Ro-Ro passenger ships – from Stockholm Agreement to SOLAS2020

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ABSTRACT

In June 2016, the European Commission (EC) appointed a consortium comprising several research and commercial organisations, to conduct an "*assessment of specific EU stability requirements for ro-ro passenger ships*". The primary aim of the study was to compare the regional requirements as specified by Directive 2003/25/EC (commonly known as Stockholm Agreement) with the provisions of the amended SOLAS regulations (SOLAS 2020). The two predominant changes in SOLAS lead to significant increase in the required index of subdivision, R, and the calculation of the survivability factor (s-factor) for the flooding cases involving vehicle/large open spaces of ro-ro passenger ships. In this paper the authors discuss various elements of the regulations that need to be considered while comparing both frameworks.

Keywords: *RoPax ships, SOLAS2020, Stockholm Agreement, damage stability, survivability.*

1. BACKGROUND

The legislation considered in this study is based on Directive 2003/25/EC (applicable to ships on international voyages visiting European ports) and Directive 2009/45/EC which makes the Directive 2003/25/EC mandatory for all new ships of classes A, B and C on domestic voyages.

The Directive 2003/25/EC is based on some assumptions fundamentally different from other regulations concerning damage stability. The main assumption is that water may accumulate on the ro-ro deck in case of a damage. Hence, the Directive requires that the stability is assessed by assuming a certain amount of water on deck in the flooded condition. The water accumulated on deck is quantified based on the freeboard after damage and the limiting wave height applicable for the area of operation.

The criteria and requirements of the Directive 2003/25/EC were introduced at a time when the deterministic damage stability standard of SOLAS90 was in force. The probabilistic damage stability concept was introduced also for passenger ships by SOLAS2009. However, the Directive was kept applicable as it was not considered evident that the amended requirements of SOLAS2009 would ensure the same safety level as Stockholm Agreement[1]. When the newly adopted SOLAS2020 enters into force, the requirements will become stricter for new ships both in terms of the formulation of survivability when the roro space (and other open spaces) is involved in a damage case as well as in terms of the required subdivision index R.

2. OUTLINE OF THE REGULATORY FRAMEWORKS

Stockholm agreement

The Stockholm Agreement provisions require demonstration of survivability in a specific damage with

- 0.5 m water head accumulated on deck if the residual freeboard is less than 0.3 m and
- 0.0 m if the residual freeboard is 2.0 m or more

with linear interpolation in between.

[1] For brevity the Stockholm agreement is referred to as SA in the following

The height of water accumulated on deck can be adjusted depending on the significant wave height (with a 10% probability of exceedance) in the specific area of operation. For areas where the significant wave height is 4.0 m or above, the height of accumulated water is as in the residual freeboard formulations while it is assumed to be 0.0 m when the significant wave height is 1.5 m or less, with linear interpolation in between.

SOLAS

The damage stability framework of SOLAS[2] is mostly probabilistic with the deterministic provisions for minor and bottom damages. The overall objective of the framework is to ensure that the attained index of subdivision, A, is equal or larger than the required index, R, that is

$$A \geq R \tag{1}$$

The attained index is nothing else than the weighted average of expected probabilities of survival (given as the so-called s-factors), namely

$$A_j = \sum_i p_i s_i$$

and (2)

$$A = \sum_j w_j A_j$$

Where

- A_j Partial subdivision index at j[th] loading condition (with the additional requirement that $A_j \geq 0.9R$)
- w_j Weighting factor representing proportion of time the ship operates in one of the three loading conditions (light draught, partial subdivision draught and deepest subdivision draught)
- p_i Weighting factor representing probability of occurrence of the specific damage case
- s_i The survival factor (s-factor) representing expected probability of survival

However, the above relationships present only the high-level and clear-cut picture of the framework. The actual implementation is, for number of reasons, much more convoluted:

- The factor s for the final stage of flooding, s_{final} is modified by two multipliers - s_{mom} and k; the former is essentially a deterministic measure accounting for (the largest of) external heeling moments due to passenger crowding, launching of life-saving appliances and wind. The factor k is an arbitrary and deterministic linear model accounting for detrimental impact of heel on ability to evacuate the ship (with $k = 0$ for heel angles in damage equilibrium equal to or larger than 15 degrees).
- The factor s used in A-index calculations is taken as the smaller of two - s_{final} (including k and s_{mom}) and $s_{intermediate}$, both calculated by the very similar models (with the latter being less stringent)
- Additional, deterministic, requirements for the minor (in terms of length and transverse penetration) damages are specified by SOLAS Ch. II-1 Reg. 8.
- Bottom damages are regulated by semi-deterministic requirements specified by SOLAS Ch. II-1 Reg. 9.

