

The values of the maximum positive righting lever GZ_{max} and the *Range* of the positive righting levers give the critical significant wave at which the ship in question still survives. Based on the examination of the best correlation with the model test results the following values of TGZ_{max} and *TRange* were proposed for conventional ships: TGZ_{max} = 0.12 m and *TRange* = 16 degrees. The model test results for RoPax ships suggested TGZ_{max} = 0.25 m and *TRange* = 16 degrees (IMO SLF 45/3/3).

In the SOLAS 2009 rules, however, the values TGZ_{max} = 0.12 m and *TRange* = 16 degrees are used for all ships. Thus it can be interpreted so that the present SOLAS 2009 rules do not model the RoPax ship survivability correctly.

In principle the probability of survival could be obtained by using the proposed function to fit the wave data given above, that is,

$$s = e^{-e(0.16-1.2H_S)} \quad , \qquad (4)$$

where

$$H_S = 4 \cdot \left[\frac{GZ_{\max}}{0.25} \cdot \frac{Range}{16} \right] \qquad (5)$$

for RoPax ships. Instead the SOLAS 2009 uses the approximate form (2). These two surfaces, as given by Equation (2) with *K*=1 and (4)-(5) are illustrated together with some experimental points in Figure 74 below. The differences between these two surfaces are not insignificant: The *s*-factor as in SOLAS 2009 classifies damage cases as safe, which according to the best data fit can be unsafe. These differences originate from two sources: (A) From the use of the value 0.12 as TGZ_{max} in Eq. (1); (B) From the use of the fourth root in equation (1) to approximate the cumulative probability of the wave height at the moment of the collision.

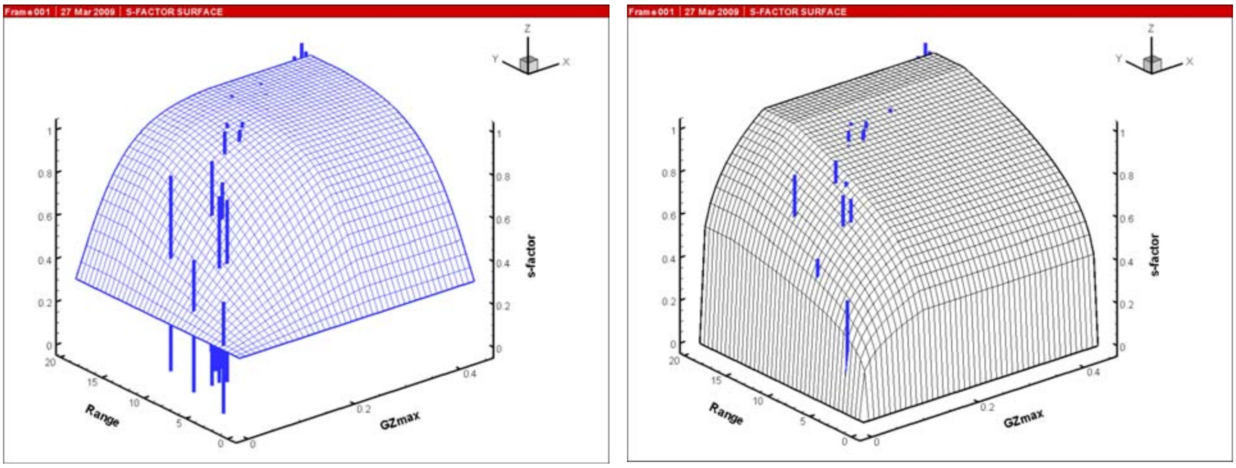

Fig. 74 s-factor based on accurate data fit on the HARDER- wave distribution and GZ-dependency according to model tests is shown in the left figure. The formulation used by the SOLAS 2009 is shown in the right figure. The columns represent model test results of RoPax ships.

Figure 74 shows these two surfaces together with columns representing the model test data on RoPax ship reported in IMO SLF 45/3/3/. It should be noticed that the formulation used in the SOLAS 2009 for s_i classifies more than about 50 percent of damage cases on RoPax ships as safe, which according to the model test results are not. If the formulation would be conservative the s_i surface would be located lower than the model tests results and the 25 columns representing the model test data would all be visible. Presently about half of them are visible.

