On the development of the new harmonised damage stability regulations for dry cargo and passenger ships

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Abstract

This paper outlines the methodological background and presents a summary of the main results of a series of undertaken international, IMO-led studies, on the harmonisation of the new probabilistic, risk-based regulations with the currently in-force regulatory provisions for assessing the damage stability of dry cargo and passenger ships. It reviews the historical development of the new regulations, to be applied to all new buildings on January 1, 2009, and the anticipated impact of the new rules on the design and indirect operation of various subcategories of dry cargo and passenger ships. It identifies certain loopholes in the existing regulations that appear cured by the new ones, though certain compromises adopted in the development of the new regulations, particularly those related to large passenger ships' survivability, have left some open issues to be addressed in the near future.

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1. Introduction

The safety of ships against sinking/capsize in case of loss of their watertight integrity is of prime interest to society, thus also to international and national regulatory bodies, and to the shipbuilding and shipping industry. Decades ago, responding to the spectacular disasters of “Titanic” and “Andrea Doria”, the International Maritime Organisation (IMO) was slow to introduce some first deterministic requirements for ships' watertight subdivision, specifying the number and arrangement of watertight bulkheads and ships’ stability after damage. This was laid down in the Safety Of Life At Sea (SOLAS) international convention of SOLAS 1929 and later amendments up to SOLAS 1960. It was recognised, however, that further study on the subject was absolutely necessary, because of the semi-empirical nature of the deterministic approach to ships’ stability that greatly relied on the characteristics of so-far known disasters.

At the time of introduction of SOLAS60, Professor Kurt Wendel from Germany introduced the fundamentals of a new, probabilistic model for the assessment of ships’ watertight subdivision, enabling the consideration of possible damage scenarios in a more rational way [1]. The particular concept was further elaborated by Comstock and Robertson [2], Volkov [3] and later on again by Wendel [4]. Based on this work and additional studies, IMO proceeded some years later to the adoption of an equivalent to the SOLAS74 [5] deterministic, damage stability standard procedure, namely, a probabilistic assessment method for passenger ships’ damage stability, as laid down in Resolution A.265 of SOLAS74 [5]. The same concept was further elaborated in the 1980s and 1990s, resulting in a probabilistic assessment method for the damage stability of dry cargo ships. This was the first time IMO addressed the damage stability of dry cargo ships and relevant regulations became applicable to all dry cargo ships constructed after 1992. Thereafter, the technical IMO sub-committees started discussing the necessity of once more revising the deterministic evaluation of watertight subdivision of passenger ships. The discussions came to the conclusion that the right way ahead was the
harmonisation of all damage stability regulations under a unified probabilistic framework for all types of merchant ships (cargo and passenger ships), instead of updating existing deterministic compartmentation standards for passenger ships. The promoted unified probabilistic assessment concept of ships’ damage stability was fully in line with the parallel introduction of risk-based assessment methods in other IMO regulatory work (notably Formal Safety Assessment procedures).

Two major casualties of Ro-Ro Passenger ships in Europe, namely the tragic losses of “Herald of Free Enterprise” in 1987 and “Estonia” in 1994, put the work of IMO on the harmonisation of existing damage stability rules for some time on hold. As a matter of urgency, IMO’s SLF (Stability, Load lines & Fishing vessels) and MSC [6] (Maritime Safety Committee) committees addressed first a revision of the existing deterministic 1990 and 1992 amendments of SOLAS [7] damage stability regulations of passenger ships to account for the ‘water on deck’ problem of Ro-Ro passenger ships. After the adoption of the particular enhanced deterministic requirements in the SOLAS convention of 1995, IMO’s relevant committees brought back the harmonisation of damage stability rules on the regulatory agenda, and a first proposal for a revision of SOLAS Chapter II-1 Parts A, B and B-1 was discussed at the Intersessional IMO-SLF42 meeting in 1998.

During this elaboration period on the way ahead, a team of European industries, classification societies, universities and research establishments, administrations and others proposed to the European Commission and received funding for the research project “HARDER”, HARDER (2000–2003). This project’s main objective was to generate lacking knowledge in the general field of ship’s damage stability by systematic fundamental and applied research and to clarify a variety of technical issues of great importance to the harmonisation work of the tasked IMO-SLF [8] sub-committee. In the framework of the HARDER project, the new harmonised damage stability, probabilistic concept, known as SLF42 proposal, under development at IMO [9], was systematically evaluated and an improved proposal was introduced for discussion at IMO, known as the HARDER-SLF46 proposal. Both concepts are extensively discussed in [10].

