ABSTRACT

This paper presents results of studies on the harmonization of a new probabilistic regulatory framework with the currently in-force damage stability regulations as well as their anticipated impact on the design of dry cargo and passenger ships.

In particular, the scope of the paper is to scientifically explain the reasons for the apparent increased impact of the proposed new regulations on some specific dry cargo and passenger ship types and to provide some guidance for the necessary design changes, where applicable.

KEY WORDS: probabilistic damage stability concept, SOLAS Ch. II-1 Part B-1, SOLAS 90, Resolution A.265, assessment of deterministic damage stability concept, new harmonized regulations, IMO-SLF47, impact on ship design.

INTRODUCTION

The fundamentals of a probabilistic assessment model for ship’s watertight subdivision were introduced by Professor Kurt Wendel (1960). The introduced concept was further elaborated by Comstock & Robertson (1961), Volkov (1963) and Wendel (1968). Based on this work and additional studies, IMO proceeded some years later to the adoption of the equivalent regulation A.265 for the assessment of passenger ships’ damage stability (IMO, 1974)). This work was continued by IMO in the 80ties and 90ties, resulting to a probabilistic assessment method for dry cargo ships’ damage stability, applicable to all dry cargo ships constructed after 1992 (SOLAS Ch. II-1, part B-1, IMO (1997)). Thereafter, relevant committees of IMO continued working on a revision of SOLAS with respect to the introduction of a new probabilistic assessment method, harmonizing existing damage stability rules pertaining to all ship types (dry cargo and passenger ships) within a new generalized probabilistic concept (see, e.g., MSC 72/21/10 (2000)).

The present paper is based on research conducted by the Ship Design Laboratory of the National Technical University of Athens (NTUA-SDL) in the framework of the European Union funded project HARDER (1999-2003) and on additional studies conducted after the completion of the above project in May 2003 in the framework of work of the Intersessional Correspondence Group IMO-ISCG-SLF47 (Eliopoulou et al. (2004)).

In the course of above work a variety of alternative damage stability probabilistic concepts were evaluated, namely the SLF42 proposal (SLF42/3/3 (1999)), the HARDER proposal submitted to SLF46 (SLF 46/3/3 (2003)) and the final SLF47 proposal (SLF47/3/3 (2004)). The paper is focusing on the development of the Required Subdivision Index (R) values for dry cargo and passenger ships and their global impact on ship design.

The process of harmonization of currently in-force damage stability regulations pertaining to dry cargo and passenger ships on the basis of a generalized probabilistic assessment concept was finalized by IMO SLF47 in September 2004. The regulatory framework adopted by SLF47 has been forwarded to MSC79 for further consideration. It is expected to be approved by the next SOLAS Convention in autumn 2005 and likely to enter into force in 2006.

METHODOLOGY

The probability of a ship’s surviving after a collision incident is expressed by the Attained Index, A. This index requires calculations of a series of different damage scenarios in predefined initial loading conditions. The general formulation of Attained Index is given next:

\[ A = \sum w_f \cdot A_i \]

where \( A_i \): attained index for each specified loading condition (draught)
\( w_f \): weighting factor of each \( A_i \)

The method of calculating the attained index for a loading condition is expressed by the following formula:

\[ A_i = \sum p_j \cdot v_j \cdot s_j \]

where,
\( i \): expresses each investigated compartment or a group of compartments.
\( t \): is the number of investigated damages for the calculation...
of the A-Index for the particular loading condition.

\[ p_i: \text{the probability that a compartment or a group of compartments may be flooded.} \]

\[ v_i: \text{the probability that the space above a horizontal subdivision may not be flooded.} \]

\[ s_i: \text{the probability that the ship may survive after flooding the compartment or group of compartments under consideration in the defined loading condition.} \]

The attained index, A, should be obviously greater than a Required Subdivision Index, R, specified by the regulations.

Considering that the currently in-force damage stability regulations for newbuildings can be assumed corresponding to a satisfactory level of safety, it follows that a harmonization of relevant rules on the basis of the probabilistic damage stability concept should aim at keeping these levels of safety on the average unchanged (see, MSC 72/21/10 (2000)). Thus, the determination of the new Required Index, Rnew, has been based on the concept of “equivalence of safety”.

