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Impact Assessment of Wave Statistics on Ship Survivability

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Abstract

This paper presents a brief summary of the work conducted by the MSRC at Strathclyde University in which the effect of operational location on the estimation of a vessel's survival probability has been investigated and new s-factor formulations proposed. Further work is presented in which updated accident wave statistics have been used in order to assess the impact of vessel specific data on the predicted survivability. A test case on a large container ship has been conducted in order to gauge the effect of the new s-factor formula on the Attained Subdivision Index and thus the vessel safety level with regards to collision damage.

Keywords: Survivability, Damage Stability, Probabilistic framework, s-factor.

1. Introduction

Accurate estimation of survivability is of paramount importance when assessing ship damage stability performance. Survivability is influenced by a multifarious range of parameters all of which are situational dependant; however, at the highest level, survivability can be viewed as an outcome involving both the post-damage restoring properties of the vessel and the prevailing sea state.

The current IMO instrument for conducting damage stability assessment and thus estimating survivability is the probabilistic framework outlined in SOLAS 2009 [1]. At the heart of this approach is the so called s-factor which accounts for the probability of a vessel surviving a given damage scenario in waves. In this case, survivability in waves refers to a distribution of wave heights formed based on recorded accident sea states at the time of collisions. This assumption, therefore, fails to directly account for the influence of operational area on survivability and more alarmingly implies that a vessel's survivability is independent of its operational environment. Furthermore, as the accident data used in the creation of the distribution of wave heights behind the SOLAS s-factor comprised of accident data relating to all ship types, it fails to account for the influence of ship specific data.

This paper aims to shed some light on the influence such parameters have on survivability. A new distribution of wave heights is derived comprising specifically vessel accident data and a new s-factor formulation is proposed. The impact of operational location on survivability is also assessed by using trade region specific significant wave height distributions to create new s-factor formulations for four key ship trade regions. Finally, the influence of the newly proposed s-factor formulations on the Attained Subdivision Index is assessed through conducting a test case on a large container ship.

2. The s-factor

The "s-factor" is a core component of the probabilistic damage stability framework, known commonly as SOLAS 2009 (IMO 2006), and is a measure of a damaged ships' survivability in waves.

With the assumption, as in SOLAS, that only H_s has bearing on the survivability and neglecting other environmental factors such as spectral shape, the probability of a ship surviving collision damage that has led to hull breach and flooding can be determined by application of total probability theorem as (Jasionowski 2009):

$$s_i = \int_0^\infty dH_s \cdot f_{Hs|Coll}(H_s) \cdot F_{surv}(H_s) \tag{1}$$

Where: $f_{H_s|coll}(H_s)$ is probability density distribution of sea states expected to be encountered during collision and $F_{surv}(H_s)$ is the survival probability when a vessel is subjected to a given damage case and exposed to a sea state characterised by significant wave height H_s.

The development of the s-factor was based largely on the findings of the EU research project HARDER (Tuzcu 2003) in which model tests were conducted with a limited exposure time of 30 minutes and thus the probability of survival, as it exists in SOLAS 2009, is in fact a conditional probability (Cichowicz 2016):

$$F_{surv}(H_s) \equiv F_{surv}(t = 30min|H_s) \tag{2}$$

This leads to the following expression of the survival probability:

$$s_i(t = 30\text{min}) = \int_0^\infty dH_s \cdot f_{H_s|coll}(H_s) \cdot F_{surv}(t = 30min|H_s) \tag{3}$$

One of the key underlying assumptions in SOLAS 2009 is that, for a given damage case, there exists a critical significant wave height H_{Scrit} such that a vessel damaged in a sea state relative to this parameter will always survive for lower H_s and always capsize for higher H_s. This theory has its roots in what is known as the capsize band (Tsakalakis 2010) which represents the range of sea states in which the capsize probability transitions from unlikely to certain, often represented by a sigmoid curve as in Figure 1 (Vassalos 2015).

