# RATIONALIZING THE PRACTICE OF PROBABILISTIC DAMAGE STABILITY CALCULATIONS

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Int. Shipbuild. Progr., **50**, no. 3 (2003) pp. 239-253

*Received: October 2002*
*Accepted: August 2003*

*An introduction is given concerning the probabilistic damage stability method as presently used in daily shipbuilding practice. In this respect some problem areas are described which may lead to difficulties in applying the method, both in actual point design and in design optimisation. These problem areas primarily relate to the bookkeeping at multicompartment damages in combination with both longitudinal and horizontal subdivision (i.e. limited penetration problem). Secondly, ambiguities that arise through naming conventions are discussed. After a detailed description and analysis of these problems, suggestions are formulated regarding possible solutions. In case where a real solution is lacking, workarounds are put forward as being (for the time being) makeshifts. These solutions or workarounds fully fit within the theoretical background of the present regulations as laid down in the SOLAS convention; they affect mainly interpretations and definitions. Numerical examples applied to two existing new building container vessels are given and the results using the conventional method are compared with those using the various proposed solutions. In these examples it appears that the sum of all probabilities of damage do not tend to reach to the expected value of unity, a phenomenon which indicates a theoretically incorrect behaviour. Finally, conclusions are made regarding these results and recommendations related to the probabilistic damage stability calculation method and statistical approach used therein are made. Furthermore a possible method is brought forward that may be used in combination with tools for optimisation of the subdivision of a newbuilding design with respect to probabilistic damage stability characteristics.*
*Keywords:* damage stability, probabilistic

## 1. Introduction

In 1992 probabilistic damage stability rules for cargo vessels over 100 m length came into effect, while in July 1998 their coverage was extended to vessels from 80 m on (see Chapter II-1, Part B- 1 of (SOLAS, 1997)). For passenger vessels with (IMCO, 1974) a probabilistic method was introduced which is considered equivalent to the SOLAS deterministic passenger regulations ((SOLAS, 1997), Chapter II-1, Part B).
One would have expected that since Wendel (Wendel, 1960) proposed the probabilistic damage stability method, and after more than a decade of massive practical experience the determination of probabilistic damage stability aspects, as well as the interpretation of the regulations, would pose no troubles in the daily practice. However, once again, practice is stronger than doctrine, and the authors experienced the past 12 years that more than once this subject leads to differences of opinion between the involved parties, which are mainly ship designers, shipyards, classification societies and national authorities. So, obviously, there is room for discussion and argumentation.
The structure of this paper is that first the aim of this paper is discussed, then we identify some sources of confusion, and make some proposals for solutions and further research.

## 2. The ship designers dream

In general the trend in the manufacturing industry is towards short product cycles, short design times, and the integrated use of knowledge over all stages of design and engineering (McMahon & Lowe, 2002). These trends are also visible in ship design and shipbuilding (see a.o. (Hengst, 1997)). Due to certain properties of the current implementation of the probabilistic damage stability method, however, it is hard to obtain a sufficiently accurate and unambiguous assessment of the probabilistic damage stability characteristics in the preliminary design phase. This phenomenon increases design times and introduces uncertainty in the early design stages, which is undesirable because it conflicts with the mentioned general trend.
In order to reduce design times and to improve the robustness of a design, a ship designer should preferably have an automated computer system at his disposal, for two reasons:

- If a ship designer has a ‘black box’ system available, and if he is confident in it, he will be able to pay attention to core design issues, instead of spending time on administrative tasks, such as the damage stability calculation.
- If a stable and reliable calculation method is available, a numerical optimization method can be applied which automatically determines an *optimal* subdivision for damage stability.

The authors are aware that others, such as (Abicht, 1990) and (Jakić, 1994) have formulated proposals for new or adapted formulae for the probability of damage. Also, at the moment of writing a EU project 'Harmonization of Rules and Design Rationale' (HARDER) is in progress, where based on Monte Carlo simulations and updated damage statistics revised factors for the probabilities of damage are presented (SLF, 2002). So, rather than proposing new statistical formulations, our analysis and proposed solutions are targeted at the practical aspects of the method, and are applicable regardless the exact nature of the used formulae. Our emphasis is on real-life vessels and compartment configurations, for it is our experience that with rectangular subdivision in barge-like vessels only (e.g. as in (SLF, 1997)) realistic aspects can be overlooked.

