A GENERAL FRAMEWORK OF NEW SUBDIVISION REGULATIONS

Maciej Pawłowski
Technical University of Gdansk, Poland, mpawlow@pg.gda.pl

ABSTRACT

A general framework of the probabilistic subdivision regulations is presented, highlighting the fact that indices of subdivision are the same as the mean conditional probability of collision survival, known as the s factor. Rules for averaging this factor are discussed. Finally, a link between the indices of subdivision and the mean sea state the ship can survive is highlighted. This link may help with the selection of the required values for the indices.

Key words: subdivision regulations, framework

1. INTRODUCTION

As is well known, many factors affecting the final consequences of ship hull damage are random in nature and their influence is different for different ships. For this reason probability of collision survival is taken as a measure of ship safety in the damaged condition (e.g., a measure of merit of a ship's subdivision).

A relatively rigorous procedure for dealing with this concept was first presented by Kurt Wendel in 1960 [1] who initiated this novel approach to the evaluation of subdivision. The idea appeared to catch on and was later developed by Comstock and Robertson [1], Volkov [3], Wendel [4], and the IMO, which resulted in establishing and adopting the equivalent regulations for passenger ships [5], discussed thoroughly by Robertson [6]. In the 1980s and 1990s IMO continued this work resulting in the new regulations for dry cargo ships [6]. Both of these regulations are based on the probabilistic concept as they take the probability of collision survival as a measure of ship's safety in the damaged condition. In the new regulations, this probability is referred to as the *attained subdivision index A*.

Generally, three measures of that kind can be postulated for judging the effectiveness of a ship's subdivision:

- O v e r a l l (global) index of subdivision, reflecting the *average* degree of subdivision for the whole ship that denotes a mean probability of survival for the whole ship in case of accidental flooding, and
- L o c a l indices of subdivision of two kinds (not in use in the regulations yet), reflecting the degree of subdivision for individual parts of the ship. They denote mean probabilities of survival either for the cases of flooding in which a given (wing, if any) compartment is flooded, or in which a given transverse bulkhead is involved. For this reason we talk about *one-compartment indices* of subdivision and *minor damage indices*. The formers express the so-called one-compartment standard on the ground of the probabilistic concept, while the latter, a two-compartment standard, so regarded by the practitioners.

The philosophy behind the probabilistic concept is that two different ships with the same index of subdivision have equal *overall* safety with respect to flooding, although these ships may have quite different actual capabilities for withstanding damage in some parts of their length. Different capabilities along the length occur, particularly in cases with relatively low values of *A*-indices. To prevent such a situation, the basic requirement regarding the level of the attained *global* index of subdivision should be supplemented by a requirement regarding the distribution of the index along the ship's length, so that no part of the ship is left with unacceptable vulnerability to flooding.

Due to psychological reasons, protection against local vulnerability is equally as important as overall safety – for passenger ships in particular. Ideally, the ability of any part of the ship to survive damage measured in the form of a *partial* or *local* subdivision index, defined later, should be the same throughout the ship length, but this is rather difficult to achieve. As in the case of the overall index, the rules should set a standard for the minimum value of the local index, best as a fraction of the required value of the global index. On the other hand, insofar as practicable, the regulations should not impose unnecessary design restrictions, therefore in the case of cargo ships this requirement might be largely relaxed.

In view of the probabilistic nature of the rules it can be argued that there is no need for special treatment of either certain parts of the ship or for the prescribed size of damage. The only parts of the ship that may be given special attention are the forward part and the bottom part, to provide for the cases of ramming and stranding, and these are dealt with by special rules in the new regulations.

2. OVERALL INDEX OF SUBDIVISION

In order to develop the probabilistic concept of subdivision, it must be assumed that the ship is damaged. This is a very important assumption worth emphasising; it means that we are not interested in the absolute damage safety of the ship but in the *conditional* safety. In other words, beyond our interest in knowing how big the risk of collision is that results in flooding or breaching hull integrity, we want to know the overall safety of the ship in the case of an accidental collision. For this reason, the regulations require the same level of safety irrespective of the area of operation that can be of various density of shipping (congestion of traffic), and thus of various levels of collision risk. However, some other aspects of shipping (e.g. environmental hazard due to harmful cargo, size of the ship, number of persons on board the ship) can be accounted for in the formulation for required level of subdivision.

Under such circumstances the probability of a ship surviving a collision is given by the equation for entire probability:

$$A = \sum_{i \in I} p_i s_i \,, \tag{1}$$

where the sum is taken for all cases of flooding in which one, two, three or more adjacent compartments are involved, where i is an index representing each compartment or group of compartments under consideration, I is the set of all feasible cases of flooding, comprising single compartments and groups of adjacent compartments, p_i is the probability that only the compartment(s) under consideration are flooded; and s_i is the (conditional) probability of surviving the flooding of compartment(s) under consideration.

As can be seen, the probability of survival, termed as the subdivision index, is given as the sum of the products for each compartment or group of compartments of the probability that a space is flooded multiplied by the probability that the ship will not capsize or sink with the considered space flooded. The attained index should be obviously greater than the required subdivision index R, given in the regulations (i.e., $A > R$), if the ship subdivision is to be considered satisfactory.

