RE-EVALUATION OF THE METHOD TO DETERMINE THE PROBABILITY OF DAMAGE

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Abstract

The past few years it has become apparent that fundamental application problems can be experienced with the current probabilistic damage stability rules. Added to the fact that the legislation will be adapted as well as broader applied in the new harmonized MSC.80 rules, it may be time for a novel application approach. Such an approach, based on numerical integration of the probability functions, is presented in this paper, along with a dedicated computer program.

1 INTRODUCTION

Since 1992 probabilistic damage stability regulations for dry cargo ships have been in effect. Although since that time a lot of practical experience was gained, ship designers and shipyards still may find these regulations irksome, for which there can be a number of reasons. Those can be the intrinsic technical problems of the regulations, a subject that will be discussed in the next section, or that a designer loses the 'touch' with the profession. And even after the damage stability properties have been established properly, the approval procedure may slow down and confuse matters further, because there appears to be room for interpretation differences, although the legislative documentation aims at a uniform application. If classification societies or shipping inspections interpret different from the designer, significant differences can occur between issued and verification calculations. This may be amplified by the fact that a designer can try to squeeze the calculation to its limits, by means of an extensive optimization procedure, while the assessment body does not always has the opportunity to cope. All these issues can lead to mutual misunderstanding or irritation.
In order to improve the situation, an ad hoc discussion forum between the administration, classification societies, yards and designers has been organized in the Netherlands. Also some elementary test cases were designed and evaluated. It was striking to see how easily errors can be made, even with simple cases. Not only human errors were noted, but also systematic or software errors. This emphasized the necessity of a detailed and open communication between all parties involved, a conclusion which was subscribed by all participants.

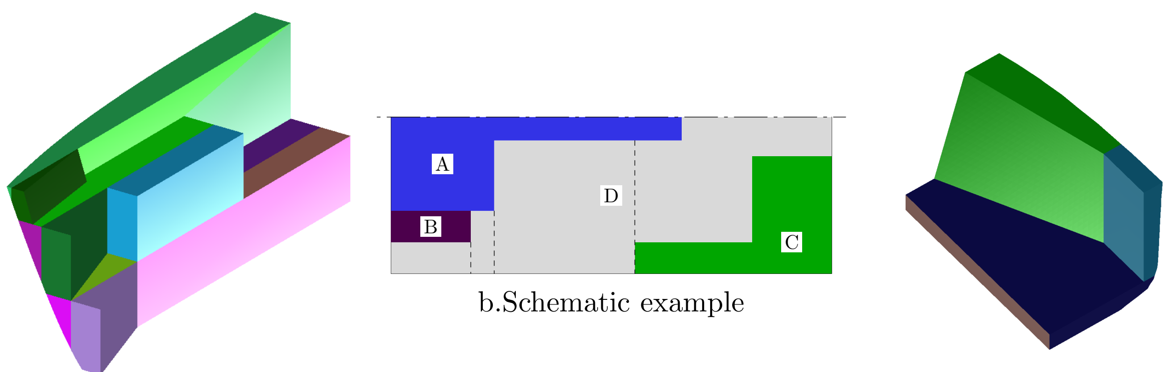
2 TECHNICAL PROBLEMS WITH THE CONVENTIONAL CALCULATION PROCEDURE

Another result of the discussions was a clear view on some problematic aspects of the damage stability regulations. The literature on these practical aspects is scarce, an overview is given

in Koelman (1995), Koelman and Pinkster (2003). It has also been observed that different computer programs give different outcomes van Dyck (2004). This is confirmed in Ravn et al. (2002), where calculations for different designs, with different degrees of subdivision and produced with different computer programs have been compared. The differences between several software packages were in the range from ≈ 0 to ≈ 0.05 on the attained subdivision index A. It also appeared that in one case a finer subdivided vessel had a 7% lower A than a coarser subdivided vessel, for which there is no obvious explanation.
The shortcomings of the conventional calculation procedure are discussed in detail in the cited references, and are summarized below. They apply to the current regulations IMCO (1974) (a.k.a. A.265) and SOLAS (2004) and, unless stated otherwise, also to the forthcoming harmonized regulations MSC (2005), which shall enter into force on January 1, 2009, because these share the underlying methodology. In the subsequent the current regulations are referred to as SOLAS 1992, and the forthcoming ones as SOLAS 2009.