In September 2003, while the work of harmonisation was actually completed, some late concerns were raised at IMO, particularly in relation to the apparent severe impact of the proposed new harmonised damage stability regulations on the design (and economy) of very large passenger ships, bringing the formal approval of relevant regulations again to a hold. The IMO-MSC instructed the SLF sub-committee to reconsider the issues of concern, and as a result a series of new studies were carried out addressing particularly the damage stability of large passenger ships. Related proposals for amendments were submitted for consideration to IMO-SLF46 and MSC78.

On the basis of the work of the formed International Correspondence Group of IMO-SLF46/47, the HARDER-SLF46 proposal was revisited and led to the SLF47 proposal that was essentially approved in September 2004 at IMO-SLF47 and shortly after at IMO-MSC79. This proposal was, however, once more revised with respect to the large ships’ assessment method on the way from MSC79 to the MSC80 meeting in May 2005, where it was finally adopted. It is noted that the finally adopted MSC80 probabilistic damage stability assessment concept will apply to all new dry cargo and passenger ships constructed after January 1, 2009.

The scope of the present paper is to explain the main scientific background and the way of development of the new probabilistic damage stability assessment concept. It also addresses the enhanced impact of the new regulations on the design of some specific dry cargo and passenger ship types and provides some guidance for the necessary design changes to comply with the new regulations.

The paper is organised as follows: Section 1 reviews the historical development of the new damage stability regulations; Section 2 explains the methodology of development of the new harmonised regulations and the way of modelling of ship’s survivability and her risk for capsizing/sinking in case of damage; Section 3 comments on the main differences between the various explored alternative damage stability assessment methods; Section 4 focuses on the analysis of data resulting from the application of the new assessment concept to existing dry cargo ships, concluding with the new required survivability levels; Section 5 elaborates on the analysis of data pertaining to passenger ships and the implementation of a risk-based procedure to conclude on the required new survivability levels for passenger ships; Section 6 comments on the impact of the new regulations on some aspects of ship design; Section 7 summarizes the paper’s conclusions and identifies subjects for further investigation.

2. Methodology of work

2.1. Probabilistic concept of ships’ damage stability

The assessment of ships’ damage stability according to the probabilistic concept is based on the calculation of the attained index $A$ and its evaluation against the required, regulatory one, $R$. Both indices may be considered expressing the probability of survival that a ship disposes vs. needs to dispose in case of collision damage. Correspondingly, the quantities $(1-A)$ and $(1-R)$ may be considered expressing the percentage of damages that the ship cannot and is not required to survive according to regulations:

$$A = p(\text{damage|collision}) \cdot p(\text{survive|damage})$$

$$\Rightarrow A = p(\text{survive|damage})$$

$$1 - A = p(\text{shiploss|collision}).$$ (1)

Thus, $1-A$ is the risk of sinking conditional on a collision with water ingress. This index needs to be
calculated for all (but practically a finite number of) probable collision damage scenarios and in different, properly weighted, ship loading conditions. The general formulation of the attained index is given as

\[ A = \sum_{i=1}^{3} w_i A_i, \]  

(2)

where \( A_i \) is the attained index for loading condition \( i, i = 1 \) full load, \( i = 2 \) partial load, \( i = 3 \) lightest service, \( w_i \) the weighting factor for loading condition \( i, w_1 = 0.4, w_2 = 0.4, \) and \( w_3 = 0.2. \)

The method of calculating the attained index for each loading condition is expressed as

\[ A_i = \sum_{j=1}^{t} p_j v_j s_j, \]  

(3)

where \( j \) refers to the \( j \)th damage scenario of a compartment or group of compartments, \( t \) is the total number of investigated damage scenarios in the particular loading condition, \( p_j \) the probability that the \( j \)th compartment or group of compartments may be flooded, \( v_j \) the probability that the space above a horizontal subdivision of the \( j \)th compartment or group of compartments may not be flooded, \( s_j \) the probability that the ship may survive the flooding of the \( j \)th compartment or group of compartments under consideration in the particular loading condition.

The obtained attained index, \( A \), representing the conditional risk of sinking in case of collision, should be obviously greater than a required subdivision index, \( R \), \( A > R \), which represents the minimum acceptable level of ships' damage stability set by the regulations. In the new harmonised damage stability regulations, this minimum acceptable level is practically the weighted average of the attained indices of a satisfactory sample of ships complying with the provisions of current damage stability regulations and a corresponding safety standard.

### 2.2. Harmonisation process of existing and new regulations

The harmonisation process of existing damage stability regulations may be defined in the sense of IMO-MSC as the introduction of a unified assessment method for the damage stability of dry cargo and passenger ships on the basis of the probabilistic concept, without change of current safety standards set by IMO that are considered satisfactory.