The factors p_i are generally not a problem from the theoretical point of view as they can be relatively easily estimated by basic probability calculus. For that purpose it is necessary to know a joint probability density function of damage dimensions, which can be satisfactorily found with the help of damage statistics. A rigorous derivation of the formulae for the factor p_i is presented in references [8–10]. Based on these works, a number of documents were subsequently submitted by the Polish delegation to the IMO that proposed formulae largely adopted eventually in the new regulations for dry cargo ships [6].

It is clear that the summation in equation(1) may cover only those cases of flooding for which both p_i and s_i are positive (i.e., which contribute to the summation). The p_i factor has thus the meaning of the maximum possible contribution of a given compartment group to index A. Because the attained subdivision index A is the entire probability, therefore $\Sigma p_i = 1$, that is, the sum of probabilities of all cases of flooding equals 1. This reflects the fact that the ship is damaged, that is to say, the probability of some damage is certain. The index A is therefore the average probability of survival, given that some damage takes place. In other words, the probability of survival, as given by equation (1), is nothing else than the *mean* probability of surviving (the mean s factor). Hence, equation (1) can be succinctly written as $A = \mathrm{E}(s)$, where E stands for the averaging operator. The factors p_i in equation (1) are therefore nothing else than weighting factors.

2.1 Ramming ships

To be accurate, equation (1) defines the probability of a *struck* ship surviving a flooding, since the unsinkability of such ships has fully random nature. In order to embrace all the problems connected with the safety of ships in the damaged condition, regulations should also provide requirements concerning the ramming (striking) ships and grounding.

The investigation of unsinkability for the striking ships is basically deterministic, since only the forepeak section is usually flooded and this does not endanger the ship. Statistics show that in nearly all cases the striking ship remains afloat, even when the striking ship had cut the struck ship in two parts. The main reason for the striking vessel surviving is that in a large majority of cases the collision bulkhead is not penetrated. Therefore, even though in collisions the bow area of the striking ship is particularly exposed to the danger of damage, this damage appears to be not so serious as to cause the total loss of the ship. In order to increase the safety of striking ships it should be required that

- For all compartments forward of the collision bulkhead the s_i value equals 1;
- For larger ships, with subdivision length $L_s \geq 120$ m, the s_i value, calculated for all compartments forward and aft of the collision bulkhead due to damage unlimited in the vertical direction and extending aft from the forward terminal not more than $l_{max} = 0.115L$ or 18 m, whichever is the lesser [11], is to be equal to 1 − for passenger ships, and 0.5 − for other ships

The l_{max} value could be updated in light of new statistical data for striking ship bow damage, which was recently made available. Such an approach to the bow's construction should lead to the practical elimination of the danger of the striking ship sinking following a collision. It is sufficient, therefore, to accept as a total measure of damaged condition safety the probability A of a struck ship surviving a collision, as given by equation (1).

2.2 Complete probability of surviving

There is yet a further possibility for improvement. The above index of subdivision denotes strictly speaking the conditional probability of surviving a collision in the case of accidental flooding, that is, when the ship hull is breached. However, not all collisions result in rapture of the hull, which is obviously beneficial for the safety of the ship. If probability of no rapture in collision is denoted by P_0, then the complete probability of surviving a collision C, comprising both categories of events, is given by

$$C = P_0 + (1 - P_0)A. \tag{2}$$

Clearly, the following holds $C > A$. In the current regulations there was not much sense to incorporate the probability of zero damage P_0 as is roughly constant for all ships and independent of subdivision. On the other hand, the probability P_0 is very sensitive to the type of ship structure and its characteristics, far more sensitive than the subdivision index is, and the difference is nearly of one order. If the complete probability of collision survival is used in future regulations, this will allow the designer to trade-off strength of ship structure against subdivision. For instance, a ship could compensate a deficient index of subdivision by a more collision resistant structure of her side. This would encourage technical innovations while maintaining overall safety. For that purpose, a reliable method is needed which cannot be develop until theoretical prediction of damage size distribution is made available from the analysis of crashworthiness of the ship side structure.

3. LOCAL INDICES OF SUBDIVISION

The use of the global measure of merit alone is not sufficient for regulatory purposes. Two different ships with the same overall index of subdivision are obviously of equal overall safety with respect to flooding, although these ships may have quite different actual capabilities for withstanding hull damage in some parts of their length. Such a situation is not neutral for the quality of subdivision and, therefore, should be accounted for in the regulations.

To prevent such an unsatisfactory situation, the basic global measure of merit (subdivision index A) should be supplemented by its local counterparts that show how the probability of survival is distributed along the ship's length. The local indices of subdivision will indicate directly if any part of the ship is left with unacceptable vulnerability to flooding. Currently, such a requirement is contained in regulation 5 of the IMO resolution A.265 for passenger ships [5], which is deterministic in nature. As we will see, this safeguard is illusory.

This type of requirement is best done by the use of the so-called local (partial) indices of subdivision of two kinds, given by the equations

$$A_j = \frac{\sum p_i s_i}{\sum p_i}, \qquad \text{for } j = 1, 2, ..., n \tag{3}$$

$$B_j \equiv A_{j,j+1} = \frac{\sum p_i s_i}{\sum p_i}, \qquad \text{for } j = 1, 2, ..., n-1 \tag{4}$$

The A_j quantities represent one-compartment indices and B_j – two-compartment indices of subdivision or bulkhead indices. The former indices reflect the uniformity of subdivision along the ship length, whereas the latter are a measure of the ship's ability to survive damage in way of a bulkhead (e.g. when at least two adjacent compartments are flooded). They are also referred to, particularly at the IMO circles, as *minor damage* indices.