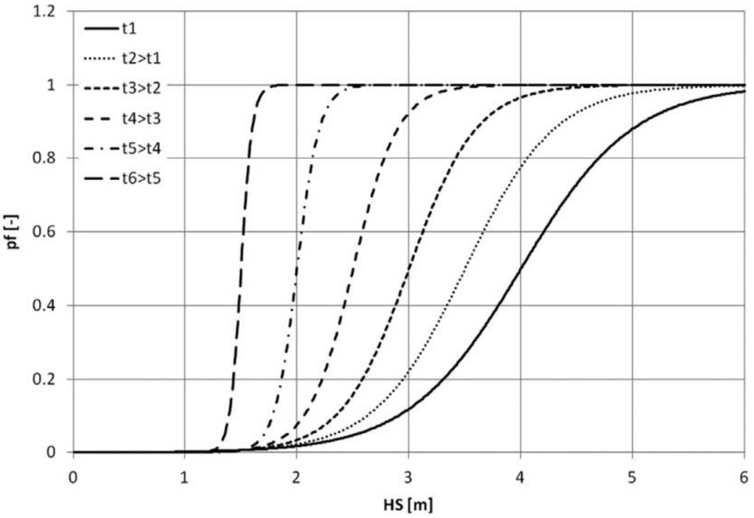

Figure 1: Example of capsize band represented by sigmoid curve and with varying observation time

H_{Scrit} is defined as the sea state at which a ship in a given loading condition and a specified damage case is exposed to the action of beam random waves for 30 minutes would have a 50% chance of survival (Tsakalakis 2010). Drawing on this, the survival probability for a specified loading condition and damage case when exposed to a given sea state for 30 minutes and could be approximated by a step function centred on the sea state H_{Scrit} (Cichowicz 2016).

$$F_{surv}(H_s) = \begin{cases} 1 \Leftrightarrow H_S \leq H_{Scrit} \\ 0 \Leftrightarrow H_S > H_{Scrit} \end{cases} \tag{4}$$

This is essentially the limiting case of the capsize band concept and substituting 4 into 3 leads to:

$$s_i = \int_0^{H_{Scrit}} dH_s \cdot f_{H_s|coll}(H_s) = cdf_{H_s}(H_{Scrit,i}) \tag{5}$$

The distribution of wave heights utilised in the formation of the SOLAS s-factor, Figure 2, was produced during project HARDER following statistical analysis of sea states encountered during collision accidents and comprising 389 recorded incidents (Jasionowski 2009).

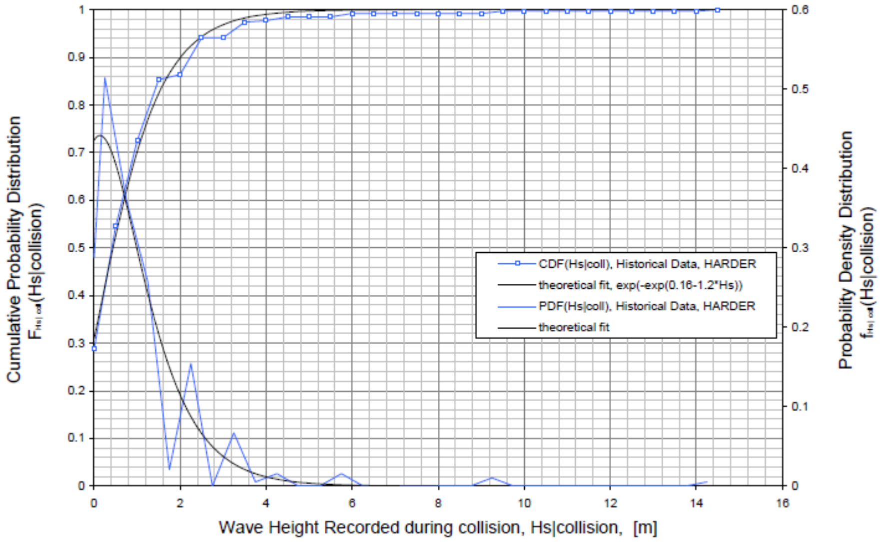

Figure 2: Accident wave statistics CDF

Following regression of the statistical distribution of sea states with respect to H_{Scrit} the s-factor could be expressed as:

$$s_i = \Pr\{H_s \leq H_{s,crit,i}\} = exp^{-\exp(0.16-1.2H_{s,crit,i})} \tag{6}$$

