Survivability of Passenger Vessels – Re-engineering of the S-Factor

Jakub Cichowicz, Nikolaos Tsakalakis, Dracos Vassalos and Andrzej Jasionowski

The Ship Stability Research Centre (SSRC), University of Strathclyde, Glasgow, UK

ABSTRACT

This paper presents a brief summary of the work carried out by the SSRC, within the EC-funded project GOALDS, on the development of a new formulation for the assessment of the survivability of a damaged ship in waves. The proposed formula is meant to be an alternative or replacement to the s-factor in use within the current SOLAS regulations for probabilistic damage stability. The authors discuss briefly concerns related to the current survivability model and present the process of development that led to the re-engineered formulation.

KEYWORDS
Damage stability, probabilistic framework, survivability, new s-factor

INTRODUCTION

The current measure of survivability of a damaged ship in a seaway has been shown to be inaccurate and inadequate practically from the moment of its introduction within the probabilistic framework of damage stability, known commonly as SOLAS 2009. Initially it was suggested that the formula penalises large cruise vessels whereas survivability of RoPax ships may be seriously overestimated. However, in the course of recent research activities it has been shown that the problem is much more complex and it is generally a consequence of ill-founded simplifications made at the time of s-factor development. It should be noted here that, given the complexity of capsize phenomena, the simplifications can be partially explained by insufficient diversity of the dataset used in the process, which resulted in inability of the formula to cater for subdivision configurations deviating from, in force at the time, SOLAS 90. This, combined with some basic notional inconsistencies related to the definition of survivability led to a situation that not only the s-factor does not guarantee an accurate prediction of survivability but also does not account for certain built-in stability-enhancing features above the deck and practically prohibits harmonisation of the stability framework with relevant goal-based regulations like the Safe Return to Port (SRtP). Furthermore, the current formulation has been often criticised in that it lacks any reference to certain key attributes of a damaged ship, such as residual freeboard, accumulation of floodwater on deck etc.

As a result, the s-factor formulation has been perceived as a flawed and inaccurate instrument that complicates the design process, misinforms the designer and compromises safety. In fact, as already pointed out, the truth has proved to be much more complex in the sense that flaws within the s-factor may not be of particular importance in calculating A-Index with contemporary designs (this in fact was part of the reason why the current s-factor formulation was adopted in SOLAS 2009), however it should be taken into account that firstly, the s-factor is a measure of damage survivability in waves and as such it plays a crucial role in decision making in emergencies. Secondly, it reflects limitations of the parameters used to predict survivability of designs deviating from the HARDER dataset, Finally, inherent imprecision of the s-factor would prohibit cost-effective designs.

BACKGROUND CONCEPTS

Modes of ship loss

In the most general case there are three distinct modes of ship loss following collision (or grounding), breech and water ingress, namely: capsize, sinking and transient capsize. The first two are to be understood as a gradual process of diminishing residual stability or residual buoyancy as a direct result of the flooding process. The mechanism of capsize or sinking is a stochastic (but not ergodic) process resulting in quasi-static loss. The third mode is a dynamic process that can be seen as a (step) response of an intact ship to the heeling moment caused by rapid floodwater ingress. Furthermore, considering that in a transient mode the potential “memory effects” should diminish within a relatively short time (a matter of seconds) for all cases reaching equilibrium post-damage, it would seem an unnecessary complication to account for the effect of waves. In the following, the term capsize shall be used to denote any kind of ship loss unless a specific mode is being discussed.

Capsize Band

Capsize band is a concept describing the transition of sea-states from those at which no capsize is observed (lower boundary) to those at which the probability of capsize equals unity (upper boundary). In simpler terms, it is a band outside which capsize is either unlikely to happen or certain (Jasionowski et al., 1999). In the light of the considerations presented in the previous section, the term “capsize” can be generalised to cater for both capsize and sinking. For a finite observation time, the probability of capsize can be approximated with a sigmoid function (Tsakalakis et al, 2010) of the form:

$$p_f = p_f\left(H_S\right) = \frac{e^{\frac{H_S - x_0}{\Delta x}}}{1 + e^{\frac{H_S - x_0}{\Delta x}}} \qquad (1)$$

Where: p_f is probability of capsize, H_S is the sea-state in question, x_0 and Δx are regression parameters – the abscissa of the sigmoid inflection point and bandwidth parameter, respectively.

Alternatively to the Bolzman’s representation, earlier publications (Jasionowski et al, 2007) used normal (Gaussian) representation, where the probability is approximated by an integral curve of the normal distribution, where x_0 would become modal value, μ, of the dp_f/dH_S distribution and Δx would be replaced by standard deviation, σ.