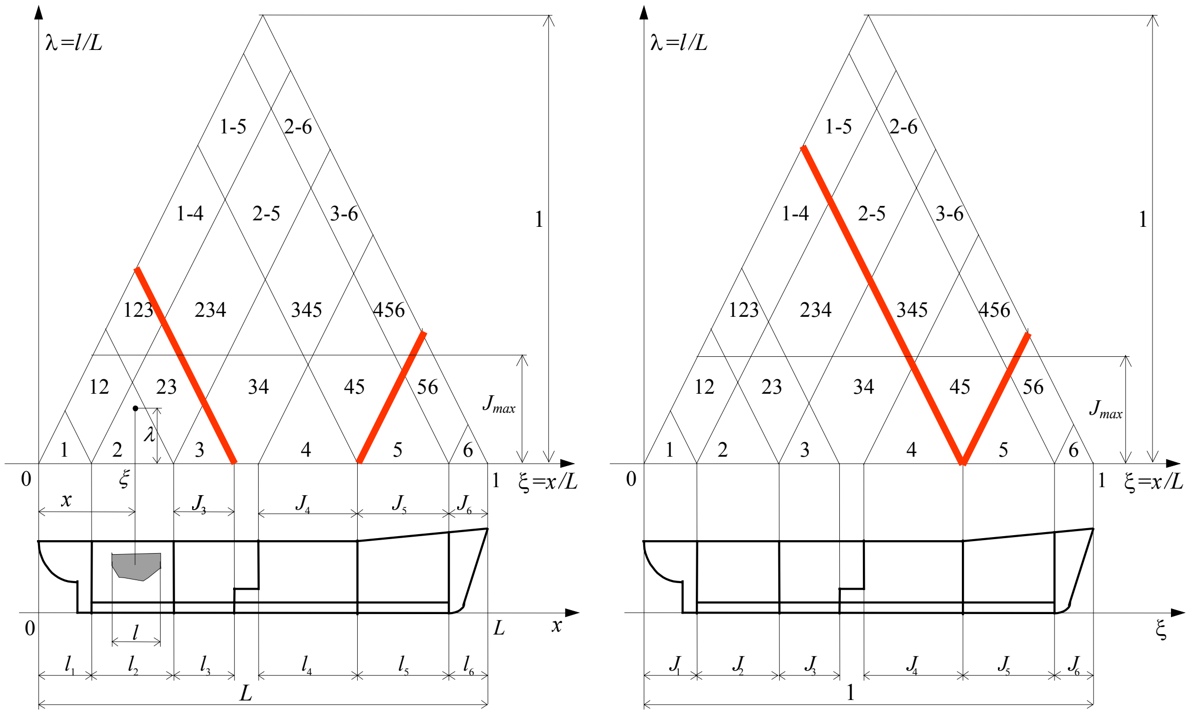

Figure 1: Subsets of flooding cases for the partial (local) subdivision index No. 4 (left), and for the local index No. 4/5 (right)

The summations in equation (3) are limited to the cases of flooding in which the given j-th (wing, if any) *compartment* (damage zone) is involved and n is the number of damage zones along the ship length. Whereas the summations in equation (4) are limited to the cases of flooding in which the given j-th *bulkhead* is damaged. Hence, like the overall subdivision index, the two kinds of local indices are also the average values of the s-factor corresponding to individual *subsets* of damage scenarios associated with a given compartment or a given bulkhead, as shown in Figure 1.

Hence, the three expressions for indices of subdivision can be summarised neatly, as follows:

$$\begin{aligned} A &= \mathrm{E}(s) \text{ on } I, \\ A_j &= \mathrm{E}(s) \text{ on } I_j, \\ B_j &= \mathrm{E}(s) \text{ on } I_{j,j+1}, \end{aligned} \tag{5}$$

where E is the averaging operator for the s-factor, whereas I_j and $I_{j,j+1}$ are the subsets of the set I that are connected, made up of the cases of flooding in which a given j-th compartment (pair of compartments) is involved alone or with any combination of adjacent compartments, as shown in Figure 1.

The idea of local indices is simple in practical application as it makes use of previously calculated values of p_i and s_i needed for determination of the overall subdivision index A. A minimum value of these indices should be greater than standards R_1 and R_2, which should be given in a new regulation 5. That is to say, min $A_j > R_1$ in the case of one-compartment indices, and min $B_j > R_2$ for two-compartment indices, if local subdivision of the ship is to be considered satisfactory. The two standards of local indices R_1 and R_2 should be given as a fraction of the overall required index R, established on the basis of tests calculations for a sample of existing ships.

The present regulation 5 as it stands for passenger ships, can be expressed in terms of the required values R_1 and R_2 for the local indices A_j and B_j, as shown in Table 1 and Figure 2. They were calculated for a compartment of minimum length acceptable by the regulation, and assuming a one compartment standard for N = 600 or less, and a two-compartment standard for N = 1200 or more.