3. MAIN ISSUES PERTAINING TO COMPARING SA WITH SOLAS

Comparison of any regulatory frameworks is always a challenging task, even if the frameworks stem from the same root. In case of SA and probabilistic regulations of SOLAS the undertaking is particularly difficult because the regulations are of fundamentally different origins and they differ even in the part promising the biggest overlap (i.e. minor damages provision of SOLAS Ch. II-1 Reg. 8). The main issues can be summarised as in the follows

- SA was intended as a purely deterministic addition to the existing set of deterministic regulations whereas SOLAS2009 is primarily a probabilistic instrument with some deterministic elements (such as k, s_{mom} or the content of Ch. II-1 Reg.8)
- SA is selectively targeting a specific damage scenario whereas SOLAS is comprehensive, accounting for the entire watertight subdivision

[2] For brevity the probabilistic framework for damage stability of SOLAS will be in the following referred to simply as SOLAS.

and all damage scenarios deriving from it. These features are a direct consequence of the regulations stemming from distinctive roots. As a result, it is easy to identify the SOLAS damages that correspond to SA and verify if they meet the SA requirements, but the opposite is not true. The SA damages are a mere (and small) subset of probabilistic damages and the compliance with SA says little more about the overall survivability other than that *all the less severe* damages should also result in survival in the wave height in question

- SA is prescriptive and sets specific requirements with respect to the combination of residual freeboard and the height of floodwater on the vehicle deck that defines the scenario in which the survival needs to be demonstrated. SOLAS is, in its main part, goal-oriented and does not consider any specific scenarios for as long as the weighted proportion of all surviving cases is larger than the required index. This implies that the SOLAS compliant ship may still fail the SA requirements.
- The SA requirements are wave-height scalable, i.e. the exact requirements can be changed depending on the prevailing wave conditions in the specific area of operation. SOLAS (for the reasons that will be discussed in the following) does not offer such possibility.
- SA compliance can be demonstrated either by calculations or by model tests. This is a unique feature of the SA. For obvious reasons, SOLAS allows proof of compliance by calculations only.

Nevertheless, considering a larger sample of vessels allows for drawing, with some confidence, conclusions about the high-level relationship between the standards. In the case of SA and SOLAS the following aspects need to be examined in order to measure how these standards relate:

- equivalence of the stability criteria by comparing the limiting sea states of the SA to the critical significant wave height, HS_{crit} (a concept implicitly present in SOLAS s-factor formulation);
- equivalence of safety levels provided by the regulations which can be achieved by comparing the attained indices of subdivision of SA-compliant ships to the required index of subdivision of SOLAS2020;
- how the operational wave-height limitations can be captured by the probabilistic framework

These will be discussed in detail in the following section.

4. COMPARISON OF SURVIVAL CRITERIA

The SA survival criteria are based on a combination of the residual freeboard and height of the floodwater accumulated on the ro-ro deck (if the freeboard is lower than 2 meters). SOLAS, on the other hand, uses the s-factor to estimate the expected probability of surviving specific damage *in waves*. The GZMAX and RANGE requirements in the s-factor formula are the measures of the ship resilience against capsize caused by the action of waves.

Customarily, the s-factor models are derived in a two-step process (Figure 1), see for example (Bird & Browne, 1973), (Project HARDER, 2000-2003). The first step involves determining the relationship between ship parameters and the critical significant wave height, HS_{crit} (the limiting sea state below which the ship can be considered safe). The critical significant wave height is damage-case and loading-condition specific. Furthermore, because the HS_{crit} is expressed as a function of ship parameters it can be considered as an attribute of the ship rather than the environment (i.e. HS_{crit} measures ability of the ship to survive a specific damage in waves).

