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CONTENTS

List of symbols and abbreviations

EMSA	European Maritime Safety Agency
GZ_{max}	Maximum righting lever
Hs_{crit}	Critical significant wave height
PoB	Persons on Board
RoPax	Ro-Ro passenger ships
SOLAS	Safety Of Life At Sea

EXECUTIVE SUMMARY

In the flooding risk models developed in Projects GOALDS, EMSA III and eSAFE, one the branches address the element of time inherent in a ship loss (fast/slow) and provides an experientially based outcome, which lacks rigorous justification. In addition, experience from using numerical simulation tools to evaluate ship survival in a damaged condition has provided evidence that whilst in RoPax ships static and dynamic evaluation of ship survivability concur, there is marked difference between the two assessments in cruise ships. This is directly relevant to risk estimation as (1-A) is the most significant element in the estimation of PLL. To address these two points, this document provides a summary of the results of numerical (time-domain simulations) and model test results of large passenger ships, including modality of loss in the latter, as documented evidence to support high-level decisions. The results are presented in two forms: (a) statistical characteristics of damage survivability of cruise ships and RoPax in terms of mean and standard deviations based on sample ships, used in various research and commercial projects and (b) the modality of the loss in terms of transient and progressive flooding as derived from time-domain simulations. Additional results from time-domain simulations in WP5 and WP7 will be accounted for in due course.

1 INTRODUCTION

The survivability of large passenger ships in flooding events has been investigated over the past few decades through various EU projects like HARDER [1], GOALDS [2], EMSA II [3], and EMSA III [4,5], and the industry-funded project eSAFE [6]. The results from these projects show that for RoPax ships, the survivability level defined based on the probability of ship capsizing or sinking of actual RoPax ships obtained from the A-index calculations match the numerical results closely. However, such simulation results and comparisons are not widely available for large Cruise ships; the latter are characterised by complex internal layouts, the impact of which on ship survivability cannot be captured by using global parameters such as the maximum righting level and range, pertinent to the residual stability characteristics. As a result, as demonstrated in project eSAFE predictions of survivability by statics appear to underestimate cruise ship survivability.

To address the aforementioned objectives, this work is aimed at collating data on the survivability of ships and present these in an easily accessible form using their mean and standard deviation to provide high level guidance concerning survivability in a collision/grounding accident. In the first instance, the previous projects were revisited to collate the results of survivability of RoPax, and Cruise ships conducted through experiments and numerical simulations. Moreover, the additional numerical results performed in FLARE are also considered.

In addition to the above, a secondary assessment has been conducted in which the results of numerical simulations have been used to better inform certain assumptions that must be made within the simplified FLARE risk model, in particular the time associated with the loss of a ship. Specifically, simulation results pertaining to a number of cruise vessels and RoPax have been utilised in order to better inform the assumed ratio of fast/slow sinking events. This then provides a more rational and a sound basis from which to determine fatalities rates in the calculation of PLL.

The following section summarises and discusses these results in detail.

2 RESULTS AND DISCUSSIONS

2.1 RoPax ships

Figure 1 shows critical significant wave heights (Hs_{crit}) for different GZ_{max} and Range obtained from physical tank testing results of actual ship samples performed in HARDER and GOALDS projects.

