LARGE PASSENGER SHIP SAFETY

Survivability investigation of large passenger ships

Submitted by Finland

SUMMARY

Executive summary: The document provides a practical assessment of how semi-watertight and non-watertight boundaries can be treated in time-domain flooding simulations

Action to be taken: Paragraph 7

Related documents: SLF 46/8, SLF 46/16, SLF 46/INF.3, SLF 47/3 and SLF 47/INF.2

Introduction

1 The Sub-Committee, at its forty-sixth session, distributed the different tasks for the “time-to-flood” work, as mentioned in paragraph 8.5.1 of SLF 46/16, and Finland contributed with a practical assessment.

2 The assessment has considered factors that influence the spread of water in the watertight compartments and in compartments above the bulkhead deck. It concentrated on three main categories of boundaries; doors, piping, ventilation and windows.

3 The doors are divided into three larger groups:
   .1 doors with a certain resistance to flooding and a required level of tightness;
   .2 doors that will leak and are not able to resist the flooded water; and
   .3 doors that must not delay the spread of flooded water.

4 The assessment also focused on the influence on progressive flooding through ventilation trunks, grey and black water piping systems as well as electrical cable penetrations.
5 The strength of windows and port lights is important and it would have required more thorough studies and tests than this assessment has provided.

6 The assessment is presented in the annex attached.

**Action requested of the Sub-Committee**

7 The Sub-Committee is invited to note the information provided and take action as appropriate.

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ANNEX

SURVIVABILITY INVESTIGATIONS OF LARGE PASSENGER SHIP

The practical assessment of features that effect the flooding survival of large passenger ships

INTRODUCTION

The aim of this study was to investigate and make a practical assessment of how semi-watertight and non-watertight boundaries should be treated in time-domain flooding simulations. Previous studies (i.e. Marin Study contained in SLF 46/INF.3) have shown that an accurate assessment of the flooding process requires an accurate model of internal compartments and the openings between them. The study concentrated on three categories;

.1 Leakage and collapse pressure heads of doors in various types of boundaries;
.2 Influence of progressive flooding through open piping, ventilation, cable distribution systems and/or non-watertight boundaries; and
.3 Watertight or weather tight integrity of port-lights and windows and the standards of construction.

1. LEAKAGE AND COLLAPSE PRESSURE HEADS OF DOORS IN VARIOUS TYPES OF BOUNDARIES

General

The time flooding simulations use a Bernoulli hydraulic model to determine the flow through openings between internal compartments as well as through openings caused by damage that allows the flooding to start. For the simulations, the quantity of flood water flowing through the opening is determined for a given time interval (normally 1/4 seconds) according to the formula:

\[ Q = C_d \times A \times (g \times h)^{1/2} \]

where,

- \( Q \) = volume flow rate (m\(^3\)/s)
- \( A \) = area of the opening (m\(^2\))
- \( h \) = difference in static pressure head (in meters) at the opening
- \( C_d \) = discharge coefficient (normally 0.6)
- \( g \) = acceleration due to gravity (= 9.8066 m/s\(^2\))

The two key quantities of the formula are the area (A) and the pressure head (h) at the opening between compartments. In the time-domain simulations, each opening between compartments is defined as a rectangle, where appropriate coordinates define each corner.

There exist openings between compartments (such as doors, AC-canals or electrical cable penetrations) that initially obstruct or restrict the flow of water through the opening until the pressure is reached at which an obstruction starts to leak or it collapses.
For obstructed openings, the characteristics of the flow through the opening can be described by four identifying parameters:

- $h_l$ = static pressure head (in meters) at which leaking starts
- $A_l$ = portion of opening area through which leaking occurs
- $h_c$ = static pressure head (in meters) at which obstruction collapse
- $A_c$ = opening area after collapse of obstruction. This value is likely to be equal to the total area of the opening.

