1. The Sub-committee, at its forty-sixth session, provided instructions to the correspondence group related to large passenger ships safety that included, *inter alia*, work to pursue the task to characterize the survivability of existing large passenger ships. Specifically, this work would undertake the suggestions put forth in document SLF 46/8, paragraphs 25 to 27, and would be accomplished by contributions to a framework of defined tasks.

2. One of these tasks was to further refine the initial time-to-flood simulation study, the report on which was submitted by the United States to the Sub-Committee in document SLF 46/INF.3. Accordingly, the United States sponsored an additional study at MARIN to perform the refinements recommended in document SLF 46/8. The final report of this study is contained in the annex.

**Action requested of the Sub-Committee**

3. The Sub-Committee is invited to note the information provided.

***
TIME TO FLOOD (TTF) SIMULATIONS FOR A LARGE PASSENGER SHIP

Final study

MARIN order No. : 19289

Ordered by : US Coast Guard HQ
2100 Second Street, S.Q.
Washington DC 20593
United States of America

Reference : Contract DTCGG8-04-C-MSE080.

Reported by : Dr. ir. A.P. van 't Veer
EXECUTIVE SUMMARY

Time domain simulations of a damaged ship with different damage extent have been performed in calm water and in waves.

The internal space of the ship was modeled to a high degree of accuracy compared to the design. The recommendation from the practical assessment by Finland (SLF 47/INF.6) concerning the influence of different door types in the progressive flooding was incorporated.

The results show that time-domain simulation and traditional naval architectural approach predict the same final equilibrium flooding condition, only when the intermediate flooding did not introduced progressive flooding to internal spaces not accounted for in the traditional approach.

The results show furthermore that the intermediate flooding stages can depend on a single downflooding opening in the ship and how this opening is modeled.

Low significant sea-states (Hs = 2.0 m) will not significantly influence the intermediate flooding conditions compared to calm water conditions (three-compartment damage).
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1 INTRODUCTION

This report refers to contract DTCG8-04-C-MSE080.

This report present the results of a ‘final’ study on the transient and progressive flooding of a large passenger ship. Previous results of the initial study were reported under contract DTCG40-02-Q-6CA015, and reported to IMO at the SLF 46 meeting [Ref. 1].

The numerical simulations performed in the final study were performed with a refined model, compared to the initial study. It incorporates greater compartment accuracy and collapsing doors and other flow conditional openings. The model was refined following the recommendations addressed in SLF 46/8 [Ref. 2], which is a review paper on the initial study by the LPS Splinter Group of the Intersessional Correspondence Group.

The parametric variation in the study includes a three-compartment flooding case and a four-compartment flooding case. These damages are beyond current SOLAS requirements.

A comparison is made between the ship response to a two-compartment damage in the final and initial study. This comparison reveals the influence of the refined model.
2 SHIP CHARACTERISTICS

2.1 Ship properties

The (intact) ship properties are given in Table 1. The lines plan of the (unbuilt) ship was provided by Fincantieri and is shown in Figure 1, including the intact draft mark.

Table 1: intact loading condition.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculrars</td>
<td>242.28 m</td>
</tr>
<tr>
<td>Maximum width on intact waterline</td>
<td>36.00 m</td>
</tr>
<tr>
<td>Depth amidships</td>
<td>26.00 m</td>
</tr>
<tr>
<td>Draught</td>
<td>8.40 m</td>
</tr>
<tr>
<td>Trim</td>
<td>0.0 m</td>
</tr>
<tr>
<td>KM</td>
<td>19.553 m</td>
</tr>
<tr>
<td>Displacement mass</td>
<td>52978 tonnes</td>
</tr>
<tr>
<td>CB</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Figure 1: Lines plan of the large passenger ship
2.2 Loading conditions

The radius of inertia of the ship were not specified by Fincantieri, so that default values were used, which is a radius of inertia for roll of 0.4*B and a pitch radius of gyration of 0.248*Lpp.

In this report two different intact loading conditions are used, GM = 1.60 m and GM = 2.10 m, see in Table 2. The location of the intact centre of gravity is the reference point for the ship motion program in damaged condition as well. The flood water is assumed to act as added weight to the ship. In the initial study the loading condition with GM = 1.55 m was used.

