Comparison of *s*-factors according to SOLAS and SEM for Ro-Pax vessels

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ABSTRACT

The paper discusses differences between the s-factors for ro-pax vessels, calculated according to the SOLAS methodology and the SEM for a middle sized Polish ferry "Polonia" and for a box-shaped vessel. Three major conclusions can be drawn from numerical results. 1) the *s*-factors according to the SOLAS Convention are *smaller* than or equal to the *s*-factors according to the SEM, 2) the smaller the damage stability, the greater the difference between them, which results from the fact that the SOLAS *s*-factor is much more sensitive to stability than the *s*-factor based on the rational SEM, 3) the SOLAS Convention underestimates the real safety of ro-pax vessels, and 4) the degree of underestimation increases with the ship size.

KEYWORDS

subdivision, damage stability, s-factor

INTRODUCTION

Since 1996 a rational methodology for the prediction of the *s*-factor has been known, which means the probability of surviving the ship with a given compartment or a group of compartments flooded. The method, developed originally for RO/RO vessels at Strathclyde University, has been known as the static equivalent method (SEM), see Vassalos *et al*. (1996, 1997), Pawłowski (2004, 2007a, b). IMO (1997), however, was in favour of adopting for the *s*-factor a simplistic methodology, based on the *GZ*-curve, reflecting so-called good engineering judgement. The original formulation was this

$$s = C\,(\tfrac{1}{2}GZ_{max}Range)^{1/2}, \qquad (1)$$

where the coefficient C accounts for the effect of the final angle of equilibrium, with $C = 1$, if the final angle of equilibrium $\phi_e \le 25^\circ$, $C = 0$, if $\phi_e > 30^\circ$, and $C = [(30 - \phi_e)/5]^{1/2}$, otherwise. GZ_{max} is the maximum righting lever (metres) within the range as given below but not more than 0.1 m. *Range* is understood as the range of positive righting levers beyond the angle of equilibrium but not more than 20˚, and not more than to the angle of immersion of non-weathertight openings.

Some years later, influenced by the HARDER project (2003), IMO (2009) decided to modify the above formulation, keeping on the same format, embedded in the *GZ*-curve, as follows

$$s = C\,(\tfrac{25}{48}GZ_{max}Range)^{1/4}, \qquad (2)$$

where GZ_{max} is not to be taken more than 0.12 m, and *Range* not more than 16˚. The above formulation has been derived using the standard IMO distribution of sea states at the moment of collision. Therefore, it is invalid for other sea state distributions. Further, it provides no information, whether the ship is safe at the given sea state after collision.

ORIGINAL SEM FOR RO/RO SHIPS

Prior to 1996, over thirty years of research failed to develop rational and accurate damaged stability criteria to predict the capsizal resistance of damaged RO/RO vessels, despite great efforts (Middleton and Numata 1970, Bird and Browne 1973). The SEM for RO/RO ships postulates that the ship capsizes in a way that is quasi-static and based on the heeling moment of the elevated water on the vehicle deck. This method was developed following observations of the behaviour of damaged ship models in waves. Among the most important observations from these model tests and subsequent investigations (Vassalos *et al*. 1996, 1997) are:

1. As the ship reaches the *point of no return* (PNR) it behaves quasi-statically, with marginal transverse stability and very subdued roll motions.
2. The PNR (the critical heel) generally occurs at an angle very close to ϕ_{max}, the angle where the static *GZ* curve for the damage ship reaches maximum.

3. The critical amount of water on the vehicle deck can be predicted from static calculations by pouring water onto the undamaged vehicle deck until the heel angle reaches ϕ_{max}.
4. The critical and unique measure of the ship's survival capability is the level h that this critical water is elevated above the sea level at the point of no return, as shown in Figure 1. This simple fact was unknown until 1996 and was the prime reason why the previous model tests were inconclusive.

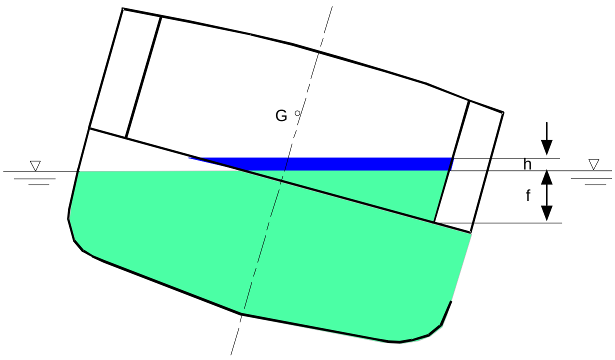

Figure 1. A damaged RO/RO ship with a rise of water on the car deck at the PNR

5. The model tests and subsequent simulations indicated that this elevation of water on deck h could be directly linked to the sea state, or H_s.
6. The higher the water elevation h at the point of no return, the higher the sea state needed to elevate the water to this level and capsize the ship.
7. Generally, the size of the damage opening, the trim and damage freeboard of the ship do not affect the survival capability.