The main elements of the harmonisation process are the development of the unified probabilistic assessment concept and the definition of proper survivability levels for dry cargo and passenger ships, which should be equivalent to those defined by currently-in-force regulations for new buildings. In Table 1, the currently-in-force damage stability regulations are listed and they are assumed associated with a satisfactory level of safety. It is noted that the equivalence remit of the IMO harmonisation process could only be met in an approximate way by the newly introduced standards and is stressed that the new regulations should not lead to an enhanced safety standard, except for some cases specifically approved by IMO-MSC.

The detailed procedure for the calculation of the attained and required indices was developed and implemented in the HARDER project, with major contributions of the Ship Design Laboratory, National Technical University of Athens and Det Norske Veritas, who were coordinators of relevant HARDER work packages [11]. The harmonisation process included the following steps:

1. Firstly, the marginal survivability level resulting from the currently in-force damage stability regulations was investigated. For a representative sample of ships, calculations were performed in order to identify their critical GM value, which is a measure of the marginal survival capability of the ship in damage condition.

   ○ For all sample ships (dry cargo or passenger ships), for which the currently-in-force relevant regulation was based on the probabilistic concept, the critical GM values were calculated based on the assumption of equality of the attained and required subdivision index:

   \[ A_{\text{EXISTING}} = R_{\text{EXISTING}} \]  

(4)

   ○ In case the currently-in-force relevant regulation was based on the deterministic model (SOLAS90, passenger ships only), the curve of critical GM values was calculated as specified in the particular damage stability regulation.

2. Secondly, having identified the critical GM values for each data sample ship, calculations of the attained subdivision indices were conducted on the basis of alternative probabilistic proposals and for the same critical GM values.

In practice and in order to ensure a smooth transition of the existing to the new damage stability standards, the following procedure was adopted:

1. The critical GM values were found for approximate fulfilment of Eq. (4), namely \( A_{\text{EXISTING}} \approx R_{\text{EXISTING}} \), with \( A_{\text{EXISTING}} \) equal to or marginally higher than \( R_{\text{EXISTING}} \).

<table>
<thead>
<tr>
<th>Basic ship type</th>
<th>In-force regulation</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cargo ships</td>
<td>SOLAS B-1</td>
<td>Probabilistic</td>
</tr>
<tr>
<td>Passenger ships</td>
<td>Resolution A.265</td>
<td>Probabilistic</td>
</tr>
<tr>
<td>Passenger ships</td>
<td>SOLAS 90/95</td>
<td>Deterministic</td>
</tr>
</tbody>
</table>

Table 1

Currently-in-force damage stability regulations for dry cargo and passenger ships
2. For ensuring the equivalence of existing and new damage stability standards, the required safety levels as expressed by the new required subdivision indices were determined as follows:

- For dry cargo ships,

\[
\frac{A_{\text{new}}}{R_{\text{new}}} \approx \frac{A_{\text{EXISTING}}}{R_{\text{EXISTING}}}
\]

\[
\Rightarrow R_{\text{new}} = A_{\text{new}} \frac{R_{\text{EXISTING}}}{A_{\text{EXISTING}}} = A_{\text{new}} \frac{R_{B-1}}{A_{B-1}},
\]

where \(R_{B-1}\) and \(A_{B-1}\) are to be calculated according to SOLAS B-1.

- For passenger ships that were built under the probabilistic concept of Resolution A.265,

\[
\frac{A_{\text{new}}}{R_{\text{new}}} \approx \frac{A_{\text{EXISTING}}}{R_{\text{EXISTING}}}
\]

\[
\Rightarrow R_{\text{new}} = A_{\text{new}} \frac{R_{\text{EXISTING}}}{A_{\text{EXISTING}}} = A_{\text{new}} \frac{R_{A.265}}{A_{A.265}},
\]

where \(R_{A.265}, A_{A.265}\) calculated values according to Resolution A.265.

- For passenger ships that were built under deterministic rules, the values of the new required indices were to be calculated as follows:

\[
\frac{A_{\text{new}}}{R_{\text{new}}} \approx \frac{A_{\text{EXISTING}}}{R_{\text{EXISTING}}}
\]

\[
\Rightarrow R_{\text{new}} = A_{\text{new}} \frac{R_{\text{EXISTING}}}{A_{\text{EXISTING}}},
\]

Herein, it could be assumed for passenger ships, complying with SOLAS90, that \(R_{\text{EXISTING}}/A_{\text{EXISTING}} = 1\).

2.3. Modelling of survivability levels

In general, the loss of the watertight integrity of a ship will have an impact (consequence) on the human lives on board, the ship and her cargo as property, and possibly the sea environment (in case of oil-carrying tankers). The risk consequences in case of ships’ damage will vary depending on the ship’s type and size, and this should be accounted for by proper weighting in a risk-based assessment of ships’ damage stability.

