Comparative study of damage stability regulations and their impact on the design and safety of modern ROPAX ships

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ABSTRACT

The present paper summarizes the results of an investigation on the survivability of ROPAX ships in damaged condition following a collision accident. A small size ROPAX design has been selected and a series of design modifications have been elaborated, to study their effect on the ship's survivability, expressed by the Attained Subdivision Index, as well as on its lifetime economic performance, using three different damage stability formulations (SOLAS 2009, GOALDS and SLF 55), all based on the probabilistic concept. The ultimate goal of this study is to investigate the feasibility of raising the current regulatory requirements on the ship's survivability, while keeping the economic impact of the corresponding design modifications within acceptable limits.

KEYWORDS

Damaged ship stability; probabilistic assessment; goal-based design; risk-based design; passenger ship safety; risk-based damage stability requirement.

INTRODUCTION

The introduction of SOLAS 2009 is probably the most important breakthrough in the evolution of damage stability regulations for several decades. Due to its paramount importance, survivability of ships in damaged condition is an evergreen topic on IMO's agenda and a subject of extensive research and investigations. In particular, the impact of SOLAS 2009 on the survivability of passenger ships received particular and continuous attention of ship designers, operators, researchers, as well as of regulatory bodies, since the introduction of the new regulation. The main objectives of the present study are:

- to compare three different alternative formulations for the calculation of the Attained Subdivision Index and
- to investigate the possibility of achieving a significantly increased

Attained Subdivision Index for a typical ROPAX design, in comparison with the Required Index currently specified by SOLAS 2009, while keeping the economic impact of the corresponding design modifications within acceptable limits.

To this end, a small size ROPAX design has been selected and has undergone a series of modifications, or so-called Risk Control Options (RCO), aiming to improve the Attained Subdivision Index, while considering also the lifecycle costs of these modifications. The Gross Cost of Averting a Fatality criterion (*GCAF*) has been used as a measure to evaluate and compare the cost effectiveness of the applied RCOs. The RCOs meeting the *GCAF* criterion were selected for more refined investigations; based on the obtained results, some indicative trends with respect to the possibility of raising the current damage stability requirements for passenger ships are derived.

THE BASIC DESIGN

The basic design used for the study is a typical, small size ROPAX ship, with transverse subdivision and no lower hold. Its elaboration was based on an existing small ROPAX ship, currently in service between Piraeus and the Aegean islands. The resulting design is fitted with two vehicles decks, one for the carriage of trucks and trailers (bulkhead deck) and one for private cars. A hoistable car deck is also arranged on the main car deck, aiming to increase the private cars transport capacity.

The ship is subdivided into 13 watertight zones by 12 main transverse bulkheads (no lower hold) and is fitted with four diesel engines. Each pair of two engines is coupled to one gear box, connected to a shaft line and a CP propeller. The main characteristics of the basic design are summarized in Table 1, while its watertight subdivision up to Deck 5, as modelled in the NAPA software, is presented in Fig. 1.