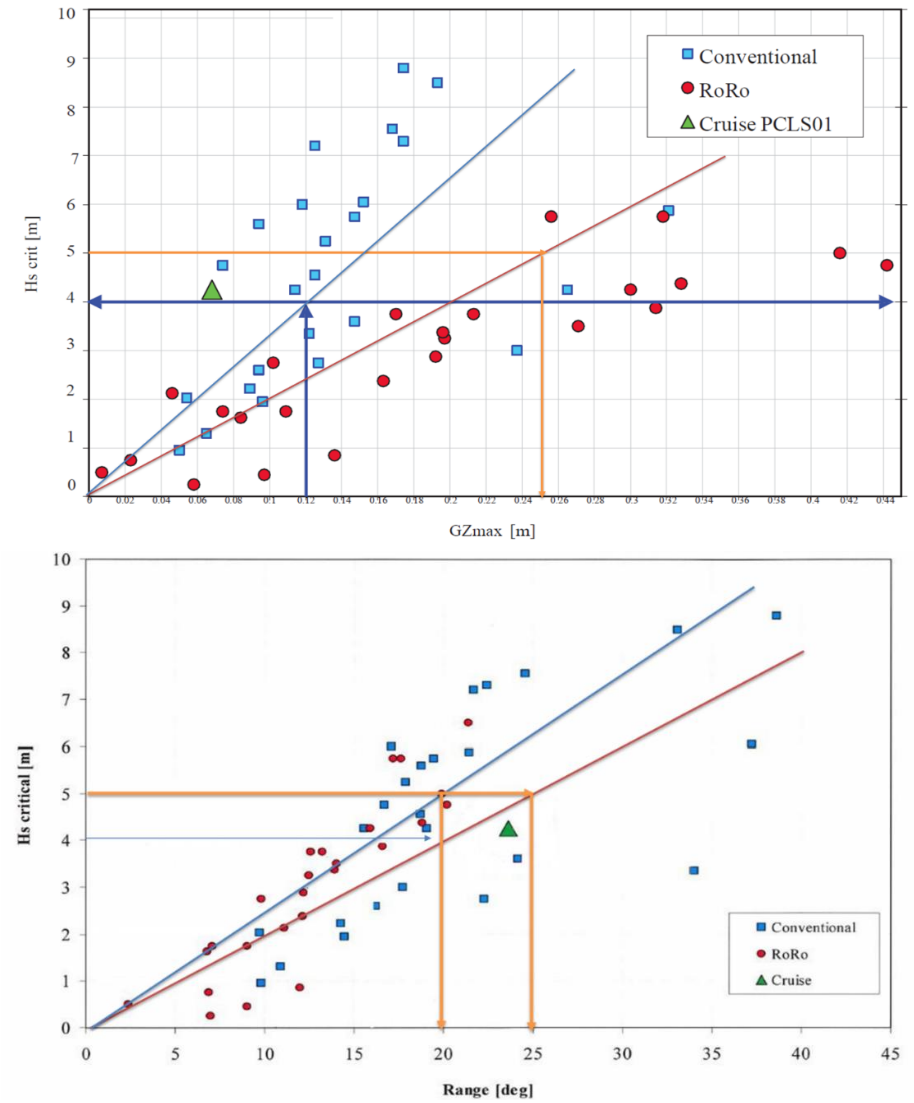

Figure 1. Results of critical significant wave height, Hs_{crit} obtained for different ships - Hs_{crit} Vs. GZ_{max} (top)and Hs_{crit} Vs. Range (bottom)

The survivability index (s) is derived from the critical significant wave height (H_{scrit}) using relation (1) next:

$$s = exp(-exp(0.16 - 1.2 \cdot H_{Scrit})) \quad (1)$$

Table 1 lists *the* resulting survivability index values of 24 RoPax ships. This *includes a numerical simulation result conducted in FLARE, i.e., 0.89, close to the mean value of 0.87 calculated from the HARDER and GOALDS test results. Figure 2 shows the resulting survivability levels obtained, including the results from the FLARE project. Based on the normal distribution assumed, the mean and standard deviation are 0.875 and 0.174, respectively.*

Table 1. Summary of survivability index of RoPax ships obtained from tank tests and numerical simulations