Table 1: Minimum values of local indices required indirectly by present regulation 5

L (m)	100	150	200	250
R_1	0.100	0.075	0.063	0.080
R (N = 600)	0.600	0.630	0.655	0.677
R_1/R	0.167	0.119	0.096	0.118
R_2	0.176	0.131	0.111	0.200
R (N = 1200)	0.677	0.697	0.714	0.730
R_2/R	0.260	0.188	0.155	0.274

It is remarkable that the values of local indices, as required indirectly by the present regulation, vary with the ship length, as can be clearly seen in Figure 2, for which no justification can be found. And it sets the required values—particularly for ships with one-compartment standard—at a very low level, surely unacceptable for the profession and the travelling public. In fact, the values required are even lower by about 20% than those shown in Table 1 and Figure 2, as they were calculated for an unrestricted depth of the damage. It is also amazing that the minimum values for a two-compartment standard are higher by as much as about twice the values for a one-compartment standard, which is illogical. Clearly, it is unrealistic for the mean s value for two and more compartments flooded simultaneously to be higher than that for a set of flooding cases comprising flooding of a single compartment. This is possible only theoretically but it is very unlikely.

These inadequacies come from the deterministic nature of regulation 5 that is thus based on heuristic premises rather than on rational principles. The low values of local indices are a much more serious defect in the present regulation 5 than its incompatibility with the probabilistic method. It is neither coherent nor does it prevent a passenger ship from having some parts of its length excessively vulnerable to flooding, thus failing to fulfil its main task.

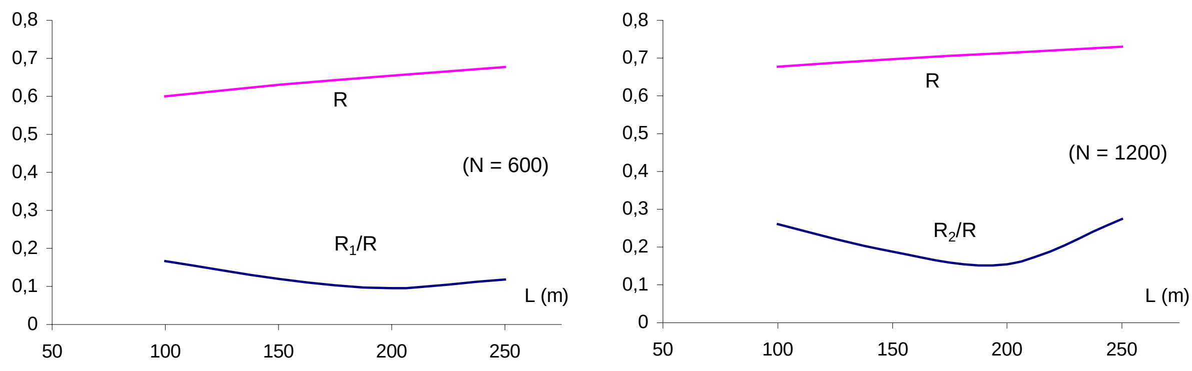

Figure 2: Minimum values of local indices required indirectly by present regulation 5

It is clear from the above that real progress in upgrading ship safety cannot be achieved until subdivision regulations are not fully based on the probabilistic concept. Detailed design of ships are not particularly important as long as they meet the basic requirements concerning their subdivision: $A > R$, min $A_j > R_1$, and min $B_j > R_2$ where the three standards for subdivision indices should be specified by the new harmonised regulations.

Positive local indices of both kinds can be easily obtained even for small ships of special types and ships with one or two cargo holds, without a greater effort if only double hull arrangement (not necessarily wide) were implemented on such ships. For many ships, positive local indices are not a problem even with single sides, as can be seen in Figure 3. It may be expected when the IMO work on harmonised probabilistic subdivision regulations is completed, the application of the double hull arrangement becomes regular, as is the contemporary case with the double bottom applied on all ship types or the double sides on tankers.

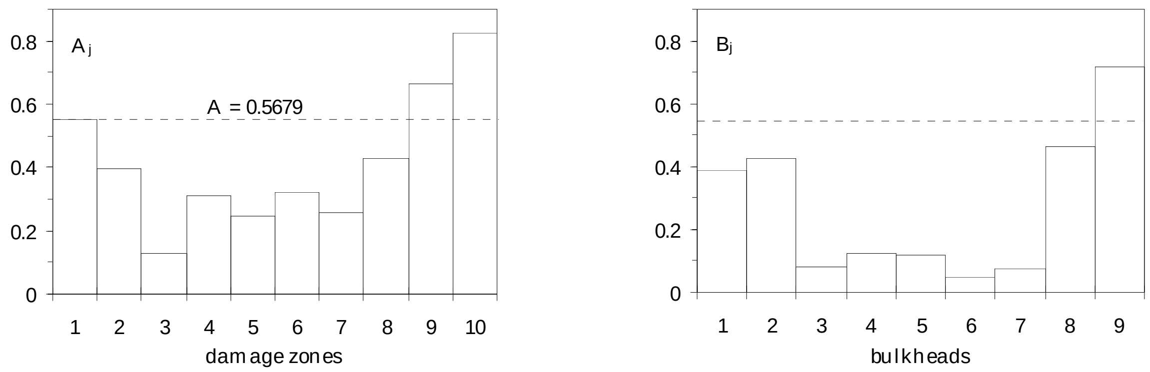

Figure 3: Local indices of subdivision for a containership of 2000 TEU; L_s *= 185.45 m,* B *= 30 m*

Protection against local vulnerability is particularly important both for passenger ships (due to psychological reasons) and cargo ships (due to economical reasons). Regrettably, the latter are not covered in the current regulations [6] by any requirement of this type. It appears that equalisation of local indices increases at the same time the overall index of subdivision and thus makes it easier to meet the basic requirement: $A > R$., as can be clearly seen in Figure 4, taken from Sen [12].