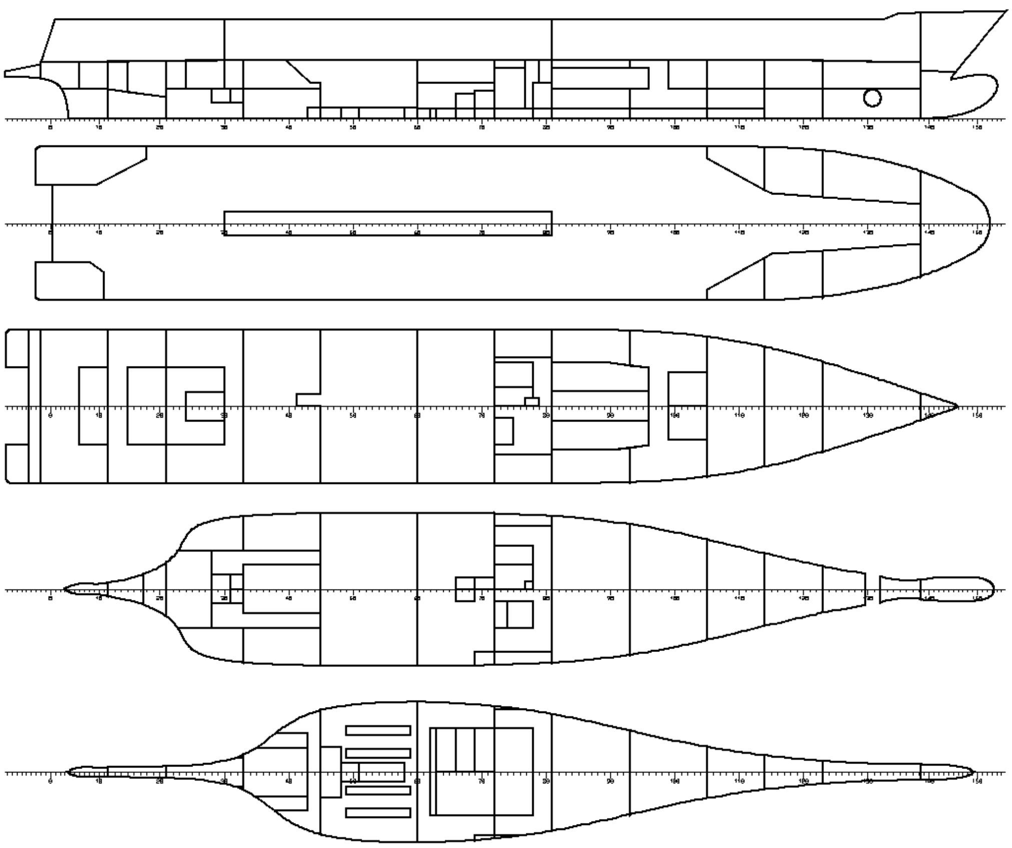

Fig. 1: Basic design – layout of watertight subdivision

Table 1: Main Particulars of the Basic Design

Length OA	124.430 m
Length BP	112.000 m
Subdivision Length	123.867 m
Beam	19.000 m
Subdivision draught / GM	4.919 m
Partial Draught / GM	4.569 m
Light Service Draught / GM	4.043 m
GM at Subdivision draught	1.889 m
GM at Partial Draught	1.717 m
GM at Light Service Draught	2.239 m
Height of bulkhead deck	6.600 m
Number of passengers	1500
Number of crew	60
Light Ship	4276.6 t
Deadweight	1994.2 t
Lane meters	360 m

With 1560 persons on board and no lifeboats, the Required Subdivision Index is, according to the SOLAS 2009 regulation, equal to 0.784. The respective Attained Subdivision Index, calculated for up to 5 zones damages is equal to 0.80846.

RISK CONTROL OPTIONS

A series of modifications (Risk Control Options) were applied to the basic design, and their impact on the survivability of the ship as well as on its economic performance over a lifetime of 30 years has been evaluated. Some of these modifications are presented in Table 2, where δB and δD correspond to the variation of beam and depth to bulkhead deck respectively. The impact of each RCO on the characteristics of the design was evaluated, based on appropriate empirical methods and formulae, developed and applied in similar studies for ROPAX ships during the elaboration of the EU-funded research project GOALDS. Using these methods and formulae, the impact of each RCO on ship's lightship weight and the corresponding weight centre, propulsion power, tonnage, transport capacity, building cost, operational cost, economic impact (gross/net), Attained Subdivision Index *A* and the associated Potential Loss of Life (*PLL*) were calculated.

Beam variations were effective up to Deck 5, limiting upwards the main vehicles deck. Above this deck, the original beam of the superstructure is maintained, therefore, the enclosed areas in the superstructure, the corresponding lightship weights and the passengers' capacity remained constant. Minor increase of the lanes length due to the increase of the ship's beam where ignored in the calculation of the annual income, while on the other hand, in case of a reduction of the lanes length, the corresponding annual income was proportionally reduced.

Damage stability formulations

The calculation of the Attained Subdivision Index for the basic design and for the evaluated RCOs was based on the following damaged stability formulations:

- the SOLAS 2009 regulation (MSC.216(82)),
- the alternative formulation discussed at SLF 55
- the GOALDS formulation for the assessment of survivability of ships following a collision accident (Papanikolaou et al., 2013).

