A New Approach for the Water - On - Deck - Problem of RoRo - Passenger Ships

Stefan Krueger, Oussama Nafouti *Hamburg University of Technology, Germany*

Christian Mains *DNV GL Hamburg, Germany*

ABSTRACT

Since the ESTONIA accident in 1994, the so called water on deck problem for RoRo-Passenger Ships has been subject to many investigations. Being the central part of the Stockholm-Agreement (MSC Circ.1891 and EU directive), the water on deck problem was included in the damage stability calculations in addition to SOLAS 74/90 II-1/8. Although some of the assumptions are not physical sound, it is obvious that the safety level of RoRo- Passenger Ships has significantly been improved by including the water on deck problem in the safety regime. Unfortunately, the SOLAS 2009 does not explicitly address this problem, and there have been indications that the present safety level of the SOLAS 2009 seems not to cover the Stockholm Agreement for most of the smaller RoRo- Passenger Ships/ Ferries. However, when accidents of ships are analysed where water on the vehicle deck plays the dominating role, one finds that in most cases the problem is more related to intact stability. This is due to the fact that the involved ships were not damaged below the waterline, and this does especially hold for all problems related to firefighting on the vehicle deck.

Therefore we tried to formulate the water on deck problem as an intact stability criterion. In a first step, the stability limiting amount of water on deck needs to be determined. Then, in a second step, righting levers for the intact condition including this amount of water on deck can be computed, and some defined intact stability criteria can be applied. When determining the amount of water on deck which shall be used as design value, it is useful to analyse the relevant accidents. As a matter of fact, the ships accumulated water on deck due to various reasons, and the crew continued their operation until the situation became irreversible. They were not aware that they had run into a dangerous situation. This led to the idea to use the alteration of the roll period with water on deck as a suitable design criterion) and as an indicator for dangerous situation which easily can be measured by the crew). Consequently, we performed numerical roll decay tests with several RoRo-Passenger ships, where we varied the amount of water on deck. As an interesting result, we found that when increasing the amount of water on deck, the roll period first increases slightly and then changes drastically with a steep gradient. As a good rule of thumb we found that when the roll period doubles, a significant amount of water has accumulated on deck, but the ship still has a significant remaining stability margin against capsizing. Thus we used this approach to come to a reasonable design value for the minimum amount of water to be considered on deck. We also found a significant influence from centre casings on the amount of water on deck, which has to be considered. The proposed stability criteria have to be complied with for the intact condition including a dedicated amount of water on deck. These loading conditions were defined in such a way that all ships which are fully compliant to Stockholm Agreement do also fulfil our new approach, which is quite robust.

Keywords: *RoRo-Passenger Vessel, Water on Deck Problem, GM required curves, safety level.*

1. INTRODUCTION

One of the critical design characteristics of RoRo-Passenger Vessels is the large vehicle deck. In case of water ingress into the vehicle deck, the water is flowing freely on the deck and substantial heeling moments can be built up. If the amount of accumulated water on such a vehicle deck is increasing up to a critical value, the (initial) stability of the ship is going to vanish and the ship rapidly capsizes or takes a substantial heeling angle which extends the evacuation time significantly. Due to the nature of capsizing, accidents with water on deck often lead to a large number of casualties that might be reduced if one can set up a simple rule for crew and officers when the amount of accumulated water would become dangerous. Water may accumulate on deck due to opened vehicle compartments (Heraklion, Estonia), or by faulty operations (Herald of Free Enterprise, Jan Hewliuscz) or due to firefighting measures (Al SALAM BOCCACIO). The ESTONIA disaster has made the water on deck problem obvious, and after this accident the damage stability regulations for RoRo-Passenger ships operating in European waters have been updated by explicitly taking into account accumulated water on deck. These regulations are known as “Stockholm-Agreement”. The basic design philosophy behind this stability standard is to reduce the amount of possible floodwater on the vehicle deck by sufficient residual freeboard between the vehicle deck and the damaged waterline. If this criterion cannot be complied with, the stability of the ship must be increased in such a way that the ship can withstand the assumed amount of floodwater which led to an increase vehicle deck for post ESTONIA RoRo-Passenger ship designs. Despite the fact that the physical background of the Stockholm- Agreement was subject to many discussions in the past, there is no doubt that the application of this regulation to RoRo- Passenger vessels has significantly improved the overall safety level of this ship type.