Figure 75 below illustrates earlier model test data reported in IMO SLF 45/3/3/ and by Tuzcu (2007). The data reported in IMO SLF 45/3/3/ shows clearly that the dependence of critical significant wave height for the vessel on its GZ_{max} is different for conventional ships and RoRo- ships. If linear approximations are used, the TGZ_{max} values at significant wave height 4 m become the mentioned values of 0.12–0.14 for conventional ships and 0.25-0.26 for RoRo or Ropax ships. This experimental data is based on testing SOLAS 90 ships.

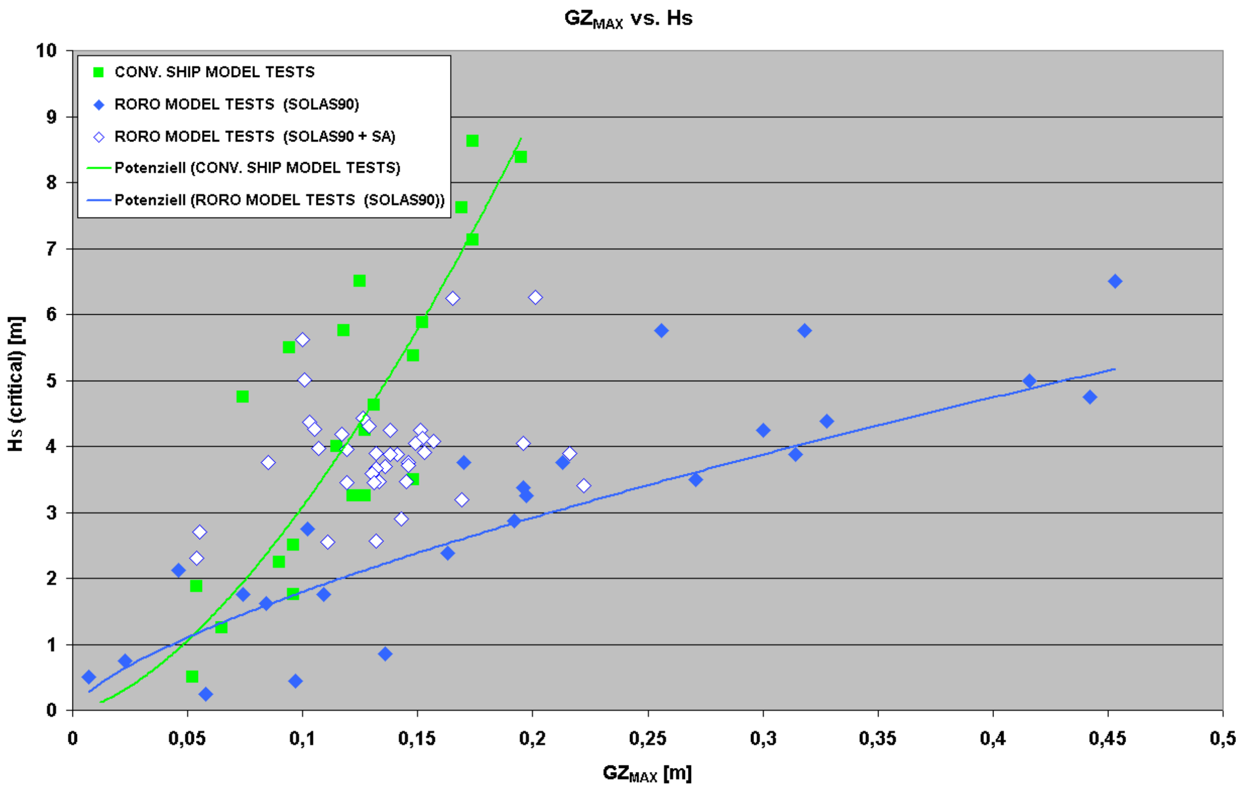

Fig. 75 The figure shows the dependence of the critical significant wave height on the value of the GZ_{MAX} for conventional ships and for RoPax ships based on the measured data given in IMO SLF 45/3/3/ and by Tuzcu (2009).

It is noteworthy that these originally tested Ro-Ro vessels were SOLAS 90 (or equivalent) compliant vessels. Tuzcu (2007) reports about an additional data set consisting of model test results with Stockholm Agreement compliant vessels, which does not scatter closely with the original Ro-Ro data set, although both sets are for Ro-Ro ships. These vessels appear to have a considerably higher resistance against capsizing than the original model test data with Ro-Ro ships. This additional data is shown in Figure 75 with white diamond markers. Linear regression of this data would results in TGZ_{max} –value of about 0.14 m. This shows quite well the effect of the improved vehicle deck layout or other measures taken to fulfill the Stockholm Agreement (SA). This comparison shows that it would be difficult to establish a reliable TGZ_{max} –value for various possible configurations of the Ro-Ro vessels.

