A RISK-BASED APPROACH TO PROBABILISTIC DAMAGE STABILITY

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SUMMARY

With the harmonisation process of probabilistic damage stability regulations just finished (SLF47, September 2004) and the expectation that the proposed regulatory framework will be adopted by SOLAS in autumn 2005 and enforced in 2006, this paper argues that with current and expected developments in the short term on risk analysis and risk-based concepts, the new rules run the danger of becoming obsolete before they are enforced as any direct relation to rigorous risk analysis is not obvious and because of gaps at concept level that may lead to undermining safety, further attempts to build upon "compromised" concepts of risk will lead to more confusion and delays in achieving real progress.

1 INTRODUCTION

The compelling need to understand the impact of the then imminent introduction of probabilistic damage stability regulations on safety and the design of cargo and passenger ships, especially in a background of progressively growing appreciation of deeply embedded problems in both the rules and the harmonisation process itself, necessitated an in-depth evaluation and re-engineering of the whole probabilistic framework. Responding to this need, a EC-funded 4.5M€ 3-year project entitled HARDER was launched March 2000 comprising a consortium of 19 organisations from industry and academia in Europe, "pooling" together major resources to evaluate in depth and re-engineer the probabilistic concept of damage stability. The overriding goal of the HARDER project was to develop a rational procedure for probabilistic damage stability assessment, addressing from first principles all relevant aspects and underlying physical phenomena for all types of ships and damage scenarios.

It is commendable and unique in the history of rule making and of European research that HARDER became an IMO vehicle carrying a major load of the rule development process and fostering international collaboration at its best – a major factor contributing to the eventual success in achieving harmonisation and in proposing a workable framework for damage stability calculations.

If there is one criticism that can be directed at HARDER, for which the author accepts full responsibility, considering that HARDER is his brain child, is that HARDER and science went their separate ways, ending up with Safety of Life at Sea rules in the 21st century without the word "sea" or any other parameter characterising the sea appearing tin the rules. This takes rule making back to SOLAS 1948!

In the interim, and stemming from the formalisation of decision making for regulatory purposes (through the adoption of FSA) and the hesitant at first but progressively more frequent steps by the marine industry in adopting this or a similar process to addressing other aspects of decision making, a stage has been reached where the momentum generated is now harnessed to ensure that the newly found understanding is put to good use. Efforts to rationalise and establish FSA at IMO level gave rise to the need for Quantitative Risk Assessment (QRA) and by extension to "Risk Acceptance Criteria", "Safety Equivalence – e.g., the whole of High Speed Craft Code being equivalent to SOLAS", SOLAS 95 Regulation 14, IMO Evacuation Guidelines and "Alternative Design and Arrangements – Fire Protection Regulation II-2/17" and ultimately to "Risk-Based Design".

What is more important, IMO is now bracing itself to setting Goal-Based Standards, reflecting aspiration and ambition to move away from prescription, empiricism and "compromised" concepts to embrace science and innovation in dealing with maritime safety.

With this in mind, this paper, will attempt to establish a clear understanding of the probabilistic concept of damage stability calculations in the context of contemporary understanding of risk analysis, seeking to identify where the two merge, how to make sense of the new harmonised rules of damage stability and, what is more important, how to make practical use of all the effort and data and knowledge that has gone into developing them.

[1] Interim guidelines for evacuation analysis for new and existing passenger ships, June 2002

2 THE PROBABILISTIC CONCEPT OF SHIP SUBDIVISION

One of the fundamental assumptions of the probabilistic concept of subdivision of ships is that the ship under consideration is damaged or more precisely that the ship hull is breached and there is (large scale) flooding. This implies that the interest focuses not on absolute collision damage safety of a ship or *total* ship safety but on *conditional* safety. In other words, irrespective of the collision risk (in terms of probability) that ends in hull breaching and flooding, it would be important to know whether the ship will survive accidental collision damage. For this reason, the regulations require the same level of "safety" irrespective of the area of operation that can be of varying density of shipping (congestion of traffic), or indeed ship type and all that this entails and irrespective of the ensuing consequences, all of which might imply considerably different levels of actual risk. However, some other aspects of shipping (e.g. environmental hazard due to harmful cargo, size of ship, number of persons on board and so on) can be accounted for in the expression for the Required Index of Subdivision (R). Under such circumstances the probability of ship surviving collision damage is given by the Attained Index of Subdivision, A, using the following expressions:

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \, . \, p_i \, . \, s_i \qquad (1)$$

Where,
- j = represents the loading conditions (draught) under consideration
- J = is the number of loading conditions considered in the calculation of the attained index (normally 3 draughts)
- w_j = is weighting factor for each draught
- i = represents each compartment or group of compartments under consideration for loading condition j
- I = is the set of all feasible flooding scenarios, comprising single compartments and groups of adjacent compartments for loading condition j; The sum is taken for all cases of flooding in which one, two, three or more adjacent compartments are involved.
- P_i= is the probability that, for loading condition j, only the compartment(s) under consideration are flooded weighted by the probability that the space above a horizontal subdivision may not be flooded (note that $\sum p_i$ =1 for each draught considered)
- s_i= is the (conditional) probability of surviving the flooding of compartment(s) under consideration for loading condition j

It is clear that the summation in equation (1) covers only flooding scenarios for which both p_i and s_i are positive (i.e., survivable scenarios – which contribute to the summation). In other words, A is the weighed average "s-factor", with "p-factors" being the weights, i.e.:

$$A = \hat{E}(s) \text{ on } I \qquad (2)$$

Of course, the Attained Index of Subdivision, A, must be greater than the Required Index, R, as specified by the regulations, i.e.:

$$A > R \qquad (3)$$

Where, given the above, R represents nothing but an "indicative level of safety".

