Damage Stability Rules in Relation to Ship Design

Contribution by

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Freedom is just another word for nothing left to lose

Abstract. Recently introduced rules for probabilistic damage stability lead to a more difficult and time consuming process of ship design. After an introduction to the legislation, the practical aspects are discussed in this paper, and the areas of difficulty are identified. The paper ends with experiences in the design process, and some suggestions for improvement.

1. Introduction

New rules for probabilistic damage stability have a great impact on ship design, both on the design itself, and on the design process. Our company has been involved in many calculations of probabilistic damage stability during the last few years. The experiences and opinions gained in those projects are discussed in this paper.

It must be noted that the software referred to is the PIAS (**P**rogram for the **I**ntegral **A**pproach of **S**hipdesign) program. PIAS, which has been developed and marketed by our company, contains a suit of integrated programs for design and analysis, including specialized tools for probabilistic damage stability.

2. Probabilistic damage stability rules

For the sake of completeness a summary of the probabilistic method is given here.

2.1. Probabilistic versus deterministic

With a *deterministic* damage stability damage assumptions are specified in the rules and regulations. For a particular vessel the damage assumptions are fixed, which gives this method a rigid character; damages unequal to the damage assumption are not taken into account with this method.

With *probabilistic* damage stability on a statistical basis the probability of occurrence of damages and the probability of survival are calculated, so the method uses no fixed damage assumptions. This gives the probabilistic damage stability method a flexible character, which leads to *freedom in design*.

2.2. Application

At this moment two probabilistic damage stability methods are valid :

- Dry cargovessels with a length over 100 m have to comply with the rules of chapter II-1, part B-1 of SOLAS 1992. These regulations are supported by so called "explanatory notes", which may stimulate uniform interpretation.
  At this moment it may be expected that from january 1, 1996, these regulations will also cover vessels with a length between 80 and 100 m.

- As an equivalent to SOLAS since 1973 for passenger vessels it may be decided to comply with IMO res. A.265(VIII), which contains a large probabilistic portion.

2.3. General principles

The basic principle of the method is that the probability of survival must have a certain minimum value. In words used in the regulations it says : "The Attained Subdivision index A must not be less than the Required Subdivion Index R".

2.3.1. Required Subdivision Index R

For cargo vessels the Required Subdivision Index is a simple function of the vessels length (Fig. 2.1). For passenger vessels R is also determined by the number of passengers. Due to the simple nature, the formula for R reveal no interesting details.

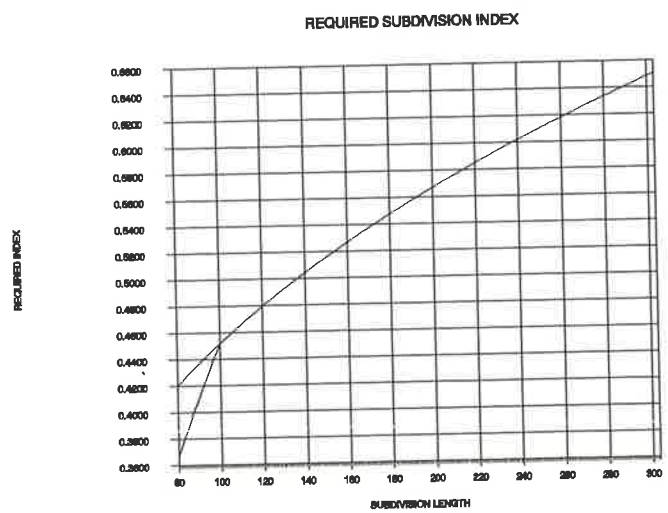

Figure 2.1. *Required Subdivision Index*

2.3.2. Attained Subdivision Index A

The attained subdivision index is determined by two things :

- Shape, dimensions and location of all possible damages

- Residual stability of the vessel after and during flooding, for all possible damages.

2.3.2.1. Shape, dimensions and location of a damage

For each damage case the probability of occurrence of damage is determined, based on the assumption that there is only one damage, in the side of the vessel, which extends from the bottom of the vessel upwards, and is shaped rectangular. Based on so-called damage statistics, distribution functions for damage dimension and damage location have been derived by IMO. On the basis of these distribution functions formulas have been derived, with which the probability of occurrence of a specific damage at a specific location can be calculated. Conceptually these formulas posess a simple nature and are included in the regulations.

