# Probabilistic damage stability of small passenger ships

S.L. van der Voort, *Rotterdam Mainport Institute, Department of Maritime Engineering, The Netherlands*
s.l.van.der.voort@hr.nl

M.K.S. Krol*, Rotterdam Mainport Institute, Department of Maritime Engineering, The Netherlands*

F.M. de Wit, *Rotterdam Mainport Institute, Department of Maritime Engineering, The Netherlands*

**ABSTRACT**

The IMO has set a new standard for the probabilistic damage stability requirements for passenger ships. One of the major changes is a new formula for the required subdivision index R which will result in a higher required subdivision index for new passenger ships. Whether very small passenger ships can meet this requirement was never investigated. This study aims to give a general indication of the possibilities for small passenger ships with a length of approximately 40 meters to meet the new required subdivision index. The scope of the study is limited to adjustments to the openings and changes of the internal subdivision. External hull form, displacement and GM’ were not varied and the cost effectiveness of the changes were not investigated.

**Keywords:** *Probabilistic damage stability, very small passenger ships, SOLAS, required subdivision index R, attained subdivision index A, internal subdivision, weathertight openings.*

## 1. INTRODUCTION

The IMO Maritime Safety Committee (MSC) agreed in her 98th session (IMO, Report of the Maritime Safety Commission on its ninety-eighth session, 2017) on a revision of damage stability requirements. Part of this revision is a new method for calculating the required subdivision index for passenger ships. In the current SOLAS the required subdivision index for passenger ships depends on the length of the ship, the number of passengers and the lifeboat capacity. As of January 2020, the required subdivision index R will depend only on the number of passengers the ship is designed to carry. The formulation of R was extensively discussed in the IMO subcommittee Ship Design and Construction (SDC). In particular for smaller passenger ships widely different views were expressed as to what extent raising the required subdivision index would be a cost effective measure to improve the safety of these ships. Where raising the R value for passenger ships carrying 400 passengers or more has been justified by several studies and publications, the possibilities for smaller ships are hardly investigated. In this paper two small passenger ships with a length of approximately 40 meters are modelled with various internal subdivisions to investigate to what extent compliance with the new R value is possible for very small passenger ships.

## 2. INTERNATIONAL LEGAL CONTEXT

As part of the IMO working program, the damage stability requirements in SOLAS Chapter II-1 have been revised by the SDC subcommittee during several sessions. Part of this revision was the establishment of a formule for the required subdivision index R as defined in SOLAS CH II-1, regulation 6.

The SDC sub-committee vividly discussed various formulas for the required subdivision index, based on extensive feasibility studies into values for R, including detailed cost analyses for RoRo passenger ships and cruise vessels (GOALDS Consortium, 2012), (Japan, 2013). Where these studies focused on the effects of raising R for small passenger ships, it is observed that the lower limit of the ships studied lies at 400 passengers (Danish Maritime Authority, 2015) (DNV GL AS Maritime, 2015) (Japan, 2015). Based on the proposals made by the SDC sub-committee, the Maritime Safety Committee of the IMO agreed to set the value for R at 0.722 for ships carrying 12 up to 400 persons on board (IMO, Report of the Maritime Safety Commission on its ninety-eighth session, 2017). For passenger ships designed to carry more than 400 persons the revised SOLAS contains formulas in Chapter II-1 regulation 6 to calculate the value of R.

For ships engaged in international voyages the 400 persons limit may seem reasonable as passenger ships with less than 400 passengers are normally not engaged in international voyages. However, in this respect two things should be observed. The first is that the SOLAS passenger ship requirements are, by definition, applicable to all ships carrying 12 or more passengers. It would be illogical to set a requirement that cannot reasonably be met by the all ships it applies to. The other observation is that (inter)national legislators tend to harmonize different sets of regulations, for which SOLAS requirements are often used as basis. For passenger ships with a length of 24 meter or more in national EU trade, the EU directive 2009/45 (EC, 2009) is applicable. Although the current damage stability requirements of EU/2009/45 are identical to the old, deterministic, SOLAS requirements, it is expected that the directive will be aligned with the new probabilistic SOLAS requirements as soon as the directive is revised.