Significantly, it can be observed that as the time of observation increases the capsize band contracts towards its lower boundary, becoming a unit step function as time approaches infinity (see figure 1). This property is of major importance and, as it is going to be shown in the following, it had become one of the key findings made during the re-engineering of the s-factor.

It is worth noting that the concept of the critical sea state, Hs_{CRIT}, as used for the s-factor in force, is associated with the sea state at which the probability of capsize (p_f) is equal to 0.5, based on half hour tests.

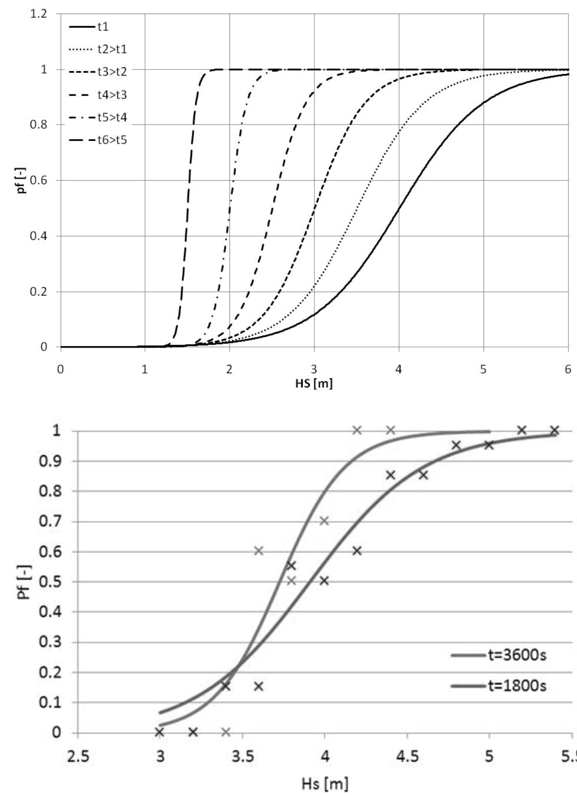
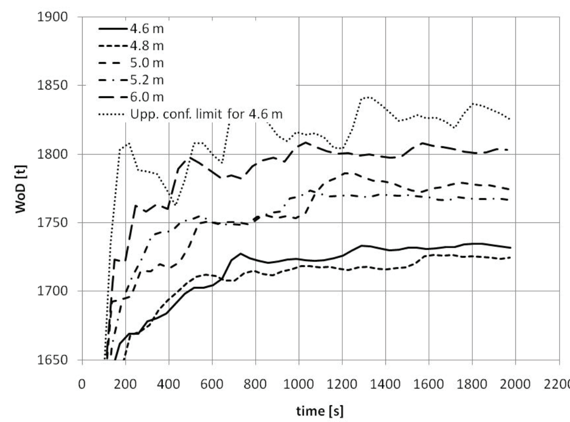


Fig.1: Assumed (top) and observed (bottom) behavior of capsize band as function of the observation time.

Water on deck

The Water-on-Deck (WoD) is a “nickname” commonly used for accumulation of floodwater on the vehicle deck of a RoPax vessel. Its importance derives from observed correlation of the amount of accumulated water on deck and survivability of the vessel. In fact, it has also been argued (internal report on project Genesis) that similar behavior can be found for cruise vessels when the floodwater enters the service corridor, located above the bulkhead deck. The major difficulty while attempting to address the WoD problem is the stochastic and non-ergodic character of the flooding process, which generally makes the analysis very complex and time consuming. The necessity of analysing very long time histories in many cases casts proper analysis impossible even for numerical data (experimental data introduce additional difficulties related to the accuracy of the measurements). It is in this context where the capsize band properties can be used to reformulate or rather address this problem appropriately. This can be done if the analysis of WoD accumulation is based not on the cases within the capsize band but just outside its lower boundary, towards which the band contracts. Such approach has certain advantages – firstly, long but finite observation time around the lower boundary practically guarantees infinite survival time (the lower boundary can be assumed time invariant, as previously shown) and secondly, analysis of surviving cases allows relaxing the limitation with respect to ergodicity of the process – i.e. flooding, similar to ship response can be assumed (for engineering purposes) ergodic. This allowed formulating a procedure for analyzing WoD (or floodwater accumulation in the general case) based on an averaged 95th percentile calculated within the cumulative time (i.e. within one wave period or its harmonics). Although the technique adopted, i.e. time domain simulations and analysis based on a relatively small number of realizations, is questionable, particularly the inclusion of the transient phase of the time history (non-stationary), it should be noted here that the main purpose is to visualize and qualitatively compare flooding processes without any attempt to withdraw any quantitative conclusions like critical amount of floodwater etc. Indeed the analysis, in spite of certain mathematical shortcomings, conveyed very important information. Firstly, it has been noticed that the 95th percentile in all the surviving cases reached an asymptote whilst lack of it indicated progressive flooding that would eventually result in a loss. Secondly, although the limiting amount of floodwater would vary with H_s, such variability proved to be statistically insignificant.



