On damaged ship survivability assessment in design and operation of passenger ships

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ABSTRACT

This paper presents an alternative to SOLAS formulation for assessing damage survivability of passenger ships.

Keywords: *survivability, damage stability, SOLAS, GOALDS*

1. INTRODUCTION

In SOLAS damage stability regulations the probability of surviving (collision) damages is given in the form of s-factor - an empirical formula derived within research project HARDER (1999-2003) and subsequently adopted by IMO for the harmonised damage stability framework often referred to as SOLAS2009. Although the new framework is based on the same principle as the earlier probabilistic instrument (resolution A.265) –in principle it requires that the attained index of subdivision A (i.e. the average probability of surviving collision damage) is at least equal to the required index R - the individual building blocks of the regulations were revisited during the harmonisation process. In the case of s-factor it led to radical change in the survivability model and understandable concerns with respect to robustness and reliability of the new formulation. Given the step change to the model the recurring question was whether the new formulation preserves the safety level of deterministic approach or that of the resolution A.265. Although a definitive answer to this question could not be given the common perception was that the SOLAS 2009 overestimates survivability of RoPax ships and underestimates safety of cruise ships. In order to investigate and resolve the issue, soon after the regulations went into force, two large cooperative research were established. One study, financed by the European Maritime Safety Agency (EMSA) looked into survivability of RoPax ships whereas the other, EU-funded, project GOALDS aimed at all passenger vessels and attempted to provide the survivability measure for collision and grounding damages.

The model discussed in this paper has been derived in the project GOALDS.

2. COMMON ASSESSMENT METHODS

The process of a ship loss following hull breach and flooding to internal spaces is driven by a number of random variables with loading conditions, sea state in the moment of incident and damage extent all having great impact on chances of survival. In specific damage case loading conditions, damage extent and even sea state are all determined but the excitation and ship response are both random (stochastic) processes. This, even under assumption of stationary character of the processes, requires significant number of trials to be conducted in order to assess probability of surviving collision or grounding damages with reasonable accuracy. How accurate the assessment is depends on many factors but the most important of them is the method employed in testing.

Physical experiments

The most traditional method is based on physical experiments with a ship model positioned in a towing tank and subjected to action of beam seas. Such tests are easy to conduct and are thought to represent well the dynamics of damaged and flooded ship but they are expensive, allow for very limited and difficult control of trial parameters and suffer from poor repeatability.

On the other end of the spectrum there are CFD calculations, flexible and readily manageable and allowing for detailed modelling of flooding even in complex arrangements. This allows achieving high-accuracy predictions but comes at the expense of computational effort. This makes the CFD-based calculations a great tool for verification or high-resolution investigations (e.g. sloshing) but renders impractical in applications requiring short calculation times.

Usually a good compromise between model tests and CFD calculations can be achieved with the help of computer codes based on linear models. Such methods allow capturing the physics of loss with reasonable accuracy - in typical applications the damaged ship is not exposed to extreme weather condition, on the contrary, the sea-state of interest does not exceed H_S of 4m.

The satisfactory in most survivability studies accuracy and relatively short computations make the numerical models a viable tool in design process, particularly when combined with techniques such as Monte Carlo sampling allowing for statistical modelling or other sampling techniques for the design space exploration.

There are however at least two applications where speed of calculations is of particular importance and for which – at present - none of the methods discussed above is practical (or at least widely utilised). These applications are regulations and decision support in emergencies, both relying extensively on empirical or semi-empirical models for their speed and ease of use.

SOLAS s-factor

Formally, SOALS s-factor is an estimate of the expected (averaged with respect to the statistical distribution of sea states in the moment of collision) probability of surviving collision damages. Its present incarnation is built around of a concept of critical significant wave height, H_{Scrit}, i.e. a sea state determining chances of survival (e.g. 50%) within a trial of specific length (e.g. 30 minutes); detailed information about the development and methodology behind the s-factor can be found in (Tagg and Tuzcu, 2002) and (Pawłowski, 2007).

If the intermediate phases and stages are neglected and only final stage of flooding is of interest, with ship already at her damage equilibrium, the s-factor is given as a product of three terms

$$s_{SOLAS} = k \cdot s_{moment} \cdot s_{final} \qquad (1)$$

where k accounts for list in the final equilibrium with $k=1$ for heel angles smaller than 7 deg and diminishing gradually to zero at 15 degrees heel, s_{moment} accounts for external moments due to wind, passenger crowding or launching life-saving appliances (whichever is largest) and s_{final} being the „proper" survivability measure, linking (implicitly) the residual stability characteristics to the critical significant sea state and the distribution of sea-states in the moment of collision.

