FLOODSTAND-deliverable:

GUIDELINES AND CRITERIA ON LEAKAGE OCCURRENCE MODELLING

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Abstract:
This report presents a summary of the full-scale tests and numerical calculations for leaking and collapsing of typical non-watertight structures on passenger ships. Based on the results, some guidelines for modelling these structures for time-domain flooding simulation are presented.

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1 EXECUTIVE SUMMARY

This report contains a summary of the results from the novel experimental study on leaking and collapsing of non-watertight structures carried out at CTO in Poland (Deliverable 2.1b) as well as the dedicated numerical analyses by MEC in Estonia (Deliverable 2.2a). The main emphasis is on a further analysis of the leakage ratio, based on the experimental results by CTO.

The simplified modelling of non-watertight structures in time-domain flooding simulation is reviewed. The first approach to this problem was presented in IMO SLF47/INF.6. The values were mainly just rough estimations. In this report, more reliable estimates are presented. Most notably, the experimental results clearly indicate that the so-called leaking area ratio (A_{ratio}) is not always a constant factor. Instead, in many cases the area ratio increases practically linearly until a point of significant structural failure (collapsing) occurs.

A method based on Bernoulli's equation for analysing the test results (leakage rates as function of pressure height) in order to assess the leakage area ratio for flooding simulation is described.

Finally some conclusions and general guidelines for modelling the leakage through non-watertight structures for time-domain flooding simulation are presented in a tabular format for different door types.

2 BACKGROUND

The use of time-domain flooding simulation tools has expanded as the computing capacity has increased. The applications vary from simple calculations of cross-flooding time to assessments of time-to-flood or time-to-capsize in damage scenarios with extensive progressive flooding.

It is an undisputable fact that the simulation results depend on the applied input data for the openings. Most notably, the leakage and collapsing of non-watertight structures, such as closed fire doors, can have a very remarkable effect on the time-to-flood. This issue was first raised in SLF 47/INF.6 in 2004[1], clearly pointing out the need for further research. One of the main objectives of the research project FLOODSTAND was to provide this much needed information.

Typically, the simulation tools are based on Bernoulli's theorem and the pressure losses in the openings are taken into account by applying semi-empirical discharge coefficients. In principle, the flooding rate Q through a small opening can be calculated with the following equation:

$$Q = C_D A_{eff} \sqrt{2gH_{eff}} \qquad (1)$$

where:

- C_D effective discharge coefficient (pressure losses in the opening)
- A_{eff} effective area of the opening (taking into account e.g. leakage)
- g acceleration due to gravity
- H_{eff} effective pressure head

This report concentrates on proper modelling of the effective area of the opening A_{eff} in leakage condition. Another important aspect is the upper limit of the pressure height H_{eff} when the structure is considered to collapse.

The previous investigation on the subject SLF 47/INF.6 was mainly theoretical. This is now used as a starting point and the results from both dedicated full-scale experiments and FEM calculations are utilized for obtaining more realistic guidelines for modelling non-watertight structures in flooding simulation.

Detailed description of the full-scale tests is given in *Jakubowski and Bieniek (2010)*. These experiments were first of a kind, including detailed measurements of the leakage rates and door deformations. In addition, the set of tested items was very extensive. The dedicated numerical analyses are reported in *Naar and Vaher (2010)*.

It is also worth noticing that the use of CFD tools, (e.g. volume of fluid (VOF) or smoothed particle hydrodynamics (SPH) for simulation of flooding progress does not avoid the need to model the leaking and collapsing of non-watertight structures.

[1] The original Annex of SLF47/INF.6 is included in the Appendix B of this deliverable.

3 WATERTIGHTNESS OF VARIOUS STRUCTURES

3.1 Categories

The different categories of water tightness for doors and other boundaries were presented in SLF47/INF.6, these are:

- Category A: Watertight
- Category B: Non-watertight with high restriction to flooding progression
- Category C: Non-watertight with low restriction to flooding progression

The subtypes of these categories are presented in Table 1. The Light watertight door (LWT) is new since SLF47/INF.6. Thus small adjustments on the category have been done. The main emphasis of this report is on the Category B doors, but a brief overview of Category A is also given.