Thus vessels designed according to slightly deviating rules, in this case according to SOLAS90 with and without SA, lead to different capsize behavior and to different regression values for the TGZ_{max}. Thus it is to be expected that the capsize behavior and regression value for the TGZ_{max} for ship built according to the requirements of SOLAS 2009 can be, but does not have to be, different than those related to SOLAS90 or SOLAS90 + SA.

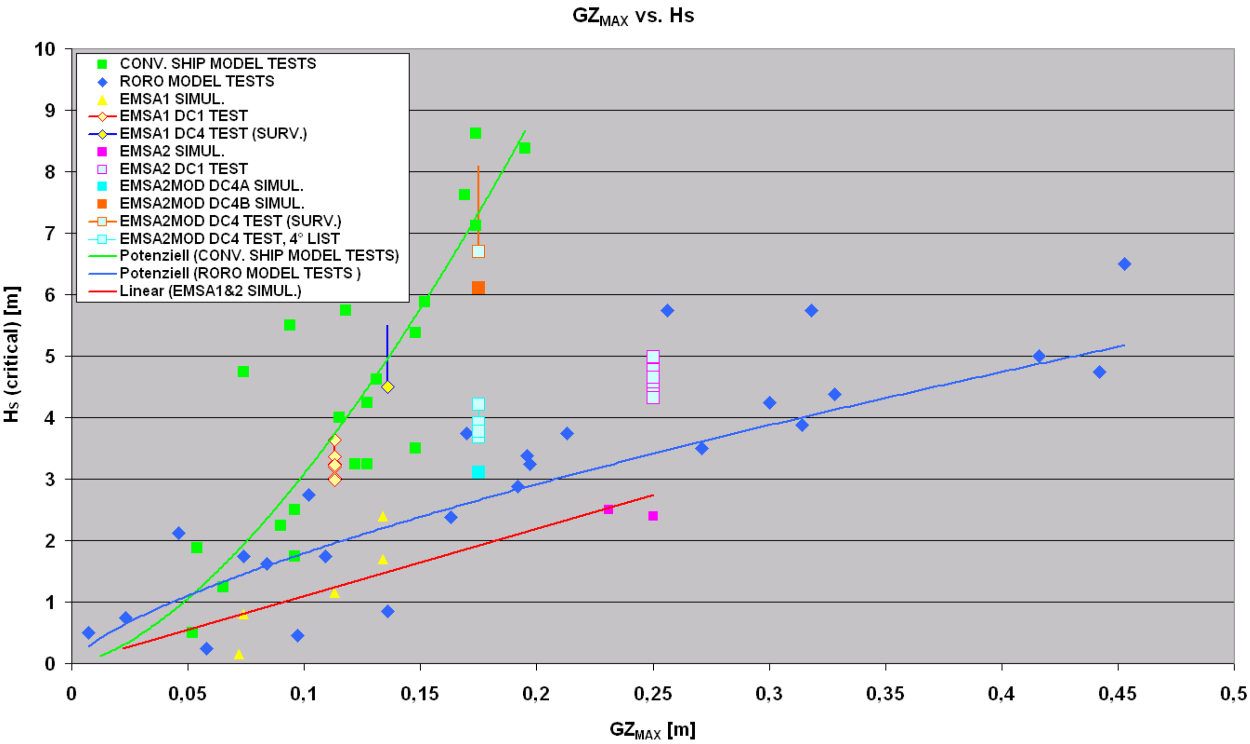

Fig. 76 The figure shows the dependence of the critical significant wave height on the value of the GZ_{MAX} for conventional ships and for RoPax ships based on the measured data given in IMO SLF 45/3/3/. In addition a few measured and computed points of the present investigation are also shown.

Figure 76 illustrates the data model test data reported in IMO SLF 45/3/3/, together with a few additional points representing the computed and the model test results of the present study. The results computed by HSVA for the ships EMSA1 and EMSA2 designed according to SOLAS 2009 are located somewhat below the experimental data for RoPax ships. This is also expected, because the numerical simulation in general gives lower survivable significant wave heights than model tests. The slope of the linear data fit of these points corresponds quite well with the slope of the model test data of the RoPax ships related to the SOLAS90 rules, that is, ships in general not fulfilling the SA requirements. These results further confirm the discrepancy between the model test data for RoRo or RoPax -ships and the formulation for s_i used in SOLAS 2009 corresponding to conventional ships. In view of the significant difference between the mainly closed vehicle decks of RoRo ships and open decks in conventional ships, from which water can easier escape, the difference in the survivability is certainly expected.