When the stability code for Passenger Vessels was updated with the enforcement of the SOLAS 2009, the damage stability regime for Passenger Vessels became a probabilistic one. In SOLAS 2009, water on deck is not explicitly addressed, but the Stockholm Agreement remains in force for all RoRo-Passenger vessels calling a European Port. As the Stockholm- Agreement is a local stability standard only, there are many discussions and research projects dealing with the question if in the framework of the SOLAS 2009 the Stockholm- Agreement is still needed or not. The results were quite controversial: Some researches came to the conclusion that the SOLAS 2009 would provide a higher safety level compared to the Stockholm- Agreement, and others pointed out that there might be still a deficiency even in the new SOALS 2009. As a consequence of this discussion, a modification of the s-factor of the SOLAS 2009 for RoRo-Passenger ships has been suggested during the last SDC- session at IMO with a future option to skip the Stockholm agreement. It is still an option (and presently under discussion) to modify the required index R of the SOLAS 2009. However this poses the difficulty that a modified R-index would also affect all vessels designed according to the SPS code, as the SPS code refers to the SOLAS 2009. In fact, the situation is quite complex. To come to possible solutions, the following two questions need to be answered:

- Is there still a need for considering water on deck for RoRo-Passenger vessels even in the frame work of the SOLAS 2009?

- If the first question is answered with “yes”, which possible options exist to improve the design of RoRo passenger ships?

Consequently, the present paper will deal with these two questions.

2. STABILITY OVERVIEW

In this chapter, we will discuss the influence of the existing different regulations on the design of RoRo-Passenger ships. This is necessary to understand if there is a need for the explicit treatment of water on deck or not.

2.1 Before 2009

Before 2009, the situation was quite clear: A RoRo- Passenger ship had to fulfil SOLAS 74/90 II-1/8 (deterministic approach) including permissible floodable lengths. If the ship was operated in Europe, it had also to fulfil Stockholm- Agreement, where the full compliance was obtained if the ship was designed for a significant wave height of 4m. Depending on the number of passengers, the ship had to withstand one or two compartment flooding. The damage length was defined as 0.03L+3m, and the penetration depth was maximum B/5. The ship had to survive all possible damages within the prescribed damage extents. Due to the deterministic nature of the stability standard, not all possible damages could be included. Otherwise it would not have been possible to design a ship. Krueger and Dankowski [1] have analysed the amount of damages covered by the SOLAS 74/90 II-1/8, depending on the ship length L (see Fig. 1, green curve).

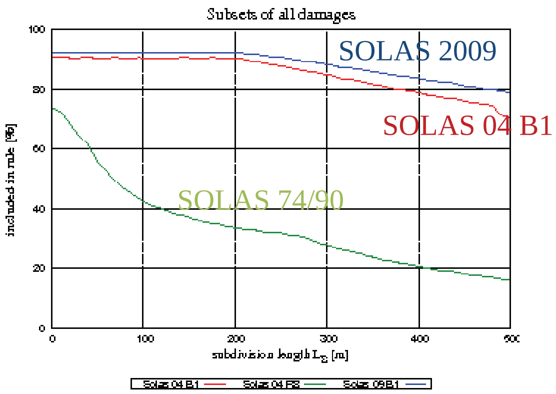

Figure 1: Percentage of possible damages covered by several damage stability standards. Green: SOLAS 74/90 II-1/8, 2- Compartment-Flooding.