In order to achieve “equivalent level of safety” between the existing regulatory body and the new proposed one, with respect to the evaluation of ships’ damage stability, the following working assumption was taken:

\[ (A/R)_{\text{new}} = (A/R)_{\text{existing}} \]

The way of implementation of the particular assumption to the Dry Cargo ships is expressed as follows:

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

\[ \frac{A_{\text{new}}}{R_{\text{new}}} = \frac{A_{\text{EXISTING}}}{R_{\text{EXISTING}}} \Rightarrow R_{\text{new}} = \frac{A_{\text{new}}}{R_{\text{EXISTING}}} \cdot R_{\text{A-265}} \]

where \( R_{\text{B-1}}, A_{\text{B-1}}; \) to be determined according to SOLAS B-1 (IMO (1997)).

With respect to the Passenger ships that were built under the probabilistic concept of Resolution A.265, the following has been considered:

\[ \frac{A_{\text{new}}}{R_{\text{new}}} = \frac{A_{\text{EXISTING}}}{R_{\text{EXISTING}}} \Rightarrow R_{\text{new}} = \frac{A_{\text{new}}}{R_{\text{EXISTING}}} \cdot R_{\text{A-265}} \]

\[ \frac{A_{\text{new}}}{R_{\text{new}}} = \frac{A_{\text{EXISTING}}}{R_{\text{EXISTING}}} \Rightarrow R_{\text{new}} = \frac{A_{\text{new}}}{R_{\text{EXISTING}}} \cdot A_{\text{A-265}} \]

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

For passenger ships that were built under deterministic rules (SOLAS 90), the values of the new required indices are calculated according to the following formulation:

\[ \frac{A_{\text{new}}}{R_{\text{new}}} = \frac{A_{\text{EXISTING}}}{R_{\text{EXISTING}}} \Rightarrow R_{\text{new}} = \frac{A_{\text{new}}}{R_{\text{EXISTING}}} \cdot A_{\text{A-265}} \]

Herein it can be assumed for passenger ships that \( R_{\text{EXISTING}}/A_{\text{EXISTING}} \) = 1 and is noted that the limit damage GM curve has to be taken into account at all specified loading conditions.

The general formulation of Required Subdivision Index, R, is given next:

\[ R = 1 - \frac{C_1}{L + C_2 \cdot N + C_3} \]

where, \( L \): Subdivision Length, in meters

\( N \): related to the persons on board and the extent of life saving 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 \( N_1 \).

As far as the Dry Cargo Ships are concerned, the \( C_2 \) coefficient was assumed equal to zero due to the fact that cargo ships have a relatively small number of persons on board, namely only officers and crew. As this number is relatively small, its significance on the formulation of the Required Subdivision Index is negligible.

In practice, “equivalence of safety” can be only achieved “on average”, within practical limitations, by proper determination of the R-formula for the addressed ships, following a regression analysis of data of collected and newly calculated Attained Indices of a statistically sufficient sample of ships. These data correspond to various dry cargo and passenger ship types, relevant sizes and loading conditions assumed marginally meeting existing SOLAS damage stability criteria, pertaining to newbuildings of the specific ship category.

**DRY CARGO SHIPS**

The HARDER-SLF46 study results (status end of 2003)

The herein presented study is based on research conducted by NTUA-SDL in the framework of the EU funded project HARDER. Two different probabilistic proposals were studied, namely SLF42 and HARDER and relevant Required Subdivision Indices assessed.

**Dry Cargo Sample ships**

The analysed sample of Dry Cargo ship consisted of 98 ships, submitted by HARDER project partners and also by members of IMO-ISCG. The sample represents fairly well the world dry cargo fleet in terms of ship type/category and size (SLF45/3/4 (2002)). The quality of the submitted raw data was reviewed by NTUA-SDL with respect to their compliance with the set study specifications, particularly the possible use of wrong GM values or with respect to the actual rules in-compliance for some submitted sample ships (they had to comply with the SOLAS Ch. II-1, Part B-1 provisions). It should be noted that loadline ships [B-60] were excluded from the sample used for the determination of the Required Index. In total, 75 ships were finally used for the evaluation of the SLF42 proposal, and 84 for the HARDER proposal.

**Comments on Attained Indices of Dry Cargo ships**

As could be expected and despite the significant scatter of data, larger ships tend to have increased attained indices, Fig.1.
The distribution of the non-weighted Ai-values per draught shows that, in general, the Attained Index of each draught increases when the draught decreases. This trend is clear for the entire set of investigated Dry Cargo Ships. Fig.2 presents as an example the non-weighted Attained indices of Dry Cargo Bulk Carriers [DCBC] for the three calculated loading conditions, with respect to the HARDER proposal.