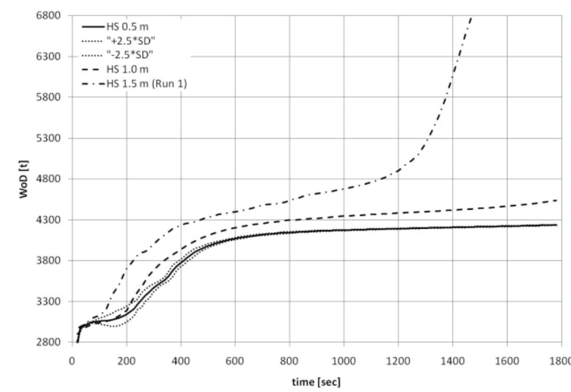


Fig. 2: Examples of accumulation of floodwater (total) for small RoPax (top) and cruise vessel (bottom). In the latter case lack of asymptote indicates progressive flooding – in fact, as longer time simulations proved, this particular damage case resulted in loss even in calm water.

Furthermore, in most of the cases, should the floodwater characteristic of any particular realization exceeded (by some statistically significant amount) the upper confidence limit, this would be a clear indication of subsequent loss.

The final outcome of the WoD analysis is that the flooding process of the surviving cases can be characterized by a statistically unique (for any given damage) limit independent of sea-state and time of observation. It is important to note that the limiting amount of floodwater coincides with the quantity obtained for the highest sea-state at which no losses were observed – lower boundary of the capsize band. Furthermore, as the analysis indicates, increasing the sea-state further does not have an impact on the limiting value but increases the probability of exceeding it. This probability is time dependent – in the extreme case of infinite time observation all realisations in lower sea-states would never exceed the limit whereas it can be expected that in higher sea states the probability of exceeding the limit would approach unity. This is in essence an equivalent of the unit-step representation of the capsize band. Finally, the analysis has proved that in spite of differences in the underlying physics, both modes of gradual loss (i.e. capsize and sinking) can be successfully approached with the same model.

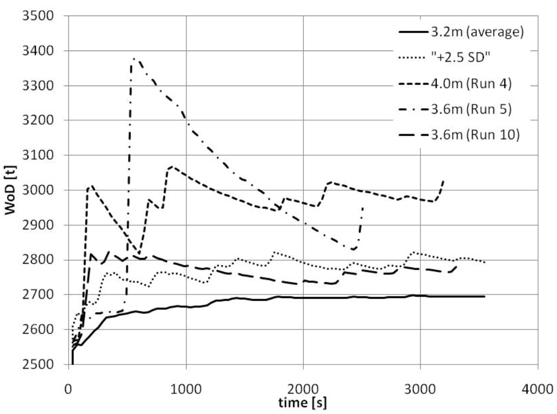


Fig.3: Capsizing realisations plotted against averaged floodwater accumulation characteristics for surviving cases (PRR01).

S-FACTOR DEVELOPMENT

Physical and numerical survivability tests

In order to provide a diversified sample of ships, a large number of physical tests and numerical simulations has been performed. Although all the ships were subdivided according to SOLAS '90 special attention was paid to diversification of the sample – ships vary in size and subdivisions include stability enhancing features above the traditional bulkhead deck (e.g. side-casings) and large unsubdivided cargo spaces below the deck (Long Lower Hold). Additionally the sample has been supplemented by HARDER, FloodSTAND and EMSA project ships. In total the dataset consists of over twenty various designs (RoPax) and three cruise vessels.

Probability of surviving collision damage

The s-factor development started with studies on identifying dominant parameters, performed in order to ensure whether the current formulation accounts for all the key influencing factors. This has been followed by the process of deriving an improved formulation. In the following there is a brief summary of this process including the milestones of the development but it is thought that some introduction on the nature of the s-factor and on the adopted approach might be found useful for better clarity of further considerations.