Deriving from the above, it is further implied that two different ships achieving the same attained (global) index of subdivision are equally safe. The philosophy behind the probabilistic concept is that two different ships with the same index of subdivision have equal *overall* safety with respect to flooding, although these ships may have quite different actual capabilities to withstanding individual damage scenarios (local) in addition to being subjected to different collision risk altogether. On the basis of the inherent fundamental assumptions,

- is A (and by extension R) meaningfully related to damage ship survivability, and
- is the probabilistic concept of damage stability directly linked to the risk-concept of damage survivability?

Evidence in support of the first question is very limited. Indeed, the only comparison between A/R and performance-based safety standards for 2-compartment SOLAS damage Ro-Ro vessels was presented by Vassalos and Tuzcu (2001) and shown here in Figure 1, demonstrating that for those ship types where a high level of technical and experiential knowledge is available, then, good correlation may be established between A/R values and other more meaningful measures of safety. To consider answering the second requires first some elaboration of the contemporary understanding of the concept of risk.

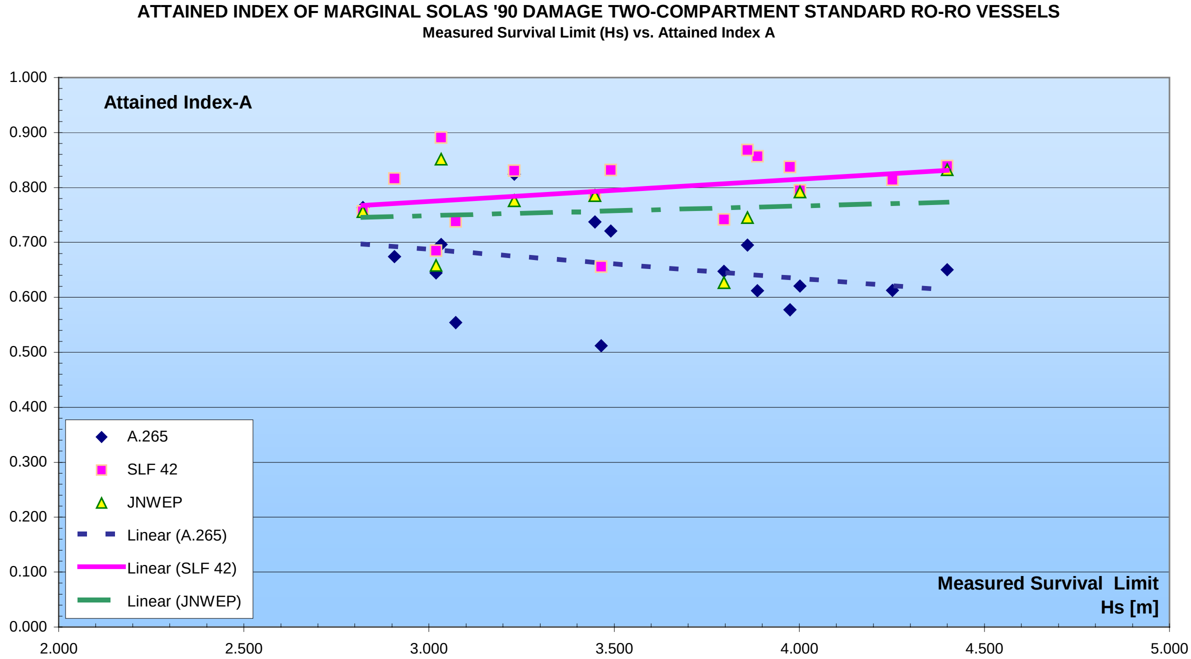


Figure 1: Comparison of Attained Index A for Various Probabilistic Instruments

3 THE RISK CONCEPT

The definitions provided below together with the graph of Figure 2, provide sufficient information to explain the concept of risk or strictly speaking of risk cost.

Hazard: A hazard is the natural presence of an unwanted incident/accident that may take place provided the barriers in place to avoid the hazard materialising into an incident/accident fail.
Risk: Risk is the combination of the likelihood and the severity of consequences pertaining to a given hazard.
Likelihood is an expression for how often a hazard materialise into an unwanted incident/accident (frequency of occurrence, usually estimated in terms of number of incidents per ship year).
Consequence is an expression for what happens when an incident/accident occurs. The severity of the consequences is what affects the risk level.

It follows therefore that

$$Risk = P_f . C_f \tag{4}$$

Where, f= represents generalised failure (undesirable event)
P_f = represents likelihood (frequency)
C_f = represents consequences (loss of property or life, environmental impact, etc.)

It is self-evident from Figure 2 that risk can be minimised by reducing either the probability of (in this case) collision damage or the consequences of damage, or both. Normally frequency reduction is associated with preventive (built-in, passive, design) measures whilst consequences with mitigating (active, operational) measures. However, in accidents, involving for example large loss of human life or large environmental impact there is a level beyond which consequences cannot be tolerated. In this case, reducing the probability of damage alone will not suffice, making it necessary, to address key questions and seek answers concerning definition of acceptable risks, definition and management of maximum tolerable consequences and procedures for dealing with residual risks.