Examples of openings for which these parameters can be used vary widely. One might be a sliding semi watertight door that would start to leak at heads ($h_l$) ranging from 2 to over 4 meters and with a small area of leaking ($A_l$) and will collapse at substantially higher pressures ($h_c$). Another example would be an intermittently welded joint between a steel bulkhead and a deck in which the head to cause leaking is low but the head to cause collapse is very high. Other examples include port-lights and windows, ventilation and electrical penetrations through steel bulkheads, open piping systems (i.e. grey and black water system) through watertight decks as well as fire doors and joiner doors. In some cases the parameters will be different depending upon the direction of the pressure on the opening obstruction. An obvious example of this would be hinged fire and joiner doors.

Therefore, openings in compartment boundaries could be grouped into similar categories that are quantified within certain ranges.

For the purpose of time-domain flooding simulation, compartment boundaries and the openings in them can be separated into three broad categories:

1. watertight;
2. non-watertight with high restriction of flooding progression; and
3. non-watertight with low restriction of flooding progression.

These categories are discussed below.

**Category A: Watertight**

There are different types of boundaries or openings in boundaries that can be called “watertight”. In every case, the boundary does not start to leak until some appreciable pressure head is reached and it collapses only after a static head of at least one deck height is reached.

Openings that have characteristics within this category may be divided further into following types;

**Type A1**: Watertight (= WT) boundaries complying with SOLAS regulations II-1/14 and 15 concerning watertight bulkheads and openings in watertight bulkheads in passenger ships.

These door types show the highest degree of water tightness, what we have available. (SOLAS regulations II-1/14 and 15). The watertight sliding doors used on the tank top (pressure head 3-4 deck heights) have been proved to take the static pressure without leakage, because the structure will become tighter with increasing pressure. Normally the same watertight door type is used on all decks below the bulkhead deck despite of the different height of static pressure head.
Watertight sliding doors used under the bulkhead deck are watertight and no progressive flooding is assumed to occur through these openings. In time-domain flooding simulations transversal watertight bulkheads below bulkhead deck are assumed as watertight.

According to existing rules (MSC/Circ. 541) watertight subdivision should be taken above the bulkhead deck, if the deck will be submerged during any stage of flooding.

Accordingly the openings in the boundaries above the bulkhead deck are to be equipped with watertight sliding doors.

In the future, if the definition of the “margin line” is removed, the importance of the watertight subdivision above the bulkhead deck will increase. And it would be reasonable to divide the A1 category doors into two types; watertight doors below and above bulkhead deck.

It is not needed to determine any collapse or leakage pressure heads for A1-type doors.

**Type A2:** Semi watertight (SWT) boundaries complying with SOLAS regulation II-1/20 and MSC/Circ.541 (They are also known as “splashtight”).

\[
\begin{align*}
& h_l > 1.0 \text{ m and } h_c > 3.0 \text{ m} \\
& A_l/A_c < 0.2
\end{align*}
\]

Semi-watertight doors located in partial watertight steel bulkheads represent a typical structure on existing large passenger ships. Partial watertight steel bulkheads restrict the flooded water from flowing further along the bulkhead deck.

Partial water tightness is extending to the equilibrium angle in the final stage of flooding plus the 15 degrees range of positive residual righting lever curve (or alternatively 10 degrees range with the increased area requirement).

According to MSC/Circ.541, SWT-doors shall be similar as WT-doors (SOLAS regulation II-1/15), except that they can take less static pressure head.

In appendix 1 is shown results of tested semi watertight doors of different sizes. In one of the tests it was observed, that when the water level was raised to 1.0 m the quantity of leaking water was measured as 6.0 l/10 min and when the water level was raised to 3.5 m the quantity of leakage water was 1.6 l/15 min. The maximum deformation of the door leaf was measured in the middle to be about 40 mm.

Based on the results of the test, one can assume that some leakage will occur in A2 doors when the pressure height is more than 1 m and that the door may collapse when the pressure head is more than 3 m.

