DAMAGE STABILITY STANDARDS
Rational Design or Gratuitous Complexity?

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Abstract

This paper reviews the ongoing developments of the new SOLAS probabilistic damaged stability criteria, and highlights a number of areas in which these criteria appear more arbitrary than rational. The combination of inadequate statistical data, inappropriate intermediate calculations, and modification factors with limited analytical background may make the proposed criteria poor predictors of survivability. Furthermore, their use may confuse future efforts to develop true 'risk based' methods for some or all ship types. The author recognizes that the horse is a long way out through the stable door, but proposes some alternative approaches to regulatory reform, and recommends measures which might, in future, make the use of probabilistic methods more justifiable.

1. Introduction

The January 1999 issue of 'Marine Technology' [1] drew the attention of the membership at large to an ongoing debate at IMO concerning the modification of the current SOLAS stability criteria. In essence, this work is intended to replace all remaining uses of deterministic criteria with a method based on Resolution A265 VIII, which already applies a nominally probabilistic approach to cargo ships. The two concerns noted in [1] related to the vertical distribution of damage and to a possible modification factor for passenger vessels. This paper discusses both issues, but also takes a broader look at the probabilistic stability concepts included in the current and proposed regulations, and highlights a number of perceived shortcomings.

The author's interest in this subject arises in part from his membership of SNAME panel O-44, which has included review of the SOLAS revisions in its activities. Another stimulus has been provided by undertaking a series of projects on ferry stability on behalf of Transport Canada (and specifically the Transportation Development Centre). However, he emphasizes that the opinions expressed here are strictly personal, and are not intended to reflect any conclusions regarding the safety of any specific vessel or ship type.

2. Risk-Based Methods

2.1 General

The use of risk- or reliability-based methods for all aspects of ship design has seen considerable expansion in recent years. For example, longitudinal strength for many types of ships is now based on a specific exceedence probability for wave bending stress levels, combining wave climate data and analytical response prediction methods. This takes account of only some components of risk (see below), the results are not yet always very accurate, and the correlation of new with old standards has caused a number of difficulties. However, the rational nature of the process is generally accepted, and work continues to improve aspects of the calculation procedures and to add other important factors to the prediction methodologies.

2.2 Damaged Stability

Risk can be defined in many ways, but one of the most useful definitions for engineering projects is:

Risk = Probability of occurrence of an event x severity of its consequences

In the context of damaged stability, overall risk can be built up from a variety of components, as outlined below:

- Probability of occurrence of collision, (and grounding, or striking):
  = function of (traffic density, waterway configuration, navigation control, environmental conditions, human factors)

- Severity of collision damage:
  = function of (relative energy of striking and stricken ship, structure in way of impact)

- Outcome:

(a) probability of foundering or capsize
  = function of (location of impact, loading condition of ship, relative environmental conditions)

(b) loss of life
  = function of (number of persons aboard, time to capsize, lifesaving equipment, human factors)

Some consideration should therefore given as to how each of these components can or should be treated with the information likely to be available for any ship design or type of operation. Most of these factors were recognized when Resolution A 265 (VIII) was formulated [2]. However, this paper outlines how the proposed new SOLAS requirements handle (or ignore) the elements listed, and some real or potential drawbacks of most aspects of the procedure.

3. SOLAS 200x

The proposed probabilistic revisions to Chapter II-1 of SOLAS are still under development, and so this paper has been based on the version provided as SLF 42/3 in 1998 [3]. It is believed that the majority of the specific provisions discussed below have not been affected by subsequent correspondence, or by the most recent meeting of the IMO SLF (Stability, Load Lines, and Fishing Vessel) subcommittee. Anyone wishing to review the paper in full can download a copy from SNAME's website under committees/tech_ops/O44.

The new standards are intended to apply to all passenger ships more than 24m in length, and to cargo ships over 80/100m (still under discussion). Currently, the equivalent probabilistic standard (part of SOLAS 90) applies to dry cargo ships over 100m, but can be used for other ship types at the discretion of the designer.

In the sections which follow, each element of the risk equation presented at 2.2 is discussed in turn, indicating how it is handled by the latest SOLAS proposals. Many of the objections which are raised have their origins in the approach which underlies both SOLAS 90 and Resolution

A265 (VIII) itself. The latter, which dates back to 1973, was based on a limited sample of damages recorded during the period 1946-1967. The changes since then in the types and sizes of ships, their structures and hull forms, onboard and shore-based navigation support and control systems, etc, makes the relevance of the underlying data seem somewhat suspect. The way in which the functions derived from it are applied aggravates these concerns, and some of the assumed mechanics of capsize are also of dubious validity.