## 3. SCOPE OF THIS PAPER

In order to investigate to what extent smaller passenger ships can be subdivided to meet the SOLAS 2020 subdivision requirements, various subdivisions were made for two different hull forms. For each subdivision the attained subdivision index was calculated and compared with the required subdivision index.

For this study the attained subdivision index A was calculated according SOLAS CH II-1; part B-1. Consequently the calculations were made for the three draughts prescribed in regulation 6 and 7, and permeabilities and openings were modelled in accordance with the specific requirements. A compliance check with SOLAS Ch. II-1 regulation 6.1 was made for each of the three partial indices and with regulation 7.1 for the weighted summation of A over the three draughts.

### *Limitations and boundaries of the scope*

The aim of this study is to determine whether small passenger ships can meet the SOLAS probabilistic damage stability index R. Other damage stability requirements from SOLAS CH II-1, with a more deterministic nature, must also be met. These requirements include, but are not limited to SOLAS CH II-1 regulation 8 (Special requirements concerning passenger ship stability) and regulation 9 (Double bottoms in passenger ships and cargo ships other than tankers). Even though it is known that the deterministic requirements may, in many cases, be limiting for passenger ship damage stability, they are not included in this study.

For this study, modifications for improving the attained subdivision index are limited to the openings and internal subdivision. External geometry, draughts, GM' and trims were not varied. The cost effectiveness of the changes to the model were not investigated.

## 4. SHIP DESIGNS

For the purpose of this paper, two hull forms were created in the stability calculation program PIAS[1]. PIAS is a calculation tool for hydrostatic calculations and has, amongst others, modules for intact and probabilistic stability calculations.

### *Design of Model A*

The first hull is based on an existing, Netherlands flagged, sailing passenger ship2, certified under the EU directive 2009/45. The external geometry, draughts, GM and internal watertight decks and bulkheads provide a subdivision standard complying with the regulations of EU 2009/45 and the SOLAS (1990) deterministic 1-compartment subdivision standard. An overview of the external hull form of model A is presented in Figure 1. The displacement and position of the center of gravity are taken from the original ship. Draughts, trims and GM' values are presented in Table 1.

The internal subdivision of model A-0 is represented in Figure 2.

**Table 1: Subdivision loading conditions Model A.**

| Subdivision loading condition | Draught [m] | Trim [m] | GM' [m] |
|---|---|---|---|
| Light | 2.000 | -1.000 | 1.20 |
| Partial | 2.138 | 0.000 | 1.10 |
| Deepest | 2.230 | 0.000 | 1.10 |

[1] PIAS is a naval architecture design software package designed by SARC B.V. based in The Netherlands. PIAS can be used for design and stability purposes. PIAS is accepted by major classification societies and statutory authorities.

[2] For reasons of privacy the name and details of the ship are not disclosed.