The herein referred as the SLF 55 formulation is otherwise similar to SOLAS 2009, with the exception of the damage cases involving flooding of one or more Ro-Ro spaces (passenger ships only). In such cases, $s_{final,i}$ is given by the following formula:

$$s_{final,i} = K \cdot \left[\frac{GZ_{\max}}{0.20} \cdot \frac{Range}{20} \right]^{\frac{1}{4}} \qquad (1)$$

where GZ_{max} and *Range* should not be taken greater than 0.20m and 20° respectively. *K* is calculated according to SOLAS 2009.

Table 2: Risk Control Options

RCO	Description
A1	$\delta B = 0.00$ m, $\delta D = 0.20$ m
B0	$\delta B = 0.20$ m, $\delta D = 0.00$ m
B1	$\delta B = 0.20$ m, $\delta D = 0.20$ m
B2	$\delta B = 0.20$ m, $\delta D = 0.40$ m
B3	$\delta B = 0.20$ m, $\delta D = 0.60$ m
C0	$\delta B = 0.40$ m, $\delta D = 0.00$ m
C1	$\delta B = 0.40$ m, $\delta D = 0.20$ m
C2	$\delta B = 0.40$ m, $\delta D = 0.40$ m
C3	$\delta B = 0.40$ m, $\delta D = 0.60$ m

The GOALDS formulation is based on the concept of the critical significant wave height, H_{Scrit} for the calculation of $s_{final,i}$:

$$s_{final,i} = \int_0^{H_{Scrit}} dH_S \cdot f_{H_{S|coll}}(\mathrm{H_S}) = \exp(-\exp(0.16 - 1.2 H_{Scrit})) \quad (2)$$

The critical significant wave height H_{Scrit} is given by (Cichowicz et al., 2011):

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

where:

A_{GZ} area under residual *GZ* curve up to the flooding angle [rad·m]

GM_f metacentric height of flooded ship [m]

V_R residual volume – volume of subdivided spaces not opened to sea [m³]

Range range of positive stability up to the flooding angle [rad]

Impact on risk

The impact on risk, associated with each design alternative, is expressed in terms of the Potential Loss of Life (*PLL*). The calculation of *PLL* is based on the following estimations, developed by the GOALDS project from the statistical analysis of accidents involving ROPAX ships:

- Collision frequency: 7.778×10^{-3} (for ROPAX ships larger than 1,000GT).
- Probability of ship being struck: 0.689655.
- Area of operation at the time of the accident: en route (4%), in limited waters (23%), at the terminal (73%).
- Probability of water ingress: equal to 0.423077, while the ship is en route or in limited waters and equal to 0.117647 when the ship is at the terminal.
- Probability of capsize/sinking: 1-*A*
- Probability of slow/fast sinking: 0.5 / 0.5.
- Fatalities in case of slow sinking: 5%
- Fatalities in case of fast sinking: 80%

In the analysis of the consequences, the number of persons on board was estimated using an average annual utilization rate of 75%, based on data from operators of ROPAX ships in European waters.

Evaluation of Risk Control Options

The Gross Cost of Averting a Fatality (*GCAF*), derived according to the IMO FSA guidelines (MSC 83/INF.2, 2007 was used as a measure of the effectiveness of each RCO. The *GCAF* measure is calculated by the following formula:

$$GCAF = \frac{\Delta C}{\Delta R} \quad (4)$$

where ΔC is the lifetime cost per ship of the risk control option and ΔR is the risk reduction per ship, in terms of ΔPLL:

$$\Delta R = \Delta PLL \qquad (5)$$

The *GCAF* limit, used in the various FSAs submitted to IMO was set equal to $3million/fatality based on societal/living standard values of the 1990s. However, it is stated in the FSA Guidelines that the proposed values for *NCAF* and *GCAF*, derived by considering societal indicators are not static, but should be actually updated frequently according to the average risk free rate of return (approximately 5%) or by use of the formula based on the Life Quality Index (LQI). In the framework of the GOALDS project, the *GCAF* limit has been updated, (as of year 2012), and a value of $7,45million has been obtained. This value has been applied also for the present study.

