

A New Method for Probabilistic Damage Stability

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1 Introduction

Since 1992 probabilistic damage stability regulations for dry cargo ships have been in effect. Since then, a lot of practical experience was gained, but ship designers still find these regulations irksome, for a number of reasons. Those can be the intrinsic technical problems of the regulations, as discussed in Section 2, or that a designer loses the ‘touch’ with the profession. 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 have 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 was organized in the Netherlands. 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, as reviewed by *Koelman (1995)*, *Koelman and Pinkster (2003)*. It has also been observed that different computer programs give different outcomes, *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 were compared. The differences between several software packages were in the range from ≈ 0 to ≈ 0.05 on the attained subdivision index A . In one case, a finer subdivided vessel had a 7% lower index 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), *IMO (2004)* and, unless stated otherwise, also to the harmonized regulations *IMO (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, i.e. 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, e.g. as sketched in Figs.1a and b. An irregular layout cannot be processed without fictitious subdivision in order to make it virtually regular.

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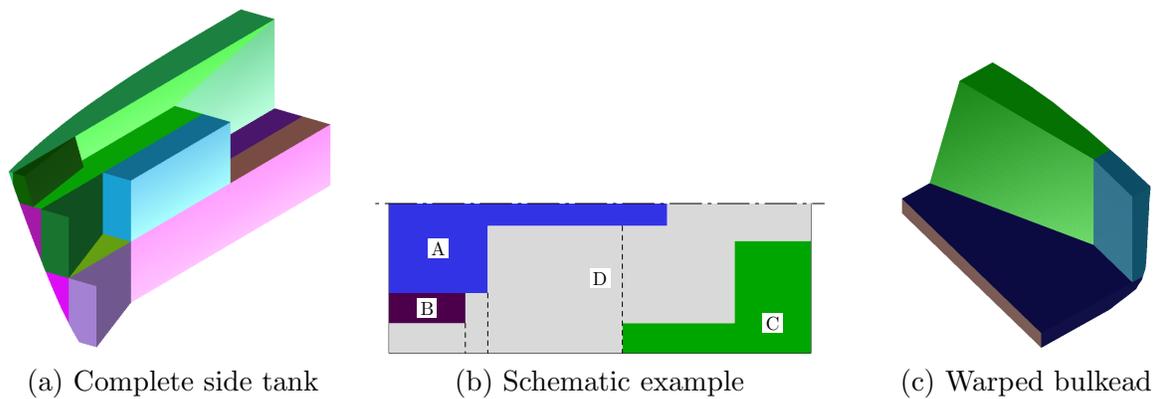


Fig.1: Examples of non-regular compartment lay-out

3. The method is designed for vessels with strictly vertical bulkheads and horizontal decks. Compartments bounded by one or more warped bulkheads, e.g. as sketched in Fig.1c, are not foreseen.
4. The formulae of SOLAS 1992 may, especially with long and narrow 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 severely. In Fig.2a 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 $b_1 = 0$ and $b_2 > 2b_1$ so the penetration limitation rule is violated. The only solution to comply with this rule is to set b_2 also to zero, which results in penetration depth b , Fig.2b. With a hollow waterline b would even become negative, which leads to a probability of damage of zero for a completely 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 $b > 2b_1$ this rule is clearly violated in Fig.2a. 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 Fig.2b would result. If the signed value of b is used, no penetration whatsoever can exist which complies with the rule.

In my opinion, this whole subject of penetration limitation is 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 Fig.1b. What is in this case 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 to

- 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 was also used in the context of probabilistic damage stability for ships, where in the fourth step, the integration, the crisp boundaries are introduced. After all the CDF is the definite integral of the PDF.