Although it is not explicitly stated in SOLAS, the s-factor is a measure of the probability of survival of a damaged ship in waves, namely:

$$s = \int_0^\infty dH_S \cdot f_{H_S|coll}\left(H_S\right) \cdot F_{surv}\left(H_S\right) \qquad (2)$$

Where: $f_{H_S|coll}\left(H_S\right)$ is the probability density distribution of sea states expected to be encountered during collision and $F_{surv}\left(H_S\right)$ is the probability of survival in that sea state when exposed to a specific flooding case.

It should be noted here that, given that all the tests performed during the s-factor development were limited to 30 minutes, the probability of survival is in fact a conditional probability:

$$F_{surv}\left(H_S\right) \equiv F_{surv}\left(t = 30\min\middle|H_S\right) \qquad (3)$$

Therefore it yields:

$$s(t = 30\text{ min}) = \\ = \int_0^\infty dH_S \cdot f_{H_S|coll}\left(H_S\right) \cdot F_{surv}\left(t = 30\text{ min}\middle|H_S\right) \qquad (4)$$

Furthermore, as mentioned earlier, it had been assumed that the probability of survival, $F_{surv}(H_S)$ can be approximated by a unit step function centered on the sea state. That is, the Hs_{crit} constitutes the 50th percentile of the significant wave height the vessel, subjected to a particular damage scenario, can survive for 30 minutes (this corresponds to the abscissa of the inflection point of the sigmoid obtained for t=30min):

$$F_{surv}(H_S)=\begin{cases}1 \Leftrightarrow H_S \le H_{S\,crit} \\ 0 \Leftrightarrow H_S > H_{S\,crit}\end{cases} \quad (5)$$

It should be noted that although replacing the p_f distribution with the step function is in this particular case supported with little evidence, it does the "trick" and allows avoiding integration with little impact on accuracy of the prediction for as long as the bandwidth of the capsize band is narrow. Eventually, the final formulation becomes:

$$s = \int_0^{H_{S\,crit}} dH_S \cdot f_{H_S|coll}(H_S) = \\ = \exp\left(-\exp\left(0.16 - 1.2 \cdot H_{S\,crit}\right)\right) \quad (6)$$

Where the $H_{S\,crit}$ is given as:

$$H_{S\,crit}\Big|_{t=30\min} = \\ = 4\left(\frac{\min(GZ_{\max},\ 0.12)}{0.12}\frac{\min(Range,\ 16)}{16}\right) = \\ = 4 \cdot s(t = 30\min)^4 \quad (7)$$

In essence, the approach adopted within the GOALDS Project is similar to that of the HARDER project with the main difference stemming from the assumption of Hs_{crit} corresponding to the lower limit of the capsize band, thus allowing for a justified assumption of very long ("infinite") time of survival. In this respect, the main problem deriving from the need of accurately predicting the critical significant wave height is considered to be a major flaw of the SOLAS 2009 s-factor formulation (although not readily obvious in the regulation).

Study on dominant parameters

The limited sample size available within the GOALDS project prohibited extensive use of advanced techniques like Design of Experiments (DoE) for sensitivity analysis. For this reason, the study was mainly based on reasoning, experience and expertise and supported where possible by quantitative assessment. At the first stage, the SOLAS formulation was investigated from the point of view of choice of parameters in order to conclude whether the GZ_{MAX} and Range are sufficient to predict accurately the critical significant sea-state.

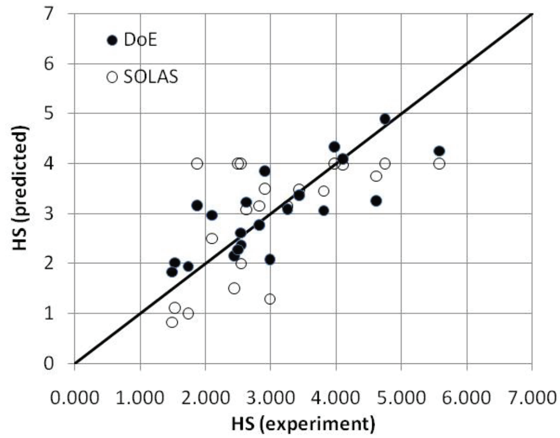


Fig.4: Comparison of SOLAS prediction against DoE regression. Please note that SOLAS is meant to predict median sea state and therefore it should generally "over predict" the experimental Hs corresponding to the lower limit of the capsize band.

As a result it has been shown that even the relatively complex expression derived from the DoE failed to significantly improve the accuracy of the prediction. Nonetheless, the correlation coefficient increased from the initial value of 0.64 to 0.79.