If we assume that the HARDER- statistics represents all possible damages (100%), we can obtain from Monte- Carlo- Simulations the percentage of damages which are covered by e.g. SOLAS 74/90 II-1/8. Fig. 1 shows that for a 200m RoRo-Passenger ship, only abt. 35% of all possible damages are included, but the ship has to survive them all. Due to this circumstance, the ship has a hidden safety reserve, because it is well possible that the ship survives damages which are not in the scope of SOLAS 74/90 II-1/8. Despite these considerations, the situation was in principle quite clear for the designer, but there remained the following practical difficulties:

- The floodable length calculation was challenging when the ship was equipped with a long lower hold.
- The safety philosophy targeted on sufficient residual freeboard, at the same time it was not allowed to submerge the Margin Line. This made double hull designs/side casings (on the vehicle deck) not attractive, and the increased residual freeboard resulted in increased VCGs and all the related problems.

But as already pointed out, the overall safety level seemed to be sufficient.

2.2 Since 2009

The SOLAS 2009 has put forward a probabilistic damage stability assessment. As a consequence, more possible damages have to be investigated (blue curve in Fig. 1) compared to the previous deterministic standard, but not all of these damages have to be survived. The amount of damages which has to be survived strongly depends on the number of passengers on board, and slightly on the ship length (exactly: The required R- index). Now the number of passengers on board determines the safety level of the ship. It is well known that if a ship is only designed according to probabilistic principles, designs may be created where a minor damage can lead to the total loss of the ship. Therefore, the SOLAS 2009 also contains a deterministic addendum which prohibits such designs. The damage assumptions of this deterministic addendum have been taken from SOLAS 74/90 II-1/8, but with a reduced maximum penetration of B/10 instead of B/5. If the ship has less than 400 persons, one compartment damage is assumed. This requirement must also be fulfilled by each ship complying with SOLAS 2009. If the ship shall operate in European waters, the Stockholm- Agreement must be additionally applied which results in B/5 damage penetration and the additional water on deck. This makes the design consideration more complicated and reduces the designer's flexibility. In the following we will discuss the problem further.

If we look at the SOLAS 2009 only, we have to fulfil two requirements: The probabilistic part and the deterministic addendum. The safety level of the probabilistic part strongly depends on the number of passengers, the deterministic part does not (except for the decision of one or two compartment flooding). It is now of utmost importance to understand which of the two elements of the SOLAS 2009 is the governing stability criterion: If the number of passengers is sufficiently high, the probabilistic part determines the safety level. On the other hand, if the number of passengers is small enough, the deterministic part of the SOLAS 2009 determines the stability. From some sample calculations we have made [1], one can roughly say that this number of passengers is about 1500. That means that for all RoRo-Passenger-Vessels with about 1500 or less passengers, the stability limit of the SOLAS 2009 is defined by the deterministic addendum (SOLAS 74/90 II-1/8, but B/10 penetration).

If such a design now needs to comply with the Stockholm- Agreement, the situation becomes at least challenging as this standard prescribes to survive all B/5 damages according to SOLAS 74/90 II-1/8. In such a case, the safety of the ship is determined by the Stockholm- Agreement. In [1] we have developed a method to quantify the difference of the absolute safety levels of different damage stability standards, as an example see Fig. 2. Concerning the ship design this simply means that if a RoRo-Passenger ship with about 1500 Pax or less shall be designed to operate in European Waters, the designer simply needs to fulfil the Stockholm-Agreement. The SOLAS 2009 is then also fulfilled, maybe with small design changes.

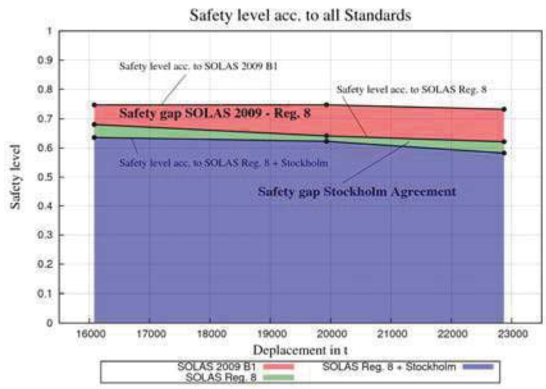

Figure 2: Determination of safety levels of different damage stability standards. Here: 1500 Pax, 200m RoPax with B/10 Lower Hold [1].