Table 2: Loading conditions

<table>
<thead>
<tr>
<th>KG [m]</th>
<th>GMT [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.433</td>
<td>2.10</td>
</tr>
<tr>
<td>17.953</td>
<td>1.60</td>
</tr>
<tr>
<td>18.000</td>
<td>1.55</td>
</tr>
</tbody>
</table>

The hydrostatic properties of the ship are calculated by SHCP (version 4.2), and the GZ-curves for the intact ship are given in Figure 2. This software prepares as well the tank tables for the damaged compartments which are used in the simulations by FREDYN.

Figure 2: GZ curves for the intact ship.
2.3 Deck heights

All relevant compartments on deck 1, 2, 3, 4 and 5 are included in the model. The deck heights are given in Table 3. The intact draught of the ship is 8.40 m, so that the deck edge of deck 3 is slightly above to the calm waterline. The bulkhead deck 4 is 3.00 m above the calm water line in intact condition. The midship ship-profile is given in Figure 3. Portlights and windows are not considered in the simulations; it is assumed that they can withstand the water pressure when they are submerged due to the ship list and sinkage. The only damage to the ship is the actual damage definition, which is defined in a following section.

Table 3: Definition of deck heights

<table>
<thead>
<tr>
<th>Deck</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deck 6</td>
<td>17.40 m above keel</td>
</tr>
<tr>
<td>Deck 5</td>
<td>14.25 m</td>
</tr>
<tr>
<td>Deck 4</td>
<td>11.40 m</td>
</tr>
<tr>
<td>Deck 3</td>
<td>8.60 m</td>
</tr>
<tr>
<td>Deck 2</td>
<td>aft frame 172: 5.40 m, fwd frame 172: 5.80 m</td>
</tr>
<tr>
<td>Deck 1</td>
<td>aft frame 82: 3.0 m, aft frame 118: 2.20 m, fwd frame 118: 1.8 m</td>
</tr>
</tbody>
</table>

Figure 3: Deck heights at midship cross section
2.4 Compartment modelling

All relevant compartments on deck 1, 2, 3, 4 and 5 have been modelled.

Deck 4 is the bulkhead deck and all watertight doors in the bulkheads on the decks 1, 2 and 3 remain closed during the simulation. Relevant for the damage stability are the following bulkheads:

<table>
<thead>
<tr>
<th>Bulkhead Frame number</th>
<th>Location wrt. APP [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 118</td>
<td>75.25</td>
</tr>
<tr>
<td>8 124</td>
<td>85.74</td>
</tr>
<tr>
<td>9 148</td>
<td>102.36</td>
</tr>
<tr>
<td>10 172</td>
<td>118.98</td>
</tr>
<tr>
<td>11 196</td>
<td>135.60</td>
</tr>
</tbody>
</table>

The splashtight type of doors in the bulkheads on deck 4 are modelled as leakage-collapsing openings, as is defined in the following section. When such an opening starts to leak and eventually collapses, the flood water is able to spread over an larger area in the ship, beyond a certain bulkhead which restricts the flooding on the lower decks. The initial study reported that accumulation of water on the bulkhead deck of the passenger ship can lead to downflooding to compartments on deck 3 and below which are not damaged. This leads to accumulation of water and to a situation with vulnerable stability. Such phenomena can be compared, to some extend, by the accumulation of water on the cargo deck of a RoRo ship. Extensive model tests and numerical simulations have shown that accumulation of water on the Roro cargo deck can eventually lead to a capsize, depending on the significant wave height and the loading condition in particular [Ref. 6, Ref. 7].

One recommendation after publication of the initial study was to model the splashtight doors and other openings in the ship more realistically, and to re-investigate the flooding [Ref. 2]. In stead of modelling the splashtight doors as being closed or open, recommendations from Finland were included in this final study: doors can withstand a certain pressure before they start to leak, and it requires an higher pressure at which the door will collapse. See the following section.

**Permeability**

All machinery compartments on deck 1 or otherwise are given a permeability of 0.85. All other compartments have a permeability of 0.95. This is slightly different then in the initial study where all compartments had a permeability of 0.95.

**Vented**

All compartments are vented. This means that air entrapment effects are not considered. It is assumed that air can escape through additional openings. To the knowledge of MARIN, all model tests currently performed for damage stability verification apply only vented compartments.
Research performed with respect to vented/non-vented compartments [Ref. 3] has concluded that air-flow effects are important. For example, it was shown that initial transient roll angles are over-estimated if air-flow effects are not considered in time-domain simulations [Ref. 3].