Effect of scale

In the analysis of results pertaining to small and large vessels (sample ships in Project GOALDS), it was made apparent that there is a significant effect deriving from scale. Indeed, one of the major concerns related to SOLAS 2009 formulation for the s-factor was that it does not, by any means, account for the ship's size and that it might be inaccurate when applied to vessels deviating significantly from the size of the vessel (PRR01) used as a basis for its derivation. In addition, the fact that the SOLAS 2009 s-factor formulation (residual GZ curve characteristics) is limited to relatively small range and maximum GZ values fails to account for the contribution of watertight volume distributed high enough not to be "seen" by the formulation, which in essence deviates from normal Naval Architecture practice, previously expressed through the explicit demand for and provision of residual freeboard.

Accounting for the above in the next step of the development, the initial parameter set was supplemented by a factor that can best be described as a measure of centroid of the residual volume, as follows:

$$z_V = \left(\frac{V_{CB\,T} - V_{CB\,D}}{T} \right)^2 \tag{8}$$

Where, $V_{CB\ T}$ and $V_{CB\ D}$, are vertical centres of buoyancy of the intact and damaged compartments, respectively and T stands for draught in intact condition. Based on this, the experimental data were approximated by the following regression formulae:

$$\begin{aligned} f_1(GZ_{\max}, z_V) &= 18.4(GZ_{\max} \cdot z_V)^{0.5} \\ f_2(Range, z_V) &= 1.5(Range \cdot z_V)^{0.9} \\ H_{S\,crit} &= \sqrt{f_1 \cdot f_2} \end{aligned} \tag{9}$$

As a result the formula offered very accurate prediction with 0.93 correlation with the experimental data. Furthermore, applying DoE, to the new parameter set led to a correlation coefficient of 0.97 (figure 5) – good indication that we were certainly on the right track. However, we were not fully satisfied yet, as explained next.

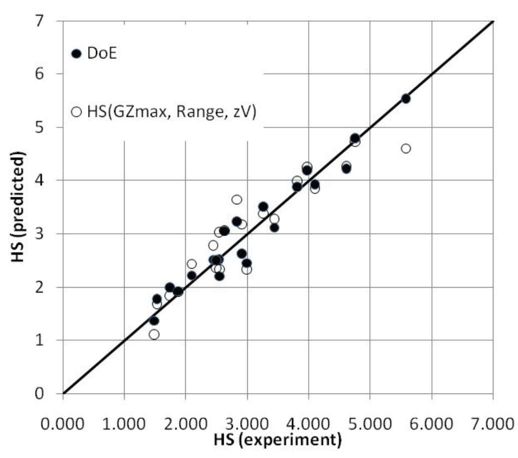


Fig.5: Comparison of the predicted and experimental H_{Scrit}.

The major concern of using a regression-based formulation is the particular dataset used for its derivation, implying uncertainty in using this for a completely different sample, say the innovative ships of the future. Nevertheless, the formula proved that GZ curve related parameters supplemented by the geometrical damage characteristics (residual volume in some form) are sufficient for predicting the survival sea-state. Moreover, during the analysis of the experimental and numerical data it has been found that one of the dominant parameters is GM_F (GM of the flooded ship),

Final formulation

Summarising the forgoing, all investigations led to the conclusion that the parameters to be included in the s-factor formulation should include as minimum GZ_{MAX}, Range, some measure of the residual volume (V_R) and GM_F. Moreover, the ensuing formulation must be generic, i.e., independent of a specific data set. In other words,

$$H_{S\,crit} = f\left(GZ\max, Range,\ \mathrm{GM}_f,\ V_R^{1/3}\right)$$

It was decided that it would be easier to use V_R directly (but scaled appropriately) rather than a measure of its centroid. On this basis, an analytical expression was sought using a combination of the above parameters. To this end, considering that the residual GZ curve for most ships is parabolic, the following relationships hold (with sufficient accuracy):

$$\begin{aligned} A_{GZ} &\approx \frac{1}{2} GZ_{\max} \cdot Range \\ GZ_{\max} &\approx \frac{1}{2} GM_f \cdot Range \Rightarrow \\ \frac{1}{2} Range &\approx \frac{GZ_{\max}}{GM_f} \end{aligned} \tag{10}$$

Considering the above it is important to note that describing, for example, the Range of the residual GZ curve by the ratio GZ_{MAX}/GM_F allows conveying additional information about the actual shape of the curve (in fact it has been found that it is not only the absolute measure of the residual stability, e.g. area under *GZ*, GZ_{MAX} or *Range*, but also its distribution that differentiates between surviving and non-surviving cases). On this basis the following expression was tested as a first step, deriving from simple dimensional analysis:

$$\left(\frac{H_{S\,crit}}{V_R^{1/3}}\right)=\left(\frac{GZ_{\max}}{GM_f}\right)\rightarrow H_{S\,crit}=\frac{GZ_{\max}}{GM_f}V_R^{1/3} \quad (11)$$