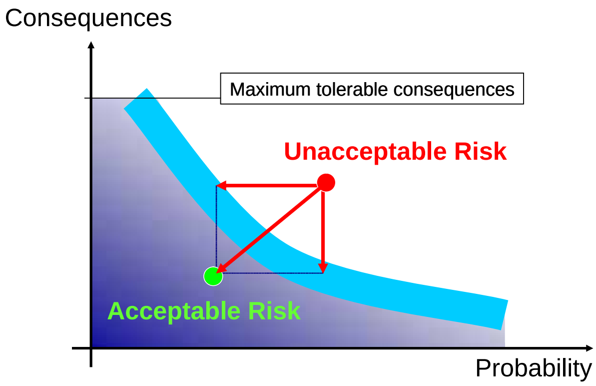


Figure 2: The Risk Concept

The band between unacceptable and acceptable risk regions is normally referred to as the ALARP (As Low As Reasonably Practicable) region where any acceptable solution must be the result of cost-benefit (cost-effectiveness) analyses

This latter point is extremely significant when it applies for example to large passenger ships as in this case, for any probable but non-survivable scenario (i.e., with s=0), consequences are likely to be intolerable and hence the risk unacceptable. Therefore, the probability of a non-survivable damage scenario must be remote or in other words there cannot be feasible damage scenarios with s=0, irrespective of what the value of A and hence R is! Realisation of this led to considerations of a new way of addressing this potential problem by ensuring that attention is shifted to local indices of subdivision, Pawlowski et al (2004).

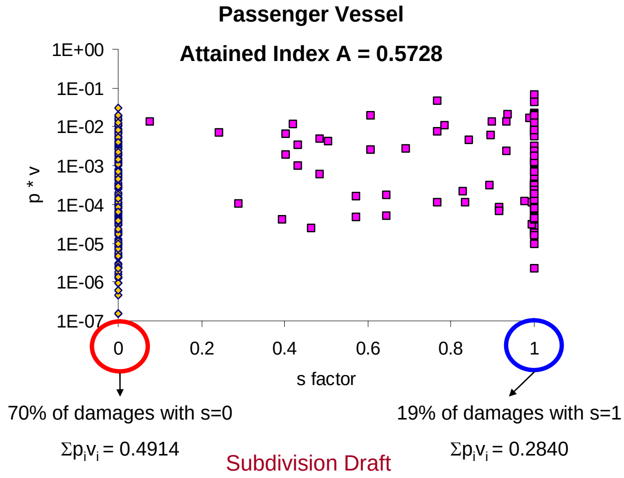


Figure 3: Probabilistic Damage Stability Calculations (Passenger Vessel)

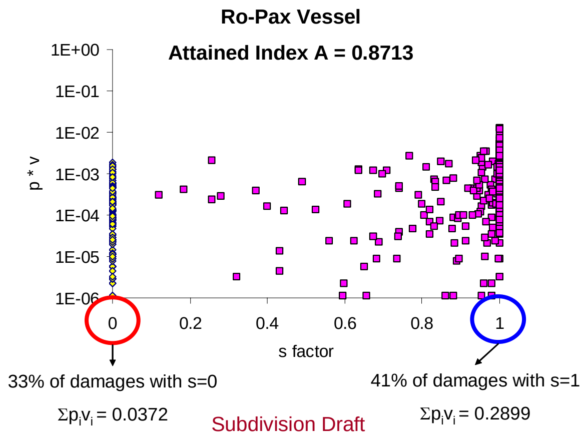


Figure 4: Probabilistic Damage Stability Calculations (Ro-Pax Vessel)

Figures 3 and 4 present results of probabilistic damage stability calculations according to the harmonised rules for a passenger ship and a Ro-Pax vessel, demonstrating a number of interesting points:

- One could speculate that the value of A is a good indicator of the vessel collision damage safety, on the basis of the observed reduction of non-survivable scenarios and the higher survival probability of the remaining scenarios.
- Even with A=0.8713, demonstrating a small (acceptable according to the new rules) collision damage risk, there are 33% of non-survivable scenarios.
- In both ships non-survivable scenarios are among the most probable.

These results alone clearly show the conceptual gap in Wendel's idea, particularly with regard to safety-critical vessels, and highlight that even though the recently proposed probabilistic framework may arguably represent a step in the right direction, in making this step diligent care should be taken to ensure that safety is not unwillingly undermined!

4 RISK-BASED APPROACH TO PROBABILISTIC DAMAGE STABILITY

On the basis of the aforementioned explanation and considering the severe consequences likely to ensue in the event of capsize/sinking of the ship, there is a need to assess (in the following order) the conditional probabilities of a number of events, such as collision, hull breaching, progressive flooding/collapse and capsize/sinking as well as assess the potential consequences. The mathematical model for collision risk will take the following form:

$$R_c = P_c \text{x} P_{w/c} \text{x} P_{f/w/c} \text{x} C_c \qquad (5)$$

Where,

P_c Probability of a collision incident, dependent on the loading condition, area of operation, geography/topology/bathymetry, route, traffic density, ship type, human factors, etc.

$P_{w|c}$ Probability of water ingress, conditional on collision (accounting for all the above)

$P_{f|w|c}$ Probability of failure (capsize/sinkage /collapse), conditional on collision and water ingress; expressed as a function of (*seas state, structural strength and time*)

C_c Consequences deriving from the collision incident, accounting for loss of (or injury to) life and property and for impact to the environment. The former will be time – dependent and will be the result of evacuation analysis (for passenger ships as presented in Figure 8) and the latter of e.g., probabilistic oil outflow using relevant models of oil spill damages and results from known accidents or through analysis from first principles tools

Notwithstanding the fact that the s-factor in the harmonised rules is a calm water statistic and cannot possibly provide any information on survival time, the relationship between the attained index A and the conditional probability of capsize/sinakage is simply

$$P_{capsize/sinkage} = 1 - A = 1 - \sum_{i=1}^{I} p_i \cdot s_i \qquad (5)$$

Lack of information on survival time makes it impossible to evaluate the ensuing consequences based on the harmonised probabilistic rules and this is likely to be one of the strongest factors that would hinder their eventual adoption by the maritime industry, as it will be explained in the following.