Fig. 1 outlines a categorisation of all types of ships, according to which the required levels of survivability in case of loss of watertight integrity may be modelled. On a first level, a subdivision according to the potential risk of loss of human lives on board is conducted. On that level, cargo ships are trivially separated from passenger ships, as the risk of loss of the crew is limited. Further on, cargo ships are subdivided into dry and liquid cargo ships, according to the dominant consequences in case of damage accidents: accidents of dry cargo ships may lead to the loss of the ship and her cargo as property/investment, whereas a tanker accident may severely pollute the marine environment and this will outweigh the loss of the ship herself [12]. Though highly disputed as quantitative assessment, all

![Fig. 1. Categorisation of ships and regulatory framework for the assessment of damage stability.](image-url)
types of consequences may be measured in monetary terms and in this way directly compared with each other, as demonstrated in Formal Safety Assessment procedures.

The risk control of a ship in case of a collision accident refers to the mitigation of unfavourable consequences by properly defined minimum levels of survivability. Fig. 2 presents qualitatively the risk control of two basic ship types: in case of dry cargo ships, the associated risk is controlled by the ship’s size, expressed by her length, whereas for passenger ships, in addition to the ship’s length, the number of persons on board is taken into account.

Based on the introduced categorisation, Fig. 1, and accounting for the expectation that a survivability level should increase with ships’ size and persons on board (for reducing the risk of respective consequences), the general formulation of the new required survivability level for dry cargo and passenger ships is given as

$$R = 1 - \frac{C_1}{L_s + C_2N + C_3},$$

where $L_s$ is the ship’s subdivision length, in metres, defined as the length between perpendiculars taken at the extremities of the deepest subdivision load line, $N$ refers to the number of persons on board and the extent of lifesaving equipment, $N = N_1 + 2N_2$, where $N_1$ is the number of persons for whom lifeboats are provided and $N_2$ the number of persons the ship is permitted to carry in excess of $N_1$, $C_2$ the coefficient, expressing the relative importance of the ship’s length (indirectly the ship’s size, thus of hardware) and a proportional number of the persons on board (thus indirectly of humanware) in risk, $C_1$ and $C_3$ the coefficients resulting from a regression analysis (best fitting) of calculated attained indices of sample ships with satisfactory survivability level.

In practice, the new required survivability/subdivision level $R_{\text{new}}$ for dry cargo and passenger ships was determined by a regression analysis of relevant newly calculated attained indices of a satisfactory level in terms of size and representative in terms of ship type and size sample of ships, assuming that the minimum required level of survivability should be approximately equal to the weighted average of that of the sample ships of equal size.

3. Exploration of alternative damage stability models

Inherent to the probabilistic assessment model of ships’ damage stability is the underlying statistical distribution of damage extent and location, derived from historical collision data. Synoptically, the following alternative probabilistic damage stability models were explored:

- The probabilistic damage stability model, embedded in existing regulations (resolution A.265 and SOLAS Part B-1), based on IMO accidental data of the 1960s.
- SLF42 proposal (1998), considers the same basis of historical accidental data but uses a partly modified assessment procedure compared with the existing probabilistic regulations.
- HARDER-SLF46 proposal (2000–2003), based on a significant revision of the earlier damage distributions by considering a strongly updated statistical sample of damage data up to year 2000 and using additionally damage data from numerical simulations of collisions.
- SLF47 proposal (2004), based on the HARDER-SLF46 proposal; however, damage distributions were modified with respect to the maximum length of damage, limited to an absolute value of 60 m.
- The finally adopted MSC80 concept (2005), based on the previous one, however, with the additional restriction of the longitudinal extent of damage for ships with length greater than 260 m.

When assessing the currently-in-force damage stability regulations and the various alternatives, including the adopted new ones [13], it is helpful to comment on their main difference in terms of the mean damage length as a function of the struck ship’s length, Fig. 3.

3.1. Comments on longitudinal extent of damage

- The same mean damage length is assumed in the currently-in-force regulation SOLAS B-1 (dry cargo ships), the Resolution A.265 (passenger ships) and the alternative SLF42 proposal (early harmonised proposal). Characteristically, the mean damage length is kept constant at 16 m for ships of length over 200 m.
- The enhancement of the initial statistical base of accidental data with new records led to an increased mean damage length in the HARDER-SLF46 proposal (first intermediate harmonised proposal) for ships of length over 220 m.
- The revised HARDER-SLF46 proposal, namely the SLF47 proposal (second intermediate harmonised proposal), considered a limitation of the maximum absolute damage length to 60 m, leading to a reduced mean damage length for ships of length below 250 m and to an increase of the mean damage length for larger ships of length over 250 m.
- The finally adopted MSC80 concept (final harmonised proposal), which is based on a revision of the SLF47...
A proposal, namely on a revised damage distribution for ships of length greater than 260 m, is (compared with the currently-in-force probabilistic assessment methods) associated with a reduced mean damage length for ships of length below 260 m and with practically the same mean damage length for ships larger than 260 m in length.