In particular, the contribution of the attained index at subdivision draught was investigated in dependence on ship’s size and subtype concluding the following:

- The larger the ship size the greater the achieved attained index at subdivision draft for the following subtypes: Dry Cargo Bulk Carriers [DCBC], Dry Cargo Container Ships [DCCS], General Cargo ships [GC], Dry Cargo Ro-Ro & Car Carriers [DCRR &CC].
- An almost constant attained index and independent of ship size was observed for the following subtypes: Other Bulk Carriers [OBC] and OTHER ships [OTH].
- Alarming: the attained index at subdivision draught for the smaller dry cargo ships (DCBCs and others) disposes values in the range of 0.2, Fig.2.

Attained Indices of DCRR & CC

This ship subtype appears to have, in general, significantly reduced attained indices according to the new probabilistic proposals in comparison to that of the existing regulation of SOLAS B-1. The new attained indices of some ships are below 0.4, regardless ship’s size and new probabilistic assessment concept, Fig.5.

Thus, considering that the noted low attained indices are common feature of both new assessment concepts (SLF42 and HARDER), the observed differences were primarily due to:

- The change of cargo permeability from the constant value of 0.70 in SOLAS B-1 to 0.90-0.95 depending on the draught at the new proposals.
- The change of v-factor has had the effect that the relatively (vertically) higher damages resulted to larger contributions to the attained index in comparison to SOLAS B-1.

In addition, though other dry cargo ship types appear to have high survivability and robustness of results at the lightest draught (almost the maximum achievable A-values in the range of 0.90-1.00), the DCRR&CC ship subtypes behave clearly differently, namely they dispose low A-values at smaller draughts, Fig.3. This could be explained by the fact that at smaller draughts, when considering the higher freeboard of at least some of these ships, for a number of damage cases the angle of heel at which the watertight deck reaches the water is comparatively large.

Also, it is notable that some Car Carriers showed significantly higher attained indices according to the new proposals, in contrary to the general behavior of the particular cargo ship subtype. This is attributed to the fact that these ships dispose by design increased watertight integrity above the bulkhead deck. The watertightness of the deck above the bulkhead deck as well as the position of this deck is a very crucial parameter for the attained indices of this subtype of cargo ships.

Evaluation of Required Indices for Dry Cargo ships

The Dry Cargo ships were first analyzed as one common category, although they comprise a great variety of ship subtypes with different inherent damage stability characteristics. Fig.4 presents the resulting Required Subdivision Indices of SLF42 and HARDER proposal, as well as the existing required standard by SOLAS B-1.

From the analysis, it was evident that the Dry Cargo Ro-Ro & Car Carriers [DCRR & CC] is the type of ship that appears mostly affected by both proposals in the way that the calculated Attained Subdivision Indices are clearly below of those of other dry cargo ships of comparable length, Fig.5.

Dry Cargo Ships, R-Indices [SLF42 & HARDER]

Dry Cargo Ships, R-Index of SLF42, HARDER and SOLAS B-1

Dry Cargo Ships, exculded ‘DCRR & CC’ ships
Fig.5 Final R-Index, HARDER proposal
Considering that the main target of the harmonization process is the equivalence of new and existing damage stability rules and the evident peculiarities of the “DRCC & CC” ships, these ships were separated from the overall sample of Dry Cargo Ships and the analysis was repeated. Fig.5 presents the resulting Required Subdivision Index of the HARDER proposal, as presented at IMO SLF46, as well as the existing required standard by SOLAS B-1.

Impact on design, comments on Required Indices per cargo ship subtype.
The Required Subdivision Index, R, was determined to be applicable to all Dry Cargo ships in terms of one common unified level of safety for the particular basic ship type.

Required indices were also determined, separately, for each cargo ship subtype (e.g. RTnew-DCBC: required index based on the sample of DCBC only) for both proposals and compared with the new general required subdivision index, Rnew, in order to have a better insight into the impact on the designs of each ship subtype, in case of adoption of the new general requirement.

Both proposals gave similar qualitative conclusions. The herein presented results are based on the calculations of the final HARDER proposal.

Dry Cargo Bulk Carriers & Other Bulk Carriers, Fig.6
- The required level of the unified type [RTnew-DCBC & OBC] is above the general R-Index [Rnew-HARDER] especially for ships with L<210m.
- DCBC have different behavior when they are compared with OBC.
- Requirement of DCBC ships [RTnew-DCBC] is slightly below the general requirement [Rnew-HARDER]. Thus, it is presumed that DCBC ships will not have major compliance difficulties in case of an approved Rnew-HARDER. Special notice should be given to the relatively small ships, as they might encounter increased difficulties.
- OBC ships of L<210 have relatively very high indices.