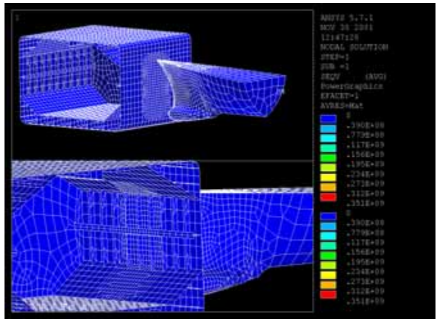
On the basis of equation (5), it can be argued that based on the work undertaken in HARDER the first two terms can be represented by the p-factor (including the effects of v and r), even though the formulae eventually put forward in the harmonised rules are inevitably generalisations. Certainly on the basis of the work by Lutzen (2001) the relevant probabilities can be calculated from first-principles. Hence, if a more specific analysis is warranted for a novel ship design concept, the probability of collision damage that leads to hull breaching and flooding can be calculated. With a (high) degree of leniency the same may be said concerning the s-factor, even though any use of statistical calm water regression formulae to address new design concepts would be unwise to say the least. However, based on the recent work of Dogliani et al (2004) and of Jasionowski et al (2004), the remaining terms could also be addressed for each pertinent scenario from first principles, thus allowing for a complete risk analysis of any damage scenario. This is illustrated through Figures 5 to 8 next.

Collision models *(Hansen and Simonsen (2001))*

- *Scenario Approach e.g., Fujii, MacDuff, etc. (blind navigation)*
- *Synthesis Approach (allowing for collision avoidance) e.g., Hansen and Pedersen using a Bayesian Networks*

$$R_i = \boldsymbol{p}_{c,\,w,\,f}\; C_i$$

Figure 5: Probability of Collision (c)



$$R_i = \boldsymbol{p}_{c,\,w,\,f}\ C_i$$

<u>Struck vessel</u>
- Main particulars and structural design given

<u>Route / Area</u>

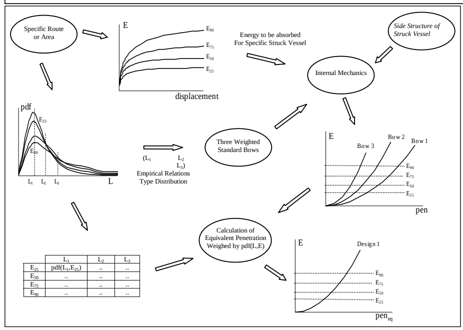
<u>Striking vessel</u>
- Type
- Length
- Loading condition

<u>Collision scenario</u>
- Striking location
- Collision angle
- Velocity of struck vessel
- Velocity of striking vessel

<u>Calculation</u>
- Energy to be absorbed (external dynamics)
- Energy absorbed by the structure (internal mechanics)

⇒ Compare energy

⇒ Estimate damage



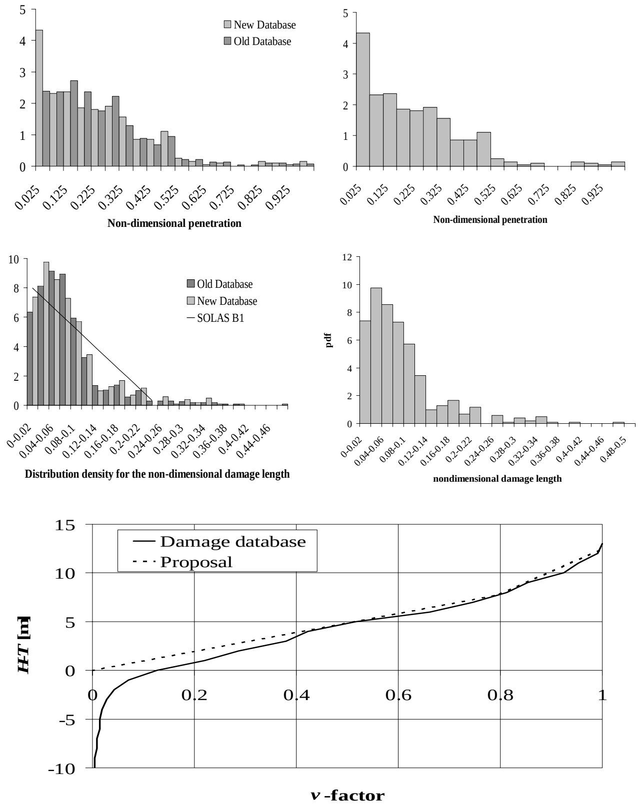


Figure 6: Probability of Water Ingress (w)