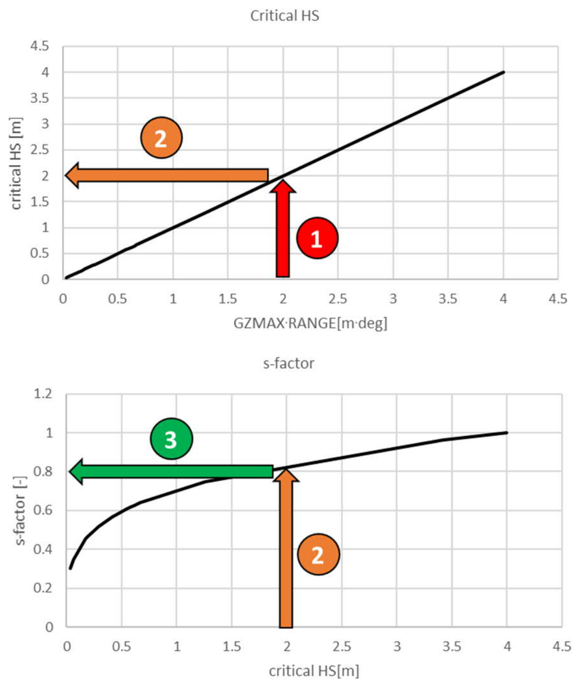

Figure 1: Two-step algorithm for calculating the s-factor. Top graph – estimating the critical HS based on the GZ curve characteristics. Bottom graph – use of the critical HS to determine the s-factor

The implicit, two-step, modelling behind the s-factor allows to isolate the HS_{crit} from the formula and use it as a yard stick against SA (noting however, that both instruments are arbitrary).

The following formula describes the relationship between the s-factor and the critical HS (Jasionowski, 2009):

$$s = \left(\frac{HS_{crit}}{4.0}\right)^{0.25} \qquad (3)$$

Thus, the critical HS is given as

$$HS_{crit} = 4.0 \cdot \frac{GZMAX}{TGZMAX} \cdot \frac{RANGE}{TRANGE} \qquad (4)$$

Where

RANGE – is the range of positive stability (up to the flooding angle) of the damaged ship

GZMAX – is maximum righting lever within the RANGE

TGZMAX and TRANGE – are *target* values for the maximum righting lever and range, respectively

Presently in SOLAS2009 the target values are given as 0.12 m for TGZMAX and 16 degrees for TRANGE. However, in a bid to mitigate the risk of capsize due to accumulation of floodwater on the vehicle, the latest amendments to SOLAS2020 bring higher requirements for the damages involving the ro-ro spaces. These new requirements are 0.2m and 20 degrees, respectively. Thus, bearing in mind that it is the concern about the vulnerability to the ro-ro-deck flooding that is addressed by Directive 2003/25/EC it is reasonable to use the following model to calculate the critical HS for relevant damages

$$HS_{crit} = 4.0 \cdot \frac{GZMAX}{0.2} \cdot \frac{RANGE}{20} \qquad (5)$$

When it comes to comparing critical HS to the limiting sea states the fact that SA compliance can be demonstrated by model tests is of great assistance. This is because the results of physical tests are generally representative and hence not affected by the arbitrariness of simple formulae. A significant number of SA model tests is reported in (Vassalos & Papanikolaou, 2002) and these results were used as basis for comparing the critical HS against the SA. The results, presented in Figure 2, show clearly that the values calculated with the SOLAS2020 target values demonstrated much higher correlation with the SA limiting wave height than the results calculated with the SOLAS2009 values. Specifically, nearly all the results based on SOLAS2009 are more lenient than SA whereas the SOLAS2020-based predictions show much better agreement with SA (although with quite significant scatter). These results indicate that the more stringent requirements of SOLAS2020 have similar effect on survivability to the requirements of SA (in terms of trends – the scatter is a consequence of the systematic uncertainty, irreducible with the present, lacking robustness, formula for the critical *HS*). Based on this it can be concluded that the new SOLAS requirements for the righting lever and range constitute survival criteria comparable to SA.