Table 1: Categories for doors and other boundaries

Type:	Study:	Description
A1	–	Watertight doors (assumed to be fully watertight)
A2	yes	Light watertight doors (LWT)
A3	no	Semi watertight doors (SWT)
B1	no	Weathertight
B2	yes	A-Class fire doors (sliding and hinged)
B3	yes	B-Class joiner doors (e.g. cabin doors)
C	–	low restriction to flooding progression, such as blow out panels and cross-flooding flaps

3.2 Watertight Doors

The generally used assumption in flooding simulation is that all closed watertight doors are fully watertight. However, real accidents have proved that this is not always the truth. An example is presented in Figure 1. The analysis method, presented in this report, can also be used for watertight doors if the doors are tested and the leakage rate is measured. However, this door type is excluded from the FLOODSTAND project’s scope.

Figure 1: Leaking through a watertight door, ***Danish Maritime Authority (2008)***

3.3 Light and Semi Watertight (LWT & SWT) Doors

Description of the use and performance of the Category A doors are listed in Table 2. The arrangement of LWT and SWT doors on large passenger ships is illustrated in Figure 2. The watertight (WT) and light watertight (LWT) doors should be kept close during navigation but special exceptions may be applied if approved by the administration. On the other hand, the semi watertight doors may be kept open.

Light Watertight Door (LWT) is same as solid watertight (WT) door with exception to sustain lesser water pressure head. The descriptions in Table 2 (on/decks above bulkhead deck) explain the general guidance on the location of different door types. However, on the bulkhead deck also other door types than LWT can be used. For example, both SWT and/or WT doors may be needed, depending on the location and expected pressure head after damage.

One of the advantages of time-domain flooding simulation is to study the consequences of an open watertight door on the damage stability of the ship and on the time-to-flood. For example, the closing of the door takes some time and thus water can progress to other compartment before the door is fully closed. This can be analysed only in time-domain. Thus also these doors should be modelled even though they can be considered as watertight if closed.

Table 2: Degrees of watertightness for Category A

Definition	Action/Performance	Description	Conditions of use
Watertight	To withstand constant pressure[2] ($p > p_L$)	Under bulkhead deck	To be kept closed during navigation (special exceptions may be applied)
Light watertight	To withstand constant water pressure[3] ($p < p_L$)	On Bulkhead deck	To be kept closed during navigation (special exceptions may be applied)
Semi Watertight	Weathertight to provide positive residual stability[4]	On bulkhead deck and above	May be kept open during navigation

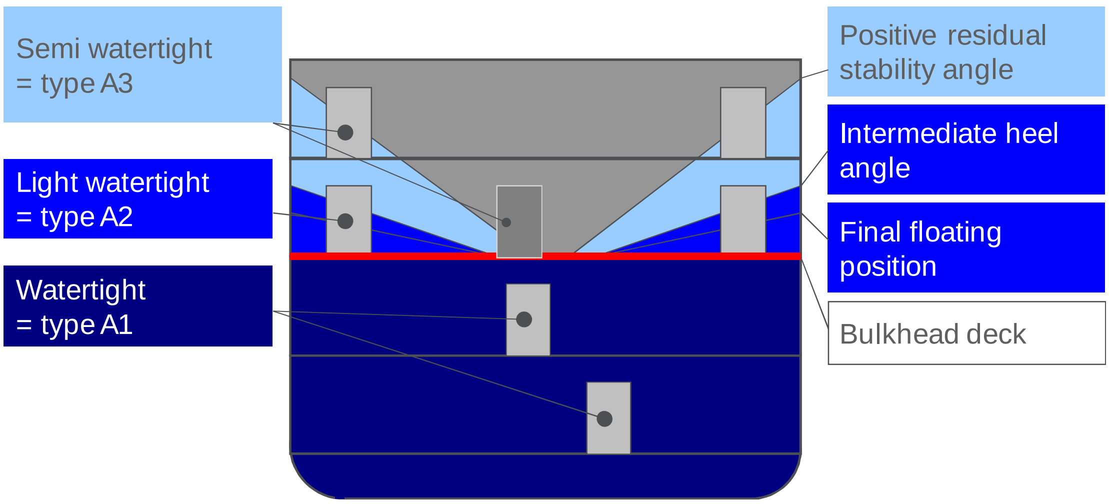

Figure 2: Category A doors in passenger ships (STX Finland)

[2] The pressure limit p_L depends on the vertical location of the door
[3] The actual maximum pressure for LWT doors depends on the door width.
[4] In SOLAS Chapter II-1 Reg. 7-2 par 1 vanishing angle is determined as follows: "the angle in any stage of flooding, where the righting lever becomes negative, or the angle at which an opening incapable of being closed weathertight becomes submerged". Thus according to rules all openings located within positive residual GZ-range (stability area) has to be provided with weathertight closing devices.