Compartment details
The following remarks on the compartment set-up on the different decks are made:

Deck 1
The compartment set-up on deck 1 is very similar to the one in the initial study. The bulkheads 8-11 separate the compartments and only vertical escapes connect deck 1 with deck 2. Near the connection of the bulkhead with the side shell down-flooding trunks exist which extend between deck 2 and 3. They are open only to deck 1 compartments. When the bulkhead is damaged at such a bulkhead at deck 2, downflooding from deck 2 to deck 1 is possible. The downflooding arrangement has been included in this study, see Figure 4.

Deck 2
Compared to the initial study, the compartment definition on deck 2 between bulkhead 10 and 11 was modified to represent the crew-space cabin area in more detail. A number of small crew cabins were grouped. In Figure 4 the compartment boundaries (thick solid lines) and the up- or downflooding points (as circles) are shown. As can be seen, not all details are modelled, which is also not required to obtain a realistic flow through this area. Not seen in the figure are the openings between the compartments. These are positioned and size to represent all individual openings between the enclosed area.

Deck 3
Similar as on deck 2 between bulkhead 10 and 11, deck 3 shows a highly divided deck area in only cabin areas forward from bulkhead 6 (frame 108). The same strategy as shown in Figure 4 is applied to build the numerical model. The compartment boundaries on deck 3 are seen in Figure 5.

Deck 4
Similar as on deck 3, deck 4 contains a large number of cabins. Grouping typically 4 to 6 cabins in one large compartment for numerical simulations was carried. The main difference with the previous study is the slightly smaller compartment set-up on this deck, that is less number of cabins are grouped to one compartment.

Deck 5
Deck 5 consist of large open areas, like the restaurant. Therefore, the number of compartments on deck 5 is limited. Partial bulkheads are modelled to accommodate the possible accumulation of water in a certain area near the side of the ship.
Figure 4: Example of grouping cabin areas (here on deck 2) to slightly larger compartments for simulations. The (blue) circles are down and up-flooding points to deck 1 and 3.

Figure 5: Compartment boundaries and down- and upflooding points on deck 3.
2.5 Internal openings between compartments

The modelling of the internal connections between compartments has been modified significantly with respect to the previous study. This required a software modification as well to cope with the desired modelling.

Following the SLF47/INF.6 note [Ref. 4], which was provided to MARIN in an early stage as results of the Practical Assessment, doors are divided into three groups:

- Weather-tight doors which start to leak, but with a high collapse pressure
- Fire door with no leakage threshold but with moderate to high collapse pressure
- Joiner door with no leakage threshold and with low to moderate collapse pressure.

For each opening type, the following parameters need to be defined:
values of leakage and collapse pressures \( (h_l \text{ and } h_c) \) and the ratio of area available for leaking to opening after collapse \( (A_l / A_c) \). The Practical Assessment [Ref. 4] suggested ranges for each of these items; for the purpose of the study, finite values are assumed, which read as follows:

<table>
<thead>
<tr>
<th>Door Type</th>
<th>( h_l ) (meters)</th>
<th>( h_c ) (meters)</th>
<th>( A_l / A_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather-tight doors, type B1 in [Ref. 4] (Hinged splashtight doors)</td>
<td>0.3</td>
<td>4.0</td>
<td>0.05</td>
</tr>
<tr>
<td>A Class fire doors, type B2 in [Ref. 4] (Fire doors)</td>
<td>0.0</td>
<td>2.0</td>
<td>0.1</td>
</tr>
<tr>
<td>B Class joiner doors, type B3 in [Ref. 4] (cabin doors)</td>
<td>0.0</td>
<td>1.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

In SLF 47/INF.6 [Ref. 4] the definition for semi watertight doors (denoted A2), also known as splashtight doors, is slightly different from the above definition adopted for hinged splashtight doors in the unbuilt design. The weather-tight doors denoted type B1 in [Ref. 4] and are categorised under non-watertight boundaries. The semi watertight boundaries (A2) or splashtight doors in [Ref. 4] are assumed to have \( h_l > 1.0 \text{ m} \) and \( h_c > 3.0 \text{ m} \) with \( A_l / A_c < 0.2 \). Apart from the leakage pressure however, the definition for the hinged splashtight doors of this unbuilt design fits within the constraints.