As this is a complex subject, only a few of the issues are addressed in any detail below. It is hoped that the points made will encourage others to undertake their own analyses of some aspects of the requirements, and bring their concerns to their IMO representatives.

3.1 Probability of Occurrence of Collision

As indicated previously, the probability of occurrence of a collision (or other impact damage) is a function of the traffic density, waterway configuration, navigation control systems, and environmental conditions along its route, and of human factors, such as the level of training of its bridge crew. None of these is accounted for in any versions of the SOLAS criteria; collision probability is effectively assumed to be equal for all Convention ships.

It can certainly be argued that this is broadly appropriate for most ship types, as they may be designed for worldwide service and their actual trading pattern may change numerous times. However, it is equally arguable that ships such as cruise liners, ferries, and many smaller freighters are intended to spend a much greater percentage of their time in coastal waters and in port calls, where both traffic densities and waterway constraints make incidents more probable.

In a truly probabilistic approach, some effort should be made to provide differentiation between ship types based on these considerations.

3.2 Severity of collision damage

The severity of the damage resulting from any collision will be related to the relative energy of the striking ship (i.e., kinetic energy in the direction of impact). When two ships are involved, the energy and momentum of the stricken ship are also important, as its continuing motion may tear a wider hole.

The structure that is impacted and the shape of both ships will also be of importance, as was seen in the “European Gateway” collision where the bulbous bow and raked stem above the waterline created two separate holes [4].

Thus, both the numbers of ship movements and their relative sizes become important. Continuing the argument from 3.1, most Convention cargo ships could be considered to have equal, or at least similar probabilities of collision with the general distribution of vessels in the worldwide fleet; though this should really be checked. However, a ferry operating out of a major fishing port, or in a popular recreational area, may have a relatively high collision probability but a low severity index, the small craft being the ones really at risk.

Current standards, including SOLAS 90 and the new proposals, effectively assume that a damage opening in a larger ship will be bigger than that in a smaller one, in horizontal and vertical extents and in penetration distance. It is by no means intuitively obvious why this should be the case for all collision damage (a stronger case could be made for groundings, though here design speed might be at least equally important). A larger ship will tend to have stronger structure, and with equal probability of collision with identical ships would normally suffer less, rather than more damage.

The explanation in [2] for the assumed trend is that large vessels are more likely to collide with each other, and small vessels likewise, because of the areas in which they operate. However, a review of Canadian accident statistics [5] shows that the largest vessels (tankers, bulkers, OBOs) are approximately twice as likely to collide with tugs, fishing vessels, etc as with each other. (Fishing vessels - which are not covered by these damage stability regulations - are certainly twice as likely to run into each other as into anything else.)

It seems equally likely that the SOLAS damage assumption is a function of the limited data set which was used to derive the various damage functions. This consisted of 296 incidents, selected rather than taken at random, and generally dealing with relatively severe incidents. A sample plot is shown at Figure 1, and shows the regression line which was derived for the earlier versions of the probabilistic regulations. Several features can be noted -

a) the huge amount of scatter (which makes the derivation of any function somewhat dubious),
b) the large number of points for small ships, and
c) the cut-off at 200 m length, which results from the lack of data for larger ships (remembering that the database only runs to 1967).

Although the regression line has been modified in the SOLAS 200x proposals, there is still a breakpoint at 200 m, despite the fact that this is now a common length for Convention ships rather than an upper bound for most types.