Discussion of results

The obtained results are summarized in Table 3. Since *PLL* and hence also *GCAF* depend on *A*, separate results are presented for calculations performed according to the three alternative damage stability formulations. The differences between the *A* Indices, calculated with the three different methods, are relatively small. As shown in Fig. 2, the difference $A_{SOLAS} - A_{SLF55}$ varies between 0.005 and 0.015 with the lower differences being observed for the design alternatives with higher A_{SOLAS} values. Due to the similarity of the corresponding formulae for the *s* factor calculation, there is a uniform variation between A_{SOLAS} and A_{SLF55} for the tested RCOs. The difference $A_{SOLAS} - A_{GOALDS}$ varies from minus 0.008 to 0.007.

A comparison of the obtained results for the *A* Index, *PLL* and *GCAF* is presented in Fig. 3 to Fig. 5 (RCO A1 with *GCAF* values from 14.87 to 35.34 is omitted from Fig. 5 to keep the scale of the vertical axis within acceptable limits). As expected, increasing the beam of the ship had always a positive impact on damaged survivability.

On the other hand, an increase of depth to the bulkheads deck did not always had a positive impact. Increasing depth from 6.60m (basic design) to 6.80m always resulted in an increase of *A* and a reduction of *PLL*. An increase of depth from 6.80m to 7.00m had either positive or negative impact, depending on the ship's beam and on the employed damaged stability formulation. A further increase of depth to 7.20m had always a negative impact on safety.

Table 3: Evaluation of Risk Control Options

RCO	ΔC m$	SOLAS 2009			SLF 55 formulation			GOALDS formulation		
		A	*PLL*	*GCAF*	*A*	*PLL*	*GCAF*	*A*	*PLL*	*GCAF*
A0	-	0.81167	3.016	-	0.79650	3.259		0.80936	3.053	
A1	1.76	0.81478	2.966	35.34	0.80059	3.193	26.87	0.81675	2.934	14.87
B0	2.98	0.85744	2.283	4.07	0.84633	2.461	3.73	0.85255	2.361	4.31
B1	4.75	0.86509	2.160	5.55	0.85458	2.329	5.11	0.86392	2.179	5.44
B2	6.53	0.86212	2.208	8.08	0.85181	2.373	7.37	0.86532	2.157	7.29
B3	8.32	0.84858	2.425	14.08	0.83764	2.600	12.63	0.85664	2.296	10.99
C0	7.68	0.88774	1.798	6.30	0.87873	1.942	5.83	0.88114	1.903	6.68
C1	9.50	0.89644	1.658	7.00	0.88921	1.774	6.40	0.89354	1.705	7.05
C2	11.31	0.89755	1.641	8.22	0.89157	1.736	7.43	0.89826	1.629	7.94
C3	13.13	0.89292	1.715	10.09	0.88708	1.808	9.05	0.89727	1.645	9.33