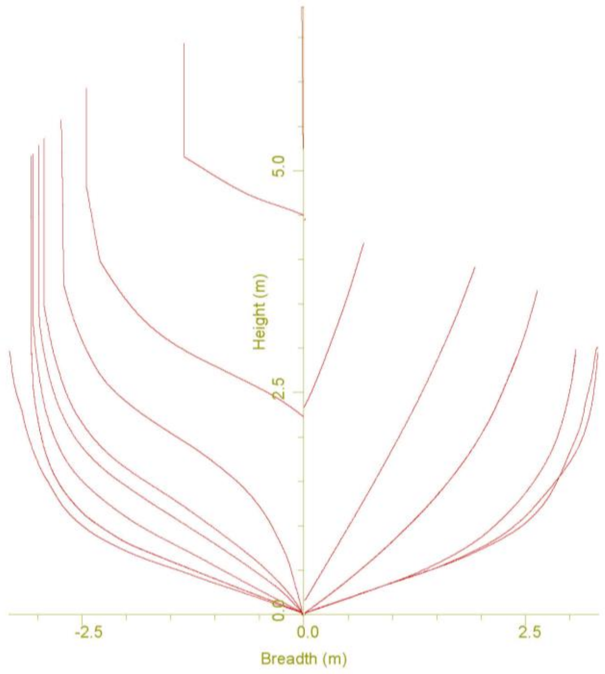


**Figure 1: Frames fore and aft ship of Model A.**

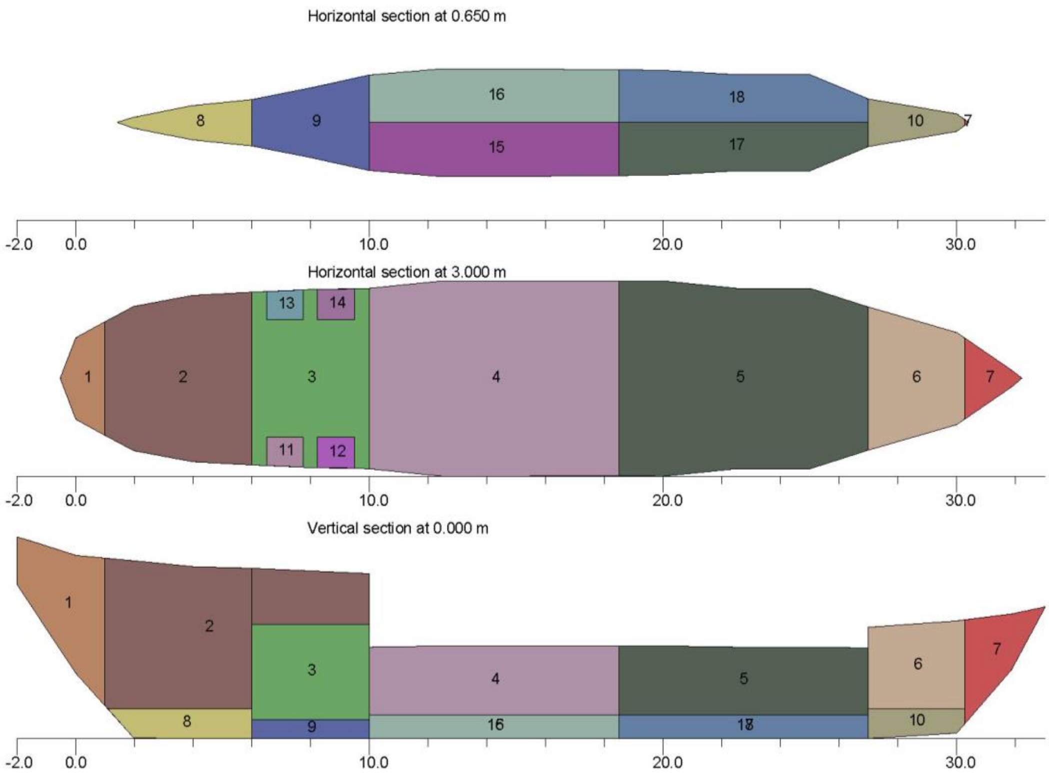


**Figure 2: Internal subdivision of Model A-0.**

### *Design of Model B*

The second hull is based on the external geometry of a fishing vessel. The initial internal subdivision was chosen to provide ample subdivision for compliance with the 1 compartment standard. Hull form and subdivision of Model B are presented in Figure 3 and Figure 4. The displacement and position of the center of gravity are based on the original fishing vessel, whereby the weight of fishing gear and fish in the holds is replaced with a weight for passengers. Draughts, trims and GM' values are presented in Table 2.