The maximum damage length resulting from the currently-in-force deterministic regulations (SOLAS90) for large passenger ships is 11 m; this damage length is significantly smaller than the mean damage length resulting from the various alternative probabilistic proposals for larger ships (actually for all ships over about 160 m). Insofar, it could be expected, when assessing the survivability of large passenger ships, built according to SOLAS90, with the alternative probabilistic models that their survivability would appear reduced, compared with relatively smaller ships.

Concerning the smaller size passenger ships of length less than 60 m, it is noted that the existing deterministic regulation SOLAS90 considers larger damages than those derived from the alternative probabilistic concepts: this could be the reason for the comparably very high attained indices found when studying the survivability of small passenger ships with the various alternative probabilistic concepts (see Figs. 5 and 7).

It should be herein noted that the various revisions introduced after the HARDER-SLF46 proposal were more ‘politically’ than ‘scientifically’ justified and aimed at a smooth transition from the currently-in-force regulations to the new probabilistic assessment concept without significant change of the currently specified safety levels that IMO considers satisfactory.

4. Analysis of dry cargo ships

A reach sample of 84 dry cargo ships representing fairly well the world dry cargo fleet in terms of ship type/category and size was assessed by the various alternative probabilistic concepts in the HARDER [14] project and in collaboration with the International Correspondence Group of IMO-SLF [15]. The quality of the submitted raw data was reviewed with respect to their compliance with the set study specifications, particularly the possible use of irrelevant critical GM values or with respect to the actual rules in-compliance for some submitted sample ships. It should be noted that loadline ships with reduced freeboard [B-60 & B-100], were excluded from the sample used for the determination of the required index of dry cargo ships, as they deviated from the specifications of the other dry cargo ships in compliance with SOLAS B-1.

From the analysis, it became evident that the Dry Cargo Ro-Ro & Car Carriers (DCRR & CC) is the type of ship that appears mostly affected by all studied alternative probabilistic proposals in that the calculated attained subdivision indices of relevant sample ships were clearly below those of other dry cargo ships of comparable length. One of the reasons for this performance was the more realistic modelling of car decks’ flooding in the new assessment methods that involve a change of the cargo permeability from the constant value of 0.60 (SOLAS B-1) to 0.90–0.95 depending on the loading condition. Considering the evident peculiarities of the “DCRR & CC” ships, these ships were finally separated from the overall sample of Dry Cargo Ships, as they were distorting the sample, and the analysis was repeated [15]. This deviation from the principle of equivalence of existing and new damage stability levels (original request of same safety standard) for ships carrying vehicles was specifically approved by IMO-MSC78.
The implemented harmonisation procedure of currently-in-force damage stability rules with the new unified probabilistic concept was else relatively smooth because the transition of damage stability levels was done under a similar assessment framework (namely, a transition from the probabilistic concept of SOLAS B-1 to a new probabilistic one). Studied ships presented in general a satisfactory trend with respect to the dependence of the survivability level on ship size, with the larger ships disposing in general greater attained survivability levels than the smaller ones despite the great variety of the studied designs for each dry cargo ship subcategory. The assessment of the sample ships relieved, however, some loopholes in current Ro-Ro cargo ship designs, as stated above, and the new harmonised regulations took care of this in a satisfactory way.

In Fig. 4, the new required subdivision index for dry cargo ships is presented. There it is noted that the required index for ships of length smaller than 100 m and not less than 80 m was not estimated on the basis of sample ships data (due to the lack of sufficient data), but specified in accordance with the existing regulations of SOLAS, Chapter II-1, Part B-1.

In order to ensure a satisfactory survivability at all loading conditions and to safeguard possible design vulnerability for the larger draughts, especially at the subdivision draught, a new requirement for a minimum attained index per draught was introduced, as follows:

\[
A_{\text{PARTIAL INDEX}} \geq kR, \quad k = 0.5. \tag{9}
\]

The particular requirement acts supplementary to the general \(R\)-index requirement, safeguarding against the fact that currently some dry cargo ships dispose very low indices at larger draughts and consequently they may fulfill the \(R\)-index, though having unacceptably low attained index at subdivision draught (SLF47/3/2 and SLF47/3/3).