It has been in principle understood that there remains a problem in the SOLAS 2009 with passenger ships carrying a smaller number of passengers. This holds for all passenger vessels. Consequently there are ongoing discussions to possibly modify the R- index for smaller number of passengers. But the difficulty remains that all SPS ships might also be affected by such a modification.

On the other hand it became obvious that at least a rough treatment of the large vehicle decks of RoRo-Passenger should be included in the damage stability. A modification of the s-factor has been suggested, where the required righting lever h and the range of positive righting levers have been increased. However, one needs to remember that the s- factor is determined from a power of ¼, and thus small alterations of the required values are not effective. It is therefore questionable whether this approach is a full compensation of the water on deck problem.

From all these findings, we can draw the following conclusions:

- There seems to be a necessity to improve the R- index for passenger ships with smaller number of passengers. This problem affects all passenger ships.
- It is not yet clear whether the modification of the s- factor is sufficient. This problem affects only RoRo- passenger ships.

What makes a solution extremely challenging is that both conclusions are coupled together: It may turn out that if a possible future R-value is conservative enough, there may be no need to explicitly include water on deck in the damage stability assessment. On the other hand one has to remember that a critical amount water on deck leads to a rapid capsize of the ship, and it is not certain in how far this failure mode is still in the scope of a possibly revised SOLAS 2009. Therefore, according to the opinion of the authors it makes sense to look for alternative possibilities to include a possible rapid capsize scenario due to a critical amount of water on deck in a stability regime. This could also help to separate problems which are only related to RoRo-Passenger ships from problems which are relevant for all types of passenger vessels.

2.3 General considerations

When we deal with the water ingress on a RoRo-Passenger ship vehicle deck, we automatically consider it as a damage stability problem. But is that really true? As a matter of fact, the bulkhead deck is the upper limit of the water tight subdivision, and all watertight bulkheads must be extended to this deck (with an exception of moveable bow ramps). Above the vehicle deck, the ship is typically weathertight, and it needs to be weathertight to fulfil the intact stability requirements. From a pure damage stability point of view, the accumulation of water on deck could simply be avoided by arranging freeing ports, but then, the ship cannot fulfil the intact stability requirements. Consequently, the ingress of water on a vehicle deck means water ingress above the watertight subdivision on the freeboard deck (which is the bulkhead deck for a RoRo-Passenger vessel). Regardless how the water has entered into the vehicle compartment, we put forward the argument that we can formally treat water on the freeboard deck as a green water problem on the freeboard deck. This becomes more obvious if we take into account one event which can lead to a substantial accumulation of water on the vehicle deck, namely firefighting. In these cases (like AL SALAM BOCACCIO) the ship did not have a structural damage which lead to a water ingress. Although in other cases water entered on the vehicle deck due to structural damages (ESTONIA and HERAKLION), these damages were always above the watertight subdivision, affecting a weathertight superstructure. The same holds for the accidents of JAN HEWELIUSZ and HERALD OF FREE ENTERPRISE. These ships did also not experience a damage of the watertight subdivision. The same holds for the RoRo-Ferry investigated by Ikeda et. Al. during model experiments, where water was allowed to enter the vehicle deck through the open bow door [6]. The only exemption known to the authors is the EUROPEAN GATEWAY accident. This ship experienced a damage below the bulkhead deck. A large heel during an intermediate stage of flooding occurred, which resulted in progressive flooding of the vehicle deck and finally the ship capsized. This is indeed a typical damage stability accident, and the failure is well covered by the existing damage stability regime.

From these findings we can conclude that most of the accidents where water ingress on the vehicle deck played a major role are actually accidents where the ship did not formally experience damage to the watertight subdivision, but water entered on the freeboard deck of an intact ship. Due to the unique design boundary condition of RoRo-Passenger vessels, no freeing ports can be arranged on the freeboard deck to allow the water to leave the deck. Consequently, this circumstance allows water to accumulate on the freeboard deck which is a potential threat to the safety of the ship. This situation is unique for RoRo-Passenger vessels, and needs according to our opinion a unique treatment. From these findings, the following arguments can be put forward:

- Due to the fact that most accidents with water on deck happened in an intact ship condition with respect to the watertight subdivision, this problem should be regulated by the intact stability regulations.
- Due to the unique design boundary condition of RoRo-Passenger vessels, the problem must be dealt with only for this specific ship type.