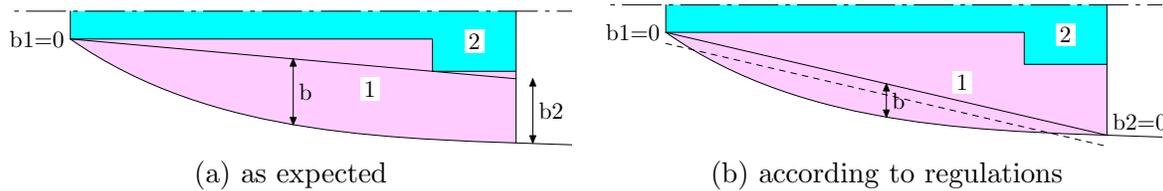


Fig.2: Limitation of penetration depth b

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. 'zone'

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 in Section 2. The zonal model is artificial; it is an abstraction of the actual subdivision, and as such will produce a less accurate result. It is funny to see that 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. 'compartment'

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

3. 'sub-compartment'

A compartment as an atomic entity may not even be small enough. In Fig.1b, 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 Fig.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.

4. None

If the PDFs are not a priori integrated, the whole usage of crisp boundaries disappears. Consequently there is no need for any atomic portion concept. Instead the PDFs are integrated

numerically, as proposed in *Koelman (2005)*. This numerical integration method, Fig.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 Finite Elements proved to be more flexible.

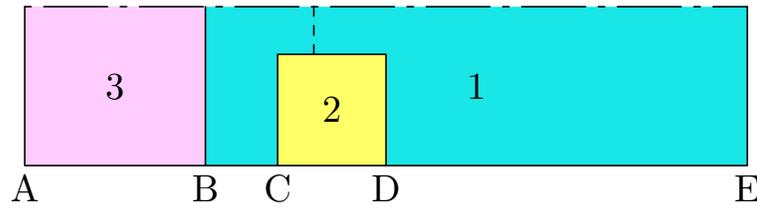


Fig.3: Compartment 1 can be struck by either damages B-C and D-E

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 PDFs from simple functions, because this makes the analytical integration process easier. See *Pawlowski (2004)* for an in-depth discussion. With numerical integration, this reason can be discarded further allowing the use of PDFs which approximate the observed events more accurately. In addition, 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 can be used. Table I presents an explorative investigation into the modeling of the damage length, based on published data *Lützen (2001)*. Table I allows to conclude that there is room for an increased accuracy, which can be exploited by the numerical integration method. I recognize 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.

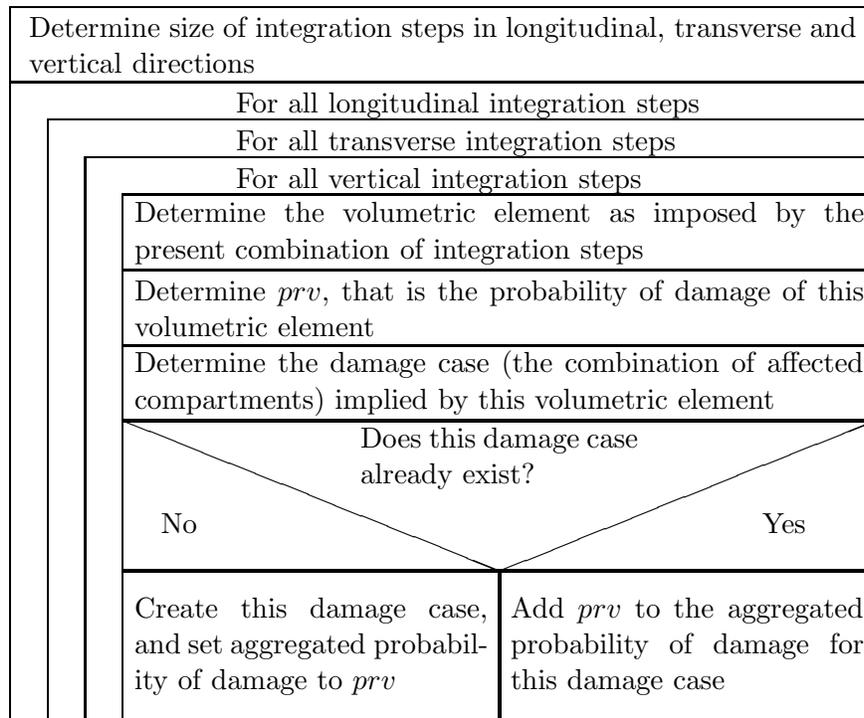


Fig.4: Program Analysis Diagram of the numerical integration method

Table I: Standard errors of a few approximation models for the PDF of the damage length