## 3. Encountered problems

### *3.1. Conceptual aspects*

*Only one damage per compartment*

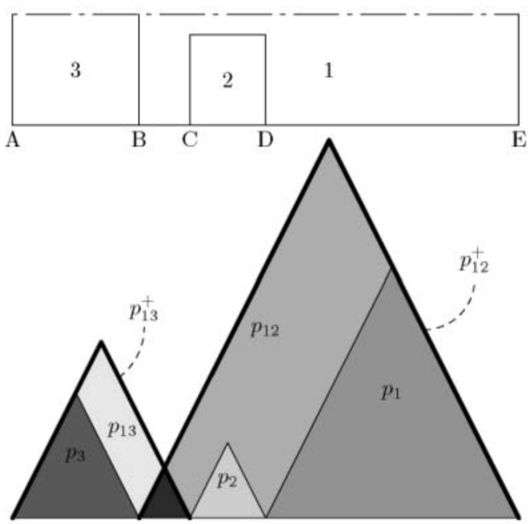


*Figure 1. Top view of lay-out, and schematic representation of the probability of damage.*

The current formulations for the determination of probability of damage lead to one $p$ for each compartment, so they imply that each compartment is affected by a single damage only. In the majority of cases that is a valid assumption, but eccentric compartment lay-outs exist where compartments can be struck by multiple, separate, damages. An example is shown in Figure 1, where, disregarding the effect of longitudinal subdivision, compartment 1 will be damaged by damage in the region B-C as well as D-E. According to standard bookkeeping is $p_{13} = p_{13}^{+} - p_1 - p_3$. A glance on the probability triangles shows that this probability will become negative.

*Combined transverse and longitudinal or horizontal subdivision*

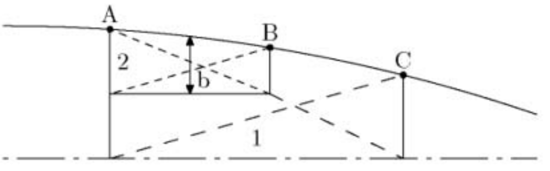


*Figure 2. Topview of combined transverse and longitudinal subdivision arrangement.*

Another example of a lay-out where a compartment can be struck by multiple damages is sketched in Figure 2. $p_1$ is based on transverse boundaries B and C, with $r = 1$ because the damage extends to centerline. $p_2$ is determined by transverse limits A and C, with a reduction factor $r_2 < 1$, where $r$ is governed by penetration depth $b$. According to standard practice $p_{12} = p_{12}^{+} - p_1 - p_2$, without reduction for longitudinal subdivision (so $r_{12} = 1$), because the combined damage to compartment 1 and 2 extends to centerline. What is missing in the bookkeeping of this damage case is $p_2(1 - r_2)$. This factor represents a second possibility of damage to both compartments, which is the damage between A and B, extending to centerline.
This adverse effect results from a separate treatment of the $p$ and $r$ factors. It can be avoided if the rule for processing multi-compartment damages would sound something like 'The probability of simultaneous damage to multiple compartments (the main damage) is obtained by subtracting the nominal probability with the probabilities of all subdamages, *as far as they fall within the main damage*', where the nominal probability equals the product $p \cdot r \cdot v^{+}$ as obtained from the damage distribution functions.

### *3.2. Practical aspects*

According to the Explanatory Notes for dry cargo vessels (IMO, 1991) the damage penetration (measured between shell and internal subdivision) must be determined so that the penetration depth at one side is not more than twice the penetration depth at the other side. In terms of the upper part of Figure 3 the penetration depth $b$ is determined so that $b1$ is greater than or equal to $b2/2$.