3.4 Category B

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.

Various non-watertight structures were tested by CTO in Gdansk, Poland within Task 2.1 of the FLOODSTAND project. The results of the tests are reported in Deliverable D2.1b, *Jakubowski and Bieniek (2010)*. This data is now further analysed in order to assess the leakage area ratio of the structures. Next the analysis method is described; the results are presented in section 5.

3.5 Category C

Some cross-flooding flaps and blow out panels were also tested, *Jakubowski and Bieniek (2010)*. However, these results are considered to be highly case specific. Consequently, these structures are not included in this conclusion and guidelines report. Instead, test (or numerical) results for the actual configuration should be used.

3.6 Windows

A typical window on lower decks of ships was tested at CTO, *Jakubowski and Bieniek (2010)*. It was found out that the collapsing pressure head is over 17 m. (that was the highest pressure that could be tested). The maximum measured deflection was about 20 mm. This result is in good agreement with the values presented in IMO SLF47/INF.6.

Consequently, **it seems to be justified to exclude the windows** from the numerical model for flooding simulation.

4 ANALYSIS OF LEAKAGE AREA RATIO

4.1 Leakage Area Ratio

In SLF47.INF6 a very simple approach was presented for assessing leakage through non-watertight closed doors in flooding simulation. The effective flooding area of the opening is obtained by multiplying the geometrical (submerged) area with a constant non-dimensional leakage area coefficient:

$$A_{ratio} = \frac{A_{leakage}}{A_{submerged}} \tag{2}$$

where $A_{leakage}$ is the leaking area of the opening that is leaking and $A_{submerged}$ is the area of the submerged part of the whole opening. Thus A_{ratio} is a non-dimensional coefficient.

4.2 Analysis Method

The measurements of the full scale tests at CTO, *Jakubowski and Bieniek (2010)*, can be further processed to obtain estimates for leakage area ratio. It is noteworthy that the test arrangement allowed only cases where the flow discharged freely into air.

In the test setup the water that flows through the test specimen discharges into air. Consequently, the flow rate through a vertical opening that has width b and height h is (see Figure 3 and *Ruponen 2007*) can be calculated with the following equation:

$$Q = C_D A_{ratio} b \frac{2}{3}\sqrt{2g}\left[H_{eff}^{3/2} - \left(\max\left(H_{eff} - h, 0\right)\right)^{3/2}\right] \tag{3}$$

where H_{eff} is the effective pressure head, measured from the bottom of the test specimen. The submerged area of the opening is:

$$A_{submerged} = b \cdot \left[H_{eff} - \max\left(H_{eff} - h, 0\right)\right] \tag{4}$$

By assuming that the discharge coefficient is known, the following equation for the leakage area ratio is obtained:

$$A_{ratio} = \frac{Q}{C_D b \frac{2}{3}\sqrt{2g}\left[H_{eff}^{3/2} - \left(\max\left(H_{eff} - h, 0\right)\right)^{3/2}\right]} \tag{5}$$

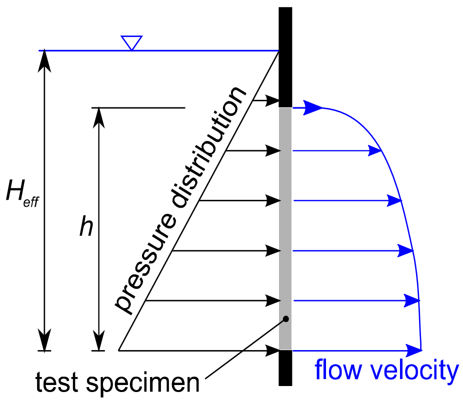

Figure 3: Distributions of pressure and assumed flow velocity for assessment of leakage area ratio from the CTO test results

4.3 Leaking through a Gap

The presented approach for accounting leakage through closed doors is based on the assumption that the leakage area is evenly distributed along the door in vertical direction. This is not fully valid, since for many doors (e.g. A-class hinged fire doors) there can be notable gap between the bottom of the door and the sill. For comparison, a further analysis was performed, assuming that the door itself is fully watertight and all leakage takes place through this gap. The situation is illustrated in Figure 4