The adopted new harmonised regulation will have a significant impact particularly on the design of Dry Cargo Ro-Ro ships, which should increase their above-water watertight integrity in order to comply with it. Some difficulties may also appear in case of smaller Dry Cargo ships, namely small General Cargo ships, Feeders and Handysize Bulk Carriers [16].

5. Analysis of passenger ships

5.1. Attained survivability and the risk boundary lines (RBL) method

Though dry cargo ships show a consistent trend of attained indices with respect to the dependence of the attained index on ship size and subtype, meaning that the larger the ship the smaller the associated risk expressed by the \((1 - A)\) value, in contrast, calculated attained indices of passenger ships showed (besides a large scatter of data) a wrong overall trend, with the smaller ships disposing greater attained indices than those of relatively large size in terms of length and persons on board (POB), Fig. 5.

In particular, the desired trend “the larger the ship with higher number of persons on board, the greater the survivability” was not achieved by the sample ships, when applying all alternative probabilistic assessment methods. This appeared to be a generic problem of passenger ships, independently of subtype (ROPAX or cruiser) and of their currently-in-force deterministic damage stability standard that obviously did not account properly for the desired general trend of increased survivability for increased number of carried persons. More specifically:

In contrast to the dry cargo ships, ‘equivalence of safety’ for the passenger ships required a direct comparison between the currently-in-force deterministic damage stability approach (SOLAS90) and the probabilistic one. This direct comparison could be expected to be intricate, considering that the probabilistic approach takes into account in a rational way all possible damage scenarios of specific extent, whereas damages in the deterministic concept are limited to maximum two compartments (maximum damage length 3 m + 3\%\(L_S\), but not more than 11 m) and are restricted transversely by the B/5 line. It is this fundamental difference between the two concepts that becomes particularly evident in the case of assessment of large passenger ships by the probabilistic concept.
In order to overcome the addressed insufficient relation of $A$-index and passenger ship size, a revision of the passenger ship sample by use of the so-called risk boundary lines (RBL) method was conducted. Following this, ships that were outside the set risk boundary regions were extracted from the sample used for the determination of the required subdivision index. The key point in this procedure is to define meaningful risk boundaries (likewise, the definition of an ALARP region in formal safety assessment studies). It is based on the following working assumptions:

1. The required index $R$ sets a standard for the probability of a ship surviving, in case of collision, a series of predefined damages; thus, the required index $R$ is a measure of relative and conditional safety; larger ships with relatively large number of persons on board should be exposed to a lower risk to not survive in case of collision; additionally, this survival standard should be in general equivalent to the currently-in-force deterministic SOLAS90 regulation.

2. The coefficient $C_2$ in the general formula of $R$-index, Eq. (8), expresses the relative importance of the carried persons and ship size. A set of different $C_2$-values (between 1/4 and 4) was systematically examined in order to find the best correlation with respect to the associated risk, and the resulting required index is calculated for each case by regression analysis of the attained indices of the retained sample ship data.

3. The high-end studied values of $C_2$, namely $C_2 = 4$, obviously tend to give a negligible effect of ship size on survivability; this corresponds in principle to a cost–benefit risk-based concept stating that the possible loss of a large ship (in terms of cost for the lost hardware) is minor in comparison to the associated societal risk of loss of a large number of human lives.

The implementation of this approach is more detailed in the next section.

5.2. Application of the RBL method

The associated risk, in terms of the survivability in the probabilistic concept, can be expressed by the value of $(1 - A)$. The passenger ship size is herein expressed in generic terms by the value of $(L + C_2 N)$, taking into account that the relative importance between ship’s length and POB, expressed by the $C_2$-value, may vary parametrically for a series of predefined values (Fig. 6).

- The set boundary lines are assumed defining an ‘ALARP’ area, on the basis of which a revision of the ship’s sample was conducted. The limiting boundary values, on the $y$-axis, are determined by the limiting values of the dry cargo ships’ requirements ($A = 0.3$, $0.7$), for which $POB = 0$, considering also a reasonably small margin, Table 2. The limiting boundary values on the $x$-axis (corresponding to zero risk) practically correspond to the margin of sizes of the passenger fleet at risk.

- For each investigated $C_2$ value, the sample was revised according to the area defined by the risk boundary lines. Ships that are out of the region were extracted from the sample as “over-satisfactorily safe” (below the lower boundary) and as “non-satisfactorily safe” (above the upper boundary). Ships that were inside the region were considered “as low as reasonably practicable safe” and were kept for the subsequent analysis, leading to the determination of the required index for passenger ships.