The HSVA model test data points of the EMSA1 and EMSA2 lie somewhat above the blue regression curve for RoPax ships, but if a regression curve would be drawn through these points its slope would not essentially deviate from the blue regression curve of the RoPax ship data related to SOLAS90 without SA.

Based on these results on the EMSA1 and EMSA2 and in view of the additional data set mentioned by Tuzcu (2007), it is to be expected that ships designed according to SOLAS 2009 can have an inferior stability or increased tendency to capsize in lower wave heights in comparison with ships designed according to SOLAS90 + SA. The ships designed according to SOLAS 2009 can be expected to have a similar resistance against capsize as ships designed before the requirements of Stockholm Agreement came into force.

The results related to the modified version of the ship EMSA2 namely the EMSA2MOD are also plotted in Figure 76. In short, the modification improves survivability of this ship enormously. Whether the extent of this modification is in all damage cases sufficient, has not been fully investigated. In any case the modification is a significant step into right direction. It should be kept in mind that the EMSA2MOD exceeds minimum requirements by SOLAS 2009.

In a very concise manner the HSVA model test results indicate that the ship designs EMSA1 and EMSA2 capsize in lower wave heights than the equation (1) of the SOLAS 2009 assumes. Keeping in mind the relation of wave height probability in Figure 73 this means that the real survivability, i.e. likelihood to survive, of the vessels EMSA1 and EMSA2 in typical damage cases can be lower than what the SOLAS 2009 rules imply.

Further it should be kept in mind that the damage cases chosen to investigated with model tests were not the worst cases. In view of this there certainly is a need for action to amend the SOLAS 2009 rules.

11.3 The Way Forward

An elementary but perhaps a premature way to improve the situation would be to elevate the TGZ_{max} value for RoPax ships from the present 0.12 to the more proper value of at least 0.25.

This approach can lead to the following situation. There is a need to classify, which ships need to fulfill (1) with TGZ_{max} 0.12 and which ships with 0.25. For many classical ship designs this should be straightforward. For novel designs, hopefully with improved safety, there is a dilemma, which criteria should they satisfy. If that for conventional ships, it may be too little. If for classical RoPax ships, the requirement for classical RoPax ships may be extensive, discouraging a novel concept. The rules should not discourage new concepts, but should judge them properly.

If we fix the TGZ_{max} –value based on conventional RoRo ship designs, new ship designs would not benefit from their possibly improved deck layout, but their safety would be assessed based on a fixed TGZ_{max} –value typical for conventional RoPax ships. This would not promote better designs. Therefore another way to bridge the gap in the safety level between the conventional ships and the RoPax ships is desired. This could imply using the TGZ_{max} –value 0.12 for all ships, but requiring that RoRo- ships would fulfill another criterion to compensate the potential danger of capsizing due to the large heeling moment caused by water on the vehicle deck, regardless of the cause of the presence of the water on the vehicle deck. Such a criterion should properly take into account the vehicle deck layout of the vessel in question and maintain the freedom of design well possible under the SOLAS 2009 rules.

For this reason a preferable way would be to leave the damage stability rules in SOLAS 2009 in the present form and to develop an additional, separate Water-on-Deck (WoD) - criterion based first principles and on the vehicle deck design of the intact ship. This criterion should judge the adverse effect of the vehicle deck flooding in a RoPax ship, primarily regardless of the reason of the vehicle deck flooding. When the criterion is based on the vehicle deck design, it should judge the design in an appropriate manner and not sanction new design concepts. The mechanisms to improve the ship stability would include the increase in the required *GZ* or improvement in the vehicle deck or ship design.

For ship design this would mean:

- Adjustment of the minimum stability (*GZ*-curve), if required.
- Introduction of additional watertight subdivision on the vehicle deck, if required.
- The criterion would assess new designs properly based on physics and the ship layout.
- The effect of the WoD-criterion is expected to be less pronounced for larger RoPax ships: These ships may already now have a better stability due to higher Required Index *R*, which also depends on the number of passengers (N).
- Such a separate WoD-criterion would be largely independent of any future checks on the attained (A) and required (R) indices in the SOLAS 2009 rules.