**Category B:** Non-Watertight boundaries with high restriction of flooding progression

There are a number of doors and hatches in boundaries that may fall into this category. As an example, fire doors and cabin doors probably starts to leak immediately, but with a relatively small opening compared to the total opening.
There is a directional component in the parameters of hinged doors. In such a case there is a difference in the characteristics of leaking and collapse that is related to the direction of the pressure head. If the flood water flow helps to close the hinged door, the leakage area tends to be less and the collapse head greater than if the flood water is pushed against the hinges and latch.

**Type B1:** Weather tight with high collapse pressure but with low leakage pressure threshold

\[ h_l > 0.3 \text{ m and } h_c > 4.0 \text{ m} \]
\[ \frac{A_l}{A_c} = 0.05 \]

Typical weather tight structures are those structures complying with 1966 Load Line Convention. In passenger ships this kind of weather tight doors are located mostly in the aft or forward mooring spaces.

SOLAS chapter II-1 and MSC/Circ.541 state; if the area, where the restricting structure is located, is not submerged during any stage of flooding the structure may be of weather tight type.

Due to the lack of tested weather tight doors, the true collapse/leakage pressure heads are not known and an assumption of reasonable values is done instead. The weather tight is assumed as a high collapse pressure and allow leakage pressure threshold. \( H_c \) is taken as higher than 4 m and \( H_l \) higher than 0.3 m.

**Type B2:** A Class Fire Door with no leakage pressure threshold, but with moderate to high collapse pressure

\[ h_l = 0 \text{ m and } h_c > 2.0 \text{ m} \]
\[ \frac{A_l}{A_c} = 0.1 \]

A-class fire doors are assumed to have no leakage pressure threshold. Reference is also made to the existence of a gap beneath the A class fire door. The gap should be less than 6 mm according to resolution A.754 (18) and SOLAS regulation II-2/8.4.4.2.

**Type B3:** B Class Joiner Door with no leakage pressure threshold but with low to moderate collapse pressure

\[ h_l = 0 \text{ m and } h_c > 1.5 \text{ m} \]
\[ \frac{A_l}{A_c} = 0.2 \]

Typical B3 doors are cabin doors. Below are mentioned relevant requirements, which apply especially to B Class joiner doors.

1. Ventilation of cabins: “Doors and door frames in “B” class divisions and means of securing them shall provide a method of closure, except that ventilation openings may be permitted in the lower portion of such doors. Where such opening is in or under the door, the total net area of any such opening or openings shall not exceed 0.05 m2.” (SOLAS regulation II-2/9.4.1.2.1. For example, cabin B-fire door with breadth of 0.9 m, the allowed gap gauge below door may be 56 mm.
.2 Evacuation routes; Additional requirement for Ro-Ro passenger ships: “The lowest 0.5 m of bulkheads and other partitions forming vertical divisions along escape routes shall be able to sustain a load of 750 N/m to allow them to be used as walking surfaces from the side of the escape route with the ship at large angles of heel.” (SOLAS regulation II-2/13.7.3.2. Note that the last requirement is relevant only for ro-ro passenger ships.

Due to the lack of tested B Class joiner doors in order to know collapse/leakage pressure heads it was needed to assume reasonable values.

**Category C: Non-Watertight with low restriction of flooding progression**

Openings within this category can be named as “porous” also. These openings are generally those that are expected not to impede the flooding progression, but will reduce the time by which flooding equalization between the compartments occurs. Examples of openings in this category includes so-called “blow-out panels”, cross-flooding and down-flooding flaps. Cross-flooding flaps are used to reduce unsymmetrical flooding. The main purpose of these kinds of structures is to increase stability after damage (down flooding flaps), or to reduce final angle of heeling. Most often these structures are located below the bulkhead deck, inside one watertight compartment. These structures never connect two separate watertight compartments.

The ideal static pressure head, when the structure will collapse, would be as low as possible. Preferred collapsed height is to less than 1 m.

**Modelling principle in cabin area**

An accurate assessment of flooding process requires an accurate model of the internal compartments. But how accurate? To determine all cabins and doors to cabins in the cabin area would be a of waste time and the size of the model would become too large.