Subsequent investigations have indicated that the immersion of the deck edge f at the damage opening is relevant to some extent, and several refinements and enhancements in the SEM are, therefore, possible based on the theoretical model for water on deck accumulation, as developed by Pawłowski (2001a, b, 2003). This effect, however, is of little importance and can be ignored.

Hence, the sought boundary stability curve may take the form of:

$$h = 0.085\, H_s^{\,1.3}, \qquad (3)$$

where both quantities are in metres, h is the elevation of water on the vehicle deck above sea level at the critical heel angle, obtained by static calculations, and H_s is the median sea state the ship can withstand with given stability, termed also as the critical sea state.

The critical heel angle (PNR) is understood here as the heel angle induced by the elevated water on deck at which the equilibrium of the ship is unstable. This angle is crucial for the SEM, as the elevation of water is calculated just at that angle, which in turn defines the critical H_s.

It is possible to find the critical heel angle, equal the angle ϕ_{max}, with the omission of the *GZ*-curve, which is particularly useful for flooding cases with trim. This characteristic value is such for which the heeling moment produced by elevated water reaches a maximum. In this concept it is sufficient to find for each amount of water on deck the *GZ*-lever at the angle of loll over a range of heel angles, and to choose the one with a maximum *GZ*-lever. To do these calculations effectively, knowledge of principal axes of inertia for actual damaged waterplanes is needed. The entire known commercial software does not provide these characteristics.

Equation (3) provides on the whole a first-rate prediction, with deviations in a large majority of cases less than the sea state resolution used to derive H_s, which was 0.5 m. The above equation is universal, i.e. independent of ship size, the type of ship subdivision, compartment flooded, loading condition, etc. The critical wave height H_s depends solely on the elevation of water at the critical heel angle, and nothing else. More details and advances in knowledge on damaged ship safety can be found in the publications of Pawłowski (2004, 2007a, b, 2008), and Bulian (2008), shedding more light on the SEM and proving its robustness.

Knowing the critical sea state H_s from equation (3) for a given damage case, the factor s (probability of collision survival) can be readily obtained from the distribution of sea states occurring at the moment of collision. The probability of collision survival equals simply the probability that the critical significant wave height H_s is not exceeded at the moment of collision. Thus, the factor s equals CDF for given H_s. For this purpose, the CDF of sea states, proposed by the IMO could be used, as shown in Figure 2.

It is noteworthy that the distribution of sea states at the moment of collision is different from the sea state distribution, obtained from regular weather statistics. In a large majority of cases, collisions happen in the proximity of ports, in confined waters, and in fog, typically associated with calm weather. It is understandable, therefore, that in such circumstances sea states are on the whole lower than those in regular weather statistics. The sea state distribution, however, may differ for certain regions.

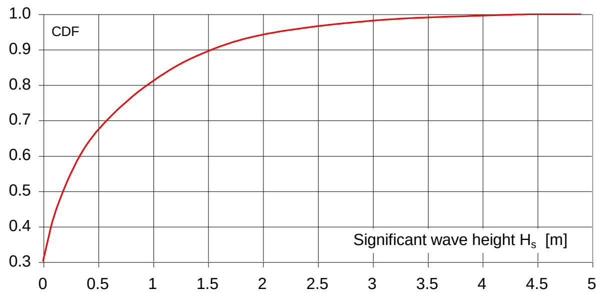

Figure 2. IMO distribution of sea states occurring at the moment of collision

Using the sea state distribution as shown in Figure 2, a very good approximation of this curve for H_s up to 5 m, which is identical with the factor *s*, is given by

$$s = (0.7494\,x^3 - 2.4095\,x^2 + 2.6301\,x + 0.0148)^{1/3}, \quad (4)$$

where $x = H_s/4$ is in meters. For $H_s > 5$ m, $s = 1$. Specific applications could consider actual distributions of sea states at the moment of collision, appropriate for the area of ship operation.

COMPARISONS

To see the differences between the two methodologies described briefly above, the *s*-factor has been calculated for a box shaped vessel, and for a medium-sized Polish ferry "Polonia". In all the cases investigated midships floodings were considered only, to ease the calculations. The box-shaped vessel had no double bottom, whereas the height of the double on the ferry was 1.85 m. In the latter case the damage extended from the double bottom upward above the car deck. Both ships had a single hull.