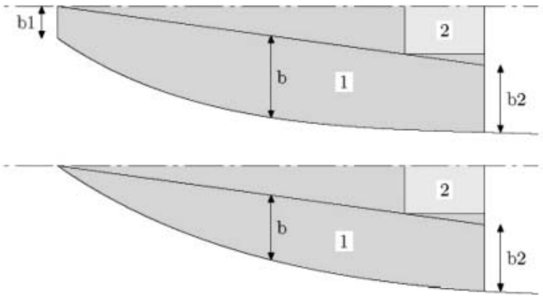


*Figure 3. Limiting ratios between penetration depths b1 and b2.*

However, if we look at the bottom part of this figure, showing at waterline level more a cruiser stern character rather than a transom stern, we see that the penetration at the aft boundary of the damage cannot be otherwise than zero. which leaves no opportunity for b1 to become greater than or equal to $b2/2$. Such a case, where $b1 = 0$ or $b2 = 0$, can be considered a singularity which might be solved with one of three options:

1. Ignore the whole $b1$/b2 rule.
2. Choose *both* $b1$ and $b2$ to be zero. This choice conforms literally to the rule, but it might have two adverse effects. The first one is a very limited penetration depth, or even a negative penetration in the case of concave waterlines. The second one is the effect that due to this limited penetration inboard compartments which *must* be damaged in the particular damage case under consideration *cannot* be damaged because they are not within the penetration boundary.
3. Use the *minimum* transverse distance to determine the penetration instead of the *mean* transverse distance which is prescribed in § 25-5.2.2 of (SOLAS, 1997). In general the Dutch Administration allows the use of minimum distance (see §5.3.10 of (IMO, 1990)) instead of mean distance, while with minimum distance the whole b1/b2 rule does not apply. It would be an option for regular cases to use the mean penetration, and switch to minimum if b1 or b2 are zero.

In a software package developed by one of the authors (SARC, 2002) the user is offered the choice of the last two options.

*3.3. Naming and semantics*

*Damage zones*

A concept which does not originate from present legislation is the *damage zone*, which can be defined as a longitudinal interval between primary transverse bulkheads. Grouping damage cases on bases of damage zones can be appropriate for presentation purposes, because a human being can digest the results of all individual damage cases better if they are sorted in some way. However, the authors do not favor the zonal approach as basis for the calculation itself. The *zone* concept is superfluous because it originates neither from present legislation, nor is it founded in the basic theory of probabilistic damage stability. It is better to stick to the *compartment* as basic subdivision entity.

*Semantical aspects*

In a number of cases semantical notions are utilized which are meaningful for a human, but which have no formal meaning, and are thus hard to incorporate in an automated environment. Examples are §3.3 of appendix 3 of (SLF, 1997), or §3.2 of (SOLAS, 1997), which reads:

> *'The factor $p_i$ for a group of three or more adjacent compartments equals zero if the nondimensional length of such a group minus the nondimensional length of the aftermost and foremost compartments in the group is greater than $J_{max}$'.*


*Figure 4. Arbitrary compartment lay-out.*

Looking at Figure 4, however, it is not at all obvious what is the *aftermost compartment*, or the *length of the foremost compartment*. These concepts require heuristics, and are less suitable for automated processing.

*3.4. Numerical aspects*

With a simple barge-like example it was demonstrated in (Jensen, 1995) that the *p* formulae of (SOLAS, 1997), applied to a barge with a length of 200 m, a breadth of 30 m and narrow side shell compartments, lead to negative probabilities of occurrence of damage. Formulae without this deficiency have been proposed in (SLF, 1997).

*3.5. Multi-compartment damages*

*Longitudinal subdivision*

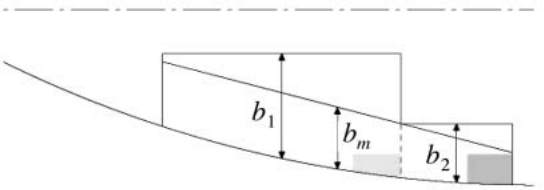


*Figure 5. Which penetration depth to use for determining r?*

Suppose that in Figure 5 *one* compartment is sketched, which consists of the two parts 1 and 2. In that case the reduction factor $r$ is based on penetration depth $b_m$. Now, suppose that the dashed bulkhead is watertight, so parts 1 and 2 are distinct compartments. According to appendix 2 of (IMO, 1991) (as well as (SLF, 1997)) the penetration depth is not $b_m$ too, as one would expect, but $\min(b_1, b_2)$ instead. It might be that this exception was necessary to keep bookkeeping proper during addition and substraction of probabilities, but two objections can be brought forward towards the $\min(b_1, b_2)$ approach :

- It is natural, and also according to the basics of the probabilistic method, to assign one probability of damage to a particular partition of the ship, regardless its internal subdivision.
- Due to the semantical problems, as discussed in subsection 3.3, it is not always obvious from which compartments the minimum b should be taken. Suppose our lay-out is further subdivided with the coloured compartments, a pure min(...) of the *b*'s of all compartments would erroneously lead to the use of a small *b* from one of the coloured compartments.