Dry Cargo Container Ships
The requirement per type [RTnew-DCCS ships] is almost at the same as the general requirement [Rnew-HARDER]. It is presumed that DCSS ships will not have major difficulties regarding the compliance with the general requirements of Dry Cargo ships. Some compliance problems could be identified for the large DCCS, namely for length greater than about 280m.

General Cargo Ships, Fig.7
GC ships of L<120m might have some difficulties of compliance with the particular general requirement. The smaller the ship, the greater the problem, as shown in Fig.7, according to the HARDER proposal.

Dry Cargo Ro-Ro & Car Carriers, Fig.8
As it was already stated, this is the only ship type that will be significantly affected by the new probabilistic concept in the way that some existing designs are expected to face major problems with their compliance with the new levels. Actually the design philosophy of these ships should be changed, in case of adoption of the proposed R Index requirement, ensuring increased watertightness of decks/spaces well above waterline.

The concept of safety equivalence between the existing and proposed probabilistic framework is clearly not kept for this particular ship subtype, when a unified dry cargo ships R-standard is accepted, as reference. It appears, however, that the majority of IMO-SLF delegations supports a unified standard for all types of dry cargo ships (see, also, re-affirmation by MSC78, 2004); therefore the above observations should be considered in future planning of the shipbuilding and shipping industry.

OTHER ships
OTH ships of L>150m might have minor difficulties with compliance with the particular general requirement.

The SLF 47 study results (status, September 2004)
The study was based on research conducted in the framework of IMO InterSessional Corresponding Group
[ISCG], where the Ship Design Laboratory of the National Technical University of Athens undertook the evaluation of data and the preparation of the proposal for the Required Index.

**SLF47 proposal, different p-factor**

A reconsideration of the damage statistics used in the HARDER project led the SLF47-ISCG committee to decide on limiting the absolute maximum damage length to 60m along with the appropriate adjustments to the damage length distribution. The particular limitation led to a slightly modified \( p \)-factor as well as \( r \)-factor, compared to the SLF46 damage length formulation [HARDER proposal].

In addition, for cargo ships other than ro-ro’s, the “s” factor did not change from that used in the HARDER project sample ship calculations (SLF46). For ro-ro cargo ships the SEM formula was adjusted slightly and a new FB-factor was introduced for consideration as a simple alternative to the SEM method.

As the impact of the particular change was not expected to be that significant, it was considered not absolutely necessary (though desired) for the deduction of the Required Subdivision Index according to the SLF47 proposal, to request the repeat of the calculations for the entire sampling plan of Dry Cargo Ships, considered in the 1ST study (HARDER-SLF46). Finally, calculations were provided for 20 Dry Cargo ships by various IMO-ISCG-SLF47 members.

**SLF47 proposal, Attained Indices**

Fig.9 shows the attained indices of the latest SLF47 proposal and those derived by the 1ST study (HARDER proposal- SLF46 submission).

Fig.9 Attained Index vs. ship size, 1ST & 2ND study

Fig.10 presents the differences [%] of the global Attained Indices according to the SLF47 compared to the indices based on the HARDER proposal (SLF46), sorted in ascending order of ship size.

**SLF47 proposal, Required Index**

Fig.11 presents the resulting R-Index formulae for dry cargo ships according to various probabilistic concepts, namely SLF47, SLF46-HARDER and SOLAS B-1.

Focusing on the SLF47 cargo ships’ sample, it is noted that only 1 vessel of length below 100m was studied, resulting to a very low attained index. For that reason and also because of the non-representative sample for ships with length below 100m, it was proposed during SLF47 to adopt a small revision of the initially proposed new Required Index for ships of length 80-100m, namely to follow mathematically, in the particular size area, the provisions of SOLAS B-1, Fig.11.

The differences of R-SLF47 as a percentage to the corresponding derived by HARDER proposal and SOLAS B-1 are shown in Fig.12.