2.3.2.2. Residual stability of the vessel after and during flooding

A truly *probabilistic* method should also contain an estimation of the probability of survival after damage. For cargo vessels no relevant statistical material is available, so a *deterministic* approach using the curve of residual statical stability was adopted. When in a damage case these three criteria are met :

Statical angle of inclination < 25°
Range of positive statical stability > 20°
Maximum righting lever > 0.10 m

then it is assumed that the vessel will survive (probability of survival = 1), otherwise it is assumed that the vessel will not survive (probability of survival = 0). In reality the regulations are slightly more complicated, so that a small transition area occurs, where the probability of survival varies between 0 and 1. Because this transition area is seldom entered it is practically of minor significance.

2.3.3. Composition of a complete calculation

A complete calculation consists of the following five steps :

a - Unique damage cases are identified which damage all compartments and combinations of compartments.

b - For each damage case the probability of occurrence is determined.

c - For each damage case the curve of residual statical stability is calculated, and the probability of survival is determined.

d - The product of the steps b and c is the combined probability of survival and occurrence of damage.

e - The summation of all probabilities determined in step d is the total probability of survival of the vessel.

2.4. Assumptions and details

- For cargo vessels the calculations are made for two drafts, the so called partial draft and the fully loaded draft. The final probability of survival is the mean value between those drafts.
  For passenger vessels the calculations are made for three drafts.

- The actual loading condition is *not* taken into account in the calculations.

- When calculating the probability of occurrence of some multi-compartment damage, bookkeeping is kept straight by deducting the probability of all damages with a smaller amount of compartments, falling into the damage case under consideration.

3. Practical aspects of the calculation of probabilistic damage stability

In concept the method of probabilistic damage stability is an elegant and straightforward one. Some apparent side issues, as mentioned in the regulations or the explanatory notes, lead to an increased number and complexity of the damage cases.

3.1. The effect of openings

When openings, or openings which are capable of being closed weathertight, are situated below the final waterline it is assumed that the vessel will not survive the damage case under consideration. Those openings also include airpipes, weathertight doors and hatch covers. So the locations of all airpipes and openings must be known before calculating probabilistic damage stability.

Besides the assumption that the vessel will be flooded by submersion of the hatch covers is a deterministic one, and its level of reality is questionable.

3.2. The effect of damage to pipes and ducts

When pipes or ducts are damaged, either arrangements are to be made that progressive flooding cannot thereby extend to other compartments, or flooding of other compartments through the pipes should be taken into account. See for example the schematic double bottom configuration in Fig. 3.1, where damage in the aftmost SB double bottom tank, leads to flooding of **all** SB double bottom tanks through the damaged pipes.

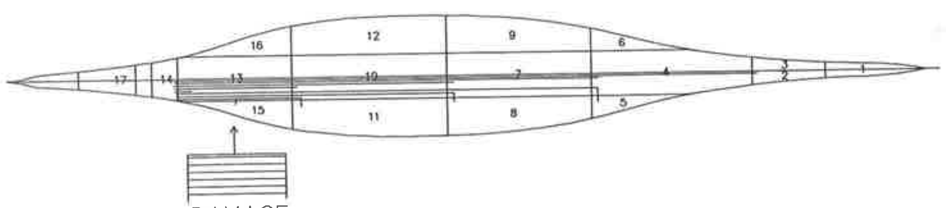

Figure 3.1. *Damage to pipes*

3.3. Minor damages

The assumed vertical extend of damage is to extend from the baseline upwards. However, if a minor damage gives worse residual stability characteristics, that extent is to be assumed. This regulation effectively increases the number of residual stability calculations *within* each damage case, because, in general, on forehand it can not be predicted whether some minor damage will have a better or a worse residual stability, so the only way is to simply calculate all minor damages.

3.4. Intermediate stages of flooding

The regulations prescribe to calculate residual stability "for any condition of flooding". That implies that also intermediate stages of flooding must be calculated, which also increase the number of calculations *within* each damage case. Intermediate stages can be of two types:

- The "standard" type, where all compartments are equally filled up to some percentage (e.g. 25%, 50% & 75%) of the final stage of flooding.