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
Log-normal	0.58
Weibull	0.53
Weibull + quadratic	0.43
Spline, or other smooth function	≈ 0

4 A new computer program for calculating probabilistic damage stability

Since 1988, our PIAS suite of naval architectural programs has been equipped with modules for probabilistic damage stability according to the existing methods, *IMO (1974,2004)*, *N.N. (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 *IMO (2004)*, and is plotted in Fig.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 Fig.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 \bar{y} and dimensionless penetration \bar{z} . People who consider the wild character of Fig.6 surprising are able to verify our findings with the stand-alone 188-line Pascal computer program `solaspdf.pas`².

Due to this anomaly, the results as obtained by numerical integration of the theoretical PDFs differ from those as acquired with the regulatory CDFs. 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 *IMO (2004)*, but gives defiant results, while the ‘Reconstructed SOLAS 1992’ method is theoretically nonsense, 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.

²Available on `www.sarc.nl`, ‘Download’ section, login as non-registered user, go to the `probability_of_damage` subdirectory.

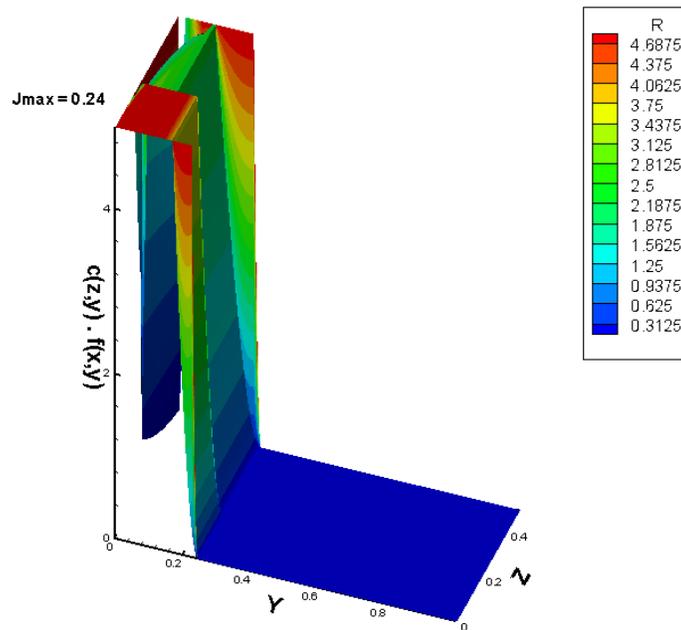


Fig.5: Underlying SOLAS 90 PDF function, *Koelman (2005)*

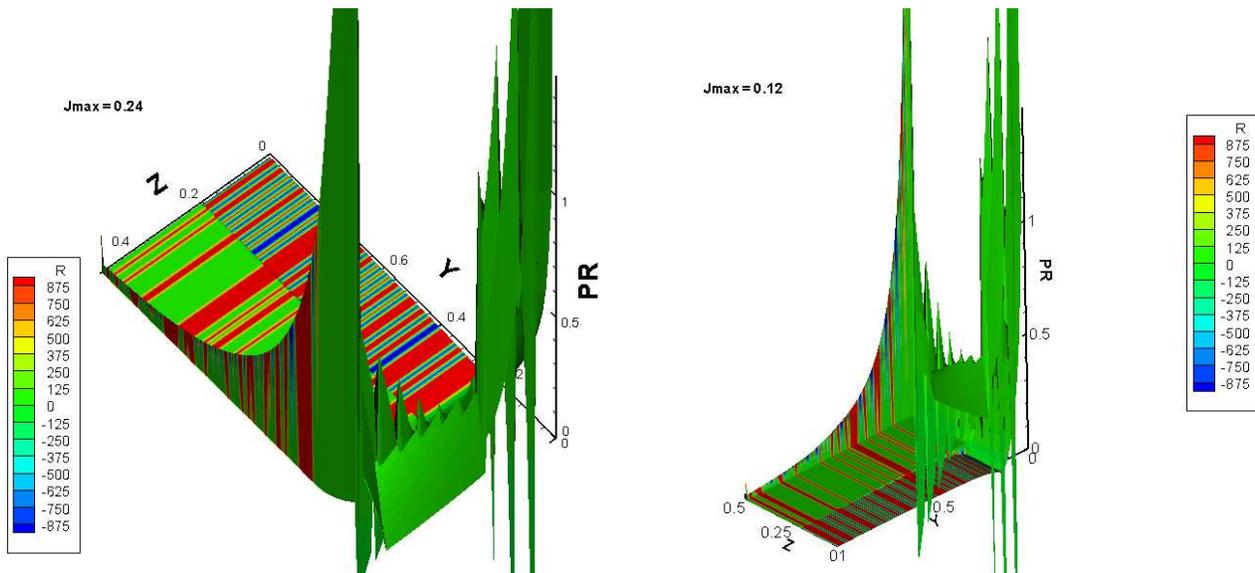


Fig.6: *pr* and *r* CDF distributions according to SOLAS 1992

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 free-board), 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, *Koelman and Pinkster (2003)*.
- Choice between two penetration limitation rules (as discussed in Sub-section 2.6): b_1 and b_2 both $< 2 \min(b_1, b_2)$ (according to SOLAS 1992) and $b_{mean} < \min(b_1, b_2)$ (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.

The program also 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). Damage cases may be generated, but also defined or modified manually. Fig.7 shows an example of the input window.
- Output of intermediate results to text file, for human reading, and to spreadsheet for further analysis.
- For higher processing speeds several tasks which can be performed simultaneously are distributed over multiple processors or processor cores, if available. In this way the processing speed is doubled on computers equipped with the latest hyperthreading or dual-core technology.