**SLF47 proposal, minimum A-values**

In order to ensure a more realistic survivability at all draughts and to safeguard possible design vulnerability at the larger ones, especially at the subdivision draught, a new

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Fig.10 Percentage of differences between the new SLF47 and the HARDER global Attained Indices

It is noted that for ships in the length range of about 135-220m the A differences are negligible (increase of values by up to +1.6%). The differences for ships well over 220m are slightly larger (still less than +4%). For small ships of length less than 135m the differences are significant and non-consistent. They range between +6% and -7%. An absolute decrease of the attained index was noted for 3 small ships.

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Fig.11 R-Indices SLF 47 and the SLF 46

The differences of R-SLF47 as a percentage to the corresponding derived by HARDER proposal and SOLAS B-1 are shown in Fig.12.
concept of minimum Attained indices per draught was adopted by SLF47, as follows:

\[ A_{\text{PARTIAL INDEX}} \geq k R, \quad k=0.5 \]

The value of above k-factor resulted as the value of one standard deviation below the average value of \( A_{\text{SUBDIVISION}}/A \) of ships in question (SLF47/3/2 (2004)).

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 fulfil the R-Index, though having very low attained index at subdivision draught.

**SLF47 proposal, Impact on design**

With respect to the impact on the design of new cargo ships, the conclusions are similar to those derived from the 1\(^{\text{ST}}\) study, outlined before, taking however also under consideration the additional minimum A per draught requirements.

**PASSENGER SHIPS**

**The HARDER-SLF 46 study results (status end of 2003)**

**Passenger Sample ships**

In total, 37 ships were submitted by HARDER and IMO-ISCG-SLF46 partners and analysed by NTUA-SDL for the evaluation of the Required Subdivision Index, from which the 19 were Passenger Ro-Ro ships [PRR] and the rest was Passenger Cruise Liner Ships and Passenger ships [PCLS/PASS]. In terms of representativeness, the sample reflects fairly well the worldwide passenger fleet per ship category and size.

**Passenger ships, Attained Indices**

Though Dry Cargo ships display a consistent trend of Attained indices with respect to the size and subtype, meaning that the larger the ship the smaller the associated risk expressed by (1-A) value, in contrary, calculated Attained indices values 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), Fig.13.

In particular, the desired trend “the larger the ship with higher number of persons on board the greater the survivability” was not achieved by both assessment proposals (SLF 42 and HARDER). Similar observations were also noted in the analysis per ship subtype (PRR or PCLS/PASS) and size.

Consequently, this appeared to be a general problem of passenger ships, independently of subtype, and can be attributed to the probabilistic damage stability framework and in particular to the assumed damage extents (damage length and penetration) as well as the concept of calculation of the passenger heeling moment. More specifically:

- In contrary to the dry cargo ships, ‘equivalence of safety’ for the passenger ships requires a direct comparison between the currently in force deterministic damage stability approach (SOLAS 90) with a 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, SOLAS 90, concept, are limited to max two compartments (max. damage length 3m + 3% of ship length, \( \text{but not more than 11m} \) 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.

- The proposed concept of calculating the passenger heeling moment acc. to HARDER appears very conservative (calculation by shifting the TCG) and consequently the impact on the large ships with large number of passengers is very significant.

- Regarding the PRR ships, a more important reason for the reduction of the A-Index of larger ships is due to the effect of flooding of lower holds. The reduction of A due to the passenger heeling moment effects is relatively small, compared to the cruiser ships, because the number of passengers is relatively small compared to the cruisers of the same size.

**Passenger ships, Non-weighted Attained Indices**

Passenger ships have in this respect clearly a different behavior in comparison to the Dry Cargo Ships. The achieved Attained Indices at each draught are of the same order regardless size. Fig.14 shows the non-weighted attained indices, based on HARDER proposal, per draught for the PCLS/PASS ships.

Fig.14 PCLS/PASS Non-weighted A-Indices, HARDER

But as it is stated before, the larger ships tend to have reduced attained indices compared to the smaller ones. This is a typical behavior regardless the examined draught as well.

**Procedure to overcome the size trend deficiency**
The ‘equivalence of safety’, among others, embodies the basic principle that larger ships should dispose higher survivability than the smaller ones and also, in case of carriage of passengers, they should be exposed to smaller risks in case of emergency. This is an adopted principle of IMO and also expresses the way ahead of the maritime safety culture in general (see, also, re-affirmation of this principle for passenger ships by MSC78, May 2004).

Several investigations were done in order to overcome the addressed problem by reasonably revising the sample data and proceeding with the evaluation of the new damage stability requirements of Passenger ships.