*Horizontal subdivision*

In (SOLAS, 1997) the reduction factor $v$, regarding the horizontal subdivision, is combined with the probability of survival $s$, to give a probability of survival including horizontal subdivision. So $a = p.s$, where $p$ represents the probability of damage based on transverse and longitudinal subdivision only, and $s$ represents the survival of damage, corrected for the effect of horizontal subdivision. However, it is more natural to rewrite $a$ as $a = (p{\cdot}r{\cdot}v){\cdot}s$ where s is the pure probability of survival, and $p{\cdot}r{\cdot}v$ the probability of damage, with $p$ representing the effects of transverse subdivision, $r$ those of longitudinal and $v$ those of horizontal subdivision. The subsequent treatment of this paper is based on this convention. According to the formula of (SOLAS, 1997)

$$v = \frac{H - d}{H_{max} - d}$$

where for vessels with $L_s < 250$ m

$$H_{max} = \min(H_D, d + 0.056 \cdot L_s(1 - \frac{L_s}{500}))$$

with $H_D$ the maximum possible vertical extent of damage.
For the compartment as sketched in Figure 6 this approach works as expected: for compartment 1 $H_{max} = H = H_A$, so $v_1 = 1$, for compartments 1&2 $H_{max} = H = H_B$, so also $v_{12} = 1$, and consequently $p_{12} = p_{12}^{+} - p_1$.

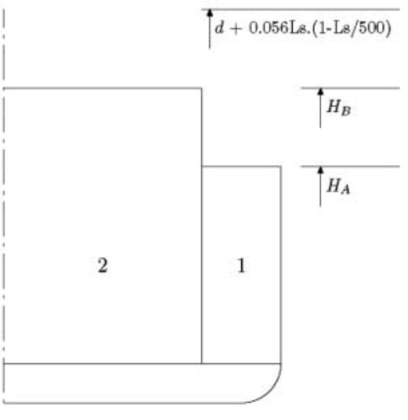


*Figure 6. Midship section without relevant horizontal subdivision.*

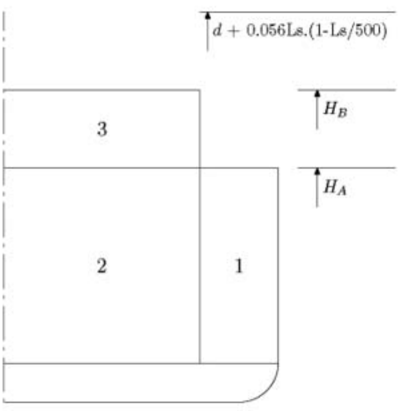


*Figure 7. Midship section with horizontal subdivision.*

A lay-out with horizontal subdivision is sketched in Figure 7. In this configuration $H_{max}$ of compartment 1 is $H = H_A$, so $v_1 = 1$. For the combined damage to compartments 1&2 $H_{max} = H_B$, while $H = H_A$, so $v_{12} < 1$. The resulting probability is $p_{12} = p_{12}^{+} \cdot v_{12} - p_1 \cdot v_1$. This expression contains two $v$'s, based on two different $H_{max}$'s. If $H_{max} >> H_A$, then $v_{12} << 1$ so the resulting $p_{12}$, and hence $a$, might even become negative!

*3.6. Accumulated probability of damage*

Theoretically, if every possible damage case i is taken into account, $P$, which equals $\sum_{i=1}^{n} p_i \cdot r_i \cdot v_i$, should be exactly unity. If such a relation would hold, ship designers as well as auditors would have a handle to check the validity of a complete calculation; if $P$ is significantly less that 1, it would indicate that not each possible damage case was included, while on the other hand a $P$ greater then 1 shows that some way or another damage cases have been counted multiply. Unfortunately, due to mechanism as described in subsections 3.4, 3.5 and 4.3 tend to a P-value not necessarily in the vicinity of unity.