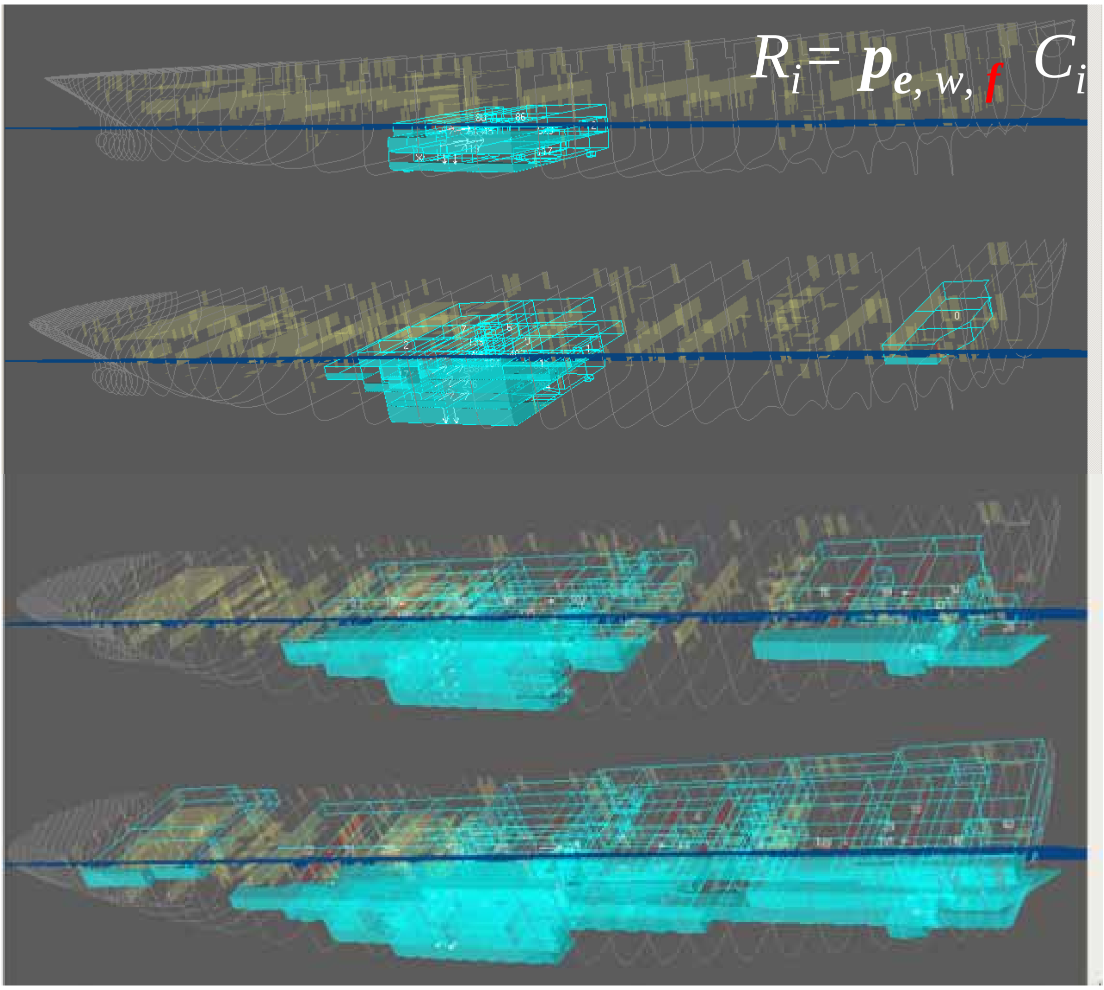


Figure 7: Probability of Capsize/Sinkage/Collapse (f)

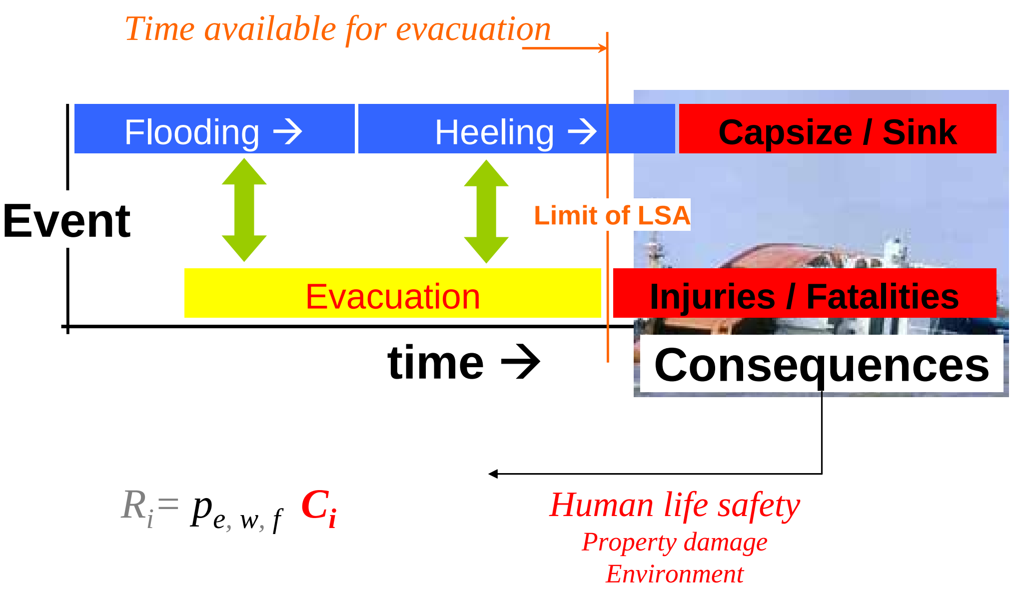
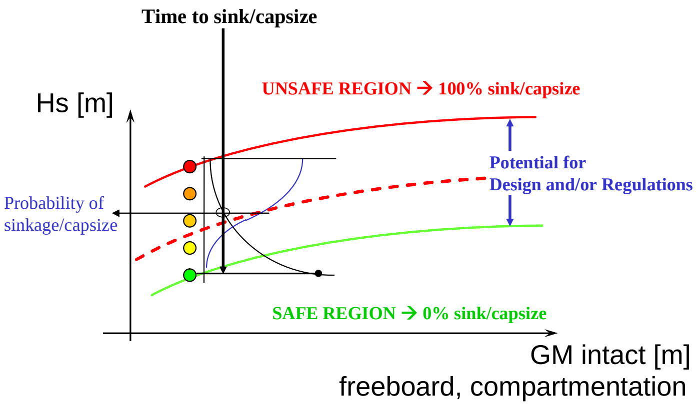
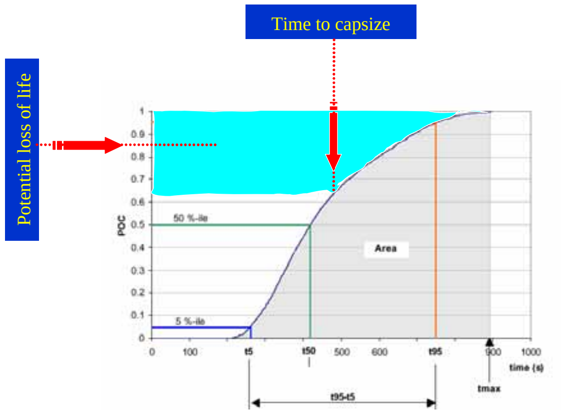