1. Only one damage per compartment is taken into account. A compartment with multiple branches must be split virtually into different parts.

2. The method relies on a regular compartment layout, which means a configuration where all transverse bulkheads extend over the entire hull, and where longitudinal bulkheads and decks extend from one transverse bulkhead to another. However, in practice these restrictions are often violated, so the layout will become non-regular, examples are sketched in Figures 1.a and 1.b. An irregular layout cannot be processed without fictitious subdivision in order to make it virtually regular.



a.A complete side tank

b.Schematic example

c.Warped bulkhead

Figure 1: Examples of Non-regular Compartment Lay-out

3. The method is designed for vessels with strictly vertical bulkheads and horizontal decks. Compartments bounded by one ore more warped bulkheads, e.g. as sketched in Figures 1.c, are not foreseen.

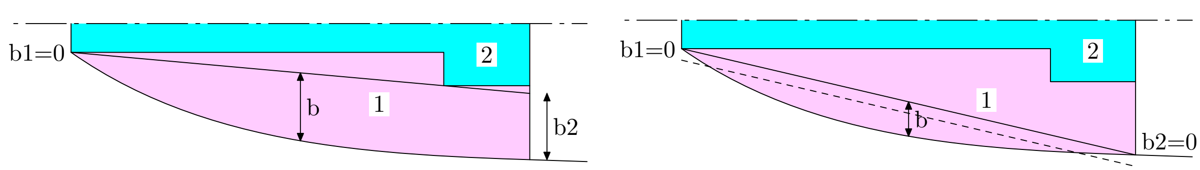
4. The formulae of SOLAS 1992 may, especially with long and arrow side-compartments, intrinsically lead to negative probabilities. This remark does not apply to SOLAS 2009, where a revised set of equations is used.

5. The probability of damage to two or more adjacent compartments involves the subtraction of the probabilities of the smaller damages. In the forward and aft regions of a ship, where the waterlines are narrowing, this may lead to negative probabilities.

6. According to the explanatory notes of SOLAS 1992, IMO (1991), the maximum penetration at side compartments shall not exceed twice the minimum penetration. This constraint

can limit the penetration depth very severely. In Figure 2.a the case is sketched where only compartment 1 is damaged. The evident penetration is according to the angled line, with the penetration depth indicated by b. However, in this case $b1 = 0$ and $b2 > 2b1$ so the penetration limitation rule is violated. The only solution to comply with this rule is to set $b2$ also to zero, which results in penetration depth b as depicted in Figure b. With a hollow waterline b would even become negative, which leads to a probability of damage of zero for this rather realistic damage case.
In the regulations of SOLAS 2009 the penetration limitation rule has been slightly changed, the criterion is now that the *mean* penetration shall not exceed twice the minimum penetration. With $b > 2b1$ this rule is clearly violated in Figure 2.a. What would be an appropriate penetration depends upon the interpretation of the rule. If the mean penetration is taken as the *absolute value* of b, and the minimum penetration is only measured at the extremities of the damage case, a penetration as indicated by the dashed line in Figure 2.b would result. If the *signed value* of b is used, no penetration whatsoever can exist which complies with the rule.
We consider this whole subject of penetration limitation rather unfortunate. It may have its purpose, but in the present form it is confusing and unrealistic.

7. For the determination of the probability of damage a number of crisp damage boundaries are applied. These may appear to be evident at first sight, but will be less appropriate when the actual compartment boundaries are not so crisp. For instance, the factor x_1 in SOLAS 1992 is defined as 'the distance from the aft terminal of L_s to the foremost portion of the aft end of the compartment being considered'. But take a damage to compartment D in Figure 1.b, what is here the *aft end of the compartment*, and the applicable foremost portion of it? Nobody can explain this on a normative basis (which might be the reason that the explanatory notes IMO (1991) contain predominantly examples, instead of explanations).
The whole concept of crisp boundaries is introduced by the modeling of stochastic events, where the common approach is 1) record the events, 2) construct a histogram on the basis of these recordings, 3) normalize this histogram, and approximate it with a Probability Density Function (PDF) and 4) integrate this PDF in order to obtain a Cumulative Distribution Function (CDF). This CDF can be evaluated conveniently to predict the occurrence of events below or above a certain magnitude. This approach should also be used in the context of probabilistic damage stability for ships, where in the fourth step, the integration, where the crisp boundaries are introduced, after all the CDF is the definite integral of the PDF.