Ship	**Source**	**Test/ Numerical**	**Survivability index**
ref1	HARDER and GOALDS	Test	0.419
ref2	HARDER and GOALDS	Test	0.503
ref3	HARDER and GOALDS	Test	0.527
ref4	HARDER and GOALDS	Test	0.623
ref5	HARDER and GOALDS	Test	0.658
ref6	HARDER and GOALDS	Test	0.851
ref7	HARDER and GOALDS	Test	0.868
ref8	HARDER and GOALDS	Test	0.870
ref9	FLARE	Numerical	0.890
ref10	HARDER and GOALDS	Test	0.916
ref11	HARDER and GOALDS	Test	0.935
ref12	HARDER and GOALDS	Test	0.960
ref13	HARDER and GOALDS	Test	0.964
ref14	HARDER and GOALDS	Test	0.978
ref15	HARDER and GOALDS	Test	0.981
ref16	HARDER and GOALDS	Test	0.983
ref17	HARDER and GOALDS	Test	0.988
ref18	HARDER and GOALDS	Test	0.988
ref19	HARDER and GOALDS	Test	0.990

ref20	HARDER and GOALDS	Test	0.993
ref21	HARDER and GOALDS	Test	0.994
ref22	HARDER and GOALDS	Test	0.996
ref23	HARDER and GOALDS	Test	0.997
ref24	HARDER and GOALDS	Test	0.999
ref25	HARDER and GOALDS	Test	0.999

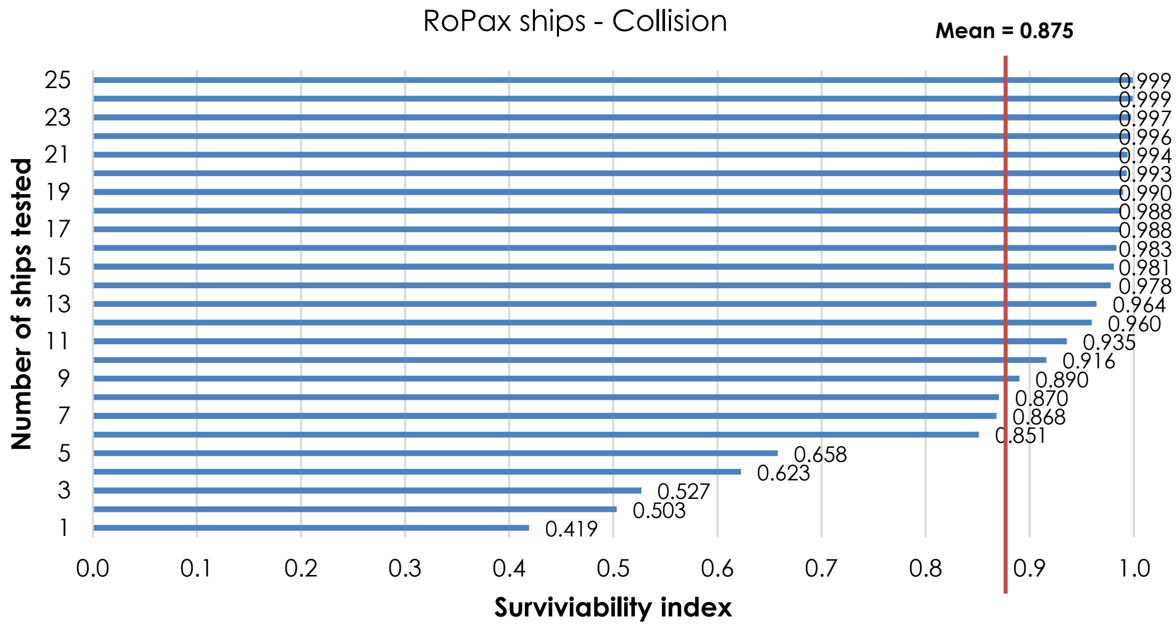

Figure 2. Survivability of RoPax ships obtained from the tank test and numerical results (mean value = 0.875).

All the above results were obtained for RoPax ships involved in collision events; however, no grounding results were available for RoPax. This will be updated once we have completed the numerical simulations in FLARE WP7.

2.2 Cruise ships

Figure 3 compares the results of static and dynamic survivability calculations from A-index calculations and survivability based on numerical simulations of different Cruise ships, respectively. It shows that the actual survivability is generally higher than that shown by the Attained index or SOLAS 2009/SOLAS 2020 formulations. The mean and standard deviation of the survivability based on numerical simulations of 10 Cruise ships of different sizes were found to be 0.96 and 0.032, respectively, which is on average 12% higher than those calculated using static Attained index calculations. This shows that the actual survivability is underestimated by the Attained Index A or SOLAS calculations for Cruise ships.