## 4. Workarounds and solutions

### *4.1. Determination of actual damage boundaries*

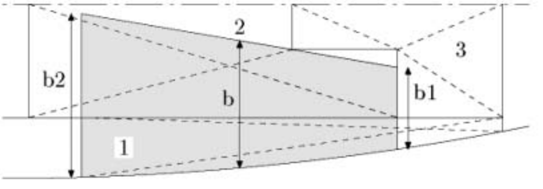


*Figure 8. Relation between compartment boundaries and damage boundaries.*

One basic assumption of the SOLAS implementation of the probabilistic method is that the damage is trapezoidal, without the inner bounding plane necessarily to be parallel to the center plane of the ship. This assumption is reflected in the definitions of the longitudinal damage boundaries: the aft boundary is the 'foremost portion of the aft end of the compartment being considered'. with for the forward boundary mutatis mutandis a similar definition. In (Koelman, 1995) the example of Figure 8 was presented, where the question is how to determine the damage which will cause flooding of compartments 1 and 2, without affecting compartment 3. There are two alternative solutions :

- Consider the problem as a constrained multidimensional optimization problem, which can be solved with standard optimization methods, e.g. as given in (Press et al., 1986). In this approach the 5 independent dimensions are the five boundaries of damage: aft, forward, inside aft, inside forward and upper. The target to be maximized could be (volume of damage itself) $\cap$ (volume of compartments to be damaged). The constraint is that compartments which *may* not be damaged are not struck by the damage, which is modelled by a penalty function which decreases the target volume by {(volume of the damage itself) $\cap$ (volume of the compartments which may *not* be damaged)} $\cdot$ (an arbitrary high constant). Also additional constraints, such as a limit on $b1/b2$ ratios, can be incorporated into such a scheme.

The result of this approach is indicated in grey in Figure 8. Alternatively, the target to be optimized could be $(p \cdot r \cdot v)^+$, but it is less easy to construct a matching penalty function to model the constraints.

- With fictitious compartments, which have been proposed in (Jensen, 1995) and (Jensen et al., 1996). A fictitious compartment is a rectangular compartment of elementary shape; the inner bounding plane is always parallel to the center plane of the vessel. A real compartment can thought to be composed of multiple fictitious compartments, while, due to the simple shape of a fictitious compartment, matching the shape of the damage to the shape of the compartments requires less effort. Another advantage of the use of fictitious compartments is that problems as sketched in subsection 3.1 vanish, but a disadvantage is that this concept lacks an explicit foundation in the regulations, although it fits in the probabilistic concept smoothly.

*4.2. Damage case generator*

Essentially, with the probabilistic damage stability method the attained subdivision index $A$ must be higher than a certain threshold $R$. Because $A = \sum_{i=1}^{n} a_i$, with $n$ the number of damage cases, it is advantageous for a ship designer and a ship owner to utilize every possible damage case with a positive $a_i$. The total number of damage cases may be several hundreds, and it is a cumbersome job to define each individual damage case manually. Dedicated software might benefit from a damage case generator, which generates every damage case in a systematic manner.

*4.3. Local vs. global b/B*

The reduction factor $r$ is proportional to the dimensionless penetration depth $b$/B, where $b$ must be measured from the subdivision loadline (= CWL), midway in the compartments length. The question remains which $b$/B, or combination of $b$/B's, to use when calculating $p \cdot r \cdot v$ of a multi-compartment damage. There are four options :

1. Use the minimum $b$/B of all involved compartments. In subsection 3.5 we have already argued why this is not a valid solution.

2. Use an individual $b$/B for each compartment, and for each group of compartments. This option is rather evident, because its leads to a probability of damage which is based purely on damage dimensions, and which is not affected by internal subdivision. A disadvantage of this approach is sketched in Figure 9. In this figure the local penetration depths are shown. The probability of damaging compartments 1 and 2 simultaneously is $p_{12} = p_{12}^{+} \cdot r_{12} - p_1 \cdot r_1 - p_2 \cdot r_2$, where $r_{12} = f(b_{12})$, $r_1 = f(b_1)$ and $r_2 = f(b_2)$.Furthermore, $b_1 < 0$, so $r_1 = 0$, $b_{12} < 0$, so $r_{12} = 0$ and $b_2 > 0$, so $r_2 > 0$. As result $p_{12}$ becomes negative, regardless of the exact formulation of $r = f(b/\text{B})$.