Where $H_{s,crit}$ is given as:

$$H_{scrit}|t = 30min = 4\left(\frac{\min(GZmax, 0.12)}{TGZmax} \cdot \frac{\min(range, 16)}{TRange}\right) \tag{7}$$

Based on the HARDER findings in which three dimensional regression was used to correlate the mean survival sea states experienced during model testing of specific damage scenarios (worst 2-compartment damage case) to GZmax and GZRange stability parameters and where TGZmax and TRange where defined as 0.12m and 16deg respectively, based on the best fit correlation (Tuzcu 2003).

The s-factor formula in its commonly known format and as expressed in SOLAS 2009 was also derived during project HARDER, where a combined formulation for predicting the survival probability was derived by using the individual model test survival sea states multiplied by the probability of sea state occurrence and then regressing a GZ-based formula to this data producing the following:

$$s = K \cdot \left(\frac{\min(GZmax, 0.12)}{0.12} \cdot \frac{\min(range, 16)}{16} \right)^{0.25} \qquad (8)$$

3. Trade region specific S-factor

As was discussed in the previous section, within the probabilistic damage stability framework the s-factor is intended to represent the probability of surviving a given damage scenario in waves. It therefore combines:

- The restoring capabilities of the vessel and thus its ability to survive in waves.
- The assumed distribution of sea states.

Through using the "critical significant wave height" concept, which is a conditional parameter, survivability is measured based on both the post damage stability properties of the vessel in a given damage scenario, which define $H_{s,crit,i}$ for that scenario and the distribution of sea states, which allows the s-factor to be determined as the likelihood the survival sea state, $H_{s,crit,i}$, will not be exceeded at the time of collision (again for that specific scenario).

During project HARDER it was asserted that there exists a certain range of sea states in which collision accidents occur and hence accident wave statistics were used in order to define the sea state distribution behind the SOLAS s-factor. However, such an assumption implies that a vessel's survivability is independent of its area of operation, meaning that two identical vessels when subjected to the same damage scenario have the same probability of survival even if one is located in the North Atlantic (0m≤Hs≤9m) and the other in the Mediterranean (0m≤Hs≤5m). This cannot be the case.

In order to capture the influence of operational area on survivability it is proposed to use localised wave distributions as a basis for trade region specific s-factor formulations. As such, four key ship trade regions have been selected for assessment including the North Atlantic (NA), Caribbean (CAR), Southeast Asia (SA) and the Mediterranean (MED) . For each location, average annual wave statistics (Dacunha 1986) have been collated and the corresponding cumulative distribution of significant wave heights, $cdf_{H_s}(H_S)$ has been fitted to the data using the following function form:

$$cdf_{H_s}(H_S) = \exp(-exp(\alpha - \beta \cdot H_s)) \qquad (9)$$

Where α and β are regression coefficients based on trade region.

In addition, Global annual wave statistics have also been assessed for comparison purposes. The results of this process are summarised in table 1 and figure 3 below.