Figure 8a: Consequence Analysis (C_i)





Evaluation of time to sink/capsize through first principles time domain simulation tools (Typical probability curves showing probability of capsize and time to capsize)

Evaluation of potential loss of life through passenger evacuation advanced simulation tools (Typical passenger objective completion curve)

Figure 8b: Consequence Analysis (C_i)

It may justifiably be argued that the state-of-the-art with many of the fist-principles tools available today render the calculation of the absolute risk (actual safety) questionable, but the relative risk values of the scenarios considered allow for prioritisation of risk control options (risk reduction measures) and hence help designers/operators/regulators direct resources towards critical development issues.

5 NEW HARMONISED RULES FOR DAMAGE STABILTY CALCULATIONS

With the harmonisation process coming to an end after such a long time and the new probabilistic damage stability framework in place, it cannot be a more appropriate time for an introspective look on what exactly has been achieved and how it can be used to ensure damage stability safety, particularly for new ships. This will be attempted by addressing the components of equation (1) and (3) on their own and in comparison with equation (5) by focusing on concept, method of calculation and utility.

(Wendel's) Probabilistic Damage Stability Concept

The correct name for this is of course "probabilistic concept of ship subdivision". The concept of subdivision needs to be brought out as it concerns a deeply embedded love affair between Naval Architects and bulkheads that goes back a long way. In fact, the first Merchant Shipping Act of 1854 is the first known legal requirement addressing safety at sea and concerns watertight bulkheads. One hundred and fifty years later, the profession still labours in trying to fathom how to design ships with adequate damage stability safety cost-effectively. In the process the list of bulkheads to choose from is growing: transverse, horizontal, longitudinal, recessed, collision, watertight, semi-watertight, splash-type, partial, full-height, retractable, fire, web, corrugated and this is just from memory. All that is needed as any first year student of Naval Architecture should know is for ships to "float" and "float upright". Opening a designer's mind to the endless possibilities of achieving these two goals without the brainwashing we have been subjected to for centuries and utilising state-of-thr-art capability to address these issues by adopting a holistic approach from first principles (e.g., risk-based design where safety is treated as an objective alongside functionality and performance) could prove re-invigorating and down right revealing (see for example Vassalos (2004)).

Based on the work of HARDER and the SDS Group at IMO, it could be argued that the p-factor addresses all relevant probabilities leading to realistic damage considerations and to correct frequency estimation of corresponding damage scenarios. It could also be conjectured that the proposed s-factor could provide assurance of damage stability safety or indeed that statistics could find a way of relating the s-factor to time and hence indirectly account for consequences. Moreover, it could (and has been) argued that R reflects an acceptable level of damage stability safety in that all relevant consequences are implicitly collated in R through evolution, considering that R is derived through regression from existing safe ships and also includes (or could do) parameters that at high level relate to risk.

This being the case, the proposed probabilistic framework could in time be calibrated and "get things right on average". But as a framework it does not conform to modern risk analysis and as indicated in the foregoing, applying it blindly could do more harm than good.

In this respect, what if anything can be used from all this effort?

- The damage statistics
- The p-factor and the developed first principles tools for frequency estimation in risk analysis
- The first-principles tools used in the attempt to develop a generalised s-factor
- The A and R values calculated for the HARDER sample ships; this data might prove useful in the quest for establishing risk acceptability criteria

A-Index

Concept: It is an arbitrary measure of safety, conditional on probabilities which may vary drastically depending on the circumstances, ship type and area of operation. Its complement can be related to risk but only at high level. As highlighted in the foregoing it could prove dangerous to accept a high value of A as a measure of actual safety, as many highly probable non-survivable scenarios could simply be ignored.

Calculation: The p-factor is a generalisation of a damage scenario frequency estimator that needs to be treated with caution; use of available first principles tools might be warranted for specific applications. The s-factor could hardly be used for any serious work. It is a calm water statistic of old ship designs, incapable of addressing new ship concepts and problems and more importantly to account for time. However, there are modern numerical simulation tools available capable of addressing the real problems of damage survivability and to support safety assurance for existing and new ships.

R-Index

Concept: Represents an acceptable level of safety standard, derived on the basis of A values of sample ships which have survived all the elements, some of these over their life span But since A is unrelated to safety then how can any claim be heard that R-values make sense?