2.6 Damage description

The external damage to the ship is defined with zero penetration depth. For a striking accident this is most likely not the case, but neither is the exact rectangular shape of the damage. A horizontal penetration can introduce downflooding points between different decks. However, since the damage is to the side of the ship this will not change the results in the simulation.

The major reasons not to include a penetration depth in the modelling is that is has insignificant effect and that is complicates the set-up to some extent.

The following damages are defined (see also Figure 6):
Two-compartment damage
In the initial study a two compartment damage at frame 148 (bulkhead 9) was used as the damage location. To compare the simulation results between the final and the initial study, the following damage was applied:

A two-compartment damage on frame 148, bulkhead 9.
- From 3 metres forward to 3 meters aft of frame 148
- From 4.80 m to 17.50 m above baseline (deck 1 to deck 5)

Three-compartment damage
A three-compartment damage extending from frame 124 to frame 196. The damage is described by:
- The bulbous bow opening:
  - from 3 meters forward of frame 172, to 3 meters are of frame 172,
  - from 2.7 meters to 8.7 meters above baseline
- Above waterline opening:
  - From 3 meters forward of frame 172, extending aft for 24 meters
  - From 8.7 meters to 15.7 meters above baseline

Four-compartment damage
A four-compartment damage from frame 104 to 216. The damage only extends below the waterline:
- Below water line opening:
  - From frame 146 (18 m aft of 172) to frame 198 (18 fwd of 172)
  - From 7.60 meters to 8.60 meters above baseline (deck 2)

In the above damage descriptions the following frames are referred to, given here for reference purpose:

<table>
<thead>
<tr>
<th>Frame</th>
<th>Location</th>
<th>Frame</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>APP</td>
<td>146</td>
<td>101.55 m</td>
</tr>
<tr>
<td>124</td>
<td>Bulkhead, 86.6 m</td>
<td>196</td>
<td>136.22 m</td>
</tr>
<tr>
<td>148</td>
<td>Bulkhead, 135.60 m</td>
<td>198</td>
<td>137.65 m</td>
</tr>
<tr>
<td>172</td>
<td>Bulkhead, 119.61 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6: Overview of two-, three- and four-compartment damage layout. Damage is located on port side. (Thus the damage view in the drawings above is from inside the ship to the outside; frame 0 is the aft perpendicular).

2.7 System of reference for ship motions

The damage is located on port side.
Heel towards starboard is positive.
Trim is positive when the bow moves down.
Sinkage is positive when the draught increases.
3 RESULTS

3.1 Two-compartment damage, calm water

Results are presented for the two-compartment damage located on bulkhead 9 (frame 148) as described in Chapter 2.

The loading condition for this damage is $GM = 1.55 \text{ m}$, $KG = 18.00 \text{ m}$

The comparison in the results between the old and new model for the two-compartment damage is seen in Figure 7. In the new formulation all doors are closed, but they start to leak and finally collapse at a certain pressure. In the old formulation only splashtight doors on deck level 4 were considered closed and collapsing, while all other connections were open at the damage event. Apart from this important difference, the new model has a slightly different compartmentation set-up.

The results show that especially the flooding condition after the transient phase is very different and leads to a much safer condition with the new model definition. This result is in close agreement with the final equilibrium flooding stage using traditional naval architectural assumptions. Where in the old modelling the ship remains at 6 degrees list towards the damage, an almost zero list is obtained with the new modelling. The first transient heel angle is somewhat smaller as well.

![Figure 7: Roll response comparing the old and new simulation model](image)

The roll angle is about 5 degrees less with the more detailed compartment definition. The intake of water per second is also reduced since the maximum heel occurs about 1 minute after damage occurring, while in the previous run this occurred after half a minute. The final condition of the ship is only a few degrees list towards the damage and this stable condition is reached in less than 10 minutes after damage.
At the end of the simulation deck 4 is not submerged anymore, and all accumulated water on deck 4 in the intermediate flooding stages that can flood down to deck 3 or to the outside has done so. In Figure 8 a snapshot is given at the end of the run. It is seen that in several spots on the bulkhead deck some water has accumulated which can not flow away anymore.