If once the argument is put forward to formulate an intact stability criterion for RoRo-Passenger ships, this has also the advantage that the water on deck problem can be completely decoupled from the current developments of the damage stability code.

With the above mentioned findings it becomes clear that there is always the risk that a critical amount of water may enter the vehicle deck on an intact RoRo- Passenger ship and will accumulate there. Consequently, a RoRo-passenger vessel must have the ability to withstand a certain amount of water on the vehicle in the intact condition. If this is once put forward, the following questions have to be answered:

- How much floodwater shall be assumed on the vehicle deck?
- How shall the stability requirements be validated?

If the first point has successfully been treated, the stability requirements could then simply be solved by taking into account the stability reduction due to the free surface of the floodwater in the vehicle deck.

These questions will be answered in the following sections.

3. AMOUNT OF DESIGN WATER ON DECK

The first step of a possible intact stability criterion covering water on the vehicle deck must be the determination of a reasonable amount of water which is to be assumed on the vehicle deck. The Stockholm-Agreement relates this amount of floodwater to the residual freeboard to the bulkhead deck. The design philosophy behind this approach is that any water ingress into the vehicle compartment should be avoided as far as possible. This approach neglects the fact water ingress due to firefighting is independent from the position of vehicle deck. The same holds for the development of the so called “static equivalent method” (SEM), which was developed by Vassalos [2] as an improvement of the Stockholm- Agreement. To cover also the firefighting problem, an alternative approach needs to be developed.

In this context it helps to analyse the most important accidents where water on deck played a major role. All these accidents followed a comparable scheme: Due to different circumstances, water entered on the vehicle deck and started to accumulate there. The crew was not aware of the fact that the situation became dangerous, and they continued their operation. When the amount of water increased to a critical value, the crew detected that there was something wrong, but then it was already too late: The ship experienced a large heel, all the water on deck flew to one side and the situation was irreversible. Consequently, a criterion for a critical amount of water on deck shall try to avoid that the stability situation leads to an irreversible condition. The irreversibility of such conditions lies in the fact that the water which has been accumulated in a quasi upright condition suddenly flows to one side when the initial stability becomes small or even negative. This circumstance has brought up the idea to analyse the roll period with water on deck. This can be done by a numerical roll decay test. We have used the nonlinear time domain seakeeping code E4ROLLS [3] to perform such calculations. Nafouti [4] has used this technique to analyse the alteration of the roll period of several RoRo-Passenger vessels where he has systematically varied the amount of water on deck. In the computations, the water on the vehicle deck is modelled by shallow water equations according to Glimm´s method [5] and it is allowed to flow freely on the vehicle deck. The method is also able to take into account the blockage of the flow due to a centre casing. The roll motion can be initiated by a non-zero roll speed at the upright condition. From the computed time series, the roll period can be determined.

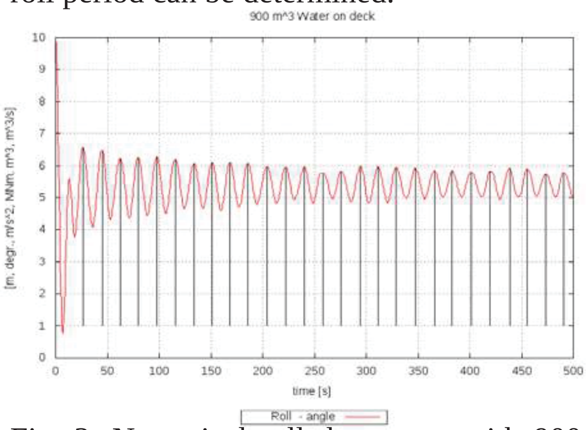

Fig. 3: Numerical roll decay test with 900m3 water on deck of the RoPax Ferry EMSA2 [4],[1].