a. As expected

b. According to the regulations

Figure 2: Limitation of Penetration Depth b

3 CALCULATION METHODS

A constituent of the probabilistic damage stability method is the assignment of a probability of damage to each portion of the vessel. In principle it should be indifferent which atomic (i.e.

undividable) portion is taken, as long as the sum of all portions covers the whole vessel. In practice, a number of choices for these portions has surfaced, enumerated from coarse to fine:

1. A *zone*. Whereas a zone is a portion of the vessel between two longitudinal boundaries (e.g. transverse bulkheads). The use of the zonal concept forces the subdivision model into regularity, thus avoiding certain pitfalls as described above. The zonal-model is artificial; it is an abstraction of the actual subdivision, and as such will produce a less accurate result. The zonal concept has become rather popular, although it is not even mentioned in SOLAS 1992 (it is mentioned, however, in the explanatory notes IMO (1991)). In SOLAS 2009 the terms *zone* and *compartment* are entangled, but the *zone* is not even defined at all.

2. A *compartment*. This is the most obvious choice, for it corresponds to the actual subdivision and it matches the terminology of the regulations.

3. A *sub-compartment*. A compartment as an atomic entity may not even be small enough. We have seen Figure 1b, where there is no single damage (with flat aft, forward and inner boundaries) which affects compartment D completely. However, a further subdivision, e.g. as indicated by the dotted lines, creates two entities which can both be damaged. Another example is presented in Figure 3, where the assumption that each compartment is affected by a single damage does not hold for compartment 1. A further division of this compartment, in entities called sub-compartments, for instance along the dotted line, will make it affected by two damages: B-C and D-E. Of course for the determination of the probability of survival, the compartment is always taken as a whole.

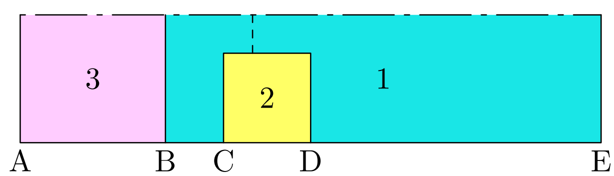


Figure 3: Compartment 1 can be Struck by Either Damages B-C and D-E

4. None. If the PDF's are not *a priori* integrated, the whole usage of crisp boundaries disappears. Consequently there is no need for any atomic portion concept. Instead the PDF's are integrated numerically, as proposed in Koelman (2005). This *numerical integration method*, for which the algorithm is depicted in Figure 4, takes into account the true compartment shape, including possible niches, irregularities and warped or even curved boundaries. The application of numerical integration on the subject of probabilistic damage stability can be compared with the developments in the area of structural strength. Initially, analytically determined standard solutions for the deflection of beams were utilized, but for more complex structures the division into very small, but *Finite Elements* proved to be more flexible.
   Apart from the practical advantages of the numerical integration method, it may offer also a benefit for the derivation of the statistical model. It is common practice that stochastic events are approximated by PDF's from simple functions, because the analytical integration process is eased that way (see Pawlowski (2004) for an in-depth discussion). With numerical integration this reason can be discarded further allowing the use of PDF's which approximate the observed events more accurately. And what's more, the events do not necessarily have to be modeled by one of the standard statistical functions. For instance, a spline or any other smooth function through the data points would also do. An explorative investigation into the modeling of the damage length, based on published data

Lützen (2001), is presented in Table 1. From this table it can be concluded that there is room for an increased accuracy, which can be exploited by the numerical integration method. The author recognizes the fact that this aspect is only theoretical, because the accuracy of the PDF modeling is at this moment not an object of practical concern, but the point remains.