Table 1: Trade region specific regression coefficients

Trade Region	Regression Coefficients
Caribbean	Alpha=1.8880, beta=1.2035
Mediterranean	Alpha=1.1780, beta=1.1320
Southeast Asia	Alpha=1.2622, beta=1.2280
Global annual	Alpha=1.1717, beta=0.9042
North Atlantic	Alpha=1.9179, beta=0.7383

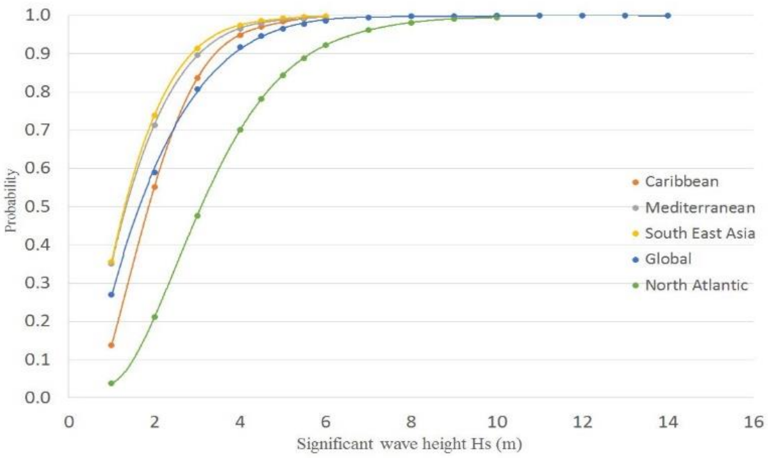

Figure 3: Accident wave statistics CDF

The survivability within each trade region can then calculated using the following formulation:

$$s_i = \Pr\left\{H_s \leq H_{s,crit,i}\right\} = exp^{-\exp(\alpha - \beta H_{s,crit,i})} \tag{10}$$

Where α and β are the trade region-specific regression coefficients.

3.1. Estimating Critical Significant Wave height

During project HARDER the regression formula for estimating $H_{s,crit}$ based on both GZmax and Range parameters was limited to Hs=4m and for this reason it cannot be applied, in its current form, to the trade regions where the probable significant wave height exceeds this value, i.e. the North Atlantic where Hs=9m has been recorded. Instead a formula in the same format as (7), has been produced for each trade region through three dimensional regression of the surface produced from the HARDER model test results which links Range and GZmax to the survival sea state, shown in Figure 4. In each case the regression has been limited to the Hs which constitutes the 99th percentile significant wave height within each trade region.

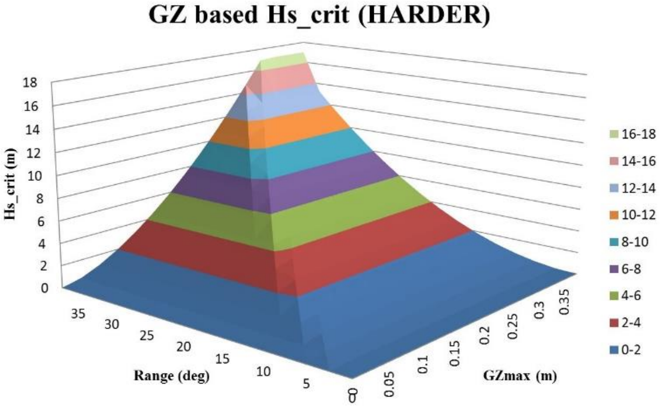

Figure 4: GZ-based Hs_crit

It should be noted that the prediction of the critical significant wave height, for a given damage case, is independent of trade region, however, regional specific $H_{s,crit,i}$ formulations have been derived in order to facilitate the creation of GZ-based trade region specific s-factor formulations. The results of this process are summarised below along with the regression accuracies:

Table 2: Summary of region specific Hscrit formulations

CAR	$H_{s_{crit}} = 6 * \left(\frac{\min\,(\text{GZmax, TGZmax})}{0.19m} \cdot \frac{\min(\,\text{Range, TRange})}{25deg}\right)$
MED	$H_{s_{crit}} = 5 * \left(\frac{\min\,(\text{GZmax, TGZmax})}{0.16m} \cdot \frac{\min(\,\text{Range, TRange})}{23deg}\right)$
SEA	$H_{s_{crit}} = 5 * \left(\frac{\min\,(\text{GZmax, TGZmax})}{0.16m} \cdot \frac{\min(\,\text{Range, TRange})}{23deg}\right)$
GLO	$H_{s_{crit}} = 6 * \left(\frac{\min\,(\text{GZmax, TGZmax})}{0.19m} \cdot \frac{\min(\,\text{Range, TRange})}{25deg}\right)$
NA	$H_{s_{crit}} = 9 * \left(\frac{\min\,(\text{GZmax, TGZmax})}{0.21m} \cdot \frac{\min(\,\text{Range, TRange})}{38deg}\right)$

Table 3: Summary of regression accuracy

Highest overestimate	Lowest Underestimate	Mean error	Sum of Squares
0.85	-1.03	0.1289	7.092
1.06	-1.18	0.10398	13.337
1.18	-0.955	-0.146	11.849
1.18	-0.955	-0.146	11.849
1.06	-1.18	0.10398	13.337
1.23	-1.553	0.0762	21.442

3.2. GZ-based combined s-factor formula

Combined s-factor formulations for each trade region in a similar format to that proposed in HARDER have also been derived. Assuming that the true survivability can be estimated using (10), a surface relating survivability to both GZmax and Range has been produced on a finely discretized grid of combinations $(GZ_{max}, Range)$ as shown in Figure 5.

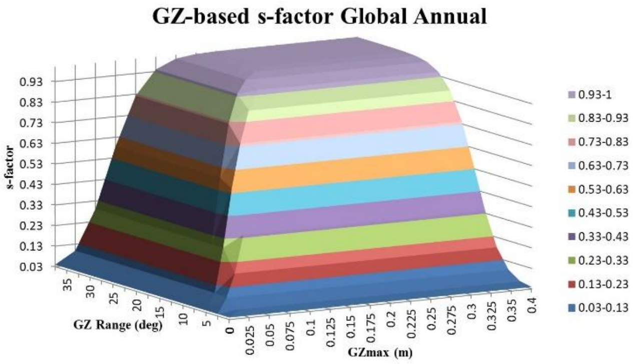

Figure 5: GZ-based s-factor

GZ-based s-factor formulations have then been created for each trade region through performing three dimensional regressions to the region specific surfaces linking survivability to stability parameters in the following format:

$$s = \left(\frac{H_{s,crit}}{H_{s,lim}}\right)^x = \left(\frac{\min(GZmax, TGZmax)}{TGZmax} \cdot \frac{\min(Range, TRange)}{TRange}\right)^x \tag{11}$$

Where $H_{s,lim}$ is the region specific 99th percentile Hs, $TGZmax$ and $TRange$ are the region-specific limiting stability parameters and x is an exponent based on the best fir correlation. The results of this process are provided below along with the regression accuracies:

Table 4: Region specific s-factor formulations

CAR	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.19m} \cdot \frac{\min(\text{Range}, \text{TRange})}{25deg}\right)^{0.7}$
MED	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.16m} \cdot \frac{\min(\text{Range}, \text{TRange})}{23deg}\right)^{0.6}$
SEA	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.16m} \cdot \frac{\min(\text{Range}, \text{TRange})}{23deg}\right)^{0.6}$
GLO	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.19m} \cdot \frac{\min(\text{Range}, \text{TRange})}{25deg}\right)^{0.6}$
NA	$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.21} \cdot \frac{\min(\text{Range}, \text{TRange})}{38deg}\right)^{0.9}$

Table 5: Regression Accuracy

Highest overestimate	Lowest Underestimate	Mean error	Sum of Squares
0.164	-0.225	0.023	0.9
0.09	-0.167	-0.018	0.478
0.099	-0.194	-0.024	0.616
0.097	-0.15	-0.009	0.543
0.103	-0.25	-0.019	0.55

4. Derivation of ship specific databases

The current SOLAS 2009 s-factor formulation utilises wave statistics based on the average significant wave height encountered during recorded accidents for all vessels and as such fails to distinguish between ship type. As an alternative, a new method is proposed in which ship specific accident data is utilised. In the following an example of this process is provided in which a new accident database namely Accidents at Sea Database (ASD) is derived comprising of passenger vessel data only and using weather data in order to fill information gaps.