The principle is shown in Fig. 3. The figure shows the time plot of the roll angle of the RoPax- Ferry EMSA2 [1] with 900m3 water on the vehicle deck. When the roll motion is excited by an initial disturbance, the ship gradually oscillates around the final static equilibrium. The roll period with water on deck can then simply be determined by counting the peaks. When the amount of water on deck is systematically varied, the alteration of the roll period can be determined as a function of the amount of water on deck. This has been done for twelve different RoRo-Passenger ship configurations. In the beginning, a centre casing was not considered. The results were quite interesting, and two of them are presented in figures 4 and 5.

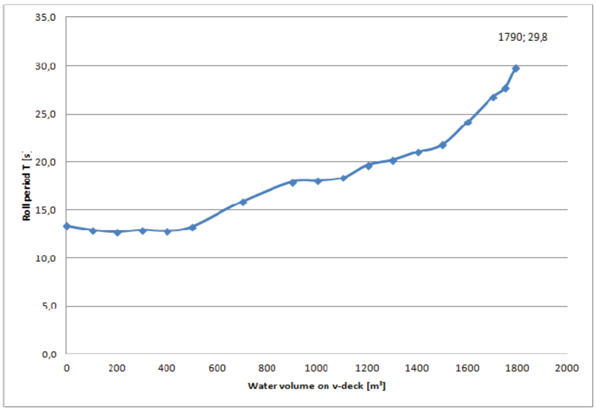

Figure 4: Alteration of the roll period as a function of the amount of water on the vehicle deck for the RoPax EMSA1 [1].

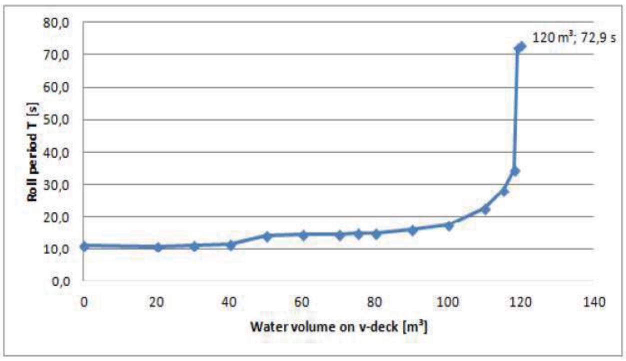

Figure 5: Alteration of the roll period as a function of the amount of water on deck, for the RoPax EMSA2.

The figures show the development of the roll period of two RoRo-Passenger vessels as a function of the water volume on deck. This has been increased until the ship reached a large heel of 30 Degree or more during the computation. This critical volume is also indicated in the figures. For smaller volumes the results show that the roll period changes slightly, and the gradient of the curve becomes steeper towards the final capsize. This can be nicely observed in Fig. 4. This general trend was found for all ships analysed. Fig. 4 leads to the idea that a doubling of the roll period due to the influence of water on deck can be taken as a first idea to determine the minimum amount of water on deck the ship has to withstand: There is still a good safety margin from the doubling of the roll period to the final capsize, and a substantial amount of water is required to actually double the roll period. Therefore we have chosen the doubling of the roll period in a numerical roll decay test to determine an amount of water which could be used for the stability evaluation in a later step (such change of the roll period can also be observed by officers and crew). We have checked this relation for other RoRo-Passenger ship designs and came to similar conclusions.

But this criterion alone is not sufficient: If for example a wide double hull would be fitted onto the vehicle deck, it will not be possible to double the roll period with reasonable amounts of water on deck. Therefore, we need a second criterion which limits the design amount of water on deck in case a doubling of the roll period cannot be achieved. From our investigations (with indeed a limited number of designs) it seemed to be most promising to limit the amount of water on deck to 6% of the total displacement. This gave the best agreement with the numerical computations. Then it finally boils down to the following procedure to determine the design amount of water on deck:

Determine the amount of water on deck which leads to a doubling of the roll period.

Determine 6% of the total displacement and take the smaller value of both evaluations.