The use of local indices prevents a ship from having compartments with excessive lengths and breadths, that is, it ensures that no part of the ship is too vulnerable to flooding. Unlike the present deterministic regulation 5 in reference [5], this goal can be achieved with full compliance with the probabilistic method. Within the probabilistic framework of subdivision regulations, there is no longer a need for setting lower limits for bulkhead spacing or for a standard depth of penetration (e.g. for a prescribed size of damage, as is given in the current regulation), which was always very speculative and doubtful. Why $B/5$, and not $B/3$ or $B/10$, among others? Now, with the use of the local indices this type of speculation is eliminated.

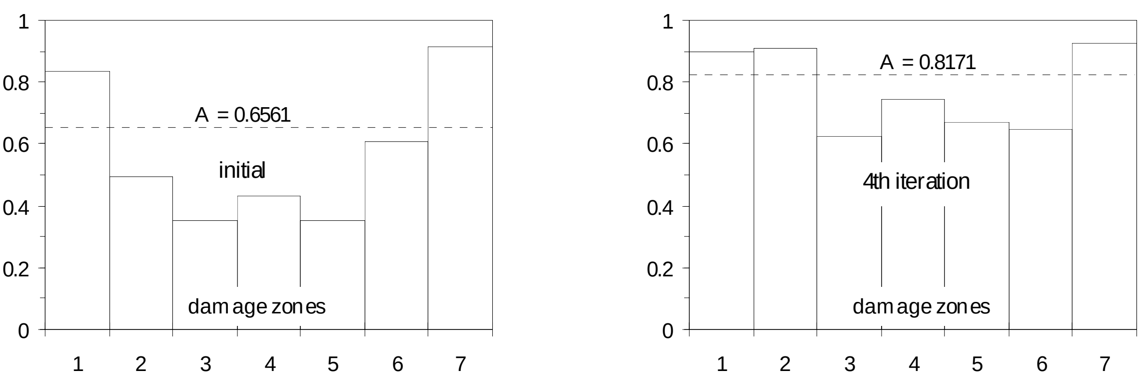

Figure 4: The effect of equalisations of local indices on the global index

4. NEED FOR SIMPLIFICATIONS

Although the ideas outlined above are simple, their practical application in an exact manner give rise to several difficulties. For example, longitudinal and vertical location as well as longitudinal, vertical, and transverse extends are necessary to provide an extensive, yet still incomplete description of the damage. Apart from the difficulties in handling such a five-dimensional random variable, it is impossible to determine its probability distribution with the currently available damage statistics. Similar difficulties exist with the variables and physical relationships involved in the calculation of the probability that a ship with a flooded space will not capsize or sink.

In order to make the probabilistic concept practically applicable, rather extensive simplifications are necessary. Although it is not possible to calculate on such a simplified basis the exact probability of survival, it is possible to develop a useful comparative measure of merit for ranking alternative longitudinal, transverse and horizontal subdivision arrangements of ships. Due to these unavoidable simplifications and the resultant approximations in the determination of the probability of survival, the index A is therefore referred to as the subdivision index and not the probability of collision survival, while p_i and s_i are said to account only for the probabilities of flooding and surviving. In other words, the index A is a *conventional* (assumed) probability of survival.

5. CONDITIONAL PROBABILITY OF COLLISION SURVIVAL

The other factor s_i has to be known in order to calculate the three measures of ship subdivision: the overall index A, given by equation (1); the one-compartment indices A_j, given by equation (3); and the two-compartment (bulkhead) indices B_j, given by equation (4). The calculation of the factor s_i is definitely the weakest part of the new regulations, both for passenger ships [5] and dry cargo ships [6] alike. The reason is that this factor cannot be established with the help of model test, or numerical simulations alone, or with the help of damage statistics, absolutely useless for this goal. For that purpose theoretical knowledge on damage survivability is indispensable, which was unavailable that time.

Although the methods on damage stability in the two IMO instruments mentioned above are not identical, the differences are not substantial. The s_i factor for dry cargo ships evolved in the late 1980s from the method developed about 20 years earlier for passenger ferries. The knowledge on damage survivability of ships, however, did not increase during that time; in fact, there was no progress whatsoever. It was decided at the IMO to abandon the idea of the effective freeboard (not very handy in practical applications and uncertain as to its correctness), and base the whole calculation on the GZ curve. Thus, in practice, the two methods are equally deficient and reflect the lack of relevant knowledge in the area of damage survivability. Nonetheless, these new probabilistic regulations provide much higher standards of safety than the original regulations for passenger ships in the SOLAS Convention. The point here is that until recently none of the existing ro-ro passenger ships have been built according to these new regulations.