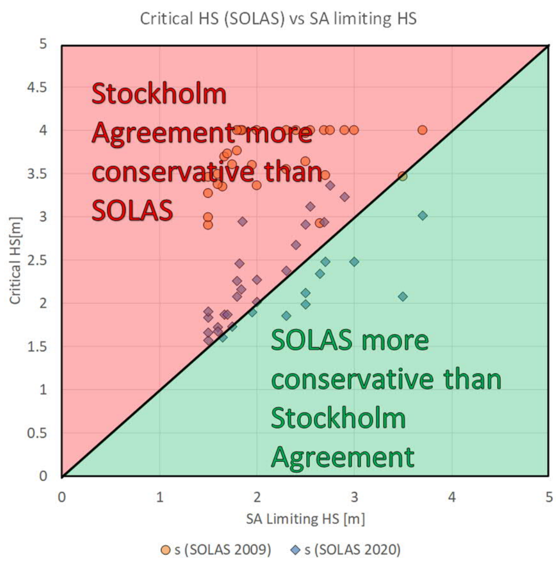

Figure 2: Comparison of the critical HS calculated with SOLAS2020 target values for GZMAX and RANGE with the experimentally derived SA limiting HS as reported in (Vassalos & Papanikolaou, 2002)

It is also noteworthy, that the present requirements are consistent with the earlier proposal made following the second EMSA study, which claimed that increase of the GZMAX and RANGE requirements to 0.25 meter and 25 degrees, respectively would make the s-factor a conservative measure with 90% confidence, see Figure 3 below.

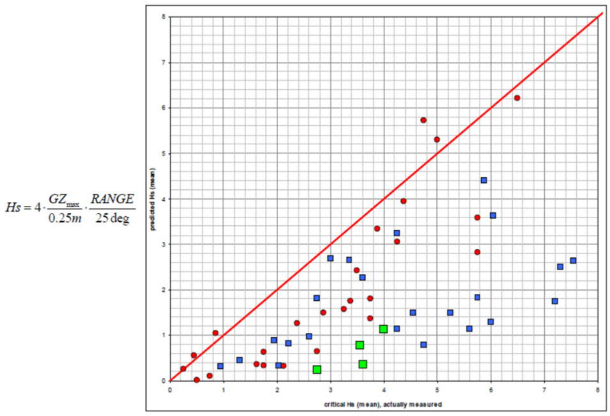

Figure 3 Comparison between critical wave height based on s-factor proposed within EMSA2 and measured during the model experiments for a sample of conventional RoRo/RoPax ships (Jasionowski, 2009).

5. COMPARISON OF SAFETY LEVELS

For a ship of passenger capacity in excess of 400 persons on board[3](POB) SA may be considered as a "2+ compartment equivalent standard[4]". This is a consequence of the additional freeboard/water-on-deck requirements imposed on the worst 2-compartment SOLAS90 damage. Obviously, for the reasons discussed in the foregoing it is impossible to establish the one-to-one correspondence between the standards. Furthermore, the actual designs are often optimised for the specific set of rules they need to comply with, hence their performance measured against another set of rules may be suboptimal. Nevertheless, it can be argued that high-enough safety standards (goal) in terms of R would eliminate most of the "blind spots" and local vulnerabilities from the design leading inadvertently to consistent and uniform safety levels.

Generally, in comparison to SOLAS2009, SOLAS2020 represents significant increase in standard, delivered primarily by the change in required index of subdivision R. In fact, the analysis carried out in the study (European Commission, 2019)[5] demonstrates that most of the sample ships carrying more than 1350 POB (in compliance with SA and SOLAS 2009 or SOLAS90) would fail to meet the requirements of the new regulations (SOLAS2020) even if the optimised GM was used in A-index calculations. This implies that the "2+ compartment equivalent standard" as delivered by SA is not high enough to meet the required index of subdivision.

The situation is, however, different in case of smaller capacity ships (carrying less than 1350 POB), where the tendency is that the majority of sample ships are able to achieve compliance with the new regulations (European Commission, 2019).

This is a notable fact for two reasons: firstly, previous research, e.g. (Project GOALDS, 2009-2012), indicates that present SOLAS s-factor model tends to overestimate survivability of smaller (in terms of dimensions) ships. The SOLAS 2020 amendments to the s-factor model result in a shift in the survivability prediction but the model remains less stringent for the small ships. Secondly (and more importantly), the level of *R* as adopted for SOLAS2020 is a political compromise which saw the level or *R* as recommended by EMSA 3 study (so-called EMSA 3.2 proposal reflecting the study involving calculations of costs of averting fatality, CAF) was reduced by IMO twice.