- The "complex" type, where compartments are not flooded equally. When for example a compartment, not situated in the damage region, is flooded through a damaged pipe, then in some intermediate stage of flooding that compartment will be partially flooded, while all compartments in the damage region will be completely flooded.

3.5. Vertical Centre of Gravity

The Vertical Centre of Gravity (VCG) has a major influence on the residual stability, and therefore also on the probability of survival and the Attained Subdivision Index. Ideally one would like to choose the VCG used at the calculation of probabilistic damage stability higher than the maximum allowable VCG which follows from intact stability requirements. In that case the probabilistic damage stability impose no operational limitations on the vessel.

If this ideal cannot be reached, a lower VCG has to be adopted, maybe only for the calculation on partial draft, and not for the calculation for fully loaded draft.

After each modification of VCG probabilistic damage stability has to be recalculated completely.

3.6. Number of damage cases

The regulations do not prescribe the number of damage cases to include in the calculation; the designer is free in choosing the number of damage cases. Of course the designer can stop adding damage cases when either the Attained Subdivision Index (A) is greater than the Required Subdivision Index (R), or the addition of damage cases has no further positive contribution. The latter will be the case when large damage cases are used, which will sink or capsize the vessel.

Experience over the last few years has shown, however, that by their nature (compartmentation and routing of pipes) or by their use (many tiers of containers, which leads to high VCG's) for many vessels it is hard to comply with the regulations. To achieve an Index A as high as possible, every damage case which might contribute to the index A should be included in the calculations. So in many cases the designer ends up with hundreds to more than one thousand damage cases.

3.7. Symmetry

When hullform, bulkheads, openings and pipes are completely symmetrical (SB/PS) then one calculation with damage to either the port or the starboard side will suffice. When one of the mentioned elements are not symmetrical the calculations must be performed twice, one for damage to the port side and one for damage to the starboard side.

3.8. Damage boundaries

Each damage is bounded by 4 planes: the aft, forward, upper and inside plane, with the inside plane not necessarily parallel to the vessels centerplane.

The location and orientation of the inside plane is governed by the definition of the penetration breadth in the regulations, which says :

> "The penetration breadth is the mean transverse distance in metres measured at right angles to the centreline at the deepest subdivision load line between the shell and a plane through the outermost portion of and parallel to that part of the longitudinal bulkhead which extends between the longitudinal limits used in this calculation."

This definition cannot be understood without the examples in the explanatory notes.

What is meant essentially, is that the extent of damage must be as large as possible, without damaging compartments not included in the damage case under consideration. To show that damage boundaries do not necessarily have to coincide with boundaries of compartments, see Fig. 3.2 where a compartment configuration is drawn.

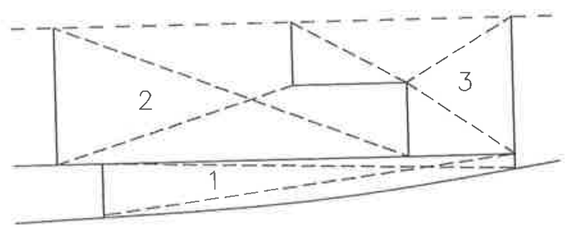

Figure 3.2. *Compartment configuration*

Assuming we want to calculate damage to compartments 1 and 2, then those compartments will be flooded (see Fig. 3.3), the extent which will damage compartments 1 and 2 *only* is sketched in Fig. 3.4.

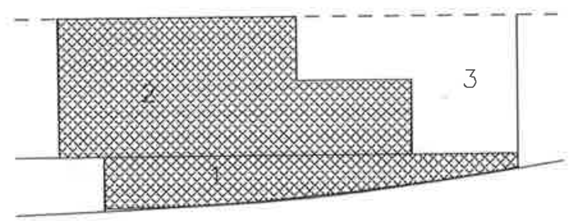

Figure 3.3. *Damaged compartments*

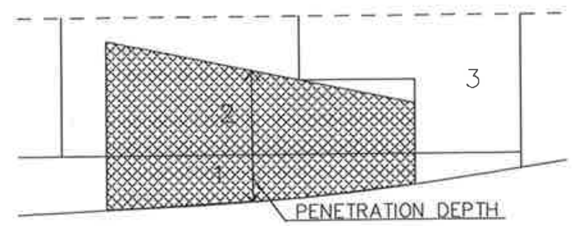

Figure 3.4. *Extend of damage*

4. Bottlenecks and nasties

As explained in chapter 2 the probabilistic method is purely based on side damage. The pie chart in Fig. 4.1, however, shows that only 12% of the total casualties in 1993 has been caused by side damage (collision).