**Table 2: Subdivision loading conditions of Model B.**

| Subdivision loading condition | Draught [m] | Trim [m] | GM' [m] |
|---|---|---|---|
| Light | 2.700 | -1.000 | 0.609 |
| Partial | 2.940 | 0.000 | 0.503 |
| Deepest | 3.100 | 0.000 | 0.539 |

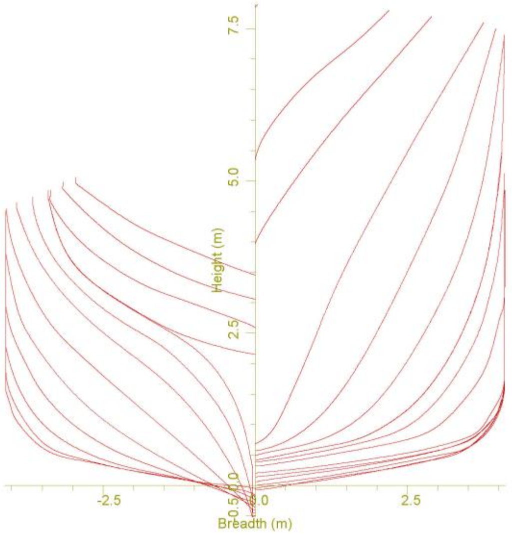


**Figure 3: Frames fore and aft ship of Model B.**

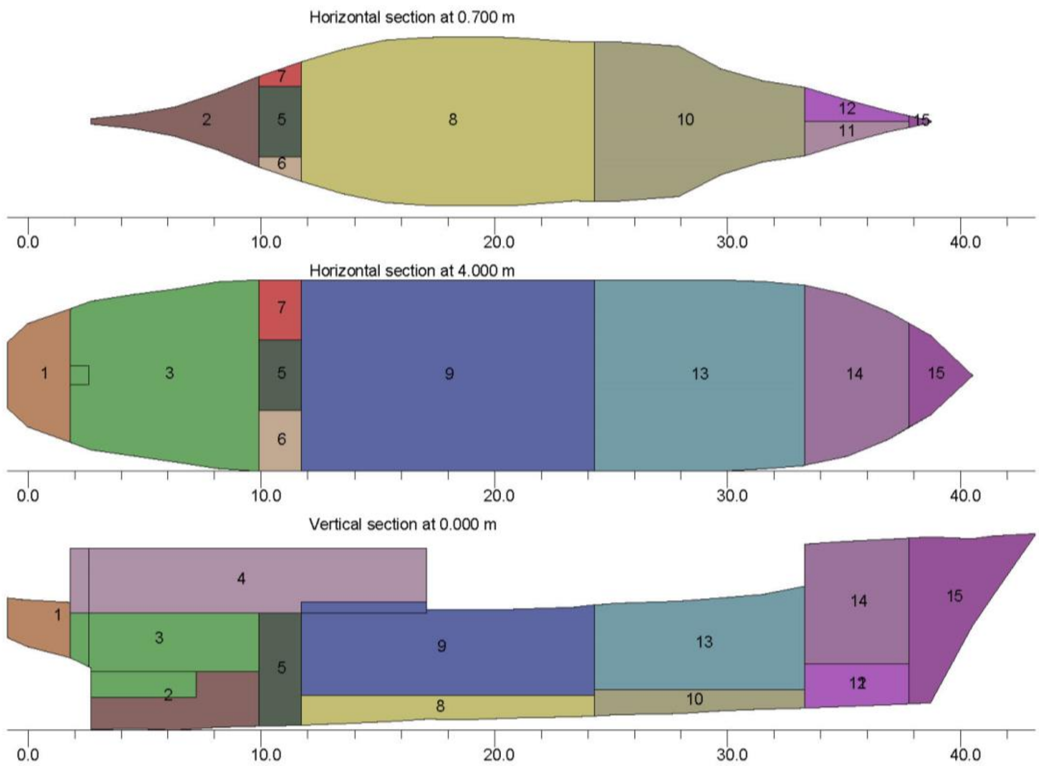


**Figure 4: Internal subdivision of Model B-0.**

## 5. MODIFICATIONS AND RESULTS MODEL A

### *Design changes*

In order to investigate possibilities of improving the attained subdivision index, five alterations of the openings and internal subdivision of model A were investigated:

A-1) Improved openings: openings are raised and/or moved towards the center line;

A-2) Improved tanks engine room: the existing tanks in the sides of the engine room are extended to form a continuous double hull;

A-3) Increased double bottom accommodation: the height of the double bottoms is enlarged;

A-4) Six tanks under two holds: the existing tank arrangement (two tanks under each hold) is changed. Two tanks are added. One starboard and one portside, both partially under the fore and aft hold;

A-5) The existing two tanks under each hold are subdivided into four tanks under each hold.