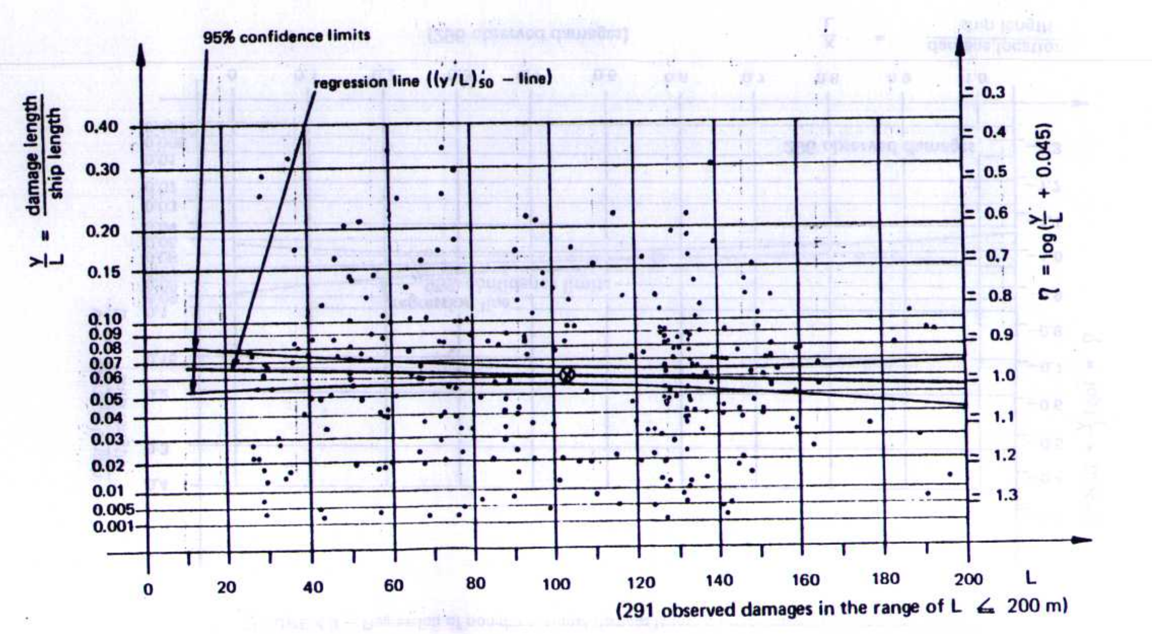


Figure 1 - Sample of Data Underlying A265 (VIII) [2]

It can also be noted that the damage size assumptions underlying SOLAS are quite different than those from MARPOL for oil outflow, although both are based on statistical analyses of actual damage. This is due to the differences in the ship characteristics in the respective databases, and the nature of the incidences accounted for in each case. It was pointed out in [6] that the assumed probability of breaching a transverse bulkhead under SOLAS 90 is roughly twice that in MARPOL, and although the formulae in the latest SOLAS proposals have changed slightly this type of ratio still exists (depending on ship size and damage location).

The damage size density underlying A265 (VIII) is shown in Figure 2, and indicates a fairly fundamental flaw with attempts to use this data in a fully probabilistic model. Many collisions lead to no holing of at least one of the ships involved. The SOLAS database ignores this possibility, as it is thus not dealing with all collision incidents, as might be derived either from full accident statistics or from traffic simulations, but only with an ill-defined subset. Although the simplified distribution applied in the method does show finite probabilities of zero damage, the size distribution is skewed upwards very considerably by the process. As an example, for a 100m ship a hole 10m in length is considered to be only 50% less likely (approximately) than one of 2m in length.

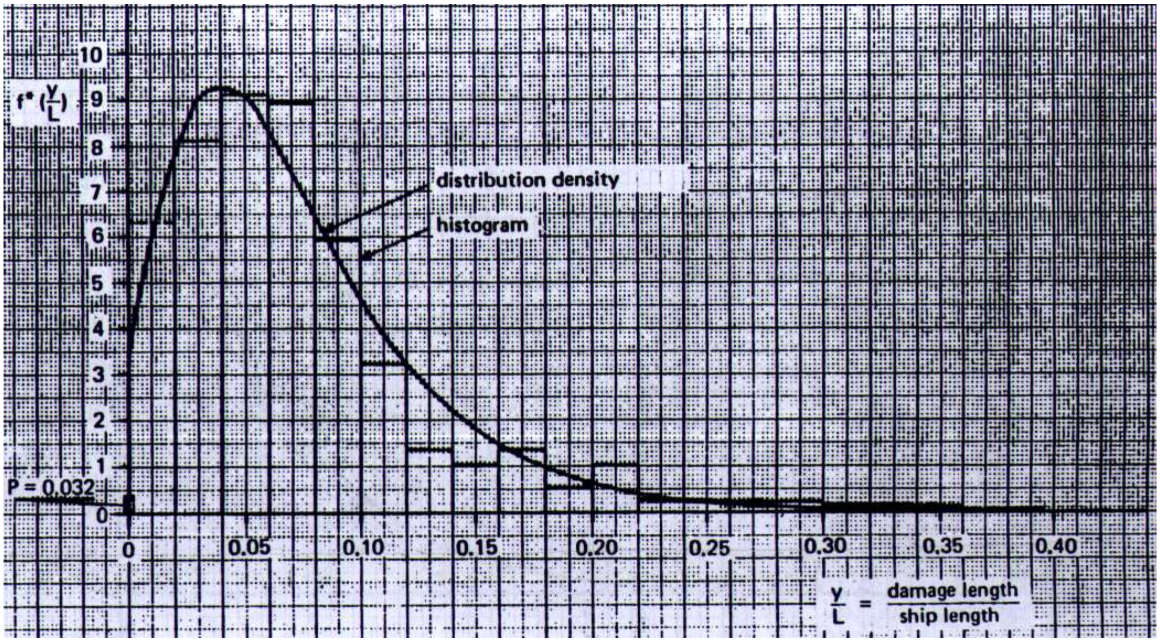
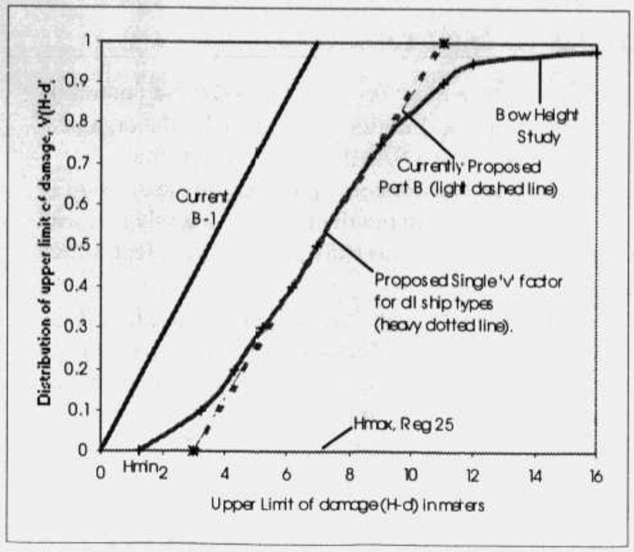