- Firstly, it was assumed that the Risk of Passenger ships in case of zero persons onboard should be less or at least equal to the corresponding one derived for the cargo ships of equal length. Note, that a comparison with the cargo ships data indicated that a small number of passenger ships did have (1-R) values, thus risk values, greater than the corresponding ones for the cargo ships (based only on length). However, even following this procedure, thus excluding some passenger ships from the sample, no significant improvement in the relation between risk and ship size for the passengers could be noted.

- Calculating separately the risks by ship type (PRR and PCLS) and size (e.g. PRR/PCLS small, medium, large) and extracting selectively ships appearing “too safe” and/or “unsafe”, did also not significantly improve the resulting overall sample’s behavior.

- Next, a different categorization of the sample according to Persons on Board was attempted \([N<400, N=400-1500, N>1500]\). The risks were calculated for each category separately and some ships were extracted, but this again did not significantly improve the resulting overall sample’s behavior.

- Finally, a new methodology was proposed by the authors for the evaluation of the required Subdivision Index, namely a revision of the sample based on the definition of so-called Risk boundary-limiting lines that were systematically varied. Ships that were outside of the set boundary regions were extracted from the sample (SLF46/3/3 (2003)). The results of this approach are given next. The significant point of this procedure is to define meaningful risk boundaries (likewise the definition of an ALARP region). This procedure appears to finally give satisfactory results.

**Definition of boundary curves - ALARP region**

The adopted methodology for defining the required subdivision index, as given below, is based on the following working assumptions:

1. The required index sets a ship’s standard for the probability of surviving, in case of collision, a series of predefined damages, thus it is a measure of relative safety. Therefore larger ships with relatively large number of persons on board should have a lesser risk to not survive in case of collision. Additionally, this survival standard should be in general equivalence with the currently in-force deterministic SOLAS regulation.

2. Factor C2 (in the general formula of \(R\)) expresses the relative importance of the carried persons and ship size. A set of different C2-values was examined in order to find the best correlation with respect to the associated risk and the resulting required index is given for each case.

3. The high-end studied values of C2, namely C2=4 obviously tend to give a negligible effect of ship size. This corresponds in principle to a cost-benefit risk concept that the possible loss of a large ship (in terms of cost for the lost hardware) is small in comparison to the associated societal risk of loss of a large number of human lives.

4. The attained indices of the calculated ships are based on the survival factor, s, expressed herein with the GZ curve requirements. The majority of the original HARDER-SLF46 sample did not contain additional effects like the heeling moments effect due to crowding and also for none ship intermediate stages were calculated. Consequently, in terms of ship size, the attained indices of Passenger ships could be directly compared with the corresponding ones of dry cargo ships and Passenger ships with lower A-values than those of cargo ships, were anyway extracted from the sample.

**Application of the ALARP boundary method**

The associated risk, in terms of the probabilistic concept, could be expressed by the value of \((1-A)\). The Passenger ship size is presented by the value of \((L+C2N)\), taking into account that the relative importance between length and Persons On Board, C2-value, varies parametrically for a series of predefined values.

- The assumed risk boundary lines defined an ALARP area, on the basis of which a revision of the ships sample was conducted. The definition of acceptable risk values, on y-axis, are coming from the variation of Dry Cargo ships’ requirements (\(A = 0.3 \pm 0.7\)) considering also a small margin. The values of limited ship size to be included in the area of ALARP region (zero risk) corresponds, practically, about to the \(N=2500 \div 5000\). Therefore, the boundary curves were defined according to the next table.

<table>
<thead>
<tr>
<th>Lower Boundary</th>
<th>Upper Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L+C2N)</td>
<td>(L+C2N)</td>
</tr>
<tr>
<td>((1-A))</td>
<td>((1-A))</td>
</tr>
<tr>
<td>0.25</td>
<td>0.75</td>
</tr>
<tr>
<td>10000</td>
<td>20000</td>
</tr>
</tbody>
</table>

- For each investigated C2-values, namely C2 = \(\frac{1}{4}, \frac{1}{2}, 1, 2\) and 4, the sample was revised according to the ALARP Risk Boundary Lines. Ships that are out of the ALARP region are extracted from the sample as “over-satisfactorily safe” (below the lower boundary) and as “non-satisfactorily safe” (above the upper boundary). Ships that are inside the ALARP region are considered “As Low As Reasonable Practicable Safe”.

Fig.15 presents the ALARP Boundary Lines and the corresponding original and revised sample for C2=4.
Fig. 15 ALARP Boundary Lines
The criterion of selection the C2-value and the corresponding revised sample that was used in the evaluation of Required Subdivision Index was based on the best regression fitting (regression R-squared) of the associated risk (1-A) with the ship size (L+C2N).