Particulars of the ferry "Polonia" are as follows:

L_{oa} = 169.90 m T = 6.20 m
L_{pp} = 159.00 m h_0 = 4.067 m
B = 28.00 m m = 18 186 ton
D = 8.65 m z_G = 11.42 m

Two compartments below the car deck of various lengths were flooded. In the case of the ferry a shorter compartment of length 24 m extended between x_1 = 67.5 m and x_2 = 91.5 m, measured from the aft perpendicular. A longer compartment of length 30 m extended between x_1 = 64.5 m and x_2 = 94.5 m. Five flooding scenarios were considered with various transverse arrangements below the car deck, including a transverse compartment, and a wing compartment with two widths: b = 0.1B and 0.2B, see Figure 3. The simultaneous flooding of the wing and the adjacent central compartment was also considered. Space above the car deck was open, with no provisions for reserve buoyancy, allowing for large scale flooding.

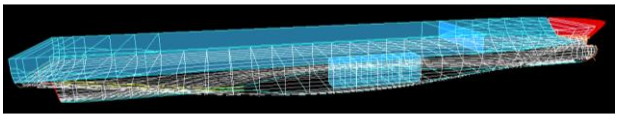

Figure 3

Particulars of the box-shaped ship were as follows:

L = 143.00 m T = 5.75 m
B = 28.00 m h_0 = 1.835 m
D = 8.00 m z_G = 12.00 m

Two transverse compartments below the car deck were flooded of length 16.5 m and 18.5 m.

The *s*-factors for the two ships according to SOLAS and SEM are compiled in Table 1 and Figure 4. As can be seen, the two *s*-factors equal each other only if they equal 1, i.e., if damage stability is sufficient. For deficient stability the SOLAS *s*-factor is *always* smaller than the *s*-factor based on the SEM, and the difference increases the more deficient the stability is.

Table 1

Polonia	*h* (m)	*factor s* SEM	*range*	GZ_{max}	*factor s* SOLAS
24 m					
C	0.580	0.997	15.6	0.381	0.994
0.1B	0.990	1.000	22.6	0.540	1.000
0.1B+C	0.436	0.991	12.2	0.243	0.934
0.2B	0.605	0.997	15.4	0.300	0.990
0.2B+C	0.290	0.969	8.4	0.131	0.851
30 m					
C	0.365	0.984	11.3	0.265	0.917
0.1B	0.797	1.000	20.4	0.462	1.000
0.1B+C	0.263	0.960	6.2	0.087	0.728
0.2B	0.356	0.983	10.6	0.155	0.902
Box ship					
	0.415	0.990	9.81	0.114	0.874
	0.441	0.992	10.13	0.133	0.892
	0.308	0.973	8.46	0.056	0.705
	0.300	0.971	7.4	0.056	0.682

The above stems from the fact that the SOLAS *s*-factor is much more sensitive to damage stability than the *s*-factor based on the SEM, clearly seen in Figure 4, reflected by a very steep trendline for the two *s*-factors. If this could be taken as a rule, it would mean that the SOLAS Convention largely underestimates the safety of damaged ships.

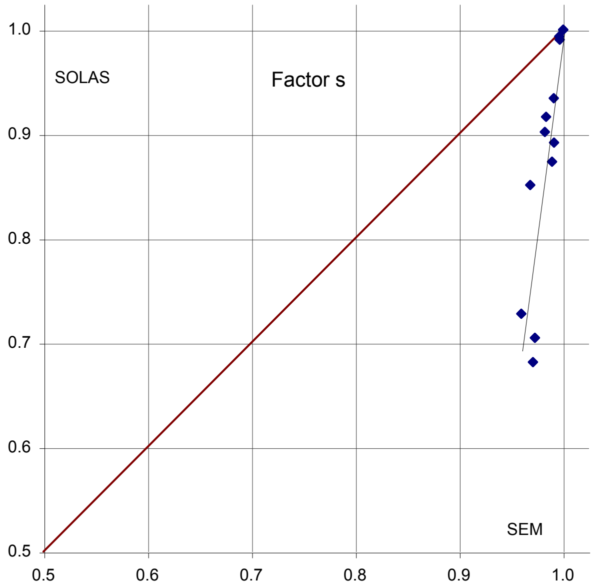

Figure 4. Factors *s* according to SOLAS and SEM

The large insensitivity of the SEM *s*-factor to damage stability explains Figure 5. If water elevation *h* is larger than about 0.15 m, the SEM-based *s*-factor is larger than 0.9. As can be seen from Table 1, to have the water head $h \approx 0.15$ m, the righting arm curve would have to be marginal, yielding a marginal *s* according to SOLAS. Hence, in the light of the SEM the *s*-factor is to a large extent of binary nature, which agrees with common sense.