Figure 2 - Damage Size Distribution, A265 (VIII) [2]

In light of these factors, it seems dangerous to utilize the A 265 (VIII) methodology to drive design in the 21st Century without at least completely revisiting the underlying assumptions and data. The IMO background papers for the new proposals include a 'validation' by Norway of the approach, but this presents little actual information and does not allow independent rederivation of the results.

As noted earlier, one of the focuses of the current debate at IMO relates to the correction factor for the vertical extent of damage, v. Figure 3, from [1], shows some of the proposed options. The ‘bow height study’ refers to an analysis by the US of ships’ bows, the assumption being that the distribution of bow heights will be strongly correlated to the vertical extent of damage expected. This seems to be a reasonable assumption, though it is worth noting that it is at variance with the other underlying assumption in A265, mentioned earlier, that big ships hit other big ships, and small vessels likewise. The only realistic way of testing either assumption would seem to be to look at more actual data in more detail.



Some Proposals for the v Factor

('H' and 'd' are defined in SOLAS Chapter II-1 regulation 25)

Figure 3- 'v' Factors [1]

3.3 Probability of Capsize

Any collision will have economic costs, but the critical accident scenario from a regulatory standpoint is that which will put large numbers of lives in danger through the loss of the stricken ship. The probability of capsize (or foundering) will be determined by the location of the damage, the prevailing environmental conditions, and the loading condition of the ship.

The distribution of damage location along the ship is skewed to give a higher probability in the forward part than aft, which seems reasonable in principle, though the formulae utilized bear limited resemblance to the underlying data - in this area at least they have been massaged for greater realism.

In addition to concerns over the probabilistic basis, the mechanics which have been associated with capsize are also questionable. The factor s_I, which is intended to serve as an indication of a ship's survivability in a given damaged condition, is calculated as follows:

$$s_i = ((2_{max}-2_o)/2_{max}-2_{min})^{0.5}.((GZ_{max}/GZ_{req}).(Range/Range_{req}).(GZarea/GZArea_{req}))^{0.25}$$

where 2_{max} , 2_{min} = vary with ship type

2_o = actual equilibrium heel angle

where the 'standard' values; GZ, Range, GZarea, and $\theta_{max,\ min}$ are defined in various ways for different types of ships, and the achieved values of GZ_{max}, etc are taken as either the actual or standard values, whichever is less. Thus, the maximum value of s_I, for any given condition, is 1. For passenger ships, the righting arm curve is calculated using various additional assumptions about wind heel, passenger crowding, deployment of lifesaving equipment, etc.