Figure 8: End condition on deck 4 for a 2 compartment damage simulation. The white area to the left in the figure is the damage opening to the sea on deck 4. Deck 4 is white and the black areas is accumulated water. All compartment boundaries on deck 4 are shown as a raster of lines.
3.2 Three-compartment damage, calm water

The heel angle response for the three-compartment damage is presented in Figure 10 for a calm water run with two different GM values. The first roll angle towards the damage is dominated by the GM; a reduced GM leads to a larger roll towards damage. The first roll angle toward the damage was as follows:

GM = 1.60 m, first maximum roll = 13.3 deg towards damage  
GM = 2.10 m, first maximum roll = 9.0 deg towards damage

The final equilibrium list of the ship differs between the two loading conditions, and is the following:

GM = 1.60 m, final equilibrium heel = 5.6 deg towards damage  
GM = 2.10 m, final equilibrium heel = 1.4 deg towards damage

The maximum roll angle at the intermediate flooding stage differs significantly. When 15 degrees list at any time event is applied, the ship condition with GM = 1.60 m would have been unsafe, while with GM = 2.10 m the ship would be safe. The maximum roll angles in the intermediate phase are as follows:

GM = 1.60 m, maximum intermediate roll angle = 15.9 deg towards damage  
GM = 2.10 m, maximum intermediate roll angle = 9.7 deg towards damage

The different behaviour of the ship in the intermediate flooding phase is due to the modelling of collapsing openings in the ship. Depending on the actual heel angle and flood water distribution in the ship, a particular door can collapse which introduces progressive flooding to a certain compartment. This means that depending on the intact loading condition (GM) a different progressive flooding occurs. Such phenomena can not be found with traditional naval architectural assumptions, since these can not predict the intermediate flooding situations correctly, if at all.

Fincantieri provided the s-factor for this particular damage using the new proposal denoted SLF 47/3/1 [Ref 3.]. In these calculations the damage compartments that contribute to the s-factor are all located within the three-compartment boundaries.

For a GM = 2.10 m the following GZ curve and related s-factor was found:
According to the proposed regulation from the document SLF 47/1 for SLF 47, Ch II-1 Part B Reg. 7.2, \( s_{\text{final}} = K \left[ \frac{GZ_{\text{max}} \cdot \text{Range}}{12} \right] \).

Following the same nomenclature of the proposed rules,
\( \theta_e = 2,658 \, \text{deg} \)
\( \text{Range} = 13.031 \, \text{deg} \)
\( GZ_{\text{max}} = 0.134 \, \text{m} \)

\( s_{\text{final}} = 0.95 \)

And for a GM = 1.60 m the following was obtained:

\( \theta_e = 15,915 \, \text{deg} \)
\( \text{Range} = 0 \, \text{deg} \)
\( GZ_{\text{max}} = 0 \, \text{m} \)
\( K = 0 \)

\( s_{\text{final}} = 0 \)

It is interesting to note that the numerical time domain FREDYN results for a GM of 2.10 m lead to about the same list angle as found in the static calculation. The s-factor is 0.95 for this GM. The result can be understood since the damage flood water does not spread outside the 3 compartment damaged area (comp 9, 10 and 11 in Figure 9).

For the lower GM value the time domain numerical simulations predict a safety of about 15 minutes when the 15 degrees list angle is used as criteria. However, the maximum heel angle was only just 1 degree larger, and finally the ship remains at a safe heel of close to 6 degrees. The \( s_{\text{final}} \) in the above calculations was however zero, with a final
equilibrium of 15.9 degrees. It is interesting to see that FREDYN predicts a maximum roll angle of 15.9 degrees towards the damage. With only this set of comparison this correlation is most likely incidentally. Figure 9 shows the flood water distribution from the simulation in the final equilibrium condition with GM = 1.60 m. Due to the collapse and leakage of openings, flood water is seen outside the 3-compartment area. This explains (to some extend) the difference between the traditional naval architectural approach and the dynamic flooding simulation route.

Figure 9: FREDYN flood water distribution at final flooding stage with three-compartment damage and GM = 1.60 m. Flooding outside the damage compartment area (comp 9-comp 11) on deck 3 and 4 are seen.

The sinkage, trim and flood water accumulation are shown in Figure 11 through Figure 13. The trim response is defined as negative is bow down. With GM 1.60 m the water accumulates the aft, which is the large machinery space area.
Figure 10: Roll response of the ship in calm water with $GM = 1.60 \text{ m}$ (grey line) and $GM = 2.10 \text{ m}$ (black line)

Figure 11: Sinkage response in calm water. Three compartment damage.
Three compartment damage

Figure 12: Trim response in calm water. Three compartment damage.