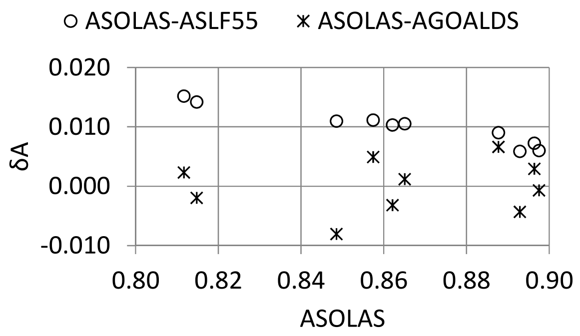

Fig. 2: Differences between the *A* Indices plotted against A_{SOLAS}

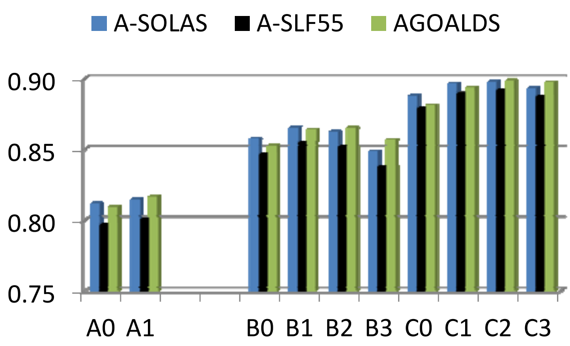

Fig. 3: Comparison of *A* Indices

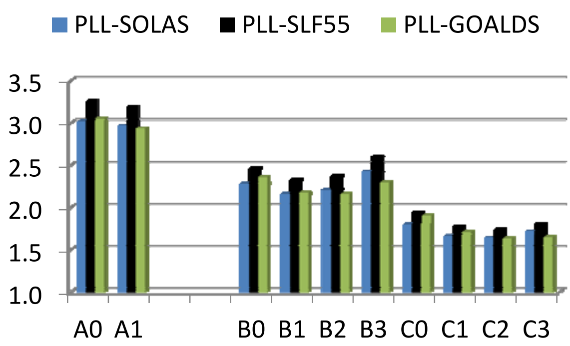

Fig. 4: Comparison of obtained *PLL* values

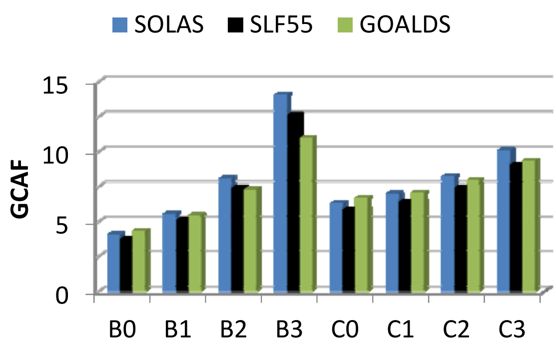

Fig. 5: Comparison of obtained *GCAF* values

According to the results presented in Table 3, almost half of the RCOs tested resulted in *GCAF* values within the $7,45million limit specified by the GOALDS project. The smaller *GCAF* values were obtained for RCO B0. The larger *A* Indices (from 0.89157 to 0.89826, depending on the applied formulation) were obtained for RCO C2, with both beam and depth increased by 0.4m. However, according to SOLAS 2009 and GOALDS formulations, this RCO failed to meet the *GCAF* criterion, while it marginally satisfies it according to the SLF 55 formulation. The second best RCO in terms of survivability is C1, with beam and depth increased by 0.4m and 0.2 respectively. This RCO meets the *GCAF* criterion and has similar *A* indices with C2, ranging from 0.88921 to 0.89644, depending on the applied formulation and corresponding *PLL* values from 1.658 to 1.774, resulting in a *PLL* reduction of 45% in comparison with the basic design.

The scatter diagrams of *GCAF* vs. *PLL*, Economic Impact vs. *PLL*, Economic Impact vs. the Attained Index *A* and Index *A* vs. the *GM* at subdivision draught are presented in Fig. 6 to Fig. 9 respectively. Since the values of Index *A*, *GCAF* and *PLL*, calculated with the three formulations are quite close to each other, only the results obtained with SOLAS 2009 are presented.

According to Fig. 6, only four RCOs (B0, B1, C0 and C1) meet the $7,45million *GCAF* criterion. Additional RCOs are fulfilling this criterion according to the other two formulations (B2 and C2 according to SLF55 and B2 according to GOALDS.

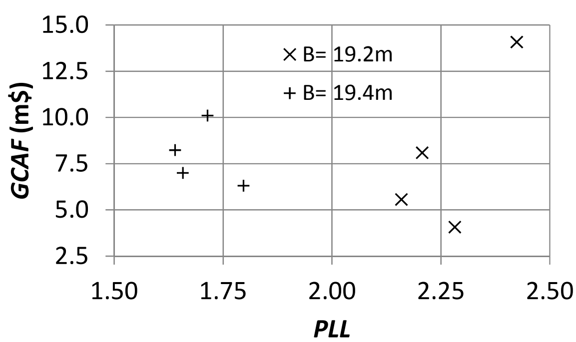

Fig. 6: Scatter diagram of *GCAF* vs. *PLL*

The lifetime cost that has to be paid for the reduction of *PLL* from around 3 persons corresponding to the basic design down to 1.65 persons (RCOs C1 and C2) and the associated increase of Index *A* from 0.81 of the basic design up to 0.896-0.897 is presented in Fig. 7 and Fig. 8.