A total of 129 accidents have been collated into a comprehensive list comprising exact accident location, time, description of the accident, name of the vessel and their IMO number. As shown in Figure 6, two passenger ship types have been considered that have been involved in a total number of 50 groundings and 79 collisions. Most of the accidents took place at open sea with only 18% close to estuaries or coastal waters. The accidents have occurred in a period spanning from 2005 to 2016.

129 Accidents			
50 Groundings		**79 Collisions**	
16 Cruise ships	**34 RoPax**	**24 Cruise ships**	**55 RoPax**

Figure 6: Database summary

The information was, however, incomplete and as such the environmental conditions at the time of the accidents were inadequate. In order to fill this information gap, accident time and date information was used to identify the significant wave height and average periods experienced during each recorded accident. For this purpose, a number of wave databases (BMT 2016) were utilised and the significant wave height at the exact time of the accident was obtained. The online data comprises wave height measurements for all days at increments of three hours taken over a 10-year period for each of the locations the accidents occurred. Knowing the date, time and location of each accident, the significant wave height could be found in each case. In cases where the time of the accident did not coincide with the time of a wave height reading, the value was estimated as the average between the two closest time points.

Using the same approach as in the previous section, a curve has been fitted to the data of the functional form as outlined in (9) producing the formula as shown in (12) and the CDF as presented in Figure 7.

$$CDF(H_s) = e^{-e^{(0.6887-1.1958\times H_s)}} \tag{12}$$

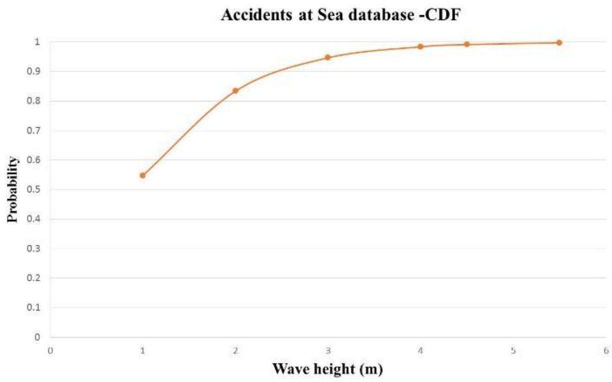

Figure 7: Accident Based Distribution of Wave Heights

Based on the wave height CDF the survivability according to the updated accident database can be expressed as:

$$s_i = \Pr\{H_s \leq H_{s,crit,i}\} = e^{-e^{(0.6887-1.1958H_s)}} \tag{13}$$

As previously, a formula for predicting the critical significant wave height can be derived through regression, this time limited to Hs=4.5m, that being the significant wave height which constitutes the 99th percentile within the distribution. The resultant expression for $H_{s,crit,i}$ is as follows:

$$H_{s_{crit}} = 4.5 * \left(\frac{\min\,(\text{GZmax}, \text{TGZmax})}{0.16m} \cdot \frac{\min(\text{Range}, \text{TRange})}{20deg}\right) \tag{14}$$

With the following regression accuracy:

Sum of squares:	7.092
Mean error	0.1289 m
Highest over estimate	0.85 m
Lowest underestimate	1.03 m

A combined formulation for predicting the survival probability can then be found through regression conducted according to the previously outlined methodology, producing the following s-factor formula:

$$s = \left(\frac{\min(\text{GZmax}, \text{TGZmax})}{0.16m} \cdot \frac{\min(\text{Range}, \text{TRange})}{20deg}\right)^{0.4} \tag{15}$$