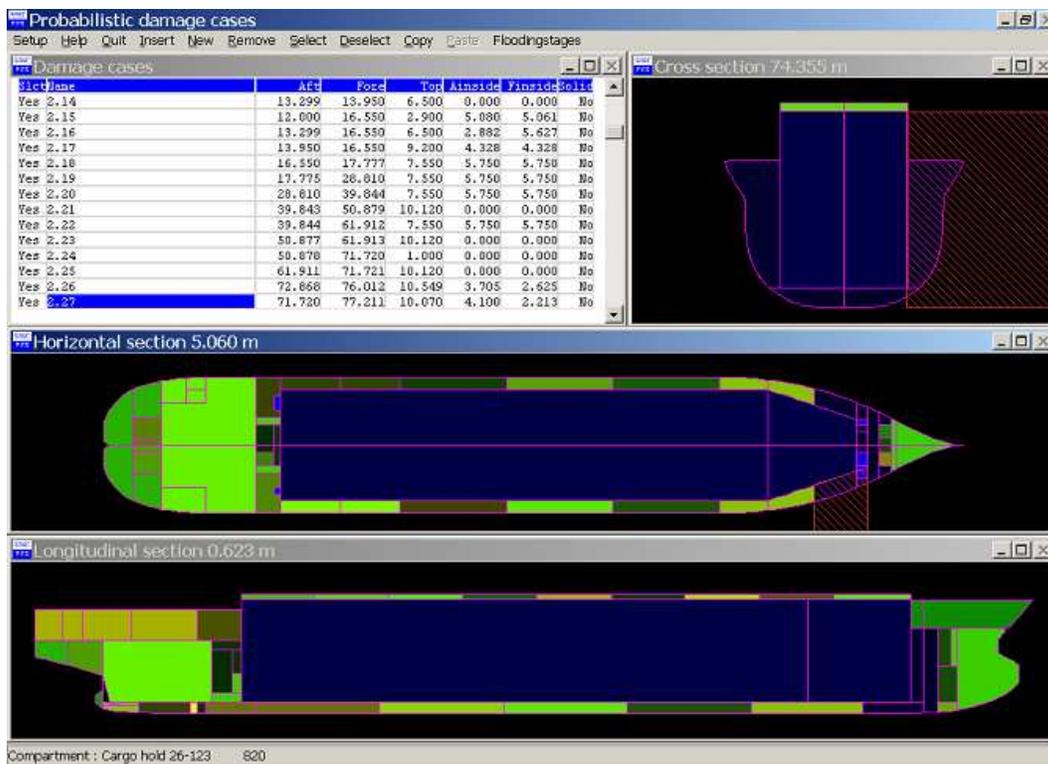


Fig.7: Damage case editor

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 completeness. A $\sum prv$ of less than 1 indicates an incomplete calculation, while a value greater than 1 is a sign of overcompleteness, although both phenomena may also be the numerical expression of the problems of Section 2. Anyway, in this respect complete must be distinguished from accurate, for instance a zonal calculation with a modest number of zones can be complete, because the whole vessel is covered, but still inaccurate, because the zonal division approximates the true subdivision only roughly. For the different calculation methods, the following observations can be made:

- Calculations according to the zonal method have a conventional output and format, see Fig.8 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 is possible, although personally, I consider this rather useless. Due to a lack of experience with the zonal method we are not in the position to indicate values for $\sum prv$ although it may be expected that due to the regular subdivision it will approximate unity.