That is, in final stage of flooding the average probability of survival is given as

$$s_{final} = \left(\frac{GZ_{\max}}{0.12} \cdot \frac{Range}{16} \right)^{0.25} \qquad (2)$$

where $Range$ is a range of positive stability (of flooded ship) and $GZ_{\max}$ is maximum righting lever within the $Range$ with maximum contribution from both parameters set at 0.12m and 16 degrees, respectively.

The formula is simple and can be readily evaluated within all Naval Architectural packages capable of calculating righting lever (GZ) curve of a damaged ship. Unsurprisingly, the very simplicity of the expression and lack of references to notions traditionally associated with stability and safety of damaged ship, such as initial metacentric height, GM, or the residual freeboard, made Naval Architects to question whether the SOLAS s-factor actually works (Dankowski and Krüger, 2010), (Sweden and the UK, 2009), (Scott, 2010). Soon after SOLAS 2009 had come into force, it became apparent that the s-factor – as implemented by IMO, not as derived by HARDER – is a flawed and unreliable instrument.

3. ALTERNATIVE ASSESSMENT METHOD

The EU-funded project GOALDS was set up in order to examine the existing formulation (and the underlying methodology) and to propose an alternative formula(e) covering both, collision and grounding damages. The project confirmed that HARDER built the formulation on solid foundations and that the core concepts of capsize band and critical significant sea-state are indeed of great importance in assessment of the probability of survival. Furthermore, GOALDS showed that a small but important re-definition of the H_{Scrit}

practically eliminates the water on deck issue and dependency on trial's duration from the problem (Cichowicz et al, 2016). Furthermore, it was shown that at the heart of the s-factor issue lies the omission of the scaling parameters accounting for size of a ship.

In the process of re-engineering of the s-factor it was proposed to use the explicit reference to H_{Scrit} and express the probability of surviving flooding (i.e. both, collision and grounding) damages as in the following

$$s_{final} = \exp(\exp(0.16 - 1.2H_{Scrit})) \tag{3}$$

with H_{Scrit} given as

$$H_{Scrit} = \frac{A_{GZ}}{\frac{1}{2} GM \cdot Range} V_R^{\frac{1}{3}} \ [m] \tag{4}$$

where A_{GZ} is an area under the righting lever curve within the positive range of stability and V_R is residual watertight volume (i.e. total volume of the watertight envelope reduced by the volume of compartments "lost" in the damage).

As the below figures illustrate the GOALDS formula proved to be more accurate than its HARDER counterpart across a diversified sample of tested ships, varying in sizes and internal arrangements. In spite of this, the model has been perceived counterintuitive because of presence of GM and $Range$ in denominator, and the argument that it is the whole combination and not the individual parameters that matters failed to convince the sceptics.

Nevertheless, the argument was right and the factor within the expression has indeed strict physical significance that could not be determined directly at the time of development.

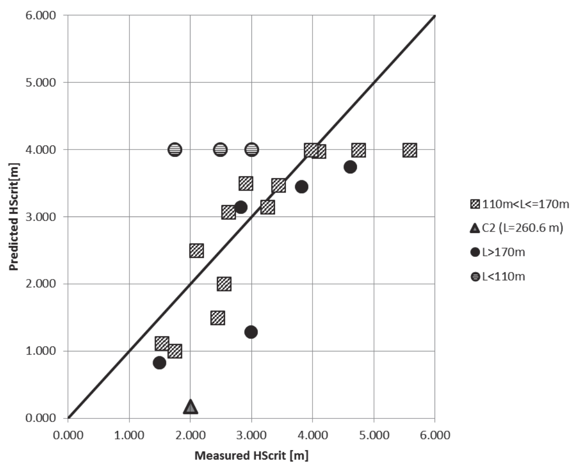

Figure 1. Comparison of measured and predicted by the HARDER model critical sea states.

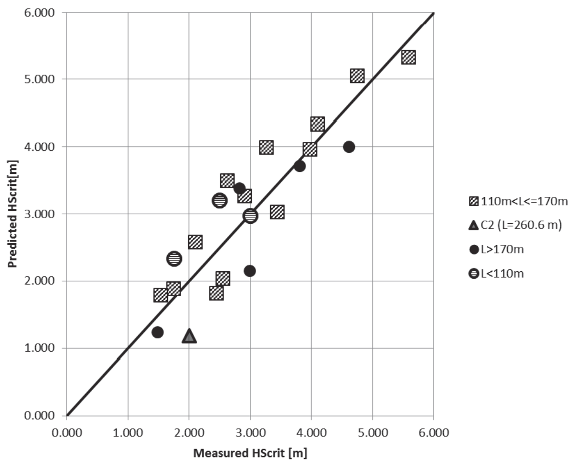

Figure 2. Comparison of measured and predicted by the GOALDS model critical sea states.