5. Impact on Attained subdivision Index

The extent of the ultimate impact on the safety level has yet to be determined. To this end, a large container ship has been subjected to a probabilistic damage stability assessment, the results of which have been used in combination with the aforementioned survivability formulae to determine the Attained Index in each case. This provides the conditional probability of the ship surviving collision damage and as such is a measure of the ship's safety level in this respect. The results of the assessment are summarised in figure 9 below:

Table 6: Main particulars

Length Overall (LOA)	196.6 m
Length between perpendiculars (LBP)	185 m
Breadth (B)	32 m
Draught (T)	9 m
Subdivision length	192.42 m
Subdivision draught	9 m

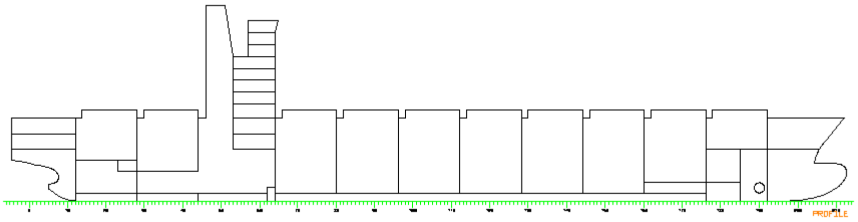

Figure 8: Vessel profile

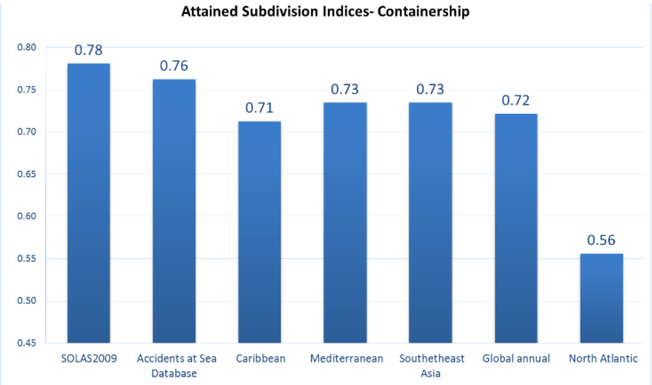

Figure 9: Trade Region Specific Attained Index Comparison

A decrease is marked in the Attained Index of each case when compared to SOLAS 2009. In the case in which North Atlantic wave statistics were used, the Attained Index decreased significantly by 28%. This highlights the stringency and impact of very high waves on vessels. Similarly, the use of Caribbean wave statistics yielded a reduction of 9%, whilst, the Accidents at Sea Database statistics almost a 2% decline. The Attained index obtained for the Accidents at Sea Database is 6% higher than the global annual statistics, which implies that the significant wave heights experienced during accidents are in fact less severe than the global statistical average.

In summary the results show that the wave statistics utilised in the determination of the survival probability hold a large influence over the magnitude of the final Attained indices. More significantly, A-Indices linked to specific operational areas could be derived to reflect survivability of the vessel linked to the operating environment.

6. Conclusions

In light of the findings of the work reported in this paper, it can be drawn that it is possible to generate trade region specific s-factor formulations using local wave statistics and assess their impact on survivability. Also, the current SOLAS s-factor through failing to account for area of operation appears to overestimate survivability through lack of consideration of the probability of wave heights being less than the critical wave height (4m). As it has been shown, weather data records can be used in order to fill information gaps for incidents in which the sea state at the time of accident was previously unknown. Additionally, passenger ship-specific accident data can be employed in order to derive ships specific s-factor formulation that better accounts for this ship type and accounts for the passenger ship trends. Using an updated ship specific accident database, the distribution of wave heights used in the formation of the SOLAS s-factor has been shown not to provide ample coverage of all wave heights experienced. As a result of the above, SOLAS overestimates the survivability in comparison to the updated database and a more accurate estimation of ship survivability can be made through utilising localised wave statistics.

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