The first compromise was made by SDC3 whilst the second, final change was done by MSC98; in both cases the changes affected mostly the ships of smaller passenger capacity (below 1,000 POB).

Table 1: Level of *R* formulations

	POB	R
EMSA 3.2	All	R=1-(C1 x 6200)/(4 x N+20,000) with C1=0.8-(0.25/10,000) x (10,000-N)
SDC3	$N \leq 1{,}000$	R=0.000088 x N+0.7488
	$1{,}000 < N \leq 6{,}000$	R=0.0369 x ln(N+89.048)+0.579
	$N > 6{,}000$	R=1-(C1 x 6200)/(4 x N+20,000) with $C1 = 0.8 - 0.25(10{,}000 - N)/10{,}000$
SOLAS 2020	$N < 400$	$R = 0.722$
	$400 \leq N \leq 1{,}350$	$R = \frac{N}{7{,}580} + 0.66923$
	$1{,}350 < N \leq 6{,}000$	$R = 0.0369\, ln(N + 89.048) + 0.579$
	$N > 6{,}000$	$R = 1 - \frac{852.5 + 0.03875N}{N + 5000}$

[3] For brevity the number of persons on board is referred to as POB in the following

[4] For the ships of capacity smaller than 400 POB SA can be considered a single compartment standard

[5] https://ec.europa.eu/transport/modes/maritime/studies/maritime_da

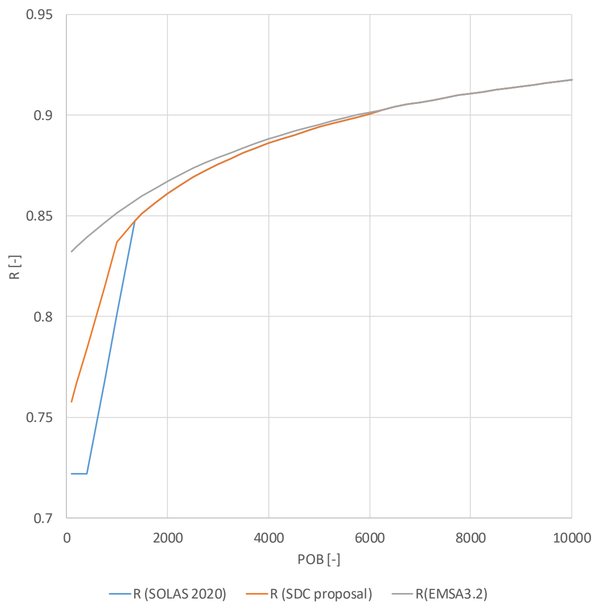

Figure 4: Alternatives for level of R

The observations made during the project can be summarised as follows (European Commission, 2019):

- The ships of capacity in excess of 1350 POB designed to comply with SA (and in conjunction with SOLAS90 or SOLAS2009) are likely to fail to meet the SOLAS2020 required index of subdivision even **with** the optimised GM (→ indication that SOLAS2020 provides **equal or higher** safety level to SA for this group of ships)
- The ships of capacity smaller than 1350 POB and in compliance with SA (and in conjunction with SOLAS90 or SOLAS2009) may comply with the SOLAS2020 required index of subdivision **without** the need to reduce the original GM margins (→ indication that SA provides **higher** safety level for the **significant proportion** of ships in this group)
- The SOLAS2020 increase of s-factor requirements led to a significant number of sample ships failing the compliance with the deterministic provision for minor damages (SOLAS Ch. II-1 Reg.8)

6. OPERATIONAL WAVE-HEIGHT LIMITATIONS

One of the important features of SA is that it allows for scaling the requirements according to the typical sea conditions in the area of operation (represented as significant wave height with 10% probability of exceedance). Since there is no similar instrument in SOLAS, the study considered including the critical wave-height limitations within the probabilistic framework by means of either

- the normalised s-factor, where both the HS_{crit} and the s-factor formulae are modified to accommodate for the operational wave heights less than 4 meters HS;
- the expected critical sea-state, the critical wave heights for all damages are averaged (with w and p being the weighting factors, just like the case of A-index) to calculate the expected value of HS_{crit}.