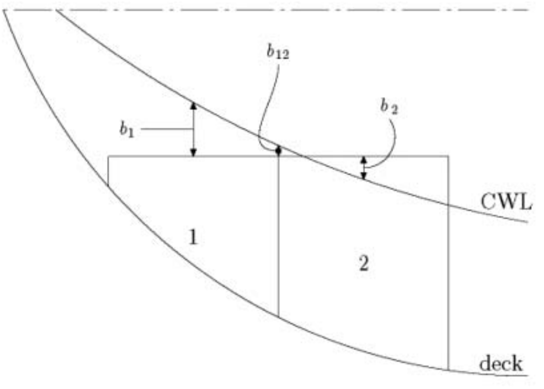


*Figure 9. Local penetration depth*

3. Use a global *b/*B for all compartments involved in a multi-compartment damage. In our example $r_1$, $r_2$ and $r_{12}$ are then all $f(b_{12})$.

4. Deviate from the regulations, and measure *b* from the deck instead of the waterline. In practical sense the negative probabilities as described under 2. will not occur, even when a local *b/*B approach is used..

The PIAS program (SARC, 2002) offers the choice of options 2. and 3, while the user can furthermore choose between the *p*, *r* and *v* formulae of (SOLAS, 1997) or those of (SLF, 1997). To investigate the numerical differences between the different approaches, we have applied them to a general cargo vessel in the 90 m range, the results are listed in table 1. Similarly, the results for a container vessel in the 130 m range can be found in table 2.
In these tables the attained subdivision indices *A* are presented, because they are the final results of a calculation. Also the probability of damage *P* is included, as a kind of quality index. As motivated in subsection 3.6, *P* should exactly be 1 if all damages are taken into account, so a deviation indicates a flaw in the used theory or algorithms. Furthermore, in these tables 'SOLAS' means a calculation according to (SOLAS, 1997), the 'SLF' calculations are according to (SLF, 1997), at calculations with the suffix 'local' the *b/*B's are determined according to the second calculation option of this subsection, while 'global' indicates a calculation according to the third option.
The first conclusion we can draw from this explorative numerical comparion is that no calculation method or *b/*B switch leads to theoretically sound behaviour. The second is, if we concentrate on the (SOLAS, 1997) calculation, that the *b*/B switch has with a maximum variation of abt. 0.05 on *A* a significant effect on the final calculation result.

*Table 1. Comparison of methods for 90 m vessel.*

| Without horizontal subdivision, up to 18 damaged compartments | | | | |
|---|---|---|---|---|
| Method | $P_{partial}$ | $A_{partial}$ | $P_{deepest}$ | $A_{deepest}$ |
| SOLAS local | 0.9934 | 0.3477 | 0.9934 | 0.3110 |
| SOLAS global | 1.0028 | 0.3017 | 1.0018 | 0.2696 |
| SLF local | 0.9945 | 0.3816 | 0.9945 | 0.3345 |
| SLF global | 1.0081 | 0.3303 | 1.0065 | 0.2894 |
| Without horizontal subdivision, up to 11 damaged compartments | | | | |
| Method | $P_{partial}$ | $A_{partial}$ | $P_{deepest}$ | $A_{deepest}$ |
| SOLAS local | 0.9798 | 0.3477 | 0.9798 | 0.3110 |
| SOLAS global | 0.9668 | 0.3017 | 0.9681 | 0.2696 |
| SLF local | 0.9931 | 0.3816 | 0.9931 | 0.3345 |
| SLF global | 0.9785 | 0.3303 | 0.9804 | 0.2894 |
| With horizontal subdivision, up to 11 damaged compartments | | | | |
| Method | $P_{partial}$ | $A_{partial}$ | $P_{deepest}$ | $A_{deepest}$ |
| SOLAS local | 1.0146 | 0.3628 | 1.0032 | 0.3206 |
| SOLAS global | 0.9652 | 0.3194 | 0.9581 | 0.2793 |
| SLF local | 1.0410 | 0.3981 | 1.0223 | 0.3462 |
| SLF global | 0.9767 | 0.3499 | 0.9753 | 0.3016 |