Calculation: R is meant to indicate relative safety which might carry some logic for same ship types and as such, it is questionable to use "equivalent safety" principles in its derivation. A cursory look on equation (5) suggests that considering only one of the terms in the equation in comparing the safety of two ships would only make sense at such a level of abstraction that would render such comparison meaningless. Moreover, how can the relative safety of two different ship types be compared (one cannot compare relatively car carriers and cruise liners, as the same A in both would imply massively different damage stability safety levels)?

The procedure adopted in the derivation of R for passenger ships also deserves a brief comment. Using risk boundaries with a concept unrelated to real risk is questionable in itself (as it prolongs the widely spread confusion that A or R represents safety in some meaningful way), but discounting 'satisfactorily safe' ships in the final regression analysis of R is difficult to comprehend. Not only is the resulting average R of lesser value (hence of lesser relative safety) but how could (large) passenger ships be satisfactorily safe with a value of, for example, 0.8 on the basis of Figure 2?

There are many more detailed points which deserve attention but going into the details of the whole probabilistic framework will not add value to this discussion and it will be avoided.

6 RECENT DEVELOPMENTS AT IMO

In the wake of the much publicised Goal-Based Standards whereby "the goals should be achieved either by compliance with published technical standards or by means of alternative solutions providing an equivalent level of safety" and massive efforts internationally to develop and apply risk-based concepts in ship design, operation and regulation, developments at IMO are happening fast and are likely to continue at an accelerated rate. In this spirit, the IMO Secretariat presented the outcome of MSC78 to SLF47 (SLF47/8, June 2004) concerning Large Passenger Ships Safety which is summarised in Figure 9, with some comments added to offer further clarification. The key noteworthy points deriving from this initiative relate to the need to address safety from a risk perspective and to bring in the element of time, i.e., time domain simulations. This is a momentous move and one that will help enormously the profession to start understanding better what the real issues are. Interestingly, in Annex 3 of this paper a link is suggested between this and Index A, but the idea is so brilliant that this should be forgiven. After all, we have been led recently to believe that the statistics can do everything!

Based on the foregoing, Figure 10 suggests a procedure on how to utilise elements of the new probabilistic framework for damage stability in combination with first-principles tools to help the industry address damage stability safety cost-effectively for existing and new ships.

In fact work along these lines is already in place at large scale. It is revealing to see that the industry understands much more than is given credit fpr!

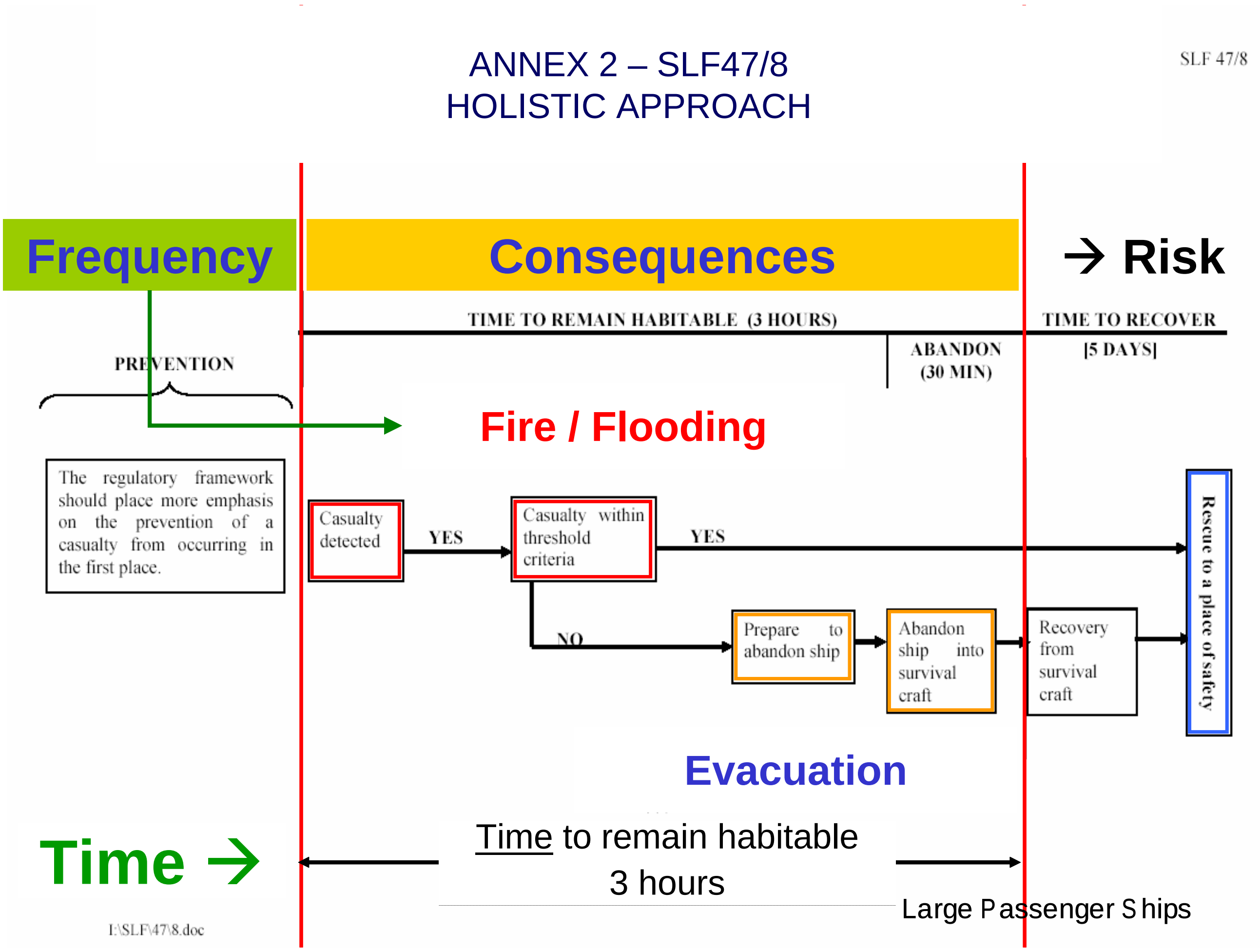


Figure 9: Large Passenger Ship Safety – Guiding Philosophy, Strategic Goals and Objectives