Development of such a criterion should be based on analysis of more than the present two ships designs according to the SOLAS 2009 rules. This is needed to gain a suitably broad basis for the development of a Water-on-Deck criterion. The development of the SOLAS 2009 rules is discussed further in Chapter 12.

12 Further Development of SOLAS 2009 for RoPax- Vessels

12.1 Introduction

The probabilistic approach of SOLAS 2009 offers a ship designer considerably more freedom than the older ship stability rules did. This approach can lead to better ship designs, but it can also lead to unexpected results. It certainly has been a demanding task to develop and introduce new ship stability rules. Even more difficult it is to anticipate all the possible problems the new designs may bring along.

The present investigation of the two RoPax- Vessels EMSA1 and EMSA2 has shown clear deficits in the new SOLAS 2009 damage stability standard for these types of RoPax vessels. Thus in the framework of the new probabilistic damage stability rules (SOLAS 2009) for passenger ships built from January 1, 2009, it is possible to create ship designs with significant deficits with regard to safety. The present investigation revealed the following deficits:

- It is possible to design ships, which have clearly ***insufficient transverse stability***.
- It is possible to design ***internal watertight subdivisions*** that may have a non-negligible ***risk of a catastrophic failure*** in case of side damage to the ship.

It cannot be closed out that investigation of further RoPax designs created in the framework of the SOLAS 2009 may bring other deficits into daylight. Therefore before suggesting changes to SOLAS 2009 some more new RoPax designs should be investigated.

Already now it can be concluded that some improvement to the damage stability standard SOLAS 2009 Reg. B-1 should be made for specific ship types and designs in order to overcome the mentioned deficits, which are not expected to occur in general for all types of RoPax- vessels, but to a subset of them. Some studies appear to indicate that the new damage stability regulations can also lead to a higher safety level compared to the deterministic SOLAS 90 Reg. II-1/8 standard.

Therefore, any improvement of the SOLAS 2009 damage stability standard should be done very properly in order to cope with the relevant physical phenomena to be addressed by the alteration.

The problems can in general be traced back to two major issues:

- Floodwater on the main vehicle deck leads to additional heeling moments, which must be accounted for.
- A damage, which opens the long lower hold, can lead to the total loss of the ship due to insufficient reserve buoyancy or lack of stability.

These issues are from the point of view of the rule making somewhat different and are best dealt with individually. At first, the water-on-deck problem is discussed. The long lower hold problem will be postponed until a concept for the water on deck problem is settled, but should after that be reconsidered: The lower hold problem can hardly be addressed without having in mind a concept for the water-on–deck problem.

12.2 Historical Overview of the Water-on-Deck Problem

From the point of view of ship stability the so called Water-On-Deck (WoD) problem, that is, accumulation of water on the freeboard deck of a vessel, causes both a shift in the Vertical Center of Gravity (VCG) of the ship and an additional transverse heeling moment.

If the amount of water on the freeboard deck is excessive the ship can capsize rapidly. This phenomenon is recognized perhaps since the late 1930's as green water entering the space between hatchway and bulwark in rough weather, which could lead to a sudden significant heel and in extreme cases to the loss of the ship due to progressive flooding, mainly through the hatches or the superstructure. In principle, this effect is implicitly accounted for in the present ***intact stability rules***, which prescribe a certain righting lever, metacentric height and minimum areas below the righting lever curve. In addition, the ***load line convention*** prescribes a sufficient freeboard, which shall protect the ship from taking excessive amounts of green water on the freeboard deck.

When the first RoRo ships were developed, the situation occurred that the freeboard deck was completely enclosed by a weather-tight superstructure, which allowed designers to reduce the freeboard significantly. The large superstructure provided sufficient reserve buoyancy in intact condition, but when the watertight integrity of the superstructure was lost, e.g. due to a damage, the freeboard deck immediately flooded and the vessel capsized.

For RoPax ships, the situation was slightly different, as the ***margin line criterion*** prevented the freeboard deck from being submerged in certain damage conditions. So if a damage occurred, the freeboard deck could not be flooded from a hydrostatical point of view, but the reserve buoyancy was to certain extent reduced or lost completely.