Physical significance

The key observation to be made in order to unveil the true meaning of the GOALDS formula for H_{Scrit} is that the ratio $A_{GZ} / Range$ corresponds to the average value of the righting lever within the range. It can be denoted as l_c and plotted against the GZ curve, as in the figure below.

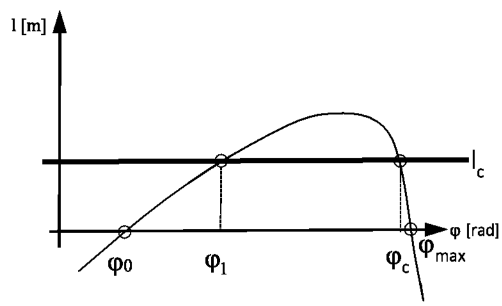

Figure 3. The average righting lever plotted against the GZ curve.

The lever l_c corresponds to external heeling moment thus the angles φ_1 and φ_c mark stable (static) and unstable equilibria. Furthermore, the tangent to GZ curve at φ_0, i.e. GM, can be approximately given as

$$GM = \frac{l_c}{\varphi_1 - \varphi_0} \qquad (5)$$

From this it follows that $\varphi_1 - \varphi_0 = \frac{l_c}{GM}$ and the H_{Scrit} formula becomes

$$H_{Scrit} = 2(\varphi_1 - \varphi_0)\sqrt[3]{V_R} \qquad (6)$$

It implies that the critical significant wave height is proportional to work of the external moment equal in magnitude to average restoring moment and heeling the ship to the angle of static equilibrium.

In fact, since the lever from the external moment is known it is possible to calculate (based on the work-energy balance) a corresponding angle of dynamic heel, φ_2, as shown in the figure below

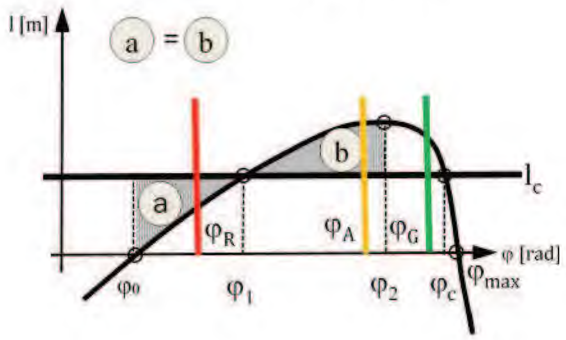

Figure 4. Dynamic heel and work-energy balance.

The red (R), amber (A) and green (G) lines are plotted in the figure above to highlight the design implications imposed by the H_{Scrit} formulation, namely that

- red (R) - no openings between φ_0 and φ_1 (except watertight); no car-deck submersion below φ_1
- amber (A) - only semi-watertight openings between φ_1 and φ_2
- green (G) - no restriction for opening type beyond φ_2 (dynamic equilibrium).

It can be readily seen from the above that the GOALDS formulation is consistent with physics of loss, rational and intuitive. For instance, the figure below shows the angle of submersion of the car-deck edge against the angle of static equilibrium φ_1 for the all RoPax cases analysed in GOALDS.

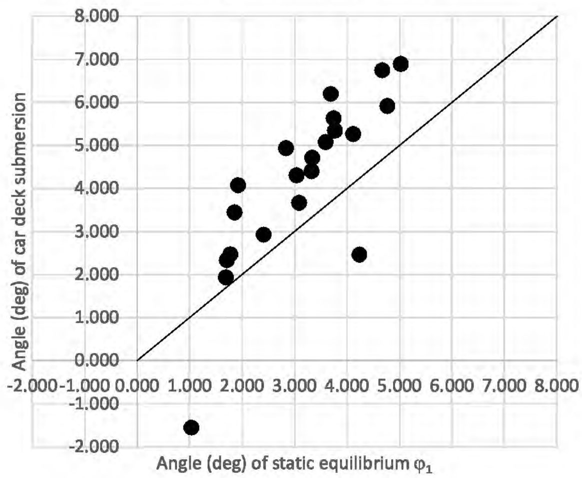

Figure 5. Car deck submersion vs static equilibrium in the GOALDS RoPax sample.