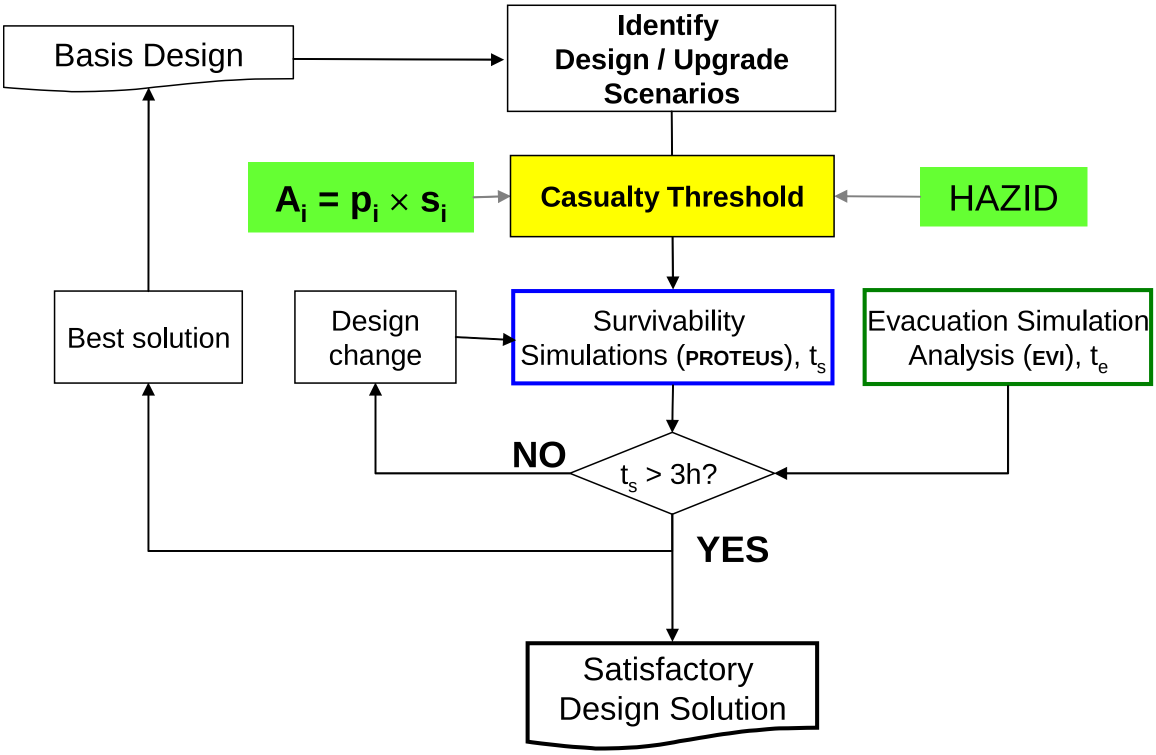


Figure 10: A Framework for Damage Stability Safety

7 CONCLUSIONS

Based on the arguments presented in the foregoing, the following concluding remarks may be made:

- The role of the HARDER project has been instrumental in finalising the harmonisation process and in proposing a probabilistic framework for damage stability calculations, which provides the first step leading to a rational treatment of damage ship stability.

- However, despite 40 years of effort to turn Wendel's idea into workable models and a framework, it would appear that the concept is already out of touch and incongruent with the modern concept of risk and risk analysis.

  Based on experience from its application so far, a belief is (unexpectedly) being formed that the industry will resist adopting it on the grounds of compromising the safety of their ships and in the knowledge that any investment in meeting the new rules might simply turn into a down payment for a (potentially) much bigger cost.

- In time, the SLF47 probabilistic regulatory framework could be calibrated and serve some useful purpose but the effort that this will take is not justified as knowledge and tools are already available to address damage stability safety in a holistic and accurate manner.

  Making use of some of the elements of the SLF47 probabilistic framework is all that can be justifiably done to help real progress achieved under frameworks currently promoted by the safety regime at large (IMO).

8 ACKNOWLEDGEMENTS

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[2] Provided the exposure considered allows meaningful representation of the sea state, hence 30 minutes is the required minimum

[3] A sequence of independent experiments each of which has the same probability of success ***P***, such as for instance coin tossing, where probability of obtaining tail is constant ***P***=0.5

[4] The criterion can be set for arbitrary level of survival time and/or confidence level by use of formulae

[5] For example, considering a vessel with given set of conditions as used in , to verify 60 minutes (95% confidence) survivability for operation at limiting sea state of $\boldsymbol{H_{crit}}$ = 3.675m, five tests with no capsizing event would be required at Hs~3.8m (P_f=0.2), or two tests at Hs ~3.9m (P_f=0.5), etc, as derived from the relation between the $\boldsymbol{Hs}$ and $\boldsymbol{P_f}$.