12.3 Physical Phenomena

In the past several accidents have occurred with RoPax ships, which resulted in the loss of many lives. One important reason for most of these accidents was that ***water could actually enter the freeboard deck*** (or vehicle deck) and ***accumulate*** on this deck, because the enclosing weather-tight superstructure effectively blocked it from flowing out (while scuppers and freeing ports have limited drainage capacity, even when fully operational) As the vehicle deck typically does not have a watertight subdivision, the accumulated water leads to significant ***heeling moments*****,** to a negative initial metacentric height for the upright condition, and sometimes also to strong adverse dynamic effects. Consequently, the ship heels ***suddenly*** to a large heeling angle, which makes it impossible or very slow to evacuate the ship. Then, progressive flooding can take place leading to the sinking of the ship.

There are several possibilities how the water can accumulate on the vehicle deck. This can either happen due to fire fighting on the ship in intact condition or due to the loss of the watertight integrity of the vehicle deck. If this happens, water can enter due to dynamic effects, i.e. forward motion in calm water or in waves, or also due to seakeeping effects: Floodwater can enter through the open bow, through an open side door or through a side damage above the freeboard deck. In any of these cases, the water on the freeboard deck can lead to a sudden significant heel as described above. Many accidents known to us have actually happened in an intact condition of the ship, where the ship remained watertight below the freeboard deck and developed a ***significant heeling moment due to the water ingress***.

Therefore, from a physical point of view, there are significant arguments why the Water-on-Deck -problem poses itself as a kind of intact stability problem:

- The WoD causes a ***significant external heeling*** moment, which occurs for a special type of ship only.
- The heeling moment leads to a ***sudden significant heeling angle***, possibly ending into a capsize.
- Due to the large sudden heeling angle, the evacuation is not anymore possible or is very difficult.
- The WoD- phenomenon can take place, also if the ship is actually **intact** (below the freeboard deck).
- The effect can hardly be influenced by any alteration of the subdivision below the freeboard deck.

12.4 Improvement for SOLAS 2009 with respect to Water on Deck

It is suggested here that the existing damage stability rules according to SOLAS 2009 should be extended with ***one additional criterion,*** which would be relevant for RoPax vessels only. This addendum should be roughly of the following type:

- Additional water on the vehicle deck should be considered.
- The initial amount of water should be determined from the condition that the initial metacentric height in the initial floating condition becomes zero.
- The hydrostatic calculations shall then be performed roughly according to the Stockholm Agreement requirements, which means that the filling height should be kept constant and water may flow in or out of the vehicle deck if applicable. But different to the damage stability calculations, the buoyant volume of the vehicle deck shall be considered (added mass method.)
- The ship should then fulfill stability criteria, which are more strict than the damage stability criteria, but less strict than the intact stability criteria applicable to all types of ships. As a first proposal, these could be the following: Minimum value of the Maximum *GZ* 0.2 m, Positive Range 20 degrees, maximum permissible heel 12 degrees, if wind moment, passenger crowding moment or life boat launching moment will additionally act on the ship.

It should be relatively easy to implement this approach into the new SOLAS 2009 rules as an ***addendum***, which would be ***relevant only for RoPax*** ships. No further alteration of the SOLAS 2009 is suggested here.

12.5 Water-on-Deck Consideration for pure RoRo-Cargo Vessels

One may argue that also for RoRo-cargo vessels, the same problem is relevant and such an addendum should also be relevant for pure RoRo cargo vessels. However, these ships are not affected by this type of problem for the following reason: For cargo vessels, equilibrium heeling angles of 25 degrees are permissible according to the rules and result in s_i=1. This is already a large heeling angle, and if s_i shall remain 1, a RoPax ship must have a positive range of 16 degrees, where no progressive flooding must take place. The evacuation of a cargo ship is still considered to be possible by a trained crew also at large heeling angles and in a shorter period of time. So for RoRo- cargo vessels, heeling angles, which shall be avoided by the addendum, are explicitly allowed in the present rules. This results in the situation that consideration of additional water on deck may not be appropriate for RoRo-Cargo ships.

12.6 Alternative Way to improve SOLAS 2009 for Water on Deck Problems

Although the present authors see the above mentioned WoD addendum as the best way to actually account for water on deck problems in the damage stability regulations, there are other formal ways to cope with this problem. If the suggested WoD addendum is not considered as a way forward, it would also be possible to introduce the requirements of the Stockholm Agreement calculation procedure more or less unchanged into the new SOLAS 2009 rules by simply ***modifying the calculation procedures of the s_i-factor***. If this is considered to be appropriate, then s_i should for RoPax vessels be calculated ***including water on the vehicle deck*** for all damage cases, where the vehicle deck is damaged. This would result in the following calculation procedure for all damage cases, where the vehicle deck is damaged:

- Determine p_i, r_i, v_i
- Calculate equilibrium floating condition and measure minimum freeboard in damage extent.
- Determine additional water on deck according to the Stockholm Agreement procedure.
- Calculate righting levers including that water on deck like before during the Stockholm Agreement procedure.
- Calculate s_i according to the new SOLAS 2009 procedure based on these righting levers.