The unsurprising but having a lot of common sense observation is that apart from two cases the car-deck edge did not submerge below the angle of static equilibrium. Interestingly, both "outliers" were ships with side-casings on the car deck (furthermore one of the ships had the deck edge submerged in the equilibrium floating position). These results are in line with expectations, namely that the damaged RoPax ship will survive in sea states below which the car deck edge is not submerged (which indirectly implies that floodwater is not accumulated on the deck or that the process of accumulation is very slow). Furthermore, the results show that adding extra buoyancy distributed at the side of the car deck has positive impact on damage survivability.

Use in design of passenger ships

The GOALDS formula was derived mainly based on survivability tests of RoPax ships but, given its rational character, it can be applied to all passenger ships. This is because, in spite of obvious differences in internal arrangements and dynamics of the flooding process, both RoPax and passenger ships are lost in a consequence of uncontrolled flooding leading to diminishing stability and capsize or sinking. In case of RoPax ships this is usually because of (rapid) accumulation of floodwater in large, un-subdivided cargo spaces whereas in case of passenger ships the likely scenario involves slow progressive flooding through unprotected openings, opened semi-watertight doors or downflooding points etc. Nevertheless, the survival criterion is same for both types of ships: there must be reserve of buoyancy and stability and the openings or design features that may lead to uncontrolled flooding should not submerge below angle of dynamic equilibrium, φ_2. Should this cannot be achieved the critical moment, l_c, has to be lowered until the criterion is met, as shown in the sketch below

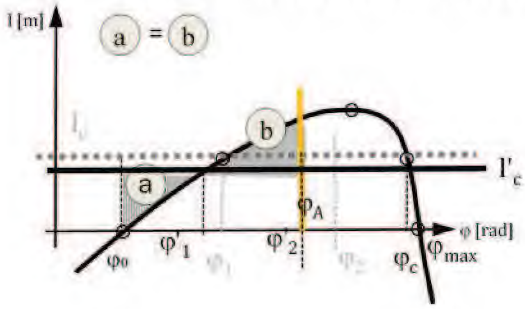

Figure 5. Lowering the survival limit to account for the design criteria.

Then for the new critical moment l'_c the critical sea state is

$$H_{Scrit} = 2(\varphi'_1 - \varphi_0)\sqrt[3]{V_R} \cong 2\frac{l'_c}{GM}\sqrt[3]{V_R}\ [m] \qquad (6)$$

Similar strategy can be adopted to accommodate for external moments due to wind, passenger crowding and LSA launching. They can be included by imposing a condition $l'_c = l_c - l_m$, where l_m is the healing lever due to largest of these moments, and reducing the H_{Scrit} accordingly.

As the following figure demonstrates these moments may have critical impact on survivability and the fact that they can be directly accommodated within the GOALDS formula can be considered as a clear advantage over the SOLAS approach.

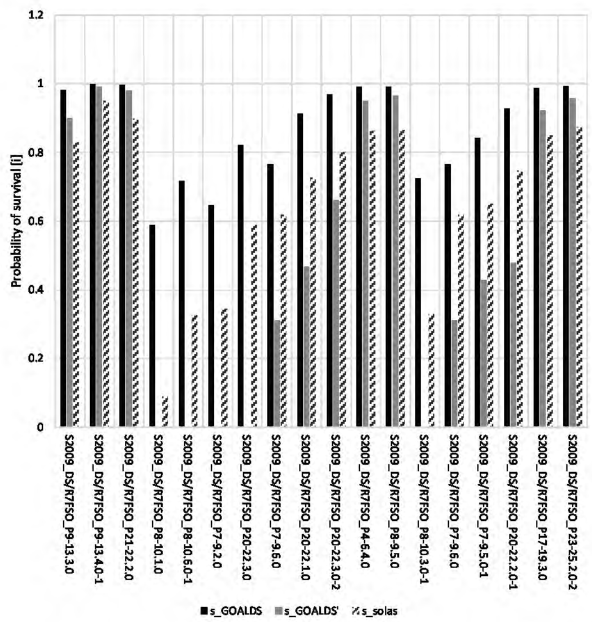

Figure 5. Probability of surviving collision damages according to SOLAS and GOALDS. SOLAS and the GOALDS series marked by apostrophe (grey bars) account for external moments

4. CONCLUDING REMARKS

The method of survivability assessment based on GOALDS formulations can be readily applied to all passenger ships irrespective of size and internal arrangement. The approach discussed in the foregoing may not capture all the fine details of the flooding and subsequent ship loss or peculiarities of a ship's response to different sea spectra but it was never designed to do so. On the contrary, the method was intended to give a quick, yet reasonably, accurate estimate of the critical (but still safe) sea state and thus, through the probability of encountering such sea state during the collision, to determine what is the expected probability of survival, given the specific loading condition and damage case. In operation the method can be determined whether the damaged ship can survive or should be abandoned.

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