An overview of the subdivision of Model A-5 is presented in Figure 5. The design choices made in model A-1 up to A-5 are arbitrary which is unavoidable because it was not possible to investigate all possible changes within the scope of this study. A-1 was chosen as adjusting (de-aeration) openings has limited impact during the design stage but may improve the attained subdivision index considerably. The same applies to a certain extent to the changes in model A-2, creating a double hull. Fitting a continuous double hull will not be much more complicated than creating separate tanks. Raising the height of the double bottom in model A-3 will result in more room to construct and maintain the tanks. The height of the compartments above the tanks remains sufficient for the passenger accommodation areas. Model A-4 with six tanks in the double bottom under the two holds, is the first step in decreasing the volume of the individual double bottom tanks. The same applies to model A-5 with eight tanks under the two holds.

### *Attained subdivision indices*

The attained subdivision index of the original model A is relatively close to the required subdivision index. Normally only small design changes would be necessary to raise A sufficiently. For the purpose of this study more thorough design changes have also been tried, some of which resulted in a decrease of A. An overview of the attained indices is presented in Table 3. In this table, the attained subdivision index is the weighted sum of the three partial indices calculated in accordance with SOLAS CH II-2 regulation 7.1. The rightmost column (A/R) indicates to which extent the attained subdivision index meets the required subdivision index; each model with A/R > 1 is compliant.

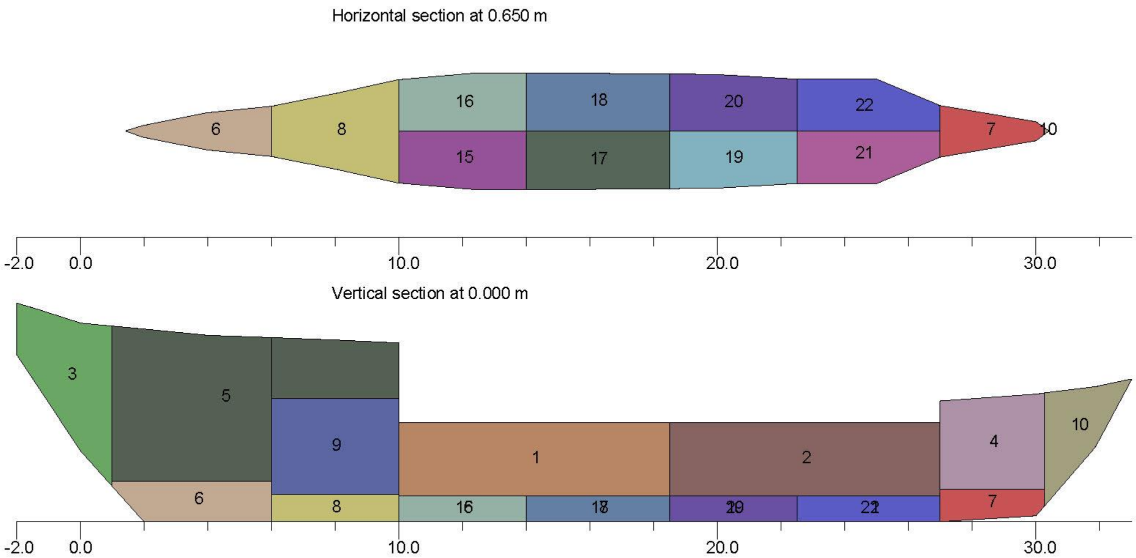


**Figure 5: Internal subdivision of Model A-5.**

**Table 3: Attained subdivision indices of Model A.**

| description | Damage cases | A | A/R |
|---|---|---|---|
| Model A-0 | 58 | 0.6899 | 0.96 |
| Model A-1 | 58 | 0.7602 | 1.05 |
| Model A-2 | 49 | 0.7623 | 1.06 |
| Model A-3 | 49 | 0.7627 | 1.06 |
| Model A-4 | 65 | 0.7041 | 0.98 |
| Model A-5 | 65 | 0.7630 | 1.06 |