Table 2 lists the results of survivability levels of Cruise ships obtained from numerical simulations of sample ships, which also includes a test result conducted in HARDER and GOALDS projects. In addition, Tables 3 and 4 show the same results for the bottom and side grounding, respectively, obtained primarily from eSAFE and FLARE projects. *Figure 4* summarise the mean and standard deviation of collision, side and bottom grounding. The survivability is highest for bottom grounding (0.996) and lowest for collision (0.969) hazards. The standard deviation is highest for collision, probably due to a large number of ships of different sizes that have been considered for collision compared to side and bottom grounding.

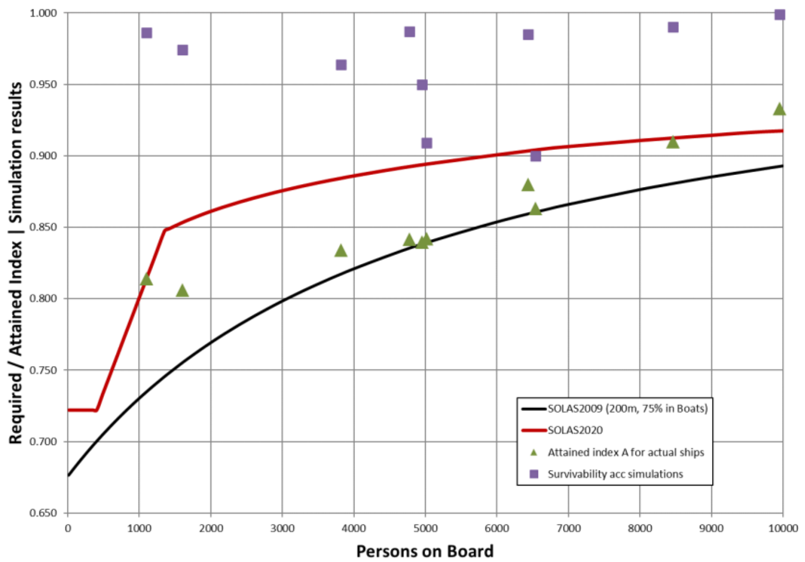

Figure 3. Comparison of survivability levels using Attained index A, SOLAS 2009/2020, and numerical simulations of actual ships.

Table 2. Survivability levels of actual Cruise ships obtained from numerical simulations and test result - collision

Ship	Source	Test/Numerical simulation	Survivability index
ref1	eSAFE	Numerical	0.95
ref2	eSAFE	Numerical	0.985
ref3	eSAFE	Numerical	0.99
ref4	eSAFE	Numerical	0.964
ref5	eSAFE	Numerical	0.999
ref6	eSAFE	Numerical	0.9
ref7	eSAFE	Numerical	0.986

ref8	eSAFE	Numerical	0.974
ref9	FLARE	Numerical	0.909
ref10	FLARE	Numerical	0.987
ref11	HARDER and GOALDS	Test	0.993
ref12	eSAFE	Numerical	0.991
ref13	eSAFE	Numerical	0.969

Table 3. Results of survivability levels of sample Cruise ships subjected to bottom grounding

Ship	Source	Survivability index
ref1	FLARE	0.9975
ref2	FLARE	0.9927
ref3	eSAFE	1
ref4	eSAFE	0.992

Table 4. Results of survivability levels of actual Cruise ships subjected to side grounding

Ship	Source	Survivability index
ref1	FLARE	0.968
ref2	eSAFE	0.995
ref3	eSAFE	0.9625