5.1 The boundary stability curve

For any ship, with given loading condition and compartment flooded, the critical sea state the ship can withstand, characterised by the significant wave height H_s, cannot be determined uniquely. This fact is now widely acknowledged. This is not because of some inaccuracies of the model tests or numerical simulations, nor because of the insufficient time of duration of test runs, but because of the random nature of water elevation on deck induced by waves at the critical sea state. The critical sea state is characterised by a certain distribution around its mean value. Therefore, any boundary stability curve is a fuzzy curve rather than distinct, indicating mean values of the critical sea states and surrounded by a confidence level. To find the distribution of water head (and its mean value first of all), it is necessary to repeat many times the same case of flooding at the same sea state but with different initial conditions and wave realisations. So, to arrive at a boundary curve, one run is insufficient. The random nature of critical sea states comes mainly from the non-linear ship motions in irregular waves.

The probability s that a ship with a given loading condition and compartment flooded will not capsize after damage is equal to the *mean* probability that the critical significant wave height related to this case is not exceeded:

$$s = \int_{H_s} F(H_s) f_c(H_s)\, dH_s, \tag{6}$$

where $F(H_s)$ is the cumulative distribution function (CDF) of sea states at the moment of collision and $f_c(H_s)$ is the probability density function (pdf) of the critical sea states for the ship with a given loading condition and compartment flooded.

The pdf for critical sea states can be obtained experimentally. It starts at the lower bound of the survival boundary, and terminates at the upper bound, shown in Figure 5. Because the pdf curve is extremely difficult for determination, typically the lower and upper bounds are found along with a median value, corresponding to a 50/50 rate of survival. Both functions occurring in equation (6) are shown in Figure 5 (the pdfs are exemplary for the two different cases of flooding).

Because for moderate and higher critical sea states $F(H_s)$ has a small rate of change, as can be seen in Figure 5, whereas for low critical sea states (when damaged stability is deficient) the range of variation of critical sea states is narrow, by virtue of the mean value theorem equation (6) yields:

$$s = F(H_{s\ mean}), \tag{7}$$

that is, in practice, the s factor can be calculated based on the mean value of the critical sea state at given damage scenario. However, the mean value of the critical sea state is difficult to be obtained with the help of model tests (for that we need the knowledge of the pdf or the CDF for critical sea states for each damage scenario). Therefore the mean value is replaced by a median value, if model tests are used. That is, the critical sea state (or the critical *KG*-value) is such at which in 50% of runs the ship capsizes and in 50% – it survives. In routine calculations the mean critical sea state is obtained by the SEM.

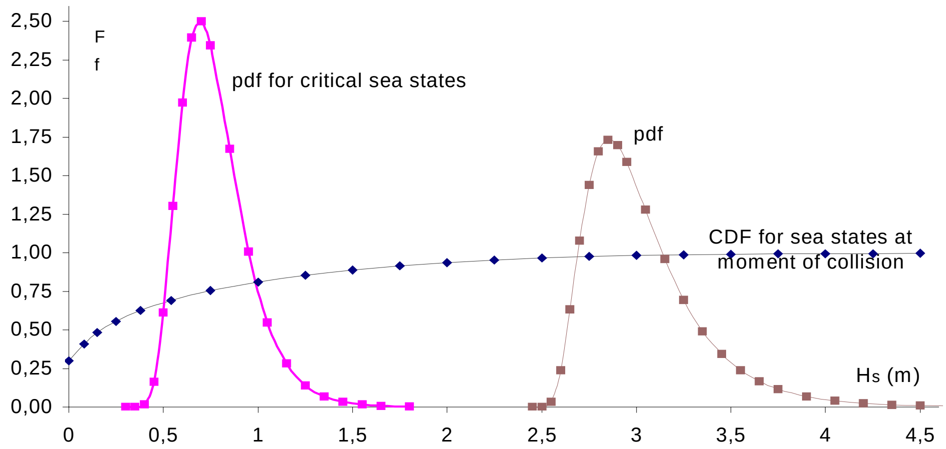

Figure 5: CDF for sea states at moment of collision and pdfs for critical sea states

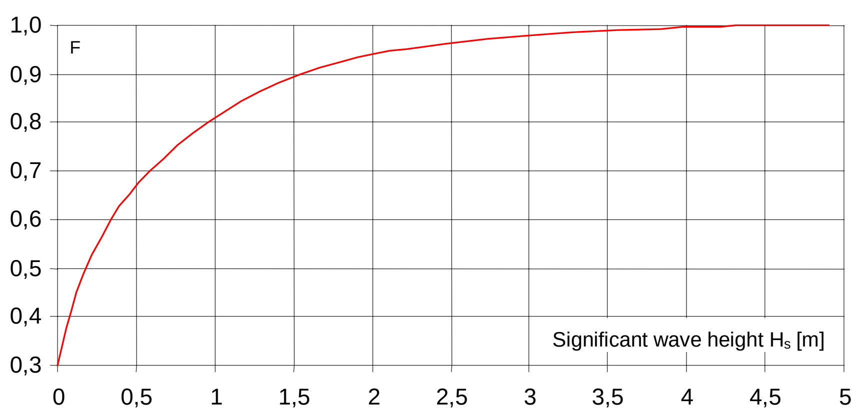

Figure 6: CDF of sea states occurring at the moment of collision according to IMO

Having determined the critical sea state H_s for a given damage case, the factor s (probability of collision survival), essential for the probabilistic subdivision regulations, can be easily obtained from the sea state distribution occurring at the moment of collision $F = F(H_s)$. This probability equals simply the probability that the critical significant wave height H_s is not exceeded at the moment of collision. Therefore the factor $s = F(H_s)$. For this purpose, the sea state distribution proposed by the IMO could be used temporarily, as shown in Figure 6.