A special consideration is required for centre casings: A centre casing has no influence on the hydrostatics of the floodwater, but it prohibits the free flow on the vehicle deck. Consequently, a larger amount of water is required to double the roll period when a centre casing is fitted. From a safety point of view, this is correct, because according to the authors’ opinion, the centre casing bears an additional risk: If the water accumulates on a vehicle deck with a centre casing, the floodwater dynamics lead to a less severe alteration of the ship`s motion, and the crew has reduced chances to detect that the situation is potentially dangerous. According to our basic assumptions this means that more water on the deck will be accumulated as without a centre casing. When the ship then begins to list, all the floodwater flows irreversibly to one side and the centre casing becomes irrelevant. Consequently, long centre casings could make the situation potentially more dangerous, and this would require a larger amount of water on deck to be considered during the design. Such behaviour is exactly demonstrated by the computations of the numerical roll decay tests. But this means that also the limiting value of the amount of water on deck needs to be corrected for the presence of a centre casing. We have performed all calculations for configurations with and without centre casing, and the length of the casings was systematically varied [4]. From the comparison of the different numerical results we suggest the following relation for the minimum amount of water which should be considered on the vehicle deck:

$$V\ (T=2T_0)\ [\%] = 6\ [\%] + 3.75\ (L_{Casing}/L_{Deck})\ [\%]$$

Here, V is the design volume of water on deck as percentage of the total displacement, LCasing denotes the overall length of the centre casing and LDeck is the length of the vehicle deck. However, one needs to take into account that due to the limited number of designs we have analyzed, this relationship may be seen as a first rough guess.

This design amount of water on deck is now used to carry out calculations of the static lever arm curves.

4. STABILITY CRITERIA

The design amount of water on the vehicle deck which has been determined by a.m.

procedure is now used to carry out computations of the static righting lever. The volume is kept constant and the ship (including the water) is allowed to trim freely. The principal shape of such a righting lever curve is shown in Fig. 6.

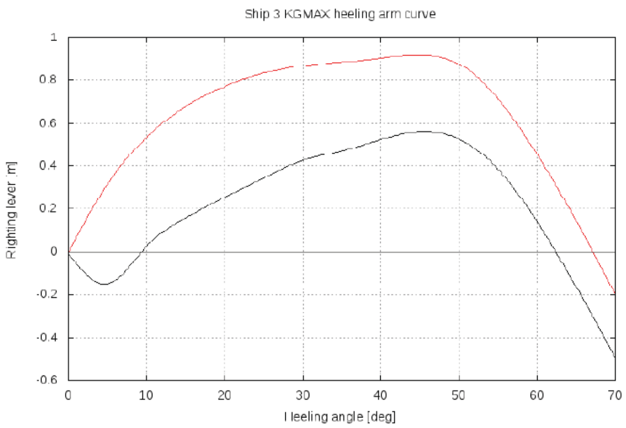

Figure 6: Righting lever curves of the intact condition (red) and with the design volume of water on deck (black) according to section 4.

Figure 6 shows the comparison of the righting lever curve for the intact condition (red) and the remaining stability when the design amount of water on deck is applied. For this particular righting lever curve stability criteria need to be developed. These criteria should be close to criteria which are already in use. They should be of the following type:

- The static equilibrium should be limited to a certain value (taking into account limitations for possible evacuation).
- The negative area under the righting lever curve should be limited in relation to the positive residual area under the righting lever curve to avoid capsizing when the ship swings over to the other side.
- There should be a requirement for the maximum lever and for the area below the righting lever curve.

These kinds of criteria are principally known from other IMO- instruments. The question is now to find reasonable minimum values.