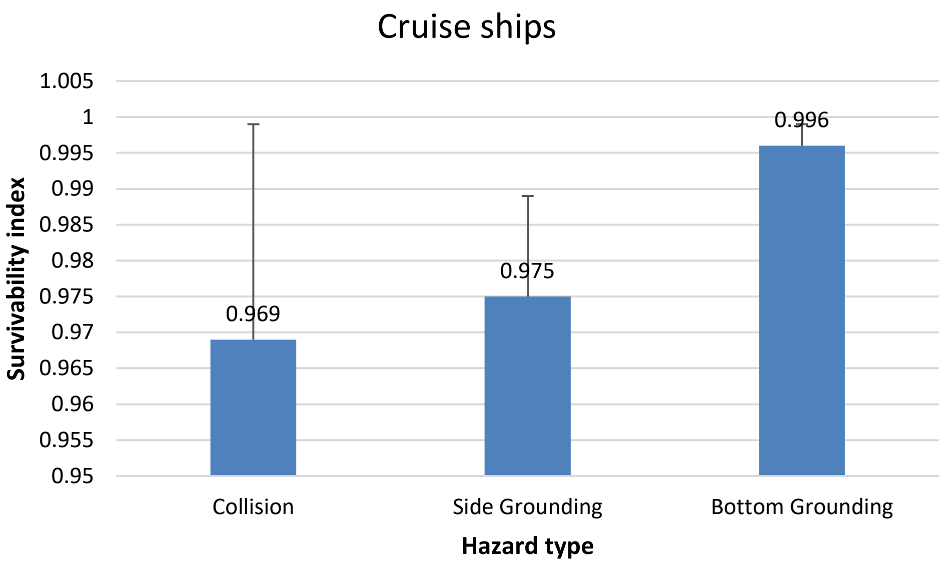

Figure 4. Mean and standard deviation of survivability levels of Cruise ships for three hazards - collision, side grounding, and bottom grounding

2.3 Comparison with previous projects

Figure 6 compares the FLARE-derived survivability index to that used in GOALDS and EMSA III risk models for RoPax involved in a collision accident. As can be seen, the survivability of RoPax ships obtained from the numerical/test results in FLARE is higher than in previous projects, especially in comparison with the GOALDS project, where the reference in the Attained index is SOLAS 2009 ships.

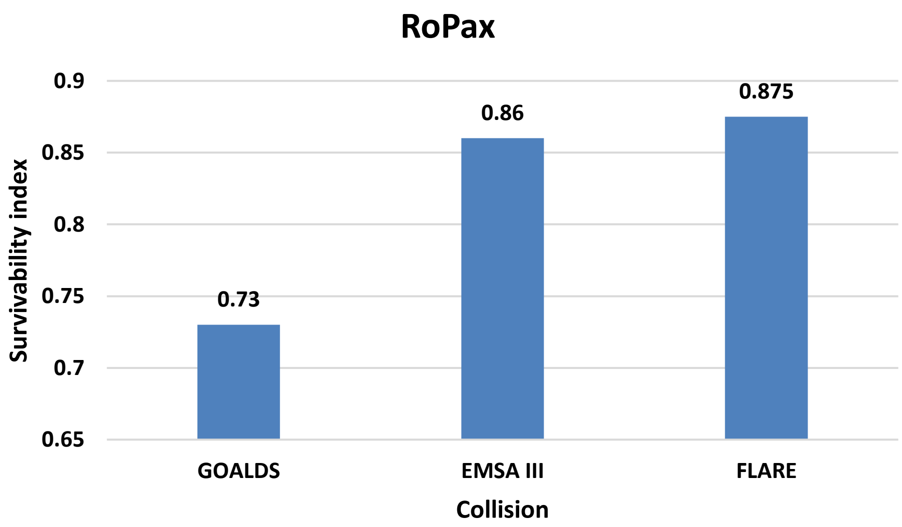

Figure 5. Comparison of survivability levels of FLARE to that used in GOALDS and EMSA III risk models

Figure 6 shows the comparison of the results derived in th the FLARE project to those used in GOALDS and EMSA III risk models for a Cruise ship involved in collision, side grounding, and bottom grounding. Again, the same trend as observed in RoPax ships can be seen here, while the difference is more significant, demonstrating once again the continuous improvement in the damage survivability of newer designs. Moreover, Cruise ships are characterised by complex internal architecture, which produces larger uncertainties in the calculation of survivability using a simplified statistical method, as represented by the Attained index used in the previous projects. Moreover, the survivability of Cruise ships in grounding is higher than collision, as observed in tanks tests performed in GOALDS, however, this difference becomes marginal in FLARE. In contrast, in EMSA III, the calculated survivability of the grounding is the lowest among all.