Normalised s-factor

The s-factor formulation estimates the average (expected) probability of surviving specific damage with the averaging carried out with respect to sea state the ship is likely to encounter during the collision incident. The normalisation accounts for the fact that the ship may be limited to operate in the areas where the normal wave heights are considerably lower than the 4 meters HS assumed by SOLAS.

By analogy with the target values for GZMAX and RANGE the denominator in the s-factor formulation as given by (3) can be interpreted as the target sea state (e.g. THS). Hence, the base in (3) is the ratio of critical HS to the target HS. In the s-factor formulation the target sea state is taken as 4.0 meters HS because virtually all collision incidents occurred in sea states below 4.0 meters HS. Thus, the normalisation of the s-factor can be achieved by replacing the target sea state of 4.0 meters HS with the corresponding limiting HS. This allows for expressing the normalised s-factor as follows:

$$s_{norm} = \left(\frac{\min(HS_{crit}, HS_{limit})}{HS_{limit}}\right)^{0.25} \qquad (6)$$

The s-factor normalisation accommodates for the fact that the ship will not operate in sea states exceeding the S_{limit} , as Figure 5 illustrates.

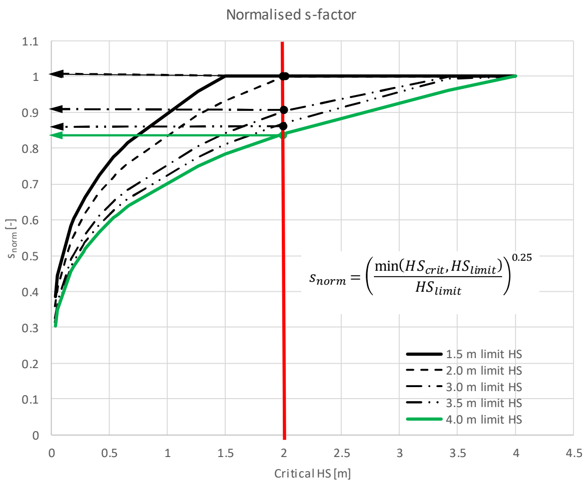

Figure 5: Effect of s-factor normalisation. The red line marks the critical HS corresponding to given damage. Should the ship be limited to operate in sea states not exceeding the 2 metres HS, the normalised s-factor formula would yield 1, while the probability of surviving the damage calculated by SOLAS s-factor would be about 0.84.

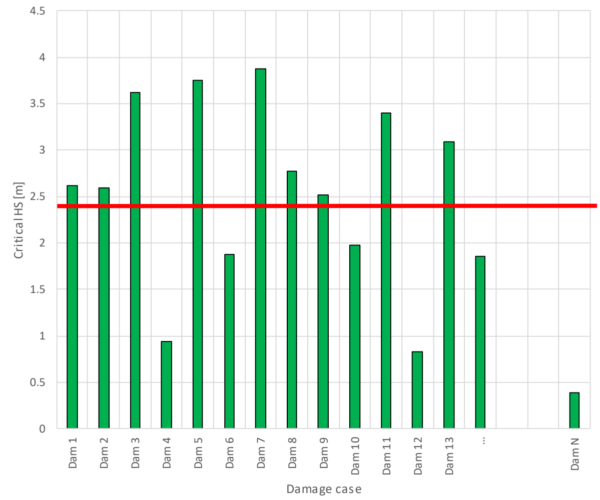

Figure 6: The calculation of expected $\boldsymbol{HS_{crit}}$ (the red line) involves calculating critical HS for individual damage cases and averaging it with respect to p and w-factors.

The attained index of subdivision with the wave-height operational limits could be calculated as in the SOLAS with the only difference that the normalised s-factor would be used in place of the regular s-factor.

$$A = \sum_j w_j \sum_i p_i s_{norm_i} \tag{7}$$

Expected critical wave height

An alternative way to account for the operational wave-height limitations is to calcluate the expected critical HS by averaging the HS_{crit} characterising invidual damage cases (as given by (4)) with respect to probability of damage occurence (p) and operation in specific loading condition (w) (i.e., by replicting the process the s-factors are averaged to calculate the A-index).

$$\overline{HS_{crit}} = \sum_j w_j \sum_i p_i HS_{crit_i} \tag{8}$$

This process is illustrated by Figure 6.