It is noteworthy that the distribution of sea states at the moment of collision is different from the 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 that in such circumstances sea states are on the whole lower than at the open sea or under normal operating conditions and, because of that, probably not much different for various sea regions. If the sea state distributions do differ for certain regions, this would provide space for regional deviation in formulae for the s factor.

Using the sea state distribution as shown in Figure 6, a very good approximation of this curve for H_s up to 6 m and more, which is identical with the factor s, is given by

$$s = [1 - (0.0825x^3 + 0.1879x^2 - 1.0405x + 0.9704)\exp(-2.5x^{1.25})]^{1/3}, \tag{8}$$

where $x = H_s/4$ is in meters. For $H_s > 6$ m, the value of the polynomial in the parentheses should be taken constant, equal to 0.1141. Equation (8) caters for the asymptotic behaviour of the sea state distribution. Specific applications could consider actual distributions of sea states at the moment of collision, appropriate for the area of operation.

5.2 Averaging the surviving factor

The calculation of the probability $s_i \equiv s$ would be relatively simple if the mean critical sea state H_s was determinate for each compartment group. However, this quantity is not determinate because it depends on such random quantities as the loading condition (draught T, trim t, metacentric height GM and permeability μ) at the moment of collision, and the vertical extent of flooding H. Therefore, in order to obtain the composite probability s_i for all possible combinations of μ, H, T, t, and GM, it is necessary to average s for each compartment group with respect to these random variables. The averaging follows from the formula for the entire probability. Hence

$$s_i = E(s) = \int_\mu \int_T \int_t \int_{GM} s f(\mu, T, t, GM)\, d\mu\, dT\, dt\, dGM, \tag{9}$$

where the probability $s = s(\mu, T, t, GM)$ is itself a function of the four random quantities, averaged previously, for ships with horizontal subdivision above the waterline, with respect to the vertical extent of flooding H that is of discrete character. As can be seen, to find the s_i factor for each compartment group it is necessary to know the joint distribution density $f(\mu, T, t, GM)$, which can only be derived from statistical data and which in practice is virtually impossible to obtain. Such a distribution might also be related to the ship type and possibly to the ship's route, but again the understandable lack of data would prevent these variables from being considered.

Remembering that the method is aimed at arriving at an assumed rather than the actual probability of survival, the averaging procedure may be somewhat simplified by accepting draught and vertical extent of flooding as the only random variables. Other variables are assumed to be determinate – either as constants or as functions of draught, chosen in such a way to err on the side of safety (i.e., to provide a conservative estimation of the s factor). Hence, equation (9) for the s_i factor reduces then to the following:

$$s_i = \int_T s(T) f(T)\, dT, \tag{10}$$

where $s(T)$ is the probability s as a function of the ship draught only, obtained by averaging the s factor (for each compartment group and draught) relative to different discrete vertical extents of flooding, if any, and $f(T)$ is the marginal distribution density of draughts at the moment of collision. Details are shown in [13].

6. THE RELATION WITH THE INDICES OF SUBDIVISION

The factor s is directly linked to the three indices of subdivision. As follows from the foregoing discussion, briefly summarised by equation (5), all the indices are the mean value of the s factor associated with given sets of damage scenarios. Hence, for the mean to be high, individual s factors have to be as high as possible and that depends directly on the design of the ship. Knowing the mean value of s, a characteristic sea state can be found from equation (8), corresponding to given mean value of s. The characteristic sea state is such a sea state, described by the significant wave height H_s, which is needed to achieve a given index of subdivision if survivability in all cases of flooding was the same. These characteristic values of sea states are shown in Table 2, or can be approximated with a good accuracy using the equation

$$H_s = (0.0089x^3 - 0.1503x^2 + 0.7305x - 0.2716)/(1 - s)^{1/3}, \tag{11}$$

where H_s is in meters, $x = -\ln(1 - s)$, and s stands here for the mean factor s. Equation (11), valid up to $s = 0.9995$, and values in Table 2 were obtained as the inverse function relative to equation (8). The differences between the two H_s values are not greater that 0.05 m.

Table 2: Characteristic sea state H$_s$ *versus the mean* s *factor*

mean s	0.50	0.60	0.70	0.80	0.90	0.95	0.99	0.999
H_s (m)	0.184	0.35	0.58	0.94	1.58	2.21	3.54	5.36