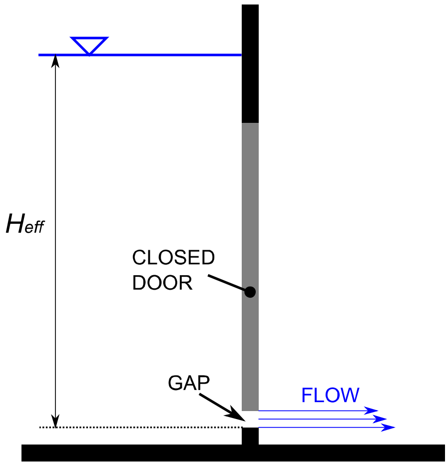

Figure 4: Leaking through gap between the door and the sill

The gap height h_{gap} can be considered to be much smaller than the effective pressure height. Consequently, if only the gap is leaking and the door itself is watertight, the flow rate through the gap is:

$$Q_{gap} = C_D b h_{gap} \sqrt{2gH_{eff}} \tag{6}$$

This has to be equal to the equation (3), and thus the area ratio can be solved:

$$A_{ratio} = \frac{h_{gap}\sqrt{H_{eff}}}{\frac{2}{3}\left[H_{eff}^{3/2} - \left(\max\left(H_{eff} - h, 0\right)\right)^{3/2}\right]} \tag{7}$$

This is based on the assumption that the discharge coefficients are equivalent. This can be further simplified for moderate pressure heights (less than the door height):

$$A_{ratio} \approx \frac{3h_{gap}}{2H_{eff}} \tag{8}$$

The area ratios for different gap heights are presented as functions of effective pressure height in Figure 5. For very small pressure heights the A_{ratio} values are very high, but quickly decreasing as the pressure height increases.

An alternative way to model large gaps is to consider them as separate openings. This makes the modelling more complicated but also more realistic.

In the following, the method described in chapter 4.1 is used to analyse the measurement data from the full-scale experiments.

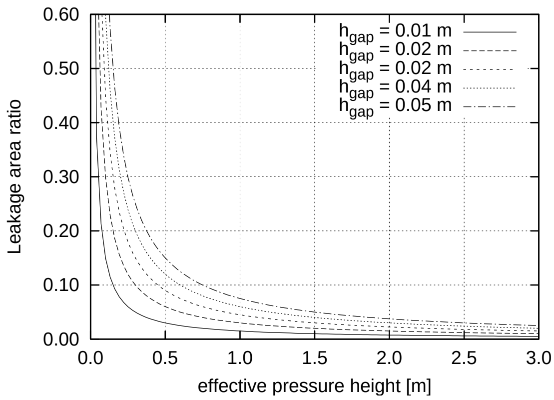

Figure 5: Average leakage area ratio for different gap heights

5 LEAKAGE THROUGH VARIOUS STRUCTURES

5.1 Light Watertight Doors

The tested door type is typically used on the bulkhead deck. It is a sliding "Light Watertight door" (LWT), that actually fills the requirements for a watertight door (category A1 in SLF 47/INF.6), but only for a smaller maximum pressure.

Leakage through the tested door started at pressure height of about 2.0 m and it was very minimal (less than 1.0 l/s) until structural damage occurred at a pressure head of about 8.0 m, *Jakubowski and Bieniek (2010)*. Even after significant structural failure, the leakage through the door was only about 40 l/s, corresponding to leakage area ratio of 0.017. The results are shown in Figure 6. Just one test was performed; the direction of the pressure was out from the doorframe. It is assumed that for the opposite direction the door could have withstood even higher pressures. Thus it seems to be justified to ignore this kind of minimal leakage in time-domain flooding simulations. Consequently, **closed semi- and light watertight doors can be considered as watertight until high pressure heights of about 8 m**. However, door-specific analysis should be considered if the door differs from the tested door.

It is also noteworthy that both the experimental results and *(Jakubowski and Bieniek, 2010)* and numerical study *(Naar and Vaher, 2010)* are in good agreement with the first test results, reported in SLF47/INF.6.