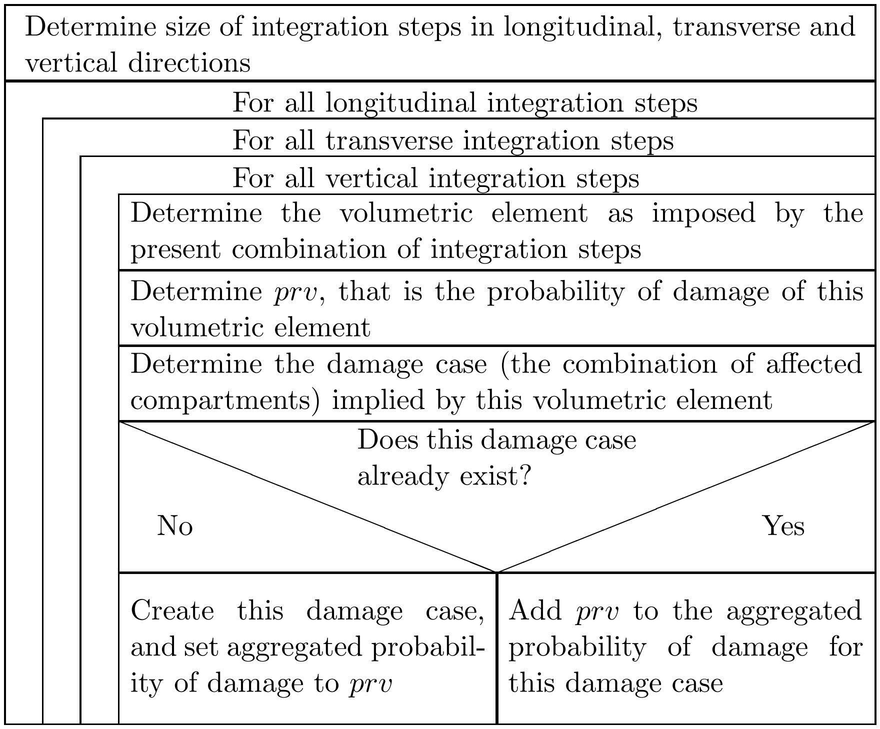


Figure 4: Program Analysis Diagram of the Numerical Integration Method

PDF model	Standard error
Linear	1.87
Cubic	0.95
Max(linear,0) (as applied in SOLAS 1992)	0.83
Bi-linear	0.83
Max(bi-linear,0) (as applied in SOLAS 2009)	0.81
Lognormal	0.58
Weibull	0.53
Weibull + quadratic	0.43
Spline, or other smooth function	≈ 0

Table 1: STANDARD ERRORS OF A FEW APPROXIMATION MODELS FOR THE PDF OF THE DAMAGE LENGTH

4 A NEW COMPUTER PROGRAM FOR CALCULATING PROBABILISTIC DAMAGE STABILITY

Since about 1988, the PIAS suite of naval architectural programs (SARC (2005)) has been equipped with modules for probabilistic damage stability according to the existing methods

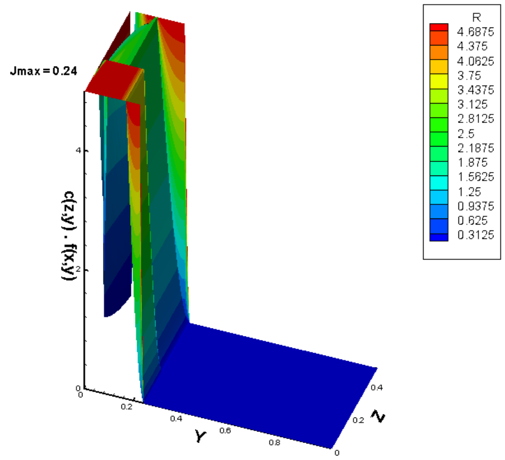


Figure 5: Underlying SOLAS 90 PDF Function (Koelman (2005))

SOLAS (2004), IMCO (1974) and NN (2000) (a.k.a. dr-67). These modules always have served us well, but the new insights as discussed in the previous section, and the new SOLAS regulations have triggered the development of one new, harmonized, computer program for probabilistic damage stability. The background and functionality of this new program is the subject of this section.