5.3. Required subdivision index

From the overall analysis of 32 sample passenger ships, it was found that the selection of the $C_2$ value and the corresponding revised sample that was used in the evaluation of the required subdivision index are the determinant factors for the definition of the new minimum
Two different criteria were used for the final evaluation of the required subdivision index and consequently two different standards were calculated.

- **Criterion 1 (best regression fitting):** The $C_2$ value was selected according to the best regression fitting of associated risk $(1-A)$ with respect to the $(L+C_2N)$ value (highest regression index $R^2$).

- **Criterion 2 (size of used sample):** Given the fact that the whole sample of passenger ships is considered by today’s safety standards acceptable and in compliance with the currently-in-force damage stability regulations, a further criterion for the selection of the $C_2$ value could be, in addition to the statistical $R^2$ regression index the representativeness of the sample, namely its absolute size or the lesser number of extracted ships from the entire original sample.

Both criteria have their own merits and disadvantages. Criterion 1 stands mathematically on a firm basis, when assuming that sample ship data are representative and sufficient in size. Criterion 2 takes into account a larger sample of data, and since every ship satisfies the current minimum requirements the resulting trend should be practically meaningful.

The application of the above two alternative criteria in the sample ships analysis leads to significant differences of the minimum required levels. In Fig. 7, the estimated required subdivision index curve $R$-Index is presented according to SLF47 proposal. Curve “Alt 1” has been calculated by application of Criterion 1, whereas curve “Alt 2” is in accordance with Criterion 2 [17]. Criterion 2 leads to significantly lower required survivability levels for large passenger ships, compared with Criterion 1.

Note that during the IMO-SLF46/47 meetings, it was decided to use Criterion 2 for the final calculations of the new required passenger ship levels. Furthermore, curve “Alt 2”, calculated from the attained indices of the sample ships on the basis of the SLF47 proposal, was later retained as the required index curve for the passenger ships in the final MSC80 concept, though the latter concept leads to higher attained indices for the larger passenger ships, due to the revised way of calculation of the longitudinal extent of damage for ships of length over 260 m. Essentially this means that larger passenger ships will easily ‘pass’ the new survivability requirements, compared with smaller ships.

Similar to the dry cargo ships, a minimum attained index per loading draught was adopted for passenger ships, as follows:

$$A_{P,\text{PARTIAL INDEX}} \geq kR, \quad k = 0.9.$$  \hspace{1cm} \text{(10)}

In contrast to the dry cargo ships, this particular requirement is considered less stringent when applied on top of the general $R$-Index requirement to passenger ships, because of the fact that passenger ships dispose inherently by design quite similar to attained indices at every draught, and consequently in case they fulfil the general $R$-Index, no further implication on ship design is expected by the draught minimum requirements.

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**Table 2**

<table>
<thead>
<tr>
<th>Lower boundary</th>
<th>Upper boundary</th>
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</thead>
<tbody>
<tr>
<td>$1-A$</td>
<td>$L+C_2N$</td>
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<tr>
<td>$0.25$ 0</td>
<td>$0.75$ 0</td>
</tr>
<tr>
<td>0 10000</td>
<td>20000</td>
</tr>
</tbody>
</table>

**Fig. 6.** Risk boundary lines for sample passenger ships, $C_2 = 4$. 

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**Definition of risk boundary lines**

<table>
<thead>
<tr>
<th>Lower boundary</th>
<th>Upper boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1-A$</td>
<td>$L+C_2N$</td>
</tr>
<tr>
<td>$0.25$ 0</td>
<td>$0.75$ 0</td>
</tr>
<tr>
<td>0 10000</td>
<td>20000</td>
</tr>
</tbody>
</table>
6. Impact on ship design

6.1. Dry cargo ship design

As it was already stated, Dry Cargo Ro-Ro & Car Carriers is the only ship type that will be significantly affected by the new probabilistic concept in that some existing designs are expected to face major problems with their compliance with the new levels. In fact the design philosophy of these ships should be changed, ensuring increased watertightness of decks/spaces well above waterline.

Furthermore, designs of small dry cargo bulk carriers and large containerships may have some difficulties in compliance with the new probabilistic concept, because of the new minimum index per loading draught requirement. In case of general cargo ships, it was clearly found that the smaller the ship the greater the problem.

6.2. Passenger ship design

From the undertaken studies, it was shown that some large passenger ships, passenger Ro-Ro & cruisers, are likely to face difficulties in achieving the new required indices developed by SLF47 if their designs remain unchanged. A separate analysis conducted for a sample of large passenger ships, originally built under the SOLAS 90 criteria, two-compartment standard, showed the following:

- Large passenger ships with relatively large number of persons on board appear to be requested to dispose an equivalent ‘deterministic 3 + compartment standard’ to achieve the derived R-index requirements, meaning that the ship must survive all damages extending up to three adjacent compartments and additionally a certain number of damages of four adjacent compartments.
- Large passenger ships with relatively small number of persons on board should have an equivalent ‘deterministic 2 + compartment standard’ to achieve the derived R-index requirements, meaning that the ship must survive all damages extending up to two adjacent compartments and additionally a certain number of damages of three adjacent compartments.