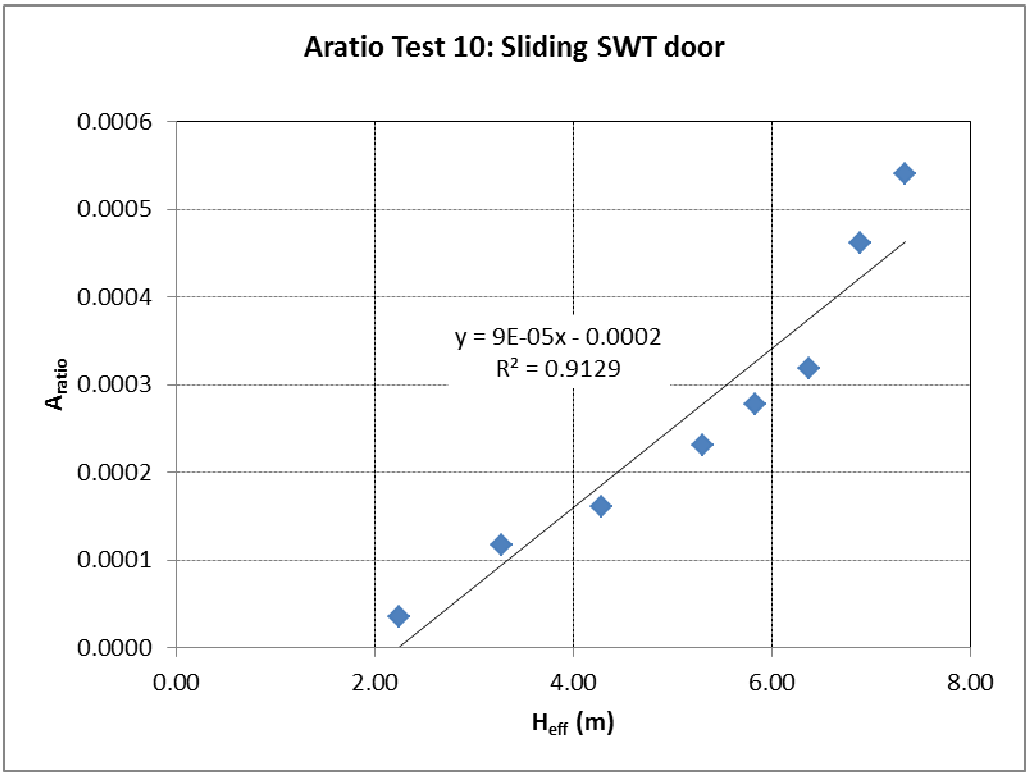

Figure 6: Leakage area ratio for the tested LWT door

5.2 A-Class Fire Doors

5.2.1 General Notes

In SLF47/INF.6 it has been properly stated that: *"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) Para 8.4.4.2 and SOLAS regulation*

II-2/9.4.1.1."[5] This is an important issue that will be discussed later. In fact, it makes it practically impossible to derive a general and accurate guideline that suits for all fire doors on a ship since the gap size may vary between the installations. The effect of the gap size was theoretically analysed in section 4.3 of this report.

5.2.2 Hinged A-Class Doors

Two different single leaf A-class fire doors were tested for both pressure directions. The doors were practically identical and from the same manufacturer. However, the gap size between the sill and the bottom of the door was different. Consequently, there is a significant difference in the leakage under the water pressure. The second door (Tests 2.3 and 2.4) was leaking so much that the maximum leakage rate of 90 l/s was achieved at very low pressure head of about 1.2 m. For this door, the direction of the pressure had only a minimal effect on the leakage rate. For the first door type (Tests 2.1 and 2.2), significant structural damage occurred at pressure height of about 2.4 m (Figure 7). Leakage was much smaller than for the second door type. Also, when pressure acted into the doorframe, leakage was even smaller. For all four test cases the calculated area ratio for leaking increased linearly as a function of pressure height.

The height of the gap between the bottom of the door and the sill has a very significant effect on the leakage rate through the door. In addition, the possible hose port in the door can significantly increase the leakage.