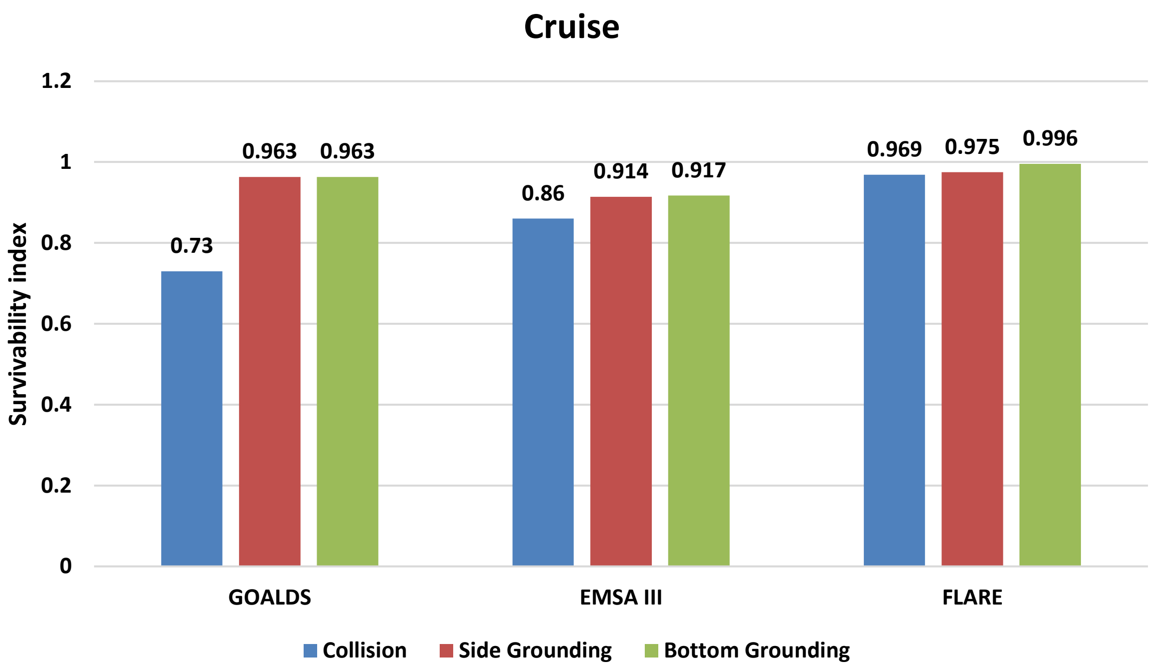

Figure 6. Comparison of survivability levels of FLARE to that used in GOALDS and EMSA III risk models – collision, side grounding and bottom grounding.

2.4 Determining Fast/Slow Ratio Based on Flooding Simulation Results

A further investigation has been conducted looking into the use of flooding simulation results as a means of informing certain assumptions that must be made within the simplified FLARE flooding risk model. One of the greatest weaknesses within existing flooding risk models is the requirement to assume a given ratio of fast to slow sinking events. This derives from the fact that simplified risk models are driven by the results of static damage stability analysis, which do not account for the element of time. However, it stands to reason that the degree of error in this approach could be significantly reduced by utilising flooding simulations to inform reasonable values relating to the expected degree of fast/slow sinking events. This is a highly important parameter as it dictates the fatality rate and, as such, bears great influence over the PLL value calculated.