As this expression produced slightly conservative results, additional parameters were introduced through various algebraic manipulations and were tested against the experimental results. These steps involved expressions like 12 and finally, introducing range and A_{GZ}, respectively, led to formulation 13, with significantly improved accuracy.

$$H_{S\,crit}=\frac{\frac{1}{2}GZ_{\max}\cdot Range}{\frac{1}{2}GM_f\cdot Range}V_R^{1/3} \quad (12)$$

$$H_{S\,crit}=\frac{A_{GZ}}{\frac{1}{2}GM_f\cdot Range}V_R^{1/3} \quad (13)$$

Deriving from the above, the survival factor, s, is given by the following expression:

$$\begin{aligned}&\forall\left(A_{GZ},V_R,Range>0\right)s=\\&=\exp\left(-\exp\left(0.16-1.2H_{S\,crit}\right)\right)\end{aligned} \quad (14)$$

VALIDATION AND ADDITIONAL CONSIDERATIONS

Accounting for the Presence of Oenings

In case of present unprotected openings (e.g. semi-watertight doors, down-flooding points etc.) within the Range of the GZ curve, the critical significant wave height should be derived from the following expression:

$$H_{S\,crit}=\frac{A_{GZ\,E}}{\frac{1}{2}GM\cdot Range}V_R^{1/3} \quad (15)$$

Where $A_{GZ\ E}$ is an effective area under the GZ curve taken up to the heel angle corresponding to the submersion of the opening in question.

Transient Capsize

As already mentioned, the evidence collected during the initial stages of the development suggested clearly that both modes of the gradual loss, i.e. capsize and sinking can be handled with the use of the same formulation but in case of a rapid capsize resulting from sudden floodwater ingress, a different formulation is warranted (Vassalos et al, 2004). In this respect, it is proposed to assess vulnerability to transient capsize with the use of the following, based on well known energy balance, expression:

$$k_i=\begin{cases}1, & if\ \varphi_i<\dfrac{E_\varphi D}{m_{fi}y_{fi}}\\ 0, & otherwise\end{cases} \quad (16)$$

Where, $E\varphi$ is a dynamic righting lever (integral of the residual GZ curve) up to the heel angle of submersion of the unprotected opening, D is displacement of intact ship, and m_{fi} and y_{fi} are mass and transverse centre of mass of floodwater respectively. The vulnerability check should be performed for all the flooding stages and the final k is simply a product of k_i. This results in the following expression:

$$s=\begin{cases}e^{\left(-e^{\left(0.16-1.2H_{S\,crit}\right)}\right)}, & \forall\left(A_{GZ},V_R,Range,k>0\right)\\ 0, & otherwise\end{cases} \quad (17)$$

The binary nature of k is dictated mainly by the need to highlight those damage cases that require special attention and unless a detailed investigation is performed they should not contribute to the A-Index summation.

Time to Capsize

In sea-states exceeding the critical significant wave height, the probability of survival and time to capsize decrease, the first following a sigmoid pattern (Jasionowski, 1999; Tsakalakis et al., 2010) the latter according to a hyperbolic manner as graphically explained in the figure 6 (Jasionowski, 1999).

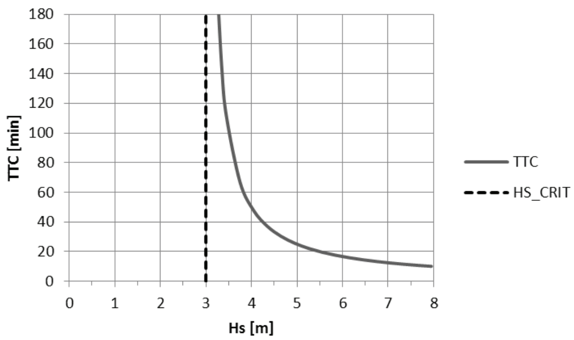


Fig.6: The concept of time to capsize

The hyperbolic behaviour of the TTC can be captured by the following formulae.

$$TTC = \frac{a}{\left(Hs - Hs_{Crit}\right)}[\text{min}] \tag{18}$$

$$a = 3 \cdot Hs_{CRIT}^{\ 1.4} \tag{19}$$

Following a systematic investigation of the acquired data, the observation was made that parameter "a" appearing in formulation 18 can also be linked with Hs_{CRIT} as shown in figure 7, where curves for various ships and damages have been plotted together. Each point in the fig. 7 corresponds to the average TTC of at least 10 realisations of each sea-state. Figure 8 depicts this relation for various experimental data, derived by means of numerical simulations. The continuous line is the regression model which can be found in formula 19.