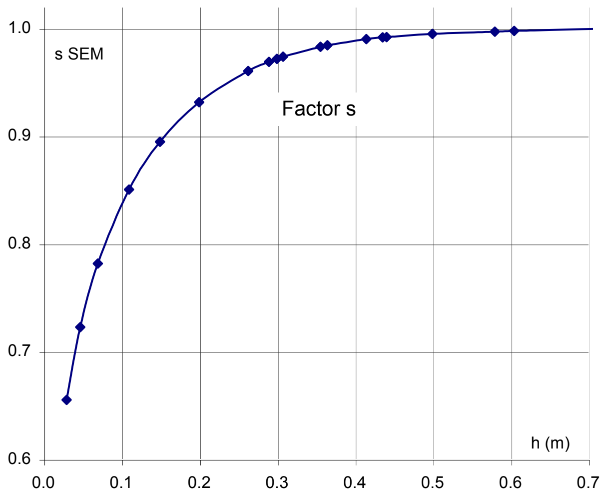

Figure 5. Variation of SEM *s* with water elevation

Water elevation *h* is a rational (physical) measure of a ship's resistance against capsizing, independent of the ship size. It is understandable that the same elevation of water on deck can occur with various *GZ*-curves, depending on the ship size. This in turn yields various *s*-factors according to SOLAS, smaller for large ships, though in the light of the rational SEM a ship's survivability remains the same for the same water head. This alone indicates that the SOLAS formulation for *s* is deficient, *panelizing* large ships. Hence, the degree of underestimation of ship safety increases with the ship size, which clearly contradicts reality.

We have to tell loudly that clinging to the *GZ*-curve in the SOLAS Convention has led IMO to a deceptive *s*-factor, allowing for a false effect of the ship size on subdivision index, panelizing large ships.

CONCLUSIONS

Based on the results and arguments presented in this paper the following conclusions can be drawn:

- for deficient stability the *s*-factors according to the SOLAS Convention are *smaller* than the *s*-factors according to the SEM
- the smaller the damage stability, the greater the difference between them
- the SOLAS Convention underestimates the safety of damaged vessels
- the degree of underestimation increases with the ship size

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REFERENCES

Bird, H., and Browne, R. P. 1973: Damage stability model experiments, *RINA Transactions*, pp. 69–91.

Bulian, G. 2008: Time-based damaged ship survivability: a quasi-static equivalent method, *Int. Shipbuilding Progress*, Vol. 55, No. 3, pp. 183–226.

HARDER – Harmonisation of Rules and Design Rationale, EU Contract No. GDRBCT-1998-00028, Final Technical Report, 31 July 2003

IMO 1997: SOLAS Consolidated Edition (International Convention for the Safety of Life at Sea, 1974, as amended)

IMO 2009: SOLAS Consolidated Edition (International Convention for the Safety of Life at Sea, 1974, as amended)

Middleton, E. H., and Numata, E. 1970: Tests of a damaged stability model in waves, *SNAME Spring Meeting*, paper No. 7, 14 pp.

Pawłowski, M. 2001a: Analytical studies for water on deck accumulation, *Transactions*, Schiffbautechnische Geselschaft E.V., Sommertagung, Danzig, TU Gdansk, Poland.

Pawłowski, M. 2001b: The capsizal resistance of RO/RO vessels, Task No. 3.4 on "Generalized s Factor", EU project on Harmonization of Rules and Design Rationale "Harder", Reference No.: 3-34-T-2001-01-0.

Pawłowski, M. 2003: Accumulation of water on the vehicle deck, *Proceedings* of the Institution of Mechanical Engineers, Part M, J. Engineering for the Maritime Environment, Vol. 217 (M4), pp. 201–211.

Pawłowski, M. 2004: Subdivision and damage stability of ships, Euro-MTEC book series, Foundation for the Promotion of Maritime Industry, Gdansk, ISBN 83-919488-6-2, 311 pp.

Pawłowski, M. 2007a, A modified static equivalency method for roll-on/roll-off vessels, *Journal of Ship Research*, Vol. 51, No. 1, March 2007, pp. 39–46.

Pawłowski, M. 2007b: Survival criteria for passenger roll-on/-roll-off vessels and survival time, *Marine Technology*, Vol. 44, No. 1. January 2007, pp. 27–34.

Pawłowski, M. 2008: Closure on survival time, Proceedings, 10th Int. Ship Stability Workshop, Daejeon, Korea, paper 8-3, 5 pp.

Vassalos, D., Pawłowski, M., and Turan, O.: A theoretical investigation on the capsizal resistance of passenger Ro–Ro vessels and proposal of survival criteria, Final report, Task 5, The North West European R&D Project, March 1996

Vassalos, D., Turan, O., and Pawłowski, M. 1997: Dynamic stability assessment of damaged passenger RO/RO ships and proposal of rational survival criteria, *Marine Technology*, Vol. 34, No. 4, pp. 241–266; see also: Criteria for survival in damaged condition, *Proceedings*, Int. Seminar on the Safety of RO/RO Passenger Vessels, RINA, London, June 1996, 15 pp.