For compliance with SOLAS regulation 6.1, the attained subdivision index of each partial draught shall be greater than 0.9 times R. Table 4 presents the results of the 6 different designs of model A. Here a ratio of A/0.9R above one indicates that the attained subdivision index for that specific draught complies with regulation 6.1. The results in Table 3 and 4 indicate that Models A-2, A-3 and A-5 comply with both regulation 6.1 and 7.1.

**Table 4: Attained partial subdivision indices of Model A.**

| description | $A_l/0.9R$ | $A_p/0.9R$ | $A_s/0.9R$ |
|---|---|---|---|
| Model A-0 | 1.22 | 1.05 | 0.99 |
| Model A-1 | 1.22 | 1.32 | 0.99 |
| Model A-2 | 1.24 | 1.24 | 1.07 |
| Model A-3 | 1.24 | 1.24 | 1.07 |
| Model A-4 | 1.24 | 1.12 | 0.97 |
| Model A-5 | 1.24 | 1.24 | 1.07 |

## 6. MODIFICATIONS AND RESULTS MODEL B

### *Design changes*

For model B, an internal subdivision complying with a 1-compartment was created. In order to investigate possibilities of improving the attained subdivision index, six alterations of the openings and internal subdivision of model B were investigated:

- B-1) The fuel tanks are relocated from transverse oriented tanks in front of the engine room to double hull side tanks in the engine room;
- B-2) Both single tanks under the holds are subdivided in six separate tanks; two SB, two PS and two center tanks;
- B-3) The SB and PS double bottom tanks under the accommodation holds are connected with a cross-flooding device;
- B-4) Both accommodation holds are fitted with side tanks in line with the double bottom tanks. In order to avoid large heel after damage, the side tanks are fitted with a cross over;
- B-5) The side tanks are only fitted in the aft hold;
- B-6) Only the aftermost two side tanks (One SB, one PS) are fitted in the aft accommodation.

An overview of the subdivision of Model B-6 is presented in Figure 6.