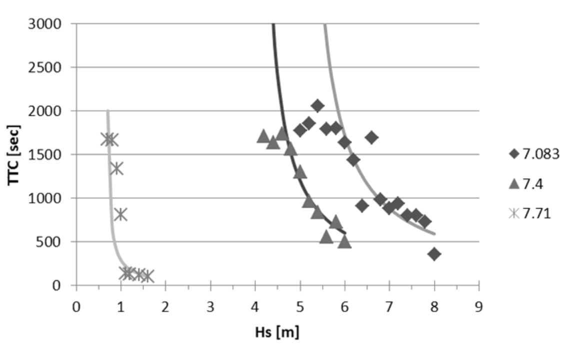


Fig. 7: Various TTC curves for 3 different KG values for a specific damage scenario

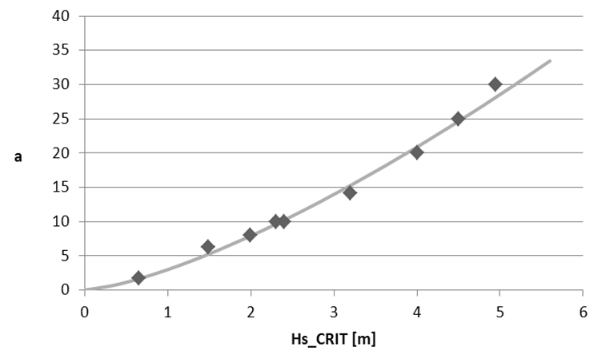


Fig.8: Parameter "a" vs. Hs_{CRIT}

The figure 9 below shows the impact of observation time on the behaviour of the model (one damage case).

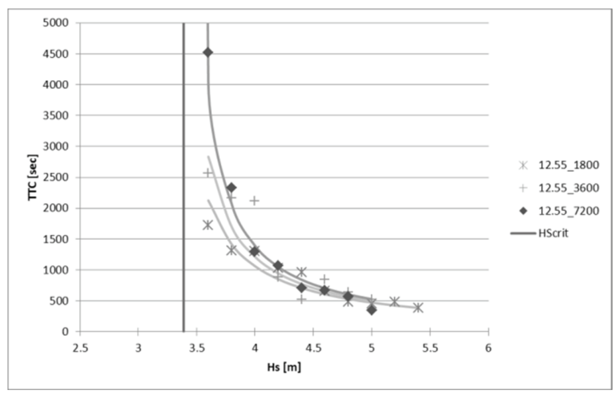


Fig.9: TTC for different simulation time

Validation of the proposed s-factor

The first stage of validation aimed at verifying whether the chosen parameter set is sufficient for exhaustive description of the dataset. This was done by once again applying the Design of Experiments (DoE) technique to the experimental data. The outcome expressed by means of combination of linear, quadratic and interaction terms resulted in 0.99 correlation with the experimental data, which can be considered as a satisfactory test concerning completeness of the parameter set.

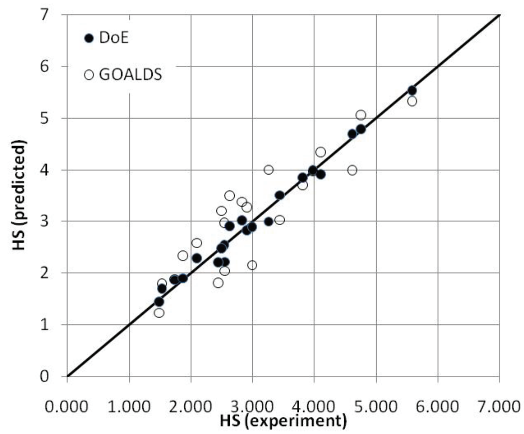


Fig.10: The DoE technique applied to the experimental data resulted in 0.99 correlation of the regression based on A_{GZ}, GM_f and *Range* parameters.

It should be noted that the GOALDS formulation applied to the experimental data resulted in 0.90 correlation as compared to 0.64 of SOLAS 2009. Further tests confirmed good agreement of the GOALDS prediction with experimental data - using again DoE as a benchmark for confidence interval (100% sample points within the +/-0.5m interval) – resulting in +/-1.0m interval compared to -2.0/+2.5 in the case of SOLAS 2009.