4.1 Applicable Regulations

The supported regulations are those currently in force, mentioned in the last paragraph, as well as SOLAS 2009. For the current regulations, a peculiar distinction is made between 'SOLAS 1992' and 'Reconstructed SOLAS 1992'. The reason lies in the way the longitudinal and transverse subdivisions, as expressed in the factors p and r, are treated. The PDF of the product of the two can be obtained by differentiation of the equations SOLAS (2004), and is plotted in Figure 5. However, according to the prescriptions of the regulation, p and r must be determined separately. For multi-damage cases this leads in effect to a product pr as plotted in Figure 6. One would expect reduction factor r to be in the interval [0,1], but instead the resulting r-values appear to have values between $-\infty$ and ∞. The reason for this phenomenon is that in some cases $pr \neq 0$ while at the same time $p \approx 0$, so that $r = pr/p$ has a very large positive or negative value. With such large values of $|r|$ it is useless to draw r as a function of dimensionless damage length $\overline{y}$ and dimensionless penetration $\overline{z}$, so in Figure 6 r is represented by a color distribution which is painted on the graph of pr, while, in order to avoid extreme values, $|r|$ is limited to 1000. People who consider the wild character of Figure 6 surprising are able to verify our findings with the stand-alone 188-line Pascal computer program (`solaspdf.pas`).
Due to this anomaly, the results as obtained by numerical integration of the theoretical PDF's differ from those as acquired with the regulatory CDF's. However, by means of reverse engineering another PDF was derived which is different from the theoretically one, but which gives numerical results in line with a conventional calculation. This alternative PDF is not available in closed form, instead tables of probabilities, similar to the output of `solaspdf.pas`, are used directly. Summarized, the 'SOLAS 1992' method is theoretically in line with SOLAS (2004), but gives defiant results, while the 'Reconstructed SOLAS 1992' method is theoretically inconsistent, but provides the user with results which are compatible with a conventional calculation. This whole question does not play with SOLAS 2009, because its foundation is much more solid by treating p and r combined.

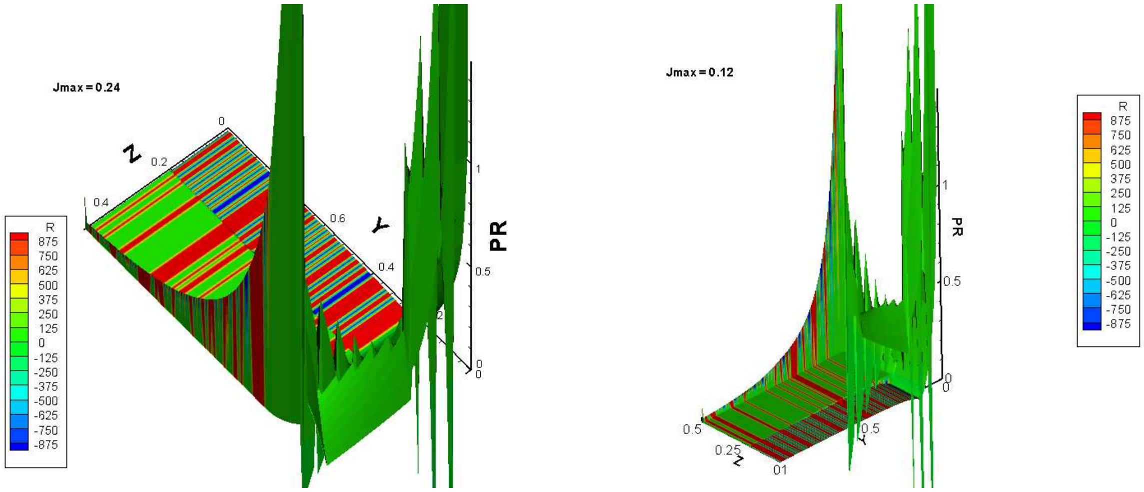


Figure 6: pr and r CDF Distributions According to SOLAS 1992

4.2 Calculation Switches and General Functionality

The new computer program was designed for maximum flexibility. That implies that as many choices as feasible are not pre-programmed, but offered to the user, at least, as long as that particular subject is applicable to the chosen calculation method. Possible switches are:

- Four calculation methods: zone-based, compartment-based, sub-compartment-based and numerical integration.
- Five supported regulations: A.265, SOLAS 2009, dr-67 (for hopper dredgers with reduced freeboard), SOLAS 1992 and reconstructed SOLAS 1992.
- Choice between mean and minimum penetration depth.
- Choice between the global and local penetration rule for multi-compartment damages (see Koelman and Pinkster (2003)).
- Choice between two penetration limitation rules (as discussed above): $b1$ and $b2$ both $< 2min(b1, b2)$ (according to SOLAS 1992) and $b_{mean} < min(b1, b2)$ (according to SOLAS 2009). Furthermore, four application scenarios for the penetration limitation rule: a) do not apply the rule, b) apply the rule, except for damages which extend to centerline, c) apply the rule, except for damages with an inner boundary parallel to centerline and d) apply the rule in all cases.
- Whether or not to set a, the contribution of each damage case to the attained subdivision index, at zero if it happens to be negative.
- Whether or not to include intermediate stages of flooding.
- Maximum number of compartments per damage case.
- Finally, the program offers a number of utilities, such as:
  - The determination of the critical VCG (at a selected draft) so that the attained subdivision index A will equal required subdivision index R.
  - Generation of damage cases (taking into account possible cross-flooding by pipes or ducts), and automatic determination of damage boundaries (for the compartment-based and sub-compartment-based methods).

– Output of intermediate results to text file, for further evaluation, and to spreadsheet for further analysis.

4.3 Results

The presentation of the results depends on the applied regulations, and particularly on the chosen calculation method. In particular, attention is focussed on the aggregated probability of damage, $\sum prv$, which should theoretically approach or equal unity, and which can be used as a measure of algorithm quality. For the different calculation methods, the following observations can be made:

- Calculations according to the zonal method have a conventional output and format, see Figure 7 for an example. In the past, the so-called probability triangle was occasionally requested to be plotted for each damage case. As shown in the example this belongs to the possibilities now, although the author considers this rather useless. Due to a lack of experience with the zonal method we are not in the position to comment on the $\sum prv$'s that are typically achieved.

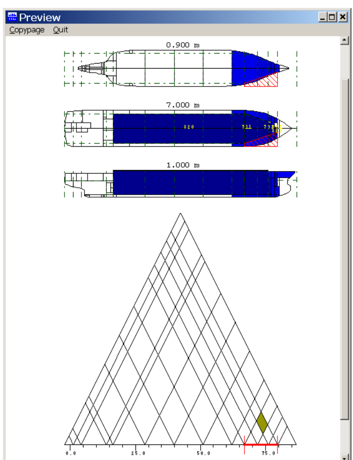


Figure 7: Computer Output of Zone-based Damage Case, including Probability Triangle

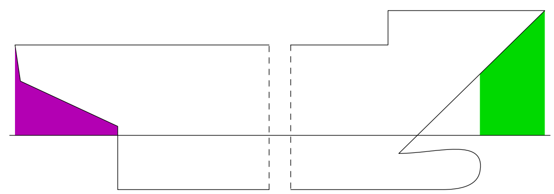


Figure 8: The Shaded Areas do also Contribute to the Probability of Damage.

- The results with the compartment-based method are essentially the same as with the older PIAS module. For SOLAS 1992 calculations $\sum prv$ commonly lie in the range between 0.9 and 1.20. For a conventional cargo vessel, a couple of hundred damage cases are typically employed.

- The sub-compartment method is a refinement of the compartment-based method. As such, the merits and output are comparable to the compartment-based method, although due to the higher level of detail an increased accuracy can be expected.

- The numerical integration method works as expected. With the *reconstructed SOLAS 1992* 'regulations' the results are more or less the same as for the compartment-based method, which is no surprise because these 'regulations' have been designed to mimic the conventional behavior of SOLAS 1992. For SOLAS 1992 and SOLAS 2009, with $0.998 < \sum prv < 1.000$ a pretty high quality has been achieved. Another phenomenon is the occurrence of zero-compartment damages. These are damage cases which can occur, according to the system of regulations, but which lie outside the vessel's hull, e.g. the shaded areas in Figure 8. Provided that the vessel complies with the survival criteria in intact condition (which will normally be the case), these damage cases contribute to the attained subdivision index.

Finally, it can be mentioned that, although the basic algorithm is rather simple, if a small integration increment is applied, the number of integration steps can become so high that the idea that the calculations can be verified by a human must be abandoned. Therefore the program is equipped with the option to store all intermediate integration steps in a text file, which could be utilized subsequently by an automated verification system.