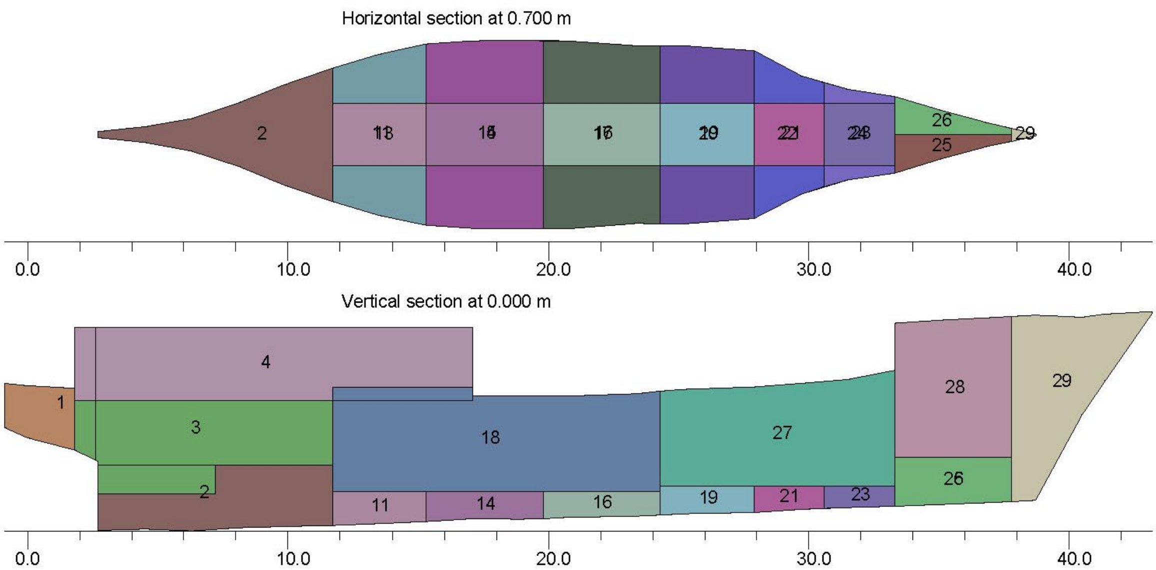


**Figure 6: Internal subdivision of Model B-6.**

For the same reasons as for model A the chosen subdivisions for model B are arbitrary. Moving the fuel tanks as proposed for model B-1 has serious impact on the design of piping and engine room lay out. Changes proposed in model B-2 and B-3 have a smaller impact as construction elements for the subdivision of tanks are already in place for structural integrity, which limits the design impact to piping and (watertight) welding. Design changes B-4, B-5 and B-6 do have more impact on the design, both in terms of construction weight as in terms of reduced available space for passengers.

### *Attained subdivision indices*

The original Model B-0 does not meet the required subdivision index. The index of all designs is presented in Table 5. It is obvious that adding a continuous double hull in the accommodation area in model B-4 has a large positive effect on the attained subdivision index. The results of Model B-3 show that a cross over between double bottom tanks has, for this ship, a negative impact on the attained subdivision index. Apparently the increase of volume of the combined compartments has a bigger influence on the stability in damaged condition than the reduction of heel. Table 4 shows that a partial double hull in one hold (model B-5) or even one third of the hold (model B-6) raises the attained subdivision index to a value above the required subdivision index.

**Table 5: Attained subdivision indices of Model B.**

| description | Damage cases | A | A/R |
|---|---|---|---|
| Model B-0 | 100 | 0.6071 | 0.84 |
| Model B-1 | 118 | 0.6096 | 0.84 |
| Model B-2 | 256 | 0.6824 | 0.95 |
| Model B-3 | 254 | 0.6656 | 0.92 |
| Model B-4 | 201 | 0.8789 | 1.22 |
| Model B-5 | 191 | 0.8688 | 1.20 |
| Model B-6 | 197 | 0.7587 | 1.05 |

Also for model B compliance with SOLAS regulation 6.1 was checked. The results of this check are presented in Table 6. These results indicated that Model B-4, B-5 and B-6 comply with both regulation 6.1 and 7.1.

**Table 6: Attained partial subdivision indices of Model B.**

| description | $A_l/0.9R$ | $A_p/0.9R$ | $A_s/0.9R$ |
|---|---|---|---|
| Model B-0 | 0.90 | 0.91 | 0.97 |
| Model B-1 | 0.87 | 0.86 | 1.05 |
| Model B-2 | 1.11 | 1.01 | 1.06 |
| Model B-3 | 1.13 | 0.92 | 1.08 |
| Model B-4 | 1.40 | 1.33 | 1.36 |
| Model B-5 | 1.34 | 1.35 | 1.33 |
| Model B-6 | 1.23 | 1.13 | 1.18 |

## 7. DISCUSSION

This study focussed on existing hull forms. As a consequence, only changes in the internal subdivision and deck openings have been investigated. When all parameters of the design could have been adjusted for improvement of the attained subdivision index, other solutions may also have been interesting to investigate. Following examples of such changes are indicative, and should not be considered as exhaustive:

- Increase of beam;
- Increase of depth;
- Increase of GM; (note: GM of the model A already is rather high as the design is a sailing ship)
- Increase of buoyant volume on deck such as forecastle, deckhouse, etc;
- External additions to the buoyant hull such as duck tails or sponsoons.