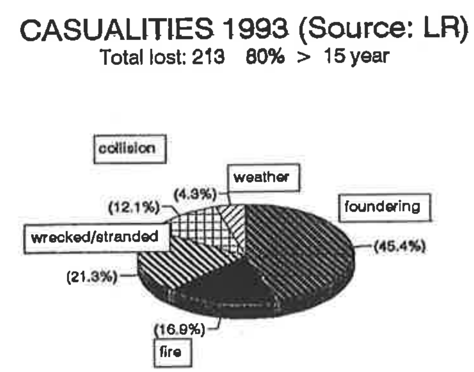

Figure 4.1. *Cause of casualties*

So we may conclude that we now have a probabilistic method, which is entirely focused on that kind of damage which is only responsible for 12% of all losses.
More practical bottlenecks are discussed below.

4.1. Processing time
For a complete damage stability calculation, consisting of several hundreds of damage cases and a few intermediate stages of flooding and minor damages, for an "average" vessel the estimated computertime for a calculation can be read in Tab. 4.1.

This calculation time is including the use of advanced features, such as automatic generation of damage cases and minor damages and automatic determination of damage boundaries, as offered by the PIAS program. Without these features pure calculation time would decrease, but the time for manual identification and definition of hundreds of damage cases, minor damages and damage boundaries would take multiple days at least !
After each change in design some or all damage cases have to be recalculated.

Table 4.1. *Estimated computertime for one complete calculation*

Computer type	Calculation time (hours)
Pentium 90 mhz	12
Sun Sparcstation 1	18
80486 66 mhz	30
Compaq 80386/80387 33 mhz	100
IBM XT 8 mhz	3500

4.2. Necessary information
Before commencing a calculation sequence, the information listed below must be available:

- Hullform.
- Light ship weight.
- Maximum allowable draft.
- Form and location of *all* compartments (including holds, engine room, forecastle etc.).
- Routing of air ducts and pipes, and the type and location of relevant valves
- Type and location of all air pipes.

So it is not possible to check probabilistic damage stability of a preliminary design. The necessary information is only available at a more detailed design stage.

4.4. Disturbing details
There are some nasty details of less significance :

- The formulas in the regulations for multi compartment damage cases sometimes lead to *negative probability* of occurence.

- Therefore the sum of all probabilities of occurence, which should be one theoretically, does not sum up to one. In practice this sum will fluctuate between 0.9 and 1.1.

Apart from the theoretical incorrectness, with this phenomena we miss a good verification tool, both for the designers and for the approval departments: A sum of probabilities far lesser than one would give the designer a hint that not yet all possible damage cases have been identified. A sum more than one would give the approval department an indication that overlapping damage cases have been used.

- The method for handling multi-compartment damages leads to inconsistencies, when used with compartments which embrace other ones, as show in Fig: 4.2

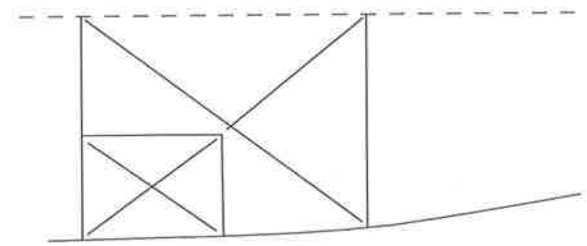

Fig. 4.2. *Topview of embracing compartment configuration*

The probabilitiy of occurence of damage cannot be determined with the formulations as used in the regulations, without the use of virtual compartments. The use of virtual compartments is both complicating matters, and inconsistent with the prior assumption that only *one* damage case is concerned per group of damaged compartments. A more consistent formulation would be:

> "The probability-value in the case of simultaneously flooding of more than 1 compartment (the main damage) is obtained by reducing the net probability of the main damage with the probabilities of all sub-damages *as far as they fall within the main damage.*"

4.5. Approval
Because large amounts of damage cases are involved, the issue of approval is a difficult one. The experience until so far shows that, if they check, approval institutes tend towards redoing the complete calculation, instead of checking the issued one. When figures of the redone calculations differ from the issued figures, the sources of difference are very hard to determine.