Table 2 gives a distorted impression regarding the prevailing sea states a damage ship can withstand. Due to the highly non-linear relationship between the s factor and the sea state at the moment of collision, as clearly seen in Figure 6, the prevailing sea states the ship can survive are much higher than those shown in Table 2. In view of the large non-linearity and predominant binary nature of the s factors (either zero or unity), the mean s tends therefore to have a meaning of the relative 'weight' of the p_i factors for surviving cases. For example, for subdivision index $A = \mathrm{E}(s) = 0.70$, Σp_i for surviving cases with $s = 1$ is close to 0.70 [1], for which surviving H_s may be well above 3.5 m, while the characteristic sea state is merely just less than 0.6 m, as seen in Table 2. Therefore, it is worth introducing an index A_s – the mean s factor, based on surviving cases only, given below

$$A_s = \frac{\sum p_i s_i}{\sum p_i} = \frac{A}{\sum p_i} \tag{12}$$

where Σp_i comprises here all the damage cases with a positive s-factor that contributed to the index A. The sea state corresponding to the above (surviving) subdivision index A_s, obtained with the help of Table 2 or equation (11), provides a characteristic *surviving* sea state H_s, which could be termed also as the *characteristic survivability* of the ship. This new characteristic value provides a palpable (physical) measure of the overall performance of the ship in the damaged condition, in addition to the (overall) index of subdivision A.

In view of the prevailing binary nature of the s factors of crucial importance for the required indices of subdivision is the sea state at which the s factor saturates. That is, the sea state at which s reaches a value of 1. According to Figure 6, this asymptotic value of sea state is equal to $H_s \approx 4.5$ m. This characteristic value denotes a sea state above which the ship survivability is no longer productive for the index, as such sea conditions (at the moment of collision) are considered unlikely. Further, a detailed run of the s factor below the saturation value is of secondary importance. Hence, we face eventually a basic question whether the 4.5-m saturation sea state is acceptable for the profession and travelling public or not in light of the weather statistics?

The three measure of merit of ship's subdivision provides also the answer to the important question: which is safer, a ship that can survive a large number of damages if in a moderate sea state, or a ship that can survive fewer damages but in high sea states? Obviously, the former is better. The ideal situation is if a ship can survive a large number of damages in a moderate sea state *above* or around the saturation sea state, for example, above a maximum sea state of practical meaning that can occur at the moment of collision.

[1] Typically s equals either 0 or 1, with only few cases of flooding with intermediate values of s.

7. CONCLUSIONS

A general framework of the probabilistic subdivision regulations has been presented, based on use of the overall and local indices of subdivision. As the indices of subdivision are the same as the mean *s* factor, higher attained indices of subdivision invariably go along with a higher mean survivability of the ship. Finally, a link between the indices of subdivision and the mean sea state the ship can survive is highlighted and may give support to the selection of the required values for the *A*-index.

REFERENCES

1. Wendel, K.: Die Wahrscheinlichkeit des Uberstehens von Verletzungen (The Probability of Surviving Damages), *Schiffstechnik*, Vol. 7, No. 36, 1960, pp. 47–61.
2. Comstock, J. P., and Robertson, J. B.: Survival of collision damage versus the 1960 Convention on Safety of Life at Sea, SNAME *Transactions*, Vol. 69, 1961, pp. 461–522.
3. Volkov, B. N.: Determination of probability of ship survival in case of damage, *Sudostrojenie*, 1963, No. 5, pp. 4–8.
4. Wendel, K.: Subdivision of Ships, *Proceedings*, 1968 Diamond Jubilee International Meeting – 75th Anniversary, SNAME, New York, 1968, paper No. 12, 27 pp.
5. International Maritime Organisation: Regulations on subdivision and stability of passenger ships as an equivalent to part B of chapter II of the 1974 SOLAS Convention, IMO, London, 1974 (114 pp.). This publication contains IMO resolutions A.265 (VIII), A.266 (VIII) and explanatory notes.
6. Robertson, J. B., Nickum, G. C., Price, R. I., Middleton, E. H.: The new equivalent international regulations on subdivision and stability of passenger ships, SNAME *Transactions*, Vol. 82, 1974, pp. 344–381.
7. International Maritime Organisation: Subdivision and damage stability of cargo ships, chapter II–1, part B–1, SOLAS Convention, Consolidated Edition, IMO 1997, pp. 89–99. This part applies to cargo ships constructed on or after 1 February 1992.
8. Pawłowski, M.: Determination of the probability of flooding a given group of compartments as a result of ship collision, Report, Department of Naval Architecture and Shipbuilding, University of Newcastle upon Tyne, December 1980, 52 pp.
9. Pawłowski, M.: Bezpieczeństwo niezatapialnościowe statków (Safety of ships in the damaged condition), DSc dissertation, Journal of Technical University of Gdansk "*Budownictwo Okrętowe*", No. 42/392, Gdansk, 1985, 132 pp.
10. Pawłowski, M.: The probabilistic concept of ship subdivision, PhD course in Naval Architecture, Technical University of Gdansk, Gdansk, 1994, 110 pp. and 2 appendices.
11. USA: Collision bulkhead of cargo ships, STAB XIV/6/3, IMCO, London 1974.
12. Sen, P., and Gerigk, M. K.: Some aspects of a knowledge based expert system for preliminary subdivision design for safety, *Proceedings*, 5th Int. Conf. on Practical Design of Ships and Mobile Units PRADS 92, Newcastle upon Tyne, Elsevier Applied Science, 1992, Vol. II, pp. 1187–1197.
13. Karaszewski, Z., and Pawłowski, M.: A general framework of new subdivision regulations, *Proceedings*, 8th Int. Marine Design Conference – IMDC 2003, 5–8 May 2003, Athens, Greece, Vol. I, pp. 254–265.