The criterion for compliance with the wave-height operational limits could read simply as shown next:

$$\overline{HS_{crit}} \geq HS_{limit} \tag{9}$$

Notes on incorporating wave height limitations to the probabilistic framework

Both methods are equivalent in that they utilise the core concepts of survivability assessment present within the probabilistic framework. Furthermore, both can be calculated alongside the typical A-index calculations.

However, the application of both methods to the sample ships demonstrated that - generally - they do not have a significant effect when accounting for operational wave heights. In particular, the use of normalised s-factors has a negligible impact on the attained index of subdivision. This is also caused by the aforementioned factors k and $s_{mom.}$. This is an important observation because the normalisation of the s-factor is an analogy to introducing the distribution of wave heights (for averaging the probability of surviving specific damage) less stringent that the one behind the regular SOLAS s-factor (i.e. distribution of sea-states recorded during the collision accidents). However, since the "SOLAS distribution" is already more biased towards the lower wave heights than most of the wave scatter data for geographical locations, it is perfectly justifiable to question the rationale for lowering it even further.

The second technique is free of such controversy as $\overline{HS_{crit}}$ is a parameter derived directly from the characteristics of the damaged ship, without any form of modification. The underlying concept is also well linked to the s-factor methodology; hence it is not an entirely foreign inclusion to the framework.

However, it should be noted that by definition[6] the probability of survival (i.e. "s-factor") calculated based on $\overline{HS_{crit}}$, would be equal to or higher than the A-index. That is, since the attained index of subdivision is as an "average s-factor" (i.e. $A = \overline{s(HS_{crit})}$ the following relationship holds[7]

$$s(\overline{HS_{crit}}) \geq A \tag{10}$$

Finally, the proposal for use of the $\overline{HS_{crit}}$ might require establishing additional compliance criteria supplementing the A ≥ R criterion.

7. CONCLUSIONS

The study as presented in (European Commission, 2019) includes technical evaluation of the safety levels provided by SA and SOLAS by sample ship investigations and impact assessment studies. Some conclusions can be highlighted:

Survival factor

- The new requierements for the target values for residual maximum GZ and range of positive stability for the damages involving ro-ro cargo spaces have an effect on survivability (as measured by Hscrit) similar to the freeboard and water on deck requirements of SA
- The impact of new s-factor on the attained index of subdivision is in general relatively small, resulting in decrease of the A-index not exceding a few percentage points

Required index of subdivision

- SOLAS2020 level of R will provide safety standard at least equal to the requirements of Directives 2009/45/EC and 2003/25/EC stability frameworks for ships of capacity exceeding 1,350 POB.
- For ships having a capacity less than 1,350 POB, SOLAS2020 may not ensure the same safety standard as the requirements of Directives 2009/45/EC and 2003/25/EC. In this case it may be necessary to implement the level of R matching the SDC3 proposal or to retain the SA requirements.

Operational wave-height limitations

- The sample ship calculations did not show that wave-height limitations accounted for by either the normalised s-factor or expected critical wave height had significant impact on the overall survivability as expressed by the attained index A. Based on this there is little merit in introducing separate requirements with respect to the operational wave-height limitations for damage stability in a probabilistic concept.

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DISCLAIMER

Even though the study was funded by the European Commission it is to be duly noted that the information and views set out in this paper are those of the authors and not necessarily reflect the official opinion of the Commission. The Commission does not guarantee the accuracy of the data included in this study. Neither the Commission nor any person acting on the Commissions' behalf may be held responsible for the use which may be made of the information contained therein.

The views as reported in this paper are those of the authors and do not necessarily reflect the views of the respective members of the consortium.

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[6] According to so-called Jensen's inequality

[7] The relationship reflects the so-called Jensen's inequality and it states simply that the average s-factor (i.e. A-index) is equal to or smaller than the s-factor calculated with the average HS_{crit}

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