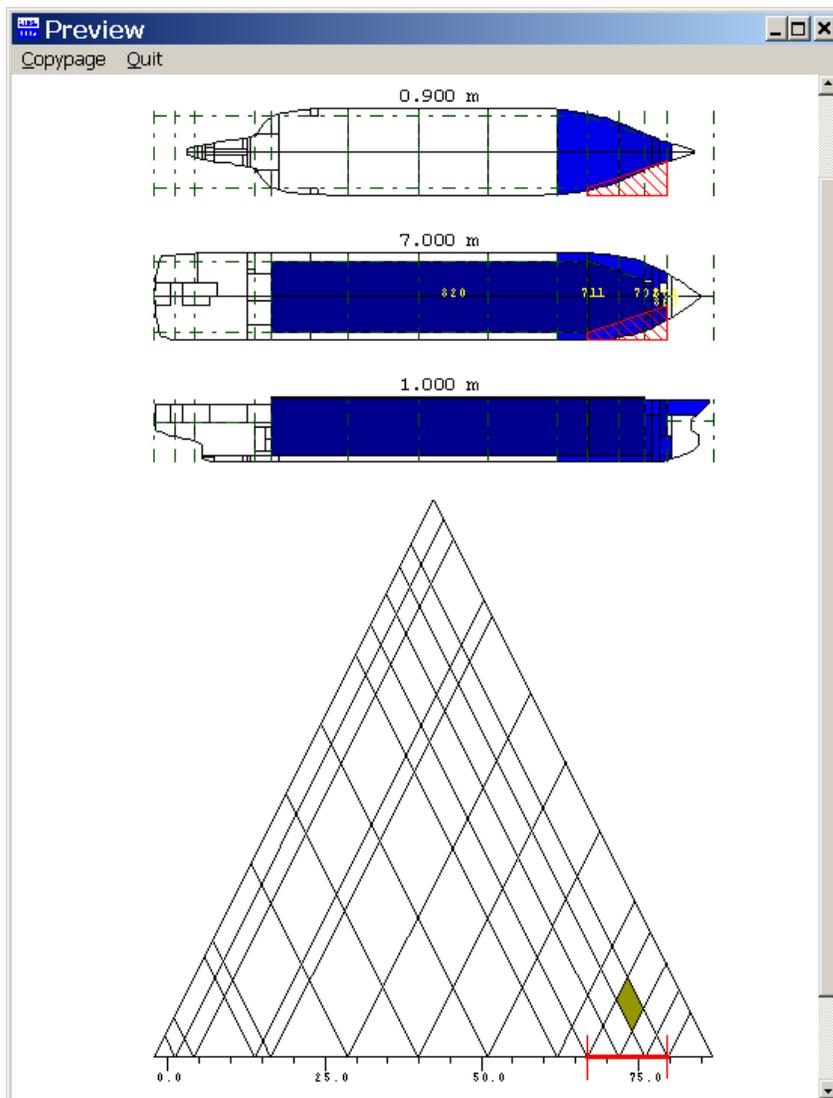


Fig.8: Computer output of zone-based damage case, including probability triangle

- 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. This is no surprise, because these ‘regulations’ have been designed to mimic the conventional behavior of SOLAS 1992. For SOLAS 1992 and SOLAS 2009, with $0.998 < \sum prv < 1.000$ the completeness is high. 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 Fig.9. 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.

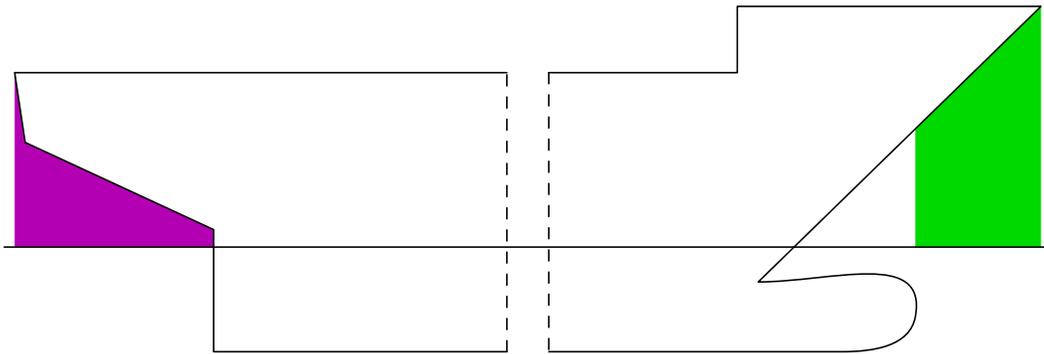


Fig.9: Shaded areas contribute also to probability of damage

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 calculations can no longer be verified by a human. 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 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 SOLAS 2009 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. It cannot firmly be concluded whether 2009 gives higher A values than 1992 or not.

A suitable measure of comparison is $\Delta I = A - R$. Table II shows such a comparison for a typical application. From this table, the following conclusions can be drawn:

- For SOLAS 1992 the achieved A is proportional to the accuracy of the applied method. The zonal method ranks low, (sub-)compartment medium, and numerical integration high. For SOLAS 2009 and reconstructed SOLAS 1992 and SOLAS 2009, the ranking from low to high is zonal, numerical integration, sub-compartment, compartment. This trend is also observed with test calculations for another vessel (not shown here).

- For this particular vessel, SOLAS 2009 is a more severe requirement than SOLAS 1992, or, in other words, has a higher safety margin.
- 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 several 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 approximately 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 of Sub-section 2.6. 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.

Table II: Differences in outcome between SOLAS 1992 and SOLAS 2009. $P = \sum prv$ for entire ship at deepest draft, $N =$ number of damage cases, $\Delta I = A - R$

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-comp. method	$P = 0.9034$ $N = 1328$ $\Delta I = -0.0733$	$P = 0.9500$ $N = 1131$ $\Delta I = -0.0081$	
Num. integration method	$P = 0.9990$ $N = 500$ $\Delta I = -0.0895$	$P = 0.9988$ $N = 435$ $\Delta I = +0.0330$	$P = 0.9989$ $N = 491$ $\Delta I = -0.0312$

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.

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