Figure 7: A-class hinged door leaking (left, p = 26 kPa) and damage

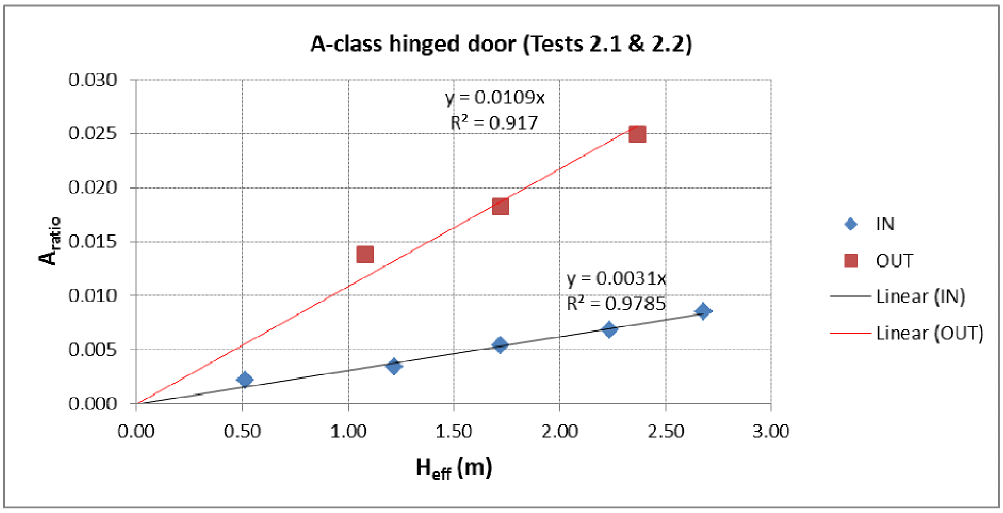

Figure 8: Calculated area ratio as a function of pressure height and a linear regression for A-class hinged door arrangement 1

[5] The reference to SOLAS has been corrected from SLF47/INF.6

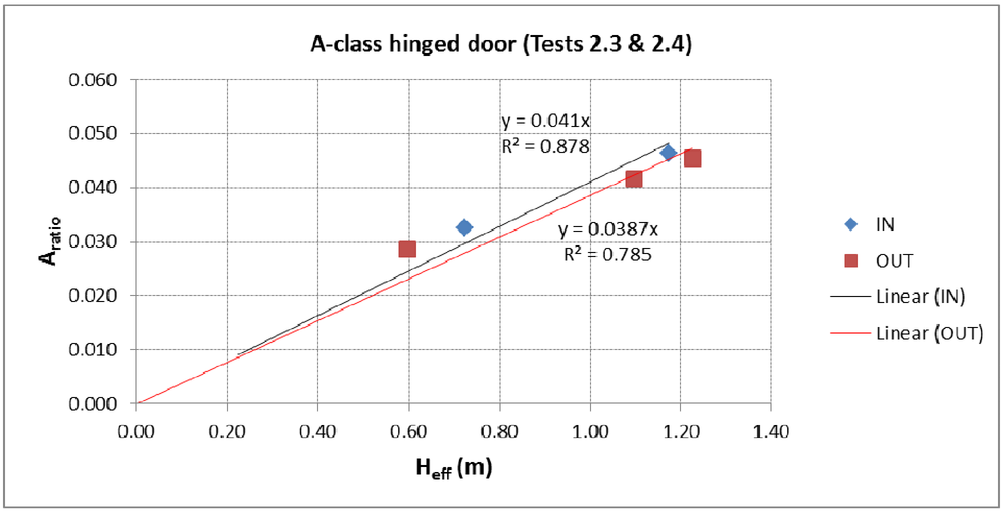

Figure 9: Calculated area ratio as a function of pressure height and a linear regression for A-class hinged door arrangement 2

5.2.3 Hinged Double Leaf A-Class Doors

One test was performed for A-class double leaf hinged door in a condition, where the pressure acted out from the doorframe. Due to the large area of the doors, the critical flow of 90 l/s was reached at low pressure height of about 1 m. Thus the collapsing pressure height could not be reached. The FEM analysis resulted in $H_{coll} \approx 2.0$ m, *Naar and Vaher (2010)*.

The calculated area ratio for leakage is about 0.025. The number of measurement points is small, but it seems that the ratio is practically constant, at least with the tested pressure heads. The leaking took place mainly underneath the doors (Figure 10).

Figure 10: Leakage through A-class double leaf hinged door (*p* = 5.1 kPa)

5.2.4 Sliding A-Class Doors

Large leakage through the door was observed in both test directions at low pressure heights. The calculated area ratio was about 0.025. Significant damage occurred also at rather low pressure of 12.8 kPa into the doorframe or 10.8 kPa out from the doorframe. That is just about a pressure head of 1.0 m, and less than the rough approximation in SLF47/INF.6. Photos from the tests are shown in Figure 11.