The individual components of this index are standard stability criteria, and one can more or less see the thinking behind their use. For example, GZ_{max} is an indicator or static stability, and Area relates to dynamic stability. However, intensive research on ferry stability in the aftermath of the 'Herald of Free Enterprise' and 'Estonia' disasters (including work in Canada, [7, 8]) showed that they are only indicators, and not particularly good predictors, whether taken alone or in combination. For ro-ro type vessels, the volume of water on the vehicle deck is the critical determinant of safety, and that is a function of wave climate and freeboard. Freeboard was a component of the original A265 (VIII) criteria, but has since been dropped, for reasons which are not clear (at least to this author).

The shape of the GZ curve is also important, but the key influences are disguised rather than clarified by the normalizing and averaging process represented by the equation. Obviously, similar criticisms can be made of the underlying deterministic criteria, but it is easier to see both the drawbacks and possible solutions to these when each criterion is considered in isolation and on its own merits.

Another methodological weakness in the use of the s_I factor is its truncation at a maximum value of 1. The 'standard' values bear some relationship to survivability under a given set of environmental conditions, including wave and wind effects, both of which obviously follow statistical distributions. Thus, $s_I = 1$ might for a given ship correspond to survival in a wave height of 2m and a beam wind of 20 km/hr, while at $s_I = 2$ both values might increase by 50%. In a true probabilistic method, a hypothetical ship where 50% of values of s_I would otherwise be greater than 2 and 50% are at 0.5 is safer than one where 50% of values are exactly equal to 1 and the rest are at 0.5. The SOLAS method considers both to be identical.

It might be argued that some simplifications always have to be made in a regulatory system. However, at the same time that this very important probabilistic element is being neglected another is being included, unfortunately once more in a pseudo-statistical way. Survivability is very definitely a function of loading condition, and in A 265 and SOLAS 200x loading variability is accounted for. This is done by calculating survivability at different drafts and permeabilities, with a higher weighting for the deeper drafts. The latest proposed version of the weighting function is significantly more conservative than that proposed in A265 (VIII), and appears to be excessively stringent for several types of ships, including ferries, car carriers, and other types, based on the author’s own experience with actual loading factors.

3.4 Consequences of Capsize

If a damage event is such that loss of the ship may ensue, the resulting loss of life will be related to the time to capsize, the nature of the lifesaving equipment available, the environmental conditions, and a range of human factors.

The current international regulatory regime requires that the lifesaving equipment should be able to evacuate those on board within 30 minutes (passenger vessels) or 10 minutes (cargo ships). The very limited number of exercises which have been undertaken suggest that this is based on a very optimistic view of how rapidly the crew and passengers could be mobilized under the best of circumstances, and with insignificant wave heights.

In principle, stability criteria could be adjusted to account for survival time requirements, and some efforts in this direction have actually been proposed [9]. However, this is an area in which it seems probable that stability and equipment criteria are likely to stay independent for the foreseeable future.

3.5 Acceptable Risk

SOLAS 90 (probabilisitic) and the proposed new regulations calculate an attained subdivision index, A, on the summation of the values of s_I for each possible damage condition as defined by the damage size and location distributions. Both the old and the proposed new requirements incorporate different acceptable levels of risk based on the required subdivision index, R, which is a function of ship length and person number. For most ships, including passenger vessels, the formula has the form:

$$R = 1 - C_1 / \left(L_s + C_2 N + C_3\right)$$

Where C_x are constants (still under discussion)
L is subdivision length, and
N is (maximum) number of persons carried

Under SOLAS 90, the length dependency was selected to achieve a similar general level of subdivision requirement to that typical of current designs - it was not truly any reflection of whether lesser risk levels should be required for larger ships, based on the more severe potential consequences of loss.

A similar approach is being taken with the current revision proposals, to try to ensure that the new requirements represent the mean values for a set of existing, minimally compliant ships (under current standards). It seems highly unlikely that the results will correlate very well with other, more general principles of what constitutes societally acceptable levels of risk. Thus, marine (passenger) transportation will continue to have a different range of risk levels from (say) air transportation. This may cause occasional embarrassment to the industry and to its regulators. Before any required new safety level is mandated by SOLAS, it would seem to be important to explore these relative safety issues in more depth.

Meanwhile, many administrations have expressed concerns that it may be possible to design high density passenger vessels which have one compartment (or less) survivability in a few possible, though improbable, damage cases; and that, irrespective of probabilistic considerations, this should not be allowed. Therefore, a number of deterministic elements are likely to be included in the final requirements to preclude the possibility of loss under any minor damage (with implicit assumptions regarding environmental conditions, as discussed earlier). Many of the strongest supporters of such elements are the same administrations which have been pushing most strongly for a general move towards probabilistic standards. This suggests a certain institutional schizophrenia, or at least a healthy scepticism as to the real accuracy of the proposed methodology's predictions.