Below has been described a principle, how the modelling of cabin and similar spaces could be more logically pursued.

In the figure below are two watertight compartments (cabins below the bulkhead deck), the arrangement has been modified to include boundaries that can be modelled with B3 type doors. While the exact layout of the cabins has not been followed in the modelling, the key concept adopted is that the actual total collapse area of the doors (B3 type) leading into the cabins should be approximately equal to the total area of doors in the compartment model. Likewise, the total area open for corridors and passageways modelled in the vertical planes should be approximately equal to but never less than that of the actual design.

Using the guidance, a model of cabin spaces might be developed as shown in the figure below. Here, the cabin spaces adjacent to the shipside are grouped together with two B3 type openings at either end of the side cabin group in which the collapse area of the two B3 openings is equal to the total area of 6 doors (in compartment #12).

The interior cabins are grouped in the centre of the compartment (comp. no 12) with two B3 openings at diagonal corners to each other. Again the total collapse area of cabin doors should be approximately equal to the total area of the B3 type openings modelled.
2 Influence of Progressive Flooding through Open Piping, Ventilation, Cable Distribution Systems and/or Non-Watertight Boundaries

Present time-domain simulations have been carried out by ignoring progressive flooding through AC-canals, open piping systems, electric cable distribution system or other smaller openings. It is a fact that doors have the biggest influence on the survivability of the ship after damage in a short time frame. In a longer time frame it is necessary to take into account the progressive flooding through smaller openings.

Below is discussed the principles, how to design watertight structures below and especially above bulkhead deck. Further how to fulfil the existing or proposed requirements of internal watertight integrity.

Design Principles to fulfil existing requirements of internal watertightness to prevent progressive flooding through other openings than doors

Internal watertightness below bulkhead deck

All penetrations carried through subdivision watertight bulkheads below the bulkhead deck shall have arrangements to ensure the internal watertightness of the bulkheads (SOLAS II-1 15.1 and 2). The number of penetrations shall be reduced to minimum. Such open systems, as AC-canals or Gray/Black Water piping, which are needed to be carried through watertight bulkheads, are to be located within B/5-line on the centre line side. Open piping systems are to be equipped with emergency shut-off valves, which are controlled from bridge. Strength of those parts of the canal that are located in adjacent watertight compartment has to be equal to the corresponding watertight bulkhead structure (pressure head).

On the other hand it should be ensured that the structure of the AC-canal will sustain the pressure head, caused by flooded water in the damaged compartment where the open end of the AC-canal is located. The opposite open end of the canal has to be located well above bulkhead deck to fulfil also the requirement for range of equilibrium angle plus 15 degrees in final stage of
flooding. Typical examples are the exhaust or inlet AC-canal from other machinery space (i.e. Separator Room), which should be carry below bulkhead deck through adjacent watertight compartments upwards into casing. According to existing requirements, the above mentioned AC-canal will remain intact in a damage case, when the adjacent compartment is damaged (penetration of damage extends inside B/5-line).

**Internal watertightness/weather tightness above the bulkhead deck**

As earlier mentioned, internal watertight integrity above the bulkhead deck has to be designed to fulfil the requirements of positive residual stability in according to SOLAS regulation II-1/8.2.3 and 20.1. Furthermore, MSC/Circ.541 states that, if the bulkhead deck is not immersed during any stage of flooding, subdivision above bulkhead deck may be weather tight otherwise watertight. The same Circular states also the requirement for so-called “semi-watertight” (or “splash watertight”) door. These doors are to be closed simultaneously from bridge (refer to A2-type door).

From a stability point of view, the best subdivision above bulkhead deck is to design partial watertight bulkheads above each transversal main watertight bulkhead. However, in practise it is not possible to continue the subdivision above the bulkhead deck at every WT-bulkheads due to general arrangement.

The bulkhead deck between the partial and main watertight bulkhead has to be “effectively” watertight (SOLAS regulation II-1/20.1). Open piping systems (i.e. grey water) from the watertight/weather tight area have to be conveyed separately to the holding tanks and equipped with separate emergency shut-off valves. No connections are allowed between piping systems of same type, which are located below the watertight deck.