With this approach the following ***problem*** identified during the investigations of the ship design EMSA2 remains: Within the framework of the new SOLAS 2009 it is possible that for a damage case, the vehicle deck is ***submerged*** (negative freeboard in damage range). For such cases, the assumptions of the existing Stockholm Agreement are ***no longer valid***, as this has been implemented on top of the deterministic requirements of former SOLAS. Due to the ***margin line criterion***, negative freeboards in damage range were simply earlier not possible. From a physical point of view the existing Stockholm Agreement requirements cannot simply be extrapolated for negative freeboards.

As the effort to solve this problem is of the same magnitude as for the WoD addendum solution, and as the latter is much more straightforward, this alternative approach is not recommended in the first place.

For any of the described improvements of the regulatory framework the effect on a wide range of sample ships should be investigated before the improvement would come into effect.

12.7 Conclusions for the Water on Deck Problem

It is recommended to keep SOLAS 2009 in the present form and to add an additional requirement, which explicitly treats water on deck separately. The result of this requirement with respect to ship design will be an adjustment of the minimum stability, if required and/or introduction of additional watertight longitudinal subdivision on the vehicle deck, if required. The effect of this requirement may be less pronounced for larger ships, as these do not seem to have the problems identified in the ship designs EMSA1 and EMSA2. This is according to our opinion the most straightforward way ahead.

It is also possible to modify the s_i- factor as mentioned above, but this option is not seen ***as really straightforward***, because some existing problems connected to the Stockholm Agreement remain and the effort is comparable to the development of an additional requirement, as explained above.

The effects of the SOLAS 2009 addendum as described above would lead to the following design consequences:

First, it assures that the general stability level of the vessel is sufficient to cope with this type of problem. All stability related problems that have been identified for the design EMSA1 would disappear. The designer of a RoPax- vessel might select to decrease the *KG* or better to increase the ship stability with design changes, if found appropriate.

Second, but not less important, this approach would give a strong stimulus for the introduction of double hulls or at least partly double hulls on the vehicle deck. These become then most attractive in a ship having a lower hold, as the design modification of the ship design EMSA2 has shown.

13 Conclusions

Two new RoPax ships were designed by the FSG to meet the new probabilistic SOLAS 2009 damage stability standard for passenger ships built after January 1, 2009. These two vessels, EMSA1 and EMSA2, fulfill the SOLAS 2009 damage stability requirements with little and practically no margin left, respectively. For the EMSA1 the Required Index *R* is 0.700 and the Attained Index *A* 0.713, for the EMSA2 these values are 0.721 and 0.722, respectively.

According to a typical shipyard design procedure each ship was optimized so that it has a maximum operational flexibility. This means that for the deepest draft the collected index is the absolute minimum (EMSA1: 0.655; EMSA2: 0.705), whereas the most of the index contributions are collected at the light and partial drafts. All calculations and assumptions were carried out in such a way that the design could be approved by an Administration. To a high degree this reflects the typical design and pre-approval process in a shipyard.

The TUHH analyzed the safety level provided by the different ship damage stability rules with a Monte Carlo simulation. For both ship designs EMSA1 and EMSA2 no reason was found to assume that the safety level presented by the new SOLAS 2009 Reg. B-1 standard would be equivalent or higher than the SOLAS 90 Reg. II-1/8 standard in conjunction with the Stockholm Agreement requirements. On the contrary, all calculations show that the safety level presented by the SOLAS 2009 Reg. B-1 rules clearly drops down to a significantly lower level.

The hydrostatic calculations showed the following significant weaknesses in the stability of these two vessels:

- The ship EMSA1 suffers from a general lack of stability, but the designed subdivision is reasonable.

- The ship EMSA2 was found to have a sufficient level of stability, but whenever the Long Lower Hold (LLH) would be damaged and flood, the ship has insufficient amount of reserve buoyancy, especially if also the RoRo Cargo hold, i.e. vehicle deck, gets damaged.