In the final stage, A-Index calculated by means of SOLAS and GOALDS survival factors have been compared against each other and against numerical simulations using Monte Carlo sampling. These results are shown in figure 11.

Fig.11: Impact of GOALDS survival factor on A-Index – comparison of partial index for DS. The letter C denotes cruise vessel while R stands for RoPax. PBA is the Performance Based Assessment using MC sampled numerical simulations

Notwithstanding the above, the impact of the new s-factor is expected to be small due to the limited (in terms of probability) share of the marginal cases of s=(0;1). As it can be seen from the above figure, the discrepancies are within a few percent, with the new s-factor giving generally higher values for all but the small RoPax (R2). The highest difference between current and new s-factors is shown in the case of the very large cruise vessel (C3) for which PBA predicts average survivability of about 98%. It should be bore in mind, however, that the generally good agreement between SOLAS 2009 and GOALDS prediction should be approached with caution as it has been proven that although average predictions may not be significantly distinct, the former exhibits much lower accuracy – which, as shown previously for the tested RoPax vessels resulted in 4.5m confidence interval covering the entire scope of applicability of the s-factor (sea states of H_S 0-4m).

Given the complexity of the physical model tests for survivability, to date, the data appropriate for comparison is very limited and consist of only two valid experimental points for C1 (although more data will be available later). These points comprise two runs with semi-watertight doors open and closed performed in waves, starting from the damage equilibrium position. These are presented below.

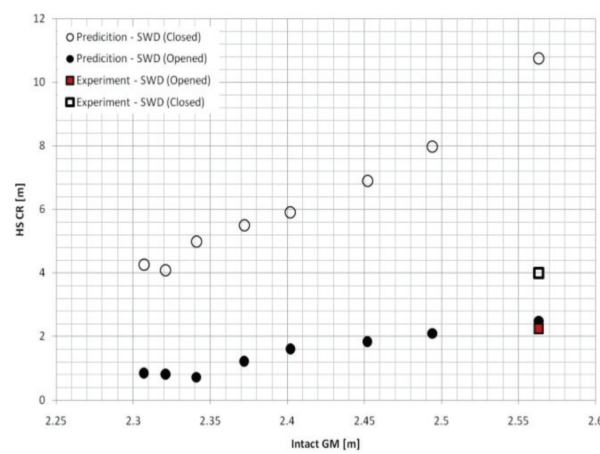


Fig. 12: Comparison of predicted and measured $H_{S\,crit}$ for the cruise vessel. Note that the tests with SWD closed had been terminated at H_S 4.0m.

CONCLUDING REMARKS

The much-awaited breakthrough in re-formulating the s-factor has now taken place. The new formulation has all the characteristics that one would intuitively expect, in particular:

- The formulation is simple, rational and readily calculable.
- It is much along the lines of the current formulation but use as basis Hs critical for infinite survivability, consistent with the SRtP philosophy. This way water on deck is accounted for but not included explicitly in the formulation.
- It accounts for scale as we all suspected it should.
- Demonstrate high degree of correlation with all available results (particularly experimental), using HARDER, GOALDS and EMSA projects data.
- It accounts for any level and mode of subdivision, including the watertight envelop above the traditional bulkhead deck.
- Finally, and most importantly, it is a generic formulation deriving from basic principles and hence expected to be applicable to all passenger ships; current to future innovations.

The next step is to use these findings and to apply the new formulation to RoPax and cruise ship designs to elucidate the potential impact on Index-A and to use this as guidance for setting new damage survivability standards. This forms part of the GOLDS Project objectives.

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REFERENCES

HARDER (1999-2003): "Harmonisation of Rules and Design Rationale". EC funded project, DG XII-BRITE, 2000-2003

Jasionowski, A., Dodworth, K., Vassalos, D. (1999)"Proposal for Passenger Survival-Based Criteria for Ro-Ro Vessels", Intl Shipbuilding Progress, Vol. 46, No 448,

Jasionowski, A., Vassalos, D., Scott, A. (2007) "Ship Vulnerability to Flooding", Proc. 3rd International Maritime Conference on Design For Safety, Berkeley, CA

Tsakalakis, N., Cichowicz, J., Vassalos, D.: (2010) "The concept of the capsize band revisited", Proc. of 11th Intl Ship Stability Workshop Wageningen, the Netherlands

Vassalos, D., Ikeda, Y., Jasionowski, A., Kuroda, T. (2004)"Transient Flooding on Large Passenger Ships", Proc. of the 7th Intl Ship Stability Workshop, Shanghai, China