To prevent progressive flooding between adjacent partial watertight compartments, longitudinal open systems such as AC-canals have to be located on centre line side from the watertight/weather tight area (equilibrium angle + 15 degrees in final stage of flooding).

If longitudinal open system has to be located in the watertight/weather tight area, as AC-canal above crew corridor in cabin area usually are, it has to be ensured that the strength of the open canal is sufficient enough to sustain the corresponding pressure head. Furthermore, the open ends of that kind of system need to be conveyed on the safe side of the needed partial watertight limit to prevent progressive flooding from “semi watertight compartment” into other intact spaces.

Other open piping systems, which need also to be considered as watertight, are scuppers from the watertight deck areas and scuppers from bunker or tender stations or lift pits. Such scuppers are not allowed to lead straight into the open bilge located in the watertight compartment below.

Existing definition, “effectively watertight” means watertightness of the part of the bulkhead deck, which is located above the adjacent watertight compartment. Down flooding is not permitted. Existing internal watertight/weather tight integrity above the bulkhead deck is based on the static damage stability requirements. Dynamic effects, such as heave, are not needed to be taken into consideration.
Some comments to fulfil internal watertightness above bulkhead deck based on the proposed revised SOLAS Chapter II-1

In proposed revised draft SOLAS chapter II-1 the survivability (s-factor) is based on the static damage stability requirements (GZ-range 16 degrees and Gzmax 0.12 m). Because the definition of “margin line” is going to be removed, the importance of watertight subdivision above the bulkhead deck will become more relevant than it is now.

Watertight subdivision above the bulkhead deck will be extended up to the immersion limit line. The definition of “immersion limit line” is explained in the proposed Explanatory Notes. Briefly, the purpose of the limit line is to keep dry all escape routes that are located on the bulkhead deck. By assuming the bulkhead deck as watertight, it will have an increasing effect on attained index (A). So it is possible to get a benefit from the “v”-factor (vertical limit above the damaged waterline).

Based on the proposed requirements for positive residual righting lever curve (“s”-factor), it can be assumed that the bulkhead deck need not to be totally watertight in order to benefit the “v”-factor in the attained index. The watertight deck shall extend up to the “immersion limit line” or to fulfil the requirements of the GZ-range of 16 degrees and the GZ-maximum of 0.12 m. In practise, to design the bulkhead deck as watertight in passenger ships means one have to provide more arrangements to prevent up-flooding by installing more emergency shut-off valves.

3 Watertight or Weather Tight Integrity of Port-lights and Windows and the Standards of Construction

Appendix 2 shows an example of the maximum allowable pressure required for port-lights and windows located on the bulkhead deck and on 2nd and 3rd tier of the superstructure. Deck 1 on the list is bulkhead deck. For example, port-lights with a diameter of 350 mm situated on the 1 deck have a maximum allowed pressure of 241 kPa. It corresponds to a static pressure of about 48 m.

It has been assumed in the first MARIN study that the hull is intact up to the 6 deck.

Due to the lack of tests of collapsed or leakage pressure of any type of windows or port-lights, it can be assumed that the hull is intact up to the 6 deck based on the required allowable maximum pressure head. Secondly, the definition of intact stability hull is assumed to reach at least up to 6 deck. The windows on 5 deck need to be of heavy construction.

In the final report of the “MV Estonia” accident it has been mentioned as follows:

“The first potential openings to be submerged were the aft windows on deck 4. In calm water this would have happened, when about 2000 tons of water or about 70 cm evenly distributed had entered the car deck and caused a heel angle of about 40 degrees. Waves with considerable impact energy would have pounded against these windows earlier. It is unlikely that the windows, although of heavy construction, withstood such impact forces.”