5 PRELIMINARY FINDINGS ON APPLICATION

Currently the software is being applied in practical tests. The purpose of these tests is twofold, the first goal is to validate the software, the second is to develop some practical insights when applying the new methods and regulations. The first finding when comparing SOLAS 1992 and 2009 is that the latter requires a significantly higher 'required subdivision index' R, for cargo vessels. However, from this aspect alone it cannot be concluded that the new regulations are more stringent than the old ones, because also the 'attained subdivision index' A differs, while it cannot firmly be concluded whether 2009 gives higher A values than 1992 or not. A suitable comparison yard-stick is ΔI, defined as $A - R$. This comparison is shown for a typical application in Table 2.

Regulations	SOLAS 2009	SOLAS 1992	Reconstructed SOLAS 1992
Zonal method	$P = 0.9999$ $N = 303$ $\Delta I = -0.1391$	$P = 0.9999$ $N = 303$ $\Delta I = -0.0573$	
Compartment method	$P = 1.0387$ $N = 578$ $\Delta I = -0.0636$	$P = 0.9915$ $N = 547$ $\Delta I = 0.0061$	
Sub-compartment method	$P = 0.9034$ $N = 1328$ $\Delta I = -0.0733$	$P = 0.9500$ $N = 1131$ $\Delta I = -0.0081$	
Numerical integration method	$P = 0.9990$ $N = 500$ $\Delta I = -0.0895$	$P = 0.9988$ $N = 435$ $\Delta I = +0.0330$	$P = 0.9989$ $N = 491$ $\Delta I = -0.0312$

Table 2: DIFFERENCES IN OUTCOME BETWEEN SOLAS 1992 AND SOLAS 2009. $P = \sum prv$ for entire ship at deepest draft, N = number of damage cases, $\Delta I = A - R$.

From this table, the following conclusions can be drawn:

- The achieved A is proportional to the accuracy of the applied method. The zonal method ranks lowest in accuracy, the (sub-)compartment medium and numerical integration high.
- For this particular vessel SOLAS 2009 is a more severe requirement than SOLAS 1992.
- The listed values are 'raw', that means that no 'optimization' is applied which could increase A. With the (sub-)compartment method, our previous experience is that by e.g. removing damage cases with a negative probability prv, the final A value can be increased by a couple of percent points.

- The number of damage cases for the numerical integration method is rather low. Indeed the program reported that missing damage cases account for a combined *prv* of abtout 0.05. Increasing the number of damage cases might rise ΔI to some extent.
- One aspect that is not evident from this table is the effect of the penetration limitation rule as discussed above. This rule is taken into account automatically with the (sub-)compartment method, while it is not applicable at all with the numerical integration method. However, with the zonal method it is the user's responsibility to choose the zone boundaries in such a fashion that this rule is complied with. However, for the ship under consideration that is a laborious task, which was not completed. Consequently, the zonal calculation does not fulfill the penetration rule.

Furthermore, at the moment of writing there are some experimental calculations in preparation, with the aim to answer the following questions:

- Do cargo vessels which complied under SOLAS 1992, also comply under 2009?
- Under SOLAS 1992, the final requirement is $A > R$, where A is the average between the A's for the partial and subdivision drafts. There was no requirement for the A's on the individual drafts, and this offered the opportunity to apply a very uneven distribution of A. For a vessel with $R < 0.5$ we have once issued a calculation with $A_{deepestdraft} \approx 0$ and $A_{subdivisondraft} \approx 1$, yielding an A of ≈ 0.5. Under the 2009, rules this approach is no longer tolerated, because for each individual draft the A must be greater than $0.5R$ (for passenger vessels even $> 0.9R$). The question is whether this additional rule has a significant impact on the design feasibility.
- Single-hold vessels will have to rely on the survivability properties of a double hull. The r formulae differ between SOLAS 1992 and 2009. Do double-shell vessel perform better under 2009 or not?
- What is the effect of the permeability of the cargo spaces?

6 CONCLUSIONS

This paper has described the application of a numerical integration method for the determination of the probability of damage, and its application on the existing and forthcoming SOLAS rules. It has been shown that this method gives more stable results than conventional approaches, while a number of practical pitfalls are avoided. Preliminary application of the different calculation methods on both types of regulations suggests that for a smaller cargo vessel, the new rules are more stringent than the existing ones. Future work will concentrate of the design-centric questions of the previous sub-section. Another subject for development is the application of the numerical integration method on the MARPOL requirements concerning the outflow of oil, for which the Probability Density Functions are readily available in MEPC (2003).

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