The scope of this investigation has, at present, been limited to collision damage events due to a lack of available data regarding side and bottom grounding damages, which would not allow any meaningful results to be derived. In total, five cruise vessels and one RoPax have been analysed, though it is hoped to expand this number as and when simulation results become available from WP5 and WP7. This will allow the ratio of fast/slow sinking events to be distinguished by ship type, and perhaps even size, depending on the variation observed. In the simulation, 10 minutes is considered as the dividing line to differentiate fast and slow sinking (in fact in most cases it is less than 5 minutes) but either way no evacuation can take place within such times.

The results of the above process are summarised in Table 5 and Figure 7 below. Here, we can observe a reasonable correlation in the ratio of transient/progressive flooding losses observed in each case. The average of these values has then been used in order to provide weighting factors for use in the simplified FLARE risk model, resulting in a factor of 0.79 for fast sinking and 0.21 for slow sinking. However, more reasonable values of 0.8 and 0.2 are recommended, which lead to a maximum error of 9.27%.

Table 5. Transient/progressive flooding capsize ratios based on flooding simulation results

ID	PoB	Survivability Index	Transient Capsize Cases	Progressive Flooding Capsize Cases	Transient Capsize %	Progressive Flooding Capsize %
CV 1	9950	0.999	25	9	73.53	26.47
CV 2	1100	0.986	17	3	85	15
CV 3	1600	0.974	30	10	75	25
CV 4	5020	0.909	110	26	80.88	19.12
RoPax 1	2400	0.89	116	48	70.73	29.27
CV 5	4773	0.987	19	3	86.36	13.64
				Average	78.58	21.42

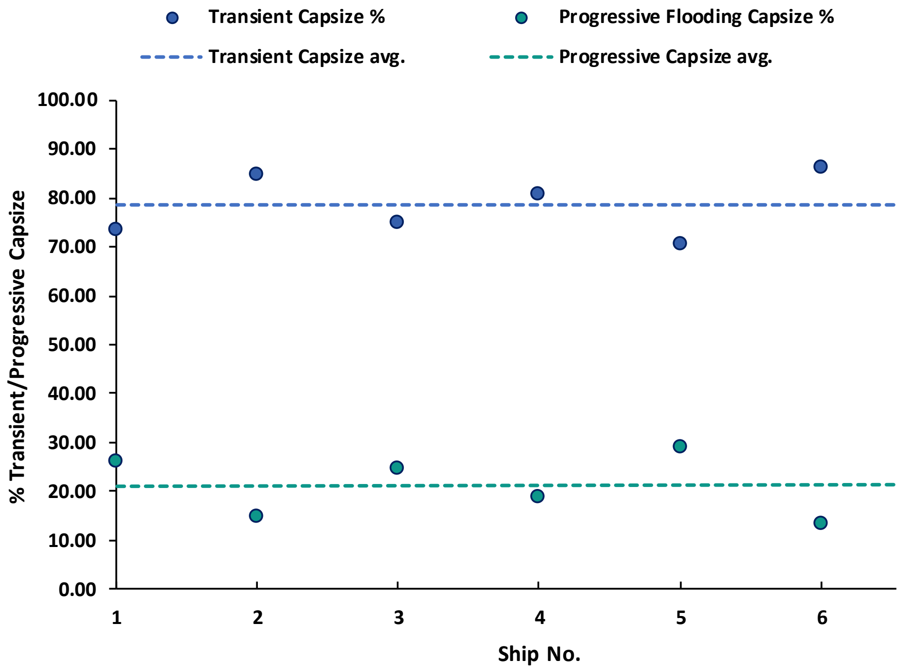

Figure 7. Transient/progressive flooding capsize ratios based on flooding simulation results

2.5 Conclusions and Recommendations

This study provides results from sample ships used in various research projects over the past two decades pertaining to the survivability of large RoPax and Cruise ships, supplemented by results from the FLARE project. The calculation of survivability using A-index as proposed by SOLAS 2009 is focussing on global ship parameters; hence it cannot capture the detailed geometric features present in large passenger ships with sufficient detail to adequately differentiate between designs. With the development of technologies and computational resources, the emphasis should be placed on the numerical examination of survivability. The results presented in this study could be utilised in high-level risk models and direct flooding risk assessment developed in WP5.

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