Finally, the scatter diagram of the Attained Index *A* vs. the *GM* at subdivision draught is presented in Fig. 9, where the effect of the Beam and Depth variation on *GM* and *A* may be observed: different symbols are marking the results for B=19.0m, 19.2m and 19.4m, while for each set of points corresponding to the same Beam value, an increase of Depth results in a monotonic decrease of *GM* (the smaller Depth value corresponds to the maximum *GM* value and vice versa).

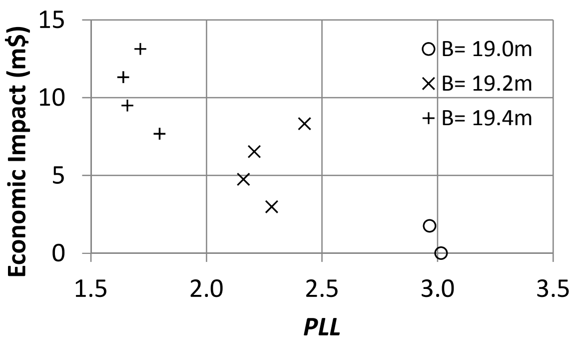

Fig. 7: Economic Impact vs. *PLL*

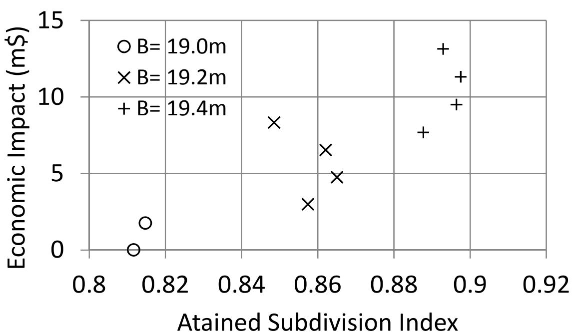

Fig. 8: Economic Impact vs. the SOLAS Index *A*

CONCLUSIONS

The results of damaged stability calculations for a small size ROPAX design, subject to systematic variations of some of its main particulars (beam and depth to the bulkheads deck) were presented.

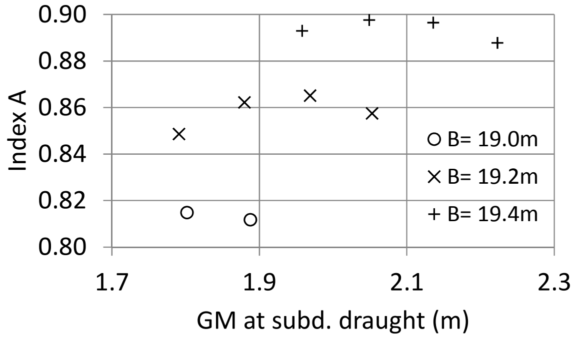

Fig. 9: SOLAS Index *A* vs. *GM* at subdivision draught

Three different formulations for the calculation of *s* factor have been applied: the SOLAS 2009 regulation, the so-called SLF55 formulation and the GOALDS proposal. The results obtained with the three different formulations are very close to each-other. As expected, SLF 55 formulation gave smaller *A* Indices than SOLAS 2009, but their difference was always smaller than 0.015. In addition, due to the similarity of the corresponding formulae for the *s* factor calculation, there is a uniform variation between A_{SOLAS} and A_{SLF55} for the tested RCOs. The difference between A_{SOLAS} and A_{GOALDS} Indices remained between ± 0.008.

The impact of the design variations on ship's survivability and on the associated risk to human life, expressed herein in terms of the Potential Loss of Life, as well as on the ship's building and operational cost has been evaluated, and the effectiveness of the employed RCOs has been assessed by the *GCAF* measure.

The obtained results confirm the conclusion derived by similar studies, elaborated within the GOALDS project, that there is room for a considerable increase of the Required Subdivision Index of passenger ships in comparison with the current SOLAS 2009 requirement.

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