Nevertheless, it was observed that some sample ships of large size could pass the new R-index requirements with their present design arrangement, and this is further facilitated by the reduction of the likely longitudinal extent of damage of the SLF47 procedure on the way to the final adoption of the probabilistic harmonised concept by MSC80.

Noting that the new harmonised probabilistic damage stability regulations will be not applied to the existing fleet, and additionally due to the introduced changes in the originally developed assessment method [18–20] for ships of length over 260 m (final adopted MSC80 concept), it can be anticipated that new passenger ship designs, resulting from optimisation procedures on the basis of the new probabilistic concept, will not face any major difficulties for compliance with the new regulations, at satisfactory efficiency.

7. Conclusions and possible way ahead

The undertaken systematic investigations of existing methodologies for evaluating ships’ survivability in case of damage after collision revealed the merits and drawbacks of each alternative methodology. In case of the deterministic approach of SOLAS90, that is considered today a satisfactory damage stability standard for passenger ships, it is proved that the currently assumed longitudinal extent of damage is significantly smaller than the mean damage length derived from recently updated statistical data of collision accidents. As a result, the survivability of ships, built according to the SOLAS90 standard, appears, by today’s knowledge, not satisfactory, especially in case of
large passenger ships. In this case the new harmonised probabilistic regulations led to an increase of the required survivability level for the larger ships, despite some relaxation of initially formulated, more stringent requirements on the way to the final adoption of the new regulations.

The evaluation of the attained survivability according to the probabilistic model is definitely more rational than the existing, semi-empirical deterministic damage stability evaluation methods. However, the probabilistic, risk-based procedure, in its present form, does not ensure a uniform distribution of the survival capability along the entire length of the ship, and there might be loopholes for relatively small damages of low probability. This particular drawback of the probabilistic concept is not solved by the introduced concept of minimum attained index at each draught that at least cures another major drawback of this assessment method in its original form. Consequently, it is proposed to reconsider the probabilistic concept by inclusion of a minimum uniformity in the distribution of a ship’s survivability along the ship. Alternatively, this might be addressed by additional deterministic requirements in the way to prescribe that the ship should survive all one-compartment (for cargo ships) and two-compartment damages (for passenger ships). It is hoped that designers of especially large passenger vessels will address this inherent drawback of the probabilistic assessment model by prudent design solutions and that administrations in charge will carefully check new designs for possible loopholes. Nevertheless, current extensive IMO discussions on large passenger ships’ safety (‘safe return to port provisions’, ‘estimation of time to flood’) indicate that maritime administrations and the maritime industry acknowledge the need for increased survivability requirements for large passenger ships, beyond the ones adopted by the new harmonised probabilistic regulations at MSC80.

One important further outcome of the studies presented herein on the definition of the required level of survivability is the identified sensitivity of the $C_2$-coefficient, Eq. (8), which expresses the relative importance of a ship’s length (size) and persons on board exposed to risk. A “small” difference in the $C_2$-coefficient leads to a significant (and undesired) change of the $R$-index, as indicated in Fig. 7, where the same probabilistic concept is presented. Thus it is recommended that the selection of $C_2$-coefficient in future studies should be done using entirely risk-based methodologies. Appropriate $C_2$-coefficient values could be determined on the basis of analyses of casualties of passenger ships’ accidents or reliable numerical simulations of the time for a ship to flood/sink and for her safe evacuation, but, at present, the sample of casualty or related numerical simulation data of passenger ships is very limited to allow a systematic quantitative analysis and related conclusions. If enough such data could be made available, then relevant F–N diagrams for passenger ships could be constructed and, considering the main characteristics of the ships involved in the accidents, the $C_2$-coefficient could be adjusted more rationally to the requirements of the ALARP Formal Safety Assessment concept (see, e.g. [21,22]).

In terms of the general framework of harmonisation of damage stability rules, tanker ships could also be addressed in the near future. The statistical data of collision accidents, from which new damage distributions were derived, include all ship types and consequently are also applicable to tanker ships. Additionally and especially for tankers, grounding accidents and their consequences should and can be considered. Nevertheless, further studies are required to ensure that current criteria for the survival factor satisfactorily reflect the survival characteristics of tankers, and also to specify the probability and extent of oil outflow, as well its impact on the marine environment in case of damage.

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References