For the analysis, the best linear fitting resulted from C2=4. The particular sample ships were also compared with the requirement of Dry Cargo Ships, in terms of length, in order to ensure that all passenger ships would have indices greater than Dry Cargo Ships.

Fig. 16 shows the associated risk vs. ship size as resulting by the above methodology that the evaluation of Required Subdivision Index was based on.

Fig. 16 HARDER proposal, Associated risk vs. ship size

Fig. 17 shows the resulting Required Subdivision Index by the HARDER proposal as well as the corresponding derived by the Resolution A.265.

Fig. 17 Required Subdivision Index, HARDER & A.265

Conclusions on the HARDER-SLF46 Study Results – Impact on Design

- Large passenger ships (N over abt. 2500) is the type of ship that appears mostly affected by both the HARDER and SLF42 R-Index proposals, as calculated A-values for a notable number of ships acc. to HARDER or SLF42 are significantly lower than for smaller passenger ships and in some cases even lower than dry cargo ships of similar size.

- “Equivalence” of both the HARDER and SLF42 proposals to SOLAS 90 for these ships would mean significantly lower R-Index values.
- It is noted, however, that if the R-Index value is accepted as a global indicator of ‘relative safety level’, that clearly the large passenger ships built acc. to SOLAS 90 appear to dispose today a notably lower ‘relative safety level’ compared to other ship types.
- In difference to the cargo ships, built under the probabilistic SOLAS B-1 concept, the direct comparison of the deterministic SOLAS 90 standard with the probabilistic HARDER and SLF42 concepts raises some fundamental questions regarding the sufficiency of the SOLAS 90 two compartment standard for large passenger ships and the importance of the SOLAS 90 damage length to the compartment length and the required ship’s subdivision standard for large passenger ships.
- Nevertheless, it appeared necessary to check the HARDER and SLF46 p-values for large ships, as the associated absolute damage lengths might have been unrealistically high, especially for the ships at the upper size boundaries (close to 300m of length).
- A separate analysis conducted for a sample of large passenger ships, originally built under the SOLAS 90, 2 compartment standard, showed the following:
  - Large passenger ships with relative large number of persons on board appear to be requested to dispose an equivalent ‘deterministic 3+ compartment standard’ to achieve the derived HARDER R Index requirements.
  - Large passenger ships with relatively small number of persons on board should have an equivalent “deterministic 2+ compartment standard’’ to achieve the derived HARDER R Index requirements.
  - The global Attained Index of large passenger ships with relatively large numbers of persons on board is significantly decreased due to the additional heeling moment considerations. The major reduction results from the 2-adjacent damage scenarios.
- The concept of calculating the heeling moment effects was considered conservative and needed to be reconsidered.

The SLF 47 study results (status, end of September 2004)

Description of SLF47 proposal
The basic differences of IMO-SLF47 proposal in comparison to the SLF46 proposal (HARDER proposal) are briefly described below:
1. The reconsideration of the damage statistics led the SLF47-ISCG to decide on limiting the absolute maximum damage length to 60m along with the appropriate adjustments to the damage length distribution. The particular limitation led to slightly modified p-factor as well as r-factor, compared to the SLF46 damage extent formulation.
2. The effect of passenger heeling moment was modified in order to better reflect the currently in-force deterministic requirements of this concept (SOLAS 90).
3. The introduction of intermediate stages of flooding was likewise introduced in equivalence to SOLAS 90 requirements.
4. Modifications on the factors related to the SEM-method (for the water on deck effect) were considered.
5. Introduction and evaluation of a new freeboard factor (FB-factor) regarding an alternative approach to the effect of water on deck.

Note that the revised SEM method as well as the newly introduced FB-factor, were separately evaluated in a different set of calculations and not additionally to the other effects.

**SLF47, Passenger sample of ships**

Calculations were provided for 32 passenger ships. With respect to the ship size, the entire length range of interest as well as the range of persons on board of the sample can be considered satisfactory.

**SLF47, Attained Indices**

The calculated attained indices (raw data) vs. the ship size and the number of persons on board did not show (as in the SLF 46/HARDER study) a satisfactory behavior (large spread and downward trend with increasing ship size), as necessary for the satisfactory formulation of the required index of passenger ships.