4.6. Presentation
The results of the calculations can be presented in a concise form, containing all probabilities for all damage cases, and the A and R values.
At one calculation we have made we have supplied the classification society involved with that concise presentation on paper, and a floppy disk containing all intermediate results of all damage cases and damage stability calculations. On the societies reply that they were not satisfied with the disk, but needed "written and consistent documentation" we had to inform them that a printout would consist of 19,888 pages, a pile of 2 meters.

4.7. Explanatory notes
The explanatory notes give many, and sometimes exclusively, sketches and examples of all kinds of damages. So it is up to the shipdesigner to derive a general rule from all specific examples. This "legislation by example" is an uncommon technique of legislation.

5. General approach for the performing of one complete calculation

It is assumed that for the probabilistic damage stability calculation efficient software is available. Without computer and appropriate software probabilistic damage stability is practically unsolvable. The common method of operation is :

- Define hullform and compartments.
- Define (or generate, if the software has that capability) all damage cases.
- Choose the VCG's on the drafts to calculate, either from the diagram of maximum allowable intact VCG, or from the actual loading conditions.
- Perform one calculation. If the vessel does not comply change hullform, compartments of VCG's.
- Remove all damage cases with a non-positive contribution to the Attained Subdivision Index.
- Define openings and recalculate. If the vessel does not comply then raise some of the openings (if possible).
- Define (or generate, if the software has that capability) flooding through damaged pipes and recalculate. If the vessel does not comply than modify the piping arrangement.
- Define (or generate) minor damages and recalculate. If the vessel does not comply then return to the first step.

6. Experiences in the design process

In general the calculations which our company has made during the last few years have led to the following conclusions.

- The experiences do not culminate in rules of thumb.
- At first sight it can hardly be predicted whether the vessel will comply.
- Openings may induce a drastic decrease of the Attained Subdivision Index A.
- Damage to pipes and air ducts, minor damages and intermediate stages of flooding may induce a significant decrease of A.

- Most of the time multiple complete calculation sessions, and some design modifications are necessary before a vessel complies.
- When a vessel does not comply the quest for the single cause is often timeconsuming. Sometimes multiple causes are involved.

7. Suggestions for improvement

The mentioned bottlenecks give reason for suggesting a number of modifications, which in my opinion will make the method faster and better to handle, without significantly reducing the level of safety.

- When in the definition of "penetration breadth" (ch. 3.8) the word "mean" is replaced by "minimum", the determination of damage boundaries will be easier.
- It may be considered if the concept "minor damage" may be deleted, or be integrated completely within the method.
- It may be considered if the assumption that flooding will take place through damaged pipes in *all* cases is a realistic one.
- Modification of the formulation for the handling of multi-compartment damage (ch. 4.4) will make the method more consistent.

8. Conclusion

I hope to have shown that the probabilistic method, which basicly is an elegant one, makes shipdesign more complicated. Some of the complicating elements can be removed without a significant decrease of the level of safety.

Compared to the deterministic method, the probabilistic method indeed increases design flexibility and design freedom, but only for the price of a far greater design effort.

Curriculum Vitae

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1975-1979	*Study Naval Architecture at Polytechnical School at Haarlem*
1979	*Bachelors degree in Naval Architecture*
1979-1984	*Study Naval Architecture at Delft University of Technology*

1984 *Masters degree in Naval Architecture, section hydrodynamics. Subject for final project: Computer Aided Design of Hullform (Hullform Generation).*

1980 *Founded SARC*

1980- *Managing director of SARC*

The company SARC (which is an abbreviation of Scheepsbouwkundig Advies en Reken Centrum, which means "Centre for Naval Architectural design, calculation and consultancy") has three major fields of activity:

1) *Development of the Naval Architectural Design softwate called PIAS (**P**rogram for the **I**ntegral **A**pproach of **S**hipdesign).*

2) *Performing designs and calculations in service for shipyards, designers and shipowners.*

3) *Consultancy in the field of design and CAD/CAM.*

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