Three compartment damage

Figure 13: Flood water accumulation in calm water. Three compartment damage.
3.3 Three-compartment damage, response in waves

Two simulations of 6 hours in a sea-state with significant wave height 2.0 m were performed and compared to the result in calm water. The response in waves is very comparable to the calm water response for the first 45 minutes of the simulations, see Figure 14. The wave forces lead to roll variations around the trend found in calm water. This finding was already noted in the first report. After 45 minutes however, the ship heel decreases rapidly to about the final roll angle obtained in calm water, and the ship roll around this mean for the duration of the simulation. The two realisations of the same sea-state predict about the same response.

The accumulation of water in the ship is presented in Figure 15. The amount of water in calm water and in waves is very similar and is about 12000 tons. Since the draft increased about 1.50 m, the total flooded displacement is about 65000 tonnes.

![Figure 14: Roll response in waves of Hs = 2.0 m. Three compartment damage with loading condition GM = 2.10 m.](image)
The rapid decrease of the roll angle in waves, but also in calm water, is due to the collapse of a few openings which lead to down flooding of water.

The three compartment damage is basically a two-compartment damage below the waterline and a three compartment damage above the waterline. The two-compartments on deck 1, 2 and 3 rapidly flood and this determines the response of the ship in the first 30 minutes. The flooding of deck 2 beyond the two compartments (aft of frame 148) is only possible by means of an escape down-flooding point, located at frame 146 in deck 3. This point is seen in Figure 16, where part of deck 3 is drawn. The damage extends on deck 3 to frame 146. Just aft of bulkhead frame 148 an escape down-flooding point exist, connecting deck 2 and 3. Apart from this, around the centre line stairs connect deck 2 and 3 as well. The escape area (and stairs) is protected by a fire door. As defined, a fire door starts to leak as soon as water reaches the door post, and will collapse at 2.0 m water pressure. If so, water will flood to the lower deck 2 and from deck 2 to deck 1 by means of an escape point in deck 1 near the centre line at frame 144. Water accumulation on deck 2 and 3 between frame 124 and 148 can not egress the ship anymore since there is no opening other than the vertical down-flooding points.

At about 1800 seconds in the simulations the fire door in front of this escape point collapses. As a result, deck 2 and deck 1 rapidly flood which decreases the list angle of the ship since the areas on deck 1 and 2 extend from side to side. How this single non-watertight opening leaks and then collapses has a critical effect on the result.
Figure 16: Detail of subdivision on deck 3 between frame 124-152 starboard side, which is a part of the compartment between bulkhead 8 and 9. The compartment has in total two down flooding points to deck 2, which are both located around frame 146 and one opening to deck 4 on frame 146 as well. The ‘Escape down’ is located at portside (±11 m from centre-line) and the stairs (DN) down is located at starboard side (±3 m from centre-line). The three compartment damage extends on deck 3, from frame 146 forward. The solid green lines represent the subdivision boundaries, the solid blue lines represent the location of the collapsing openings. The blue circles refer to the location of the openings between the decks.

3.4 Effect of a single down flooding point and it’s protection

The influence of how the door in the escape area collapses has a significant effect on the intermediate flooding condition of the ship. In Figure 17 the three different door-types as previously defined were applied and an additional watertight door was located (which means no flooding through the escape down to deck 2). As soon as the door starts to leak water can flood down at a low rate. When the door completely collapses water floods much faster down and filling the compartments at deck 1 and 2 will reduce the heel. When the door remains closed the downflooding from deck 3 to deck 2 has to start by the stairs around centreline of the ship (at frame 146), and when this occurs the
heel reduces. This explains while the ship response with a watertight door in front of the escape will eventual reduce heel after 1.5 hours. In that time period the heel increased till a significant 13 degrees.

Figure 17: Roll response of the ship with different modelling of the door-type in front of the downflooding point (escape) at frame 146 between deck 3 and 2.
3.5 Four-compartment damage in calm water

The simulations in this section were performed with a GM = 1.60 m and 2.10 m. The roll response is presented in Figure 18. The maximum roll angle is obtained 3 minutes after damage and depends on the GM condition, similar as for the three-compartment damage.