Figure 11: Leakage (*p* = 6 kPa) and damage to sliding A-class fire door (*p* = 12.8 kPa)

5.3 Cold Room Doors and Panels

Cold room walls and doors are considered to be a notable restriction for the progress of the floodwater. The doors are usually closed and the cold rooms are often large and asymmetric rooms on the lower decks of passenger ships. A typical sliding cold room door, installed in a small piece of cold room panel wall, was tested (Figure 12). With a pressure height of about 2.4 m, the leakage rate was 84 l/s. If only the door area is taken into account, the corresponding calculated area ratio is 0.036. With lower pressures also the area ratio was smaller. Most of the leaking was underneath the door. Collapsing could not be achieved due to the high leakage. The calculated area ratios are presented in Figure 13. The increase is practically linear, but the last measurement point at 2.4 m pressure height does not fit to this regression line. This is likely caused by significant structural deformation and it is possible that collapsing would have taken place at only slightly higher pressure. However, the FEM analysis resulted in higher critical collapsing pressure head of 3.8 m, *Naar and Vaher (2010)*.

Figure 12: Cold room sliding door in test setup (left) and leaking (*p* = 22 kPa)

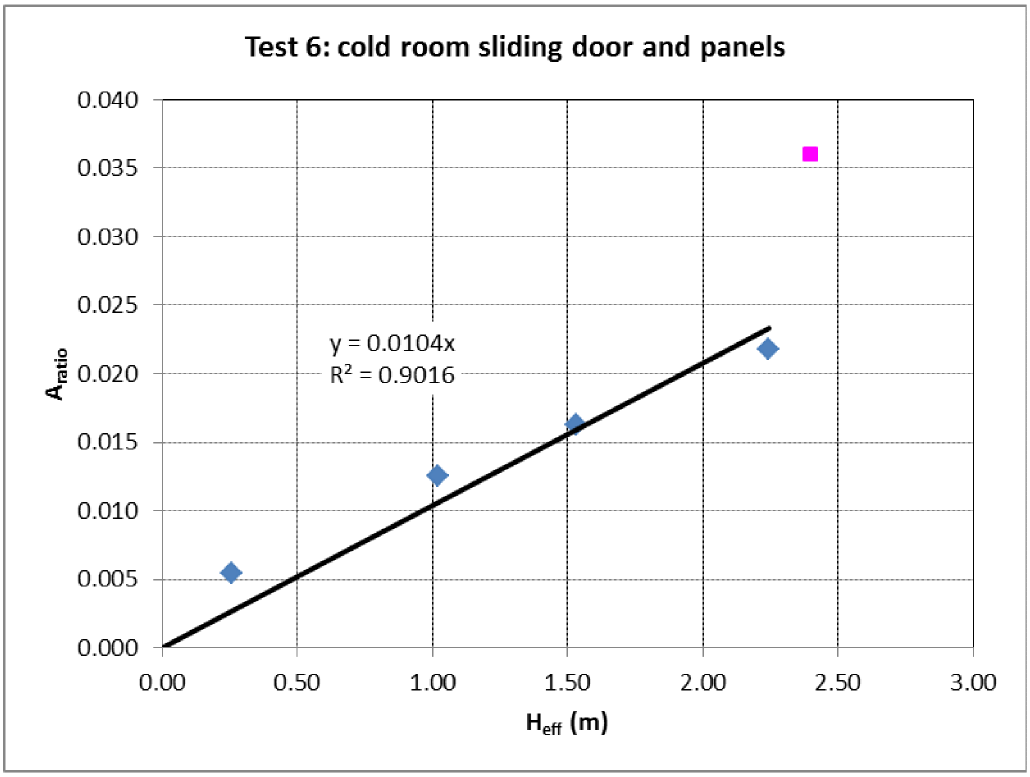

Figure 13: Leaking area ratio for the cold room sliding door

5.4 B-Class Boundaries

5.4.1 B-Class Joiner Doors

Two different kinds of B-class joiner doors were tested, both water pressure into and out from the doorframe. Most notably, the direction of the pressure had a significant effect on the structural failure (Figure 14). When the water pressure acted into the doorframe, the wall panels around the door were the weakest point. The behaviour of the two different doors was very similar. The calculated area ratios for all tested cases (two different doors, two directions) are presented in Figure 15.

Figure 14: Leakage of a B-class joiner door under 11.9 kPa pressure into the doorframe (left) and damage to the wall panels when the pressure direction was the opposite (right)