One possible approach to set up the limiting values is that the safety level of a RoRo-Passenger ship according to the newly proposed criterion shall be equivalent to the existing safety level. For most of the ships we have analyzed, the safety level was determined by the Stockholm- Agreement. Only the two ships EMSA1 and EMSA2 did not comply with the Stockholm Agreement. For our investigations, they were additionally fitted with a double hull on the vehicle deck until they were compliant with the Stockholm Agreement. All our ships were then evaluated by the described procedure. If all Stockholm Agreement - compliant ships should pass the newly developed criterion, the following stability values need to be obtained including the design amount of water on the vehicle deck:

- The static heel should be limited to 12 Degree.
- The area under the righting lever curve from the equilibrium to the angle of no return or possible progressive flooding must be three times larger compared to the (negative) area under the righting lever curve from 0 to the equilibrium.
- The maximum righting lever should be 0.2m or more.
- The area under the righting lever curve from the equilibrium to 30 Degree should be 55mmrad or more.

These are reasonable values which are close to those used by the Intact Stability Code 2008. According to our investigations, a RoRo-passenger ship which fulfils these requirements including the design amount of water on the vehicle deck has an equivalent level of safety with respect to water ingress on the vehicle deck as a ship which fulfils the Stockholm-Agreement damage stability standard. Therefore our approach seems to offer a reasonable alternative to cover water on vehicle decks by keeping the existing safety level without the necessity of including this problem in the damage stability regulations.

5. SHIPS INVESTIGATED

The following table summarizes the most important data of the RoRo- Passenger ships. Design alternatives of the basic designs were created by adding additional double hulls and/or center casings of different lengths.

Ship	L	Pax	Lower Hold	Doub.Hull
1	80	300	No	No
2	200	600	Yes	No
3	150	600	No	No
4	160	1600	No	No
5	115	650	No	Yes
6	165	1500	No	No

The ships 3,4,5 and 6 fulfill the Stockholm-Agreement Standard, the Ships 1 and 2 did not. In our investigations they were made with the Stockholm- Agreement by fitting a double hull on the vehicle deck.

6. CONCLUSIONS

An alternative method was presented which covers the effect of entrapped water in the vehicle deck of a RoRo- Passenger ship on the stability. In contrary to the existing stability standards, our method treats the problem as an intact stability problem. This is justified by the fact that in the relevant accidents, no damage below the bulkhead deck occurred. Further, the newly proposed method covers water accumulation due to fire fighting. As a first step of the analysis, a design amount of water on the vehicle deck needs to be determined. This can be obtained by the calculation of the roll period, and the design water volume is reached when the roll period takes twice its initial value. If this cannot be achieved, the design water volume is limited. A centre casing is accounted for by an increased design water volume. Static lever arm curves can be calculated including this amount of water on deck, and stability criteria have been proposed which ensure a lever of safety which is equivalent to the Stockholm Agreement. The method is in principle straight forward and quite simple. But it should be further developed: Instead of performing numerical roll decay tests, it could also be possible to establish a relation between hydrostatic parameters of the righting lever curve including water on deck and the resulting roll period, although this might be challenging for the centre casings. And the proposed criteria need further evaluation due to the fact that we investigated a limited number of designs only.

7. ACKNOWLEDGEMENTS

Part of this research has been funded by the German Federal Ministry of Economics and Energy in the framework of the research project LESSEO. Without this funding, this project would not have been possible.

8. REFERENCES

Valanto, P., Krüger, S., Dankowski, H.: Research for the Parameters of the Damage Stability Calculation 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. HSVA- Report No. 1669, Hamburg, 2009

Vassalos, D. et al: SEM- Static Equivalent Method- Background and Application. The Ship Stability Research Centre, University of Strahclyde, Glasgow, UK, June 2000.

Kröger, P.: Simulation der Rollbewegung von Schiffen im Seegang. Report 473, Hamburg University of Technology, Hamburg, Germany, February 1987.

Nafouti, O.: Development of an Intact Stability Criterion for RoRo-Passenger Ships against Capsizing due to Trapped Water on Vehicle Deck. Hamburg University of Technology, Report A-55. June 2014

Glimm, J.: Solutions in the Large for Nonlinear Hyperbolic Systems of Equations. Commun. Pure Appl. Math, 18:697-715,1965

Shimizu, N., Roby, K., Ikeda, Y.: An experimental study on Flooding into the Car Deck of a RORO Ferry through Damaged Bow Door. J. Kansai N.A., Japan, No. 225, March 1996

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