“If the windows and doors had remained unbroken the vessel may have remained in a stable heel condition for some time. It is however, less unlikely that any reasonable strength of the large windows would have been adequate to withstand the wave impact forces. It can be concluded that, although the vessel fulfilled the SOLAS damage stability
requirements valid for its building period, she had no possibilities to withstand progressive flooding through the superstructure openings once the heel angle approached 40 degrees. When windows on the accommodation decks were broken by wave forces, subsequent sinking was inevitable.”

It has been emphasized that the stability hull in Estonia has been defined up to the 4. deck. So the windows on deck 4, were located in the superstructure. However, it would be interesting to examine more in detail the construction of windows or portlights that are located in the “intact stability hull” area.

**Conclusions**

The aim of this study was to analyse the flow of water through any opening or non-watertight boundaries in case of damage and how to create a more accurate model for time-domain flooding simulations.

The practical assessment of the integrity of semi watertight fire or joiner doors indicated that the most important factor is to determine the leakage \( h_l \) and the collapse \( h_c \) pressure threshold. Three main categories of doors have been determined based on their ability to sustain leakage of water or collapsing.

Only a few semi watertight doors have been tested. The lack of testing results of fire and joiner doors has lead to assumed values of leakage and collapse pressure. There is a need for systematic tests of various types of doors to give a more detailed input into the process of time-domain flooding simulation.

Secondly, the flow of water through any other openings except doors has been studied. The finding was, that the effect of smaller openings, e.g. open piping or cable penetrations, are of minor importance in a short time frame. While in the long time frame, the flooding through these types of openings has to be taken into account.

More investigations are needed in the future about progressive flooding on the bulkhead deck through semi watertight bulkheads and further downwards through any staircase or escape trunk. It should also be studied what kind of effect the “immersion limit line” will have on the process of the progressive flooding.

Thirdly it has been shortly described an example of maximum allowable pressures required for port-lights and windows located on the bulkhead deck and on the 2nd and the 3rd tier of superstructure. More tests are needed of different types of windows to establish the leakage and collapse pressure thresholds.

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Doors have been approved and certified by DNV

Doors may be used on passenger and cargo vessels

SOLAS II-1, Part B, Reg.8
SOLAS II-1, Part B-1, Reg.25.9
SOLAS II-1, Part B-1, Reg.20-2.2

Condition, when the doors will be collapsed completely, has not been tested
RESULT OF WATERTIGHT TEST FOR DOOR NO 1 (900*2000)

Date of test  8 April 2002  
Door Type    A-60 semi watertight sliding door 

Final result at 4.1 m pressure head the leakage water quantity at door leaf side is 28 litre/hour.

No bending info available.

Note! At 4.1 m pressure head the door started to leak from the closed handle cover plate.

RESULT OF WATERTIGHT TEST FOR DOOR NO 3 (2300*2000)

Date of test  19 June 2001  
Door Type    A-60 semi watertight sliding door 

Final result at 2.4 m pressure head the leakage water quantity at door leaf side is 0.5 litre/hour.

No bending info available.

RESULT OF WATERTIGHT TEST FOR DOOR NO 2 (1500*2000)

Date of test  8 April 1998  
Door Type    A-60 semi watertight sliding door 

Final result at 3.0 m pressure head the leakage water quantity on the opposite side of the sliding rails is 6.0 litre/hour.

Bending of the door is 27 mm.

When the water level was raised from 3.0 m to 3.5 m leakage water quantity was 10 l/min and bending 31 mm.
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<th>CLEAR LIGHT</th>
<th>DECK</th>
<th>FRAME</th>
<th>DISTANCE X FROM #7</th>
<th>THE DESING PRESSURE</th>
<th>MAXIMUM ALLOWABLE PRESSURE</th>
<th>CHOSEN GLASS THICKNESS</th>
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<td>45 kPa</td>
<td>69 kPa</td>
<td>25 mm</td>
</tr>
<tr>
<td>7</td>
<td>Ø 1100</td>
<td>3</td>
<td>243</td>
<td>208.5 m</td>
<td>68 kPa</td>
<td>69 kPa</td>
<td>25 mm</td>
</tr>
</tbody>
</table>