**SLF47, Methodology for the definition of Required Index**

The same methodology (ALARP boundaries concept) was adopted, as in the SLF46/HARDER study, in order to evaluate the new probabilistic damage stability requirement, R-Index, with the following differences:

1. A larger variation of C2-values was investigated, namely \( C2 = \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, 1, 2, 2.5, 3, 3.5 \) and 4.

2. The analyzed attained indices were considering the effects of heeling moment and intermediated stages of flooding, \( A_{1, \text{heel, int}} \), thus they contained consistently all effects that are also included in the currently in-force damage stability SOLAS 90 regulations.

**SLF47, Required Index**

Two different criteria were used for the evaluation of the Required Subdivision Index and consequently two different standards were proposed.

- With respect to the correlation of results of calculated associated risk with the \( (L+C2N) \) value, the best regression analysis fitting appears for \( C2=3.5 \) (highest regression \( R^2 \)). The relevant coefficients of the formula of Required Index are given in the Fig.18.

- 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 C2-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 sample. The least number of extracted ships is met in 2 cases:
  - For \( C2=2 \), seven ships were extracted from the entire sample.
  - For \( C2=2.5 \), seven ships were extracted from the entire sample.

For the above two cases, the best regression fitting is given for \( C2=2.5 \), consequently the resulting required index is shown in Fig.19 along with the Alternative 1 and R-A.265.

**SLF47 proposal, minimum A-values**

In order to ensure a more realistic survivability at all draughts and to safeguard against possible design vulnerability at the larger ones, especially at the subdivision draft, minimum Attained indices were proposed and adopted as follows:

\[
A_{\text{PARTIAL INDEX}} \geq k \cdot R, \quad k=0.9
\]

In contrary to the Dry Cargo ships, the particular requirement is considered less stringent when applied on top of the general R-Index requirement, due to the fact that Passenger ships dispose inherently by design quite similar attained indices at every draught and consequently in case they fulfil the general R-Index, no further impact on ship design is expected by the draught minimum requirements.

**SLF47 proposal, Impact on design**

With respect to the impact on the design of new Passenger ships, the conclusions are similar to those derived from the first study, outlined before. The only exception is the minimum A per draught requirements that are assumed to have a negligible effect.

**OVERALL CONCLUSIONS**

The Dry Cargo ships SLF47 proposal approved in September 2004 and forwarded to MSC79 on the way to the SOLAS Convention in 2005 is commented next. Fig. 11 shows the approved Required Subdivision Index, R-SLF47 along with that derived from the HARDER-SLF 46 study and the existing SOLAS B-1 requirement.

The following can be concluded:

- The proposed R Index formulation resulting from the ISCG-SLF47 sample ships analysis and relevant formulations for the probabilistic factors leads, compared to the SLF 46-HARDER proposal, to higher
values of R, practically for all ships over about 130m. The percentage difference reaches a maximum of about 8% for the larger ships over 300m length, Fig.12.

- For ships of length less than about 130m the values of R-index are decreased, reaching a minimum of about -20% at 80m length.
- Considering the ‘equivalency’ of the investigated various probabilistic concepts (A/R to remain about the same), the results suggest that calculated A-values according to the ISCG-SLF 47 proposal, tend to be higher than the corresponding ones acc. to SLF 46-HARDER for ships over about 130m and lower for ships of length below about 130m.
- Independently of the overall index requirements, the minimum A per draught requirements might have a significant impact on some small cargo ship types, like the handysize Bulk Carriers, Feeder Container ships and also the small General Cargo ships, as these ships appear to have today by design very low attained indices at subdivision draught.

The passenger ships SLF47 proposal is commented next. Fig. 20 shows the approved Required Subdivision Index, R-SLF47 (reference to the Alternative 2) along with that derived from the HARDER/SLF 46 study and the existing optional to SOLAS 90 Resolution A.265 requirement.

The following can be concluded:

- From both studies, it was indicated that some large Passenger ships, PRR & cruisers, might encounter difficulties in achieving the proposed Required Indices, if their designs remain unchanged. It is noted, however, that these designs were optimized with respect to the deterministic SOLAS 90 requirements. Nevertheless, it was observed that some sample ships of size at the high-end did pass the proposed R Index requirements.
- Due to the fact, that this regulation, if adopted by the SOLAS Convention, is not expected to be applied to the existing fleet, it can be anticipated that new designs, resulting from optimization procedures on the basis of the new probabilistic concept, will not face major difficulties for compliance with the new regulations, at satisfactory efficiency.

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