In addition to the hydrostatic calculations by TUHH and SDC also the simulations with the HSVA Rolls show that the ship EMSA2 with the mentioned LLH damage capsizes or sinks rapidly also in calm water. Any damage deeper than B/10 in the midship area can penetrate the Long Lower Hold having a length of 39 percent of the L_{bp} and cause this.

In order to analyze the LLH damage in a suitable RoPax, a modification of the EMSA2 was developed by the FSG. This modification EMSA2MOD exceeds the minimum requirements of the SOLAS 2009 Reg. B-1 with a clear margin. The attained Index for the EMSA2MOD is 0.797.

Based on the TUHH analysis of the ships with Monte Carlo simulation and other considerations 4-5 different damage cases were chosen for the numerical simulations of each ship in seaway.

In general the numerical simulations give an excellent picture of the heeling and vehicle deck flooding process, but they underestimate the time (duration) to capsize or to survival criterion. The same applies to the critical significant wave height. Thus results of the numerical simulation of the behavior of the damaged ships EMSA1 and EMSA2 are on the safe side, but the simulations predict a somewhat too low survivability for these two vessels.

Some of the damage cases selected by the TUHH and HSVA showed so clear and rapid capsizing behavior in the numerical simulations with the HSVA ROLLS also in relatively low sea states that these cases were not considered as candidates for the investigation with the model tests. Instead cases considered to be most representative or typical were chosen for the model tests, which are considered to give the best estimates for the critical wave height leading to capsize or non-survival according to the applied survival criterion. The following results were obtained with the model tests:

- The ship design EMSA1 capsized at H_S 3.0 m, T_P 6.9 s and H_s 3.2 m, T_P 7.2 s
- The ship design EMSA2 capsized at H_S 4.32 m, T_P 11.6 s and H_s 4.58 m, T_P 8.6 s.
- The modified version EMSA2MOD with LLH damage survived at H_s 4.0 m even up to 6.7 m, which is a very good result. However, after reduction of the trim and introduction of initial heel of 4° to the undamaged side the ship did not survive in waves of H_s 3.8 m. Remember, however, that the EMSA2MOD clearly exceeds the requirements of SOLAS 2009 Reg. B-1.

Further it should be kept in mind that the damage cases chosen to investigated with model tests were not the worst cases.

All the analysis carried out by the HSVA Consortium points out to the following:

The ship EMSA1 would not survive in likely damage cases in a sea state having a significant wave height of 4.0 m. In some damage cases not tested with model tests the ship is expected to capsize in much lower waves, also when there is no water on the vehicle deck.

The ship EMSA2 would probably survive some likely damage cases in a sea state having a significant wave height of 4.0 m, but would capsize or sink rapidly, if the LLH would be damaged. As the Long Lower Hold has a length of 39 percent of the L_{bp} the probability that a collision damage at the ship side would extend to the LLH is considerable.

The modification of EMSA2 into EMSA2MOD greatly improved the survivability of the larger RoPax with the LLH. The modified version EMSA2MOD provides sufficient buoyancy for the vessel also in the case the Long Lower Hold is damaged. Whether this design is safe in all phases of flooding, particularly in the initial transient phase, in all initial floating conditions (heeling, trim) is not yet established. There is no doubt, however, that the suggested modification can be extended, if needed, to provide a safe ship also in case of a LLH-damage.

The probabilistic approach of SOLAS 2009 offers a ship designer considerably more freedom than the older ship stability rules did. This approach can lead to better ship designs, but it can also lead to unexpected results.

The present investigation of the two RoPax- Vessels EMSA1 and EMSA2 has shown clear deficits in the new SOLAS 2009 damage stability standard for these types of RoPax vessels. Thus in the framework of the new probabilistic damage stability rules (SOLAS 2009) for passenger ships built from January 1, 2009, it is possible to create ship designs with significant deficits with regard to safety.

In view of this it is difficult to come into any other conclusion that the ship stability required by the SOLAS 2009 rules is not likely to be sufficient in all cases. Corrective action should be taken to amend the SOLAS 2009 rules. In order to reliably make the right changes, some more new RoPax designs according to the probabilistic SOLAS 2009 rules should be investigated.

In view of the present results from the EMSA1 and EMSA2 the HSVA Consortium found the idea to leave the damage stability rules in SOLAS 2009 in the present form and to develop an additional, separate Water-on-Deck (WoD) -criterion based on first principles for the amendment of the SOLAS 2009 rules as best.

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