Another possibility, only taken into account to a limited extent in this study, is to investigate the effects of small changes of the position of bulkheads. Minor transverse shifts of longitudinal bulkheads may be very effective in reducing heel after damage. This may increase the survivability after damage, while the influence on the probability of that damage is relatively small. The same applies in principle to the longitudinal position of transverse bulkheads.

In a further study the effect of the proposed measures such as adding or replacing bulkheads, on the light ship weight and the position of the centre of gravity of the ship should be taken into account and the values of the light service draught, VCG' (or GM') should be adjusted accordingly

Both models presented in this study require more or less significant changes in the internal subdivision to meet the new R index. In other, more detailed studies (DNV GL AS Maritime, 2015), The life time costs of all suggested changes are calculated in order to validate whether the proposed improvements are cost effective. The determination of the costs of the proposed measures are beyond the scope of this study. It would be interesting to quantify costs and effects of these measures. However, the majority of the changes proposed are, from a structural point of view, rather limited. Repositioning a bulkhead in the first stages of the ship design hardly affect the final costs for building or operating a ship. With respect to more extensive changes such as adding a double hull, these do affect the building price significantly and should be carefully considered.

This study only focused on the required and attained subdivision index. Compliance with other revised requirements of SOLAS Chapter II-1 are outside the scope of this paper. It may be expected that other parts of the revised damage stability requirements such as the ban on open watertight doors at sea, have a significant impact on the design and operation of smaller passenger ships.

A second interesting topic for further research would be the whether the factor $s_i$[3] with a value of 1 does represent a sufficient probability of survival for small ships.

## 8. CONCLUSION

This study proves that it is possible to meet the new increased SOLAS probabilistic damage stability required subdivision index with small passenger ship designs. Whether the measures necessary for compliance are cost effective was not investigated. Some changes in the internal subdivision such as adding a double hull, will most certainly affect the costs of operation and construction. Others, such as raising openings, will probably have a smaller impact.

To meet the required subdivision index, the original designs had to be refined to a certain extent. For model A, the necessary adjustments affect the design to a limited extent. For model B, the necessary changes include the fitting of a double hull in the engine room and a partial double hull in the under deck passenger area. These measures have quite an impact on the design and would possibly not be cost effective.

Other likely effective design changes such as raising the GM' were not investigated in this study, but may prove to be highly effective in reaching the required subdivision index.

The results of the calculated indices show that, in general, the required subdivision indices for the partial draughts $A_l$, $A_p$ and $A_s$ are also met when the combined index A is met.

It can be concluded that meeting the required subdivision index is possible for small passenger ships. Whether the additional deterministic requirements from SOLAS Chapter II-1 regulation 8 an 9 can also be met is not investigated.

[3] The factor $s_i$ accounts for the probability of survival after flooding. $S_i$ is defined in SOLAS CH II-1 regulation 7-2 and depends on the stability characteristics after damage.

## REFERENCES

Danish Maritime Authority. (2015). *Small Ro/pax Vessel stability study.* Valby: DMA.

DNV GL AS Maritime. (2015). *Combined assessment of cost effectiveness of previous parts, FSA compilation and recommendations for decision making.* Høvik: DNV-GL.

EC. (2009). *2009/45 safety rules and standards for passenger ships* . Brussels: EU.

GOALDS Consortium. (2012). *Development of new damage stability requirement based on Cost-Benefit assesment.*

Group, R. E. (2019). *Red Ensign Group Yacht Code.* United Kingdom: Red Ensign Group.

IMO. (2008). *Code on safety for Special Purpose Ships -SPS-Code.* London: IMO.

IMO. (2017). Report of the Maritime Safety Commission on its ninety-eighth session. (p. Annex 3). London: IMO.

Japan. (2013). *SDC1/INF.7 Review of the damage stability regulations for Ro-Ro passenger ships.* London: IMO.

Japan. (2015). *SDC 3/3/8; Proposal on the required* subdivision *index 'R' taking into account the risk level of small passenger ships.* london: IMO.