4. Potential Ways Ahead

Like most ship safety criteria, those for damaged (and intact) stability are not perfect. Improvements to the criteria can either achieve the same general levels of safety at reduced cost, or can allow higher standards to be attained cost-effectively.

In the area of damaged stability, the objectives of standards modification seem to include an overall upgrade in safety levels (though this is not universally accepted), coupled with a reduction in the scatter inherent in current requirements; i.e. the use of some improved predictor of sinking and capsize.

In the medium or longer-term future, this could be done by using a truly representative damage incident database to establish overall predictions of damage occurrence, location, and severity. This would be coupled with a prediction tool which would represent the probable response of the ship to each statistical distribution (or discretization of these) of the damage parameters. In the author's opinion, neither of these components exists at present.

It does not seem insuperably difficult to collect the data needed for the damage incidents within a relatively short timeframe. In Canada alone, the average year sees in the order of 250 (reported) incidences of collision, striking, or grounding, close to 40% of which involve at least one large vessel. The number worldwide is obviously many times greater. Even if only a few nations contributed to a systemmatic program of data collection, it should thus not take very long to assemble a statistically meaningful database capable of providing a more comprehensive picture of most components of risk. If IMO's own reporting system is inadequate to this task (which is itself somewhat disturbing) then it should consider requesting IACS to assist.

In the shorter term, two basic alternatives seem to exist; one being to do nothing until the steps outlined above have been taken, and the other being to try to develop some better damaged stability criteria using data which already exists. The first option is not necessarily inappropriate, given the quite low recent level of large ship losses which can be attributed unambiguously to inadequate damaged stability.

However, if some 'improved' method is desired for some or all ship types, it might be possible to use some variant of the Safety Case approach, in which the ship is evaluated against one or more service-specific scenarios. Doing this rigorously requires the same sorts of incident statistics which are generally lacking, but puts the onus for the collection of these on the operator, and/or the responsibility for the selection of realistic scenarios onto the designer. Administrations could thus expect to receive much interesting material at relatively low direct cost, and could then use this to construct more generalized guidelines. During a transitional period it would be advisable to maintain current deterministic standards on a 'minimum of' basis, to minimize potential problems due to incompetent or unscrupulous derivations of the safety cases.

5. Concluding Remarks

The international regulatory regime for shipping is becoming ever more complicated, and an increasing number of requirements come from the less-than-transparent processes of the IMO and IACS. Technical societies, such as SNAME, have a responsibility to keep their members aware of regulatory trends. They should also be more ready to contribute the expertise of their members to the development of soundly formulated standards. In recent years, SNAME has taken several initiatives in this area, and hopefully more will follow. However, we lack a good mechanism for ensuring that all important issues are recognized and acted on in sufficient time to influence the outcome. The current SNAME Strategic Planning initiative may wish to take this into consideration, and perhaps develop a joint approach with other societies such as RINA, SNAJ, etc to ensure involvement at IMO and elsewhere.

On the specific topic of damaged stability, this paper has shown how future generations of naval architects could be required to greatly increase the volume of work required to ensure safety levels no greater or more consistent than those which now exist. Hopefully, it will encourage some other members with influence at the national and international levels to consider alternative approaches.

References

[1] "Two Damage Stability Issues to be Settled at IMO" Marine Technology, January 1999

[2] "Regulations on Subdivision and Stability of Passenger Ships (etc)" IMCO Resolution A265 (VIII), 1974

[3] "Development of Revised SOLAS Chapter II-1 Parts A, B, and B1" IMO SLF 42/3, June 1998

[4] "The Technical Investigation of the Sinking of the Ro-Ro Ferry EUROPEAN GATEWAY" J. Spouge, The Naval Architect, March 1986

[5] Transportation Safety Board Casualty Statistics, website bst-tsb.gc.ca

[6] "On Probalistic Damage Stability" Anders Bjorkman, The Naval Architect, September 1995

[7] “Model tests to determine the survivability of damaged ro-ro ferries in waves” D.Molyneaux, J. Rousseau, D. Cumming, and M. Koniecki, Trans SNAME, 1997

[8] "Flooding Protection of Ro-Ro Ferries, Phase III" Fleet Technology Ltd, TP 13216E, 1998

[9] "Time-based Survival Criteria for Ro-Ro Vessels" D. Vassalos and T. Allan, Trans RINA, 1998