![Four compartment damage](image)

Figure 18: Roll response in calm water, two different GM conditions, four-compartment damage.

Due to the large extent of damage a significant amount of flood water enters the ship rapidly and after 10 minutes 15000 tonnes has accumulated. This means a flooding rate of about 15000 tonnes / 10 minutes = 1500 tonnes/min. The time trace in Figure 18 shows several peaks in the roll response due to collapsing openings in the ship after which water progresses to other compartments.

The maximum heel of the ship (which occurs at the first transient roll towards damage) is found to be:

- GM = 1.60 m, maximum intermediate roll angle = 18.1 deg towards damage
- GM = 2.10 m, maximum intermediate roll angle = 15.0 deg towards damage

The final list angle is very small due to the large flooded area on deck 1 and 2 from port to starboard. The results are:

- GM = 1.60 m, final equilibrium heel = about 1 deg towards damage
- GM = 2.10 m, final equilibrium heel = about 1 deg towards damage

Apart from the large amount of flood water in the ship, which is accumulated on deck 1, 2 and 3, the intermediate heel angles are only several minutes around 10 degrees. It can be expected that effects not modelled in the simulation (such as the striking force)
affect the intermediate flooding angles as well. Due to the large amount of flooding on the lower decks the final equilibrium condition is expected to be reasonably stable.

![sinkage and flood water graph](image)

**Figure 19:** Sinkage and amount of flood water in the ship. Four compartment damage.
4 CONCLUSIONS

The new modelling used in this report differs in the following points from the modelling used in the previous study:

- All cabin doors are closed, but start to leak and collapse at low pressure
- All fire doors are closed, but start to leak and collapse at medium pressure
- All hinged splashtight doors are closed, but start to leak and collapse at high pressure
- The degree of modelling represent the ship in more detail on especially the bulkhead deck 4 and deck 3. The modelling on deck 1, 2 and 5 is very similar as used before.
- Account is taken of the downflooding trunks in the side of the ship.

The following conclusions are based on the simulation results in this report, performed for a limited number of loading conditions, and damage descriptions:

- A good definition of the down-flooding points between two decks, it’s protection by which kind of door types, and the way such doors behave under water pressure is of paramount importance for the outcome of the simulation.
- The heel angle towards the damage due to the first transient flooding of the ship depend mainly on the loading condition (GM) of the ship and very little on the wave environment the ship is located in.
- The heel angles in the transient flooding phase are always larger than the final equilibrium heel angle, although the amount of flood water in the intermediate flooding phase is less than the amount of flood water in the final stage.
- The intermediate flooding condition (heel angle and flood water distribution) can trigger progressive flooding due to a collapsing opening. As such, different loading conditions can lead to a different flood water distribution in terms of which compartment are being (partial) flooded.
- Traditional naval architectural assumptions cannot predict the intermediate flooding conditions of the ship.

The following conclusions are specific for the damages considered:

Two-compartment damage – effect of modelling internal spaces:
- The ship behaviour for a two-compartment damage is similar between the two different models in the initial and final study. But, the results show as well that a more detailed description (including a higher degree of subdivision and more realistic door-type modelling) can reduce the final and intermediate heel angle.

Three-compartment damage:
- The intact loading condition of the ship significantly influenced the transient behaviour of the ship and thereby determined the final equilibrium flooding condition.
• A single downflooding point and its protection by means of a door type determine the response of the ship in intermediate flooding conditions.

• When downflooding occurs through an opening outside the damaged area, water cannot egress since the ship is closed in that particular compartment. Downflooding can reduce the heel angle when the flooded compartment extents from port to starboard.

• The effect of beam-waves imposed on the ship does hardly affect the first heel angle towards the damage, but has an effect on progressive flooding.

Four-compartment damage:

• In the four-compartment raking damage downflooding to the lower decks occurs almost immediately which reduces the roll angle to very small values.

• Due to the large damage extent, the intact GM condition has an effect on the first roll towards the damage, but the final equilibrium roll angle is not effected.
5 REFERENCES


[5] SLF 47/3/1, June 2004, Submitted by Sweden and the United States: Development of revised SOLAS Chapter II-1, Parts A, B, and B1, Report of the Intersessional Correspondence Group Part I (Chapter II-1 draft text), Reference is made to the ANNEX.