*Table 2. Comparison of methods for 130 m vessel.*

| With horizontal subdivision, up to 13 damaged compartments | | | | |
|---|---|---|---|---|
| Method | $P_{partial}$ | $A_{partial}$ | $P_{deepest}$ | $A_{deepest}$ |
| SOLAS local | 1.0194 | 0.5678 | 1.0358 | 0.3974 |
| SOLAS global | 1.0611 | 0.5264 | 1.0256 | 0.3836 |
| SLF local | 1.0429 | 0.5945 | 1.0664 | 0.4315 |
| SLF global | 1.0928 | 0.5324 | 1.0479 | 0.4066 |

### *4.4. Vertical distribution of damage*

The options for the nature of *b*/B (local or global) are mutatis mutandis also applicable on the vertical distribution of damage, see also subsection 3.5 for an experienced problem when working with a local $H_{max}$, and hence local *v*. A possible workaround is use local $H_{max}$ and *v*, with the additional rule that *v* of a sub-damage, which is subtracted from the main damage, may not be greater than *v* of that main damage.

## 5. Conclusion and recommendations

In this paper we have discussed some deficiencies of the current probabilistic damage stability method, which can also superficially be observed by the occurence of probabilities smaller that zero or greater than one. The majority of problematic aspects have been experienced in practice, and are independent from the nature of the formulae of probability distributions. We have also proposed a few practicable solutions to improve the coherence and logic of the probabilistic method, but qualitative considerations and numerical examples demonstrate that these are not sufficient to convert the current implementation of the probabilistic method into a sound one.

In order to improve the method, we recommend that when new formulae are proposed, it is to be advised to co-develop generic and very accurate definitions and preferred interpretations, in order to minimize adverse effects. In this respect it is also wise to take the complicating effects of realistic hull forms and arbitrary compartment lay-outs into account integrally. However, the authors are not confident that it will be possible to avoid all problems on a natural way, as long as the probability of damage of a compartment or a group of compartments remains divided into distinct formulations for transverse, longitudinal and horizontal subdivision: $p_{total} = p(\text{transverse}) \cdot r(\text{longitudinal}) \cdot v(\text{horizontal})$. For the near future, the authors have identified two topics for further research:

• Development of functions of damage distribution where the probability of damage is a combined function of transverse, longitudinal as well as horizontal subdivision, so $p_{total} = p(\text{transverse, longitudinal, horizontal})$;

• Use 'Response Surface Modelling' optimization methods in order to optimize the compartment configuration with respect to probabilistic damage stability characteristics. Currently, in cooperation between the Delft University of Technology and SARC, this area is investigated. The purpose of this project is to supply the ship designer with an aid for an optimal subdivision of the vessel.

## Nomenclature

| | |
|---|---|
| $A$ | = Attained subdivision index = $\sum a$ |
| $a$ | = $p \cdot r \cdot v \cdot s$ = Combined probability of damage and survival of one compartment or a group of compartments |
| B | = The greatest moulded breadth of the ship at or below the deepest subdivision loadline |
| $b$ | = Penetration depth |
| $d$ | = Draught |
| $H$ | = Vertical extent of damage |
| $H_{max}$ | = Maximum possible vertical extent of damage above the baseline |

$L_s$ = Subdivision length (≈ extreme length of closed vessel)
*p* = Probability of damage of one compartment or a group of compartments, based on transverse subdivision only
*P* = Cumulative sum of probabilities of damage = $\sum p \cdot . r \cdot v$
*R* = Required subdivision index
*r* = Reduction factor on *p*, taking into account the effect of longitudinal subdivision
*s* = Probability of survival after flooding
*v* = Reduction factor on *p*, taking into account the effect of horizontal subdivision

Sub/superscript :
.*i* = Index which refers to the $i^{th}$ damage case
.+ = Refers to the nominal probability, that is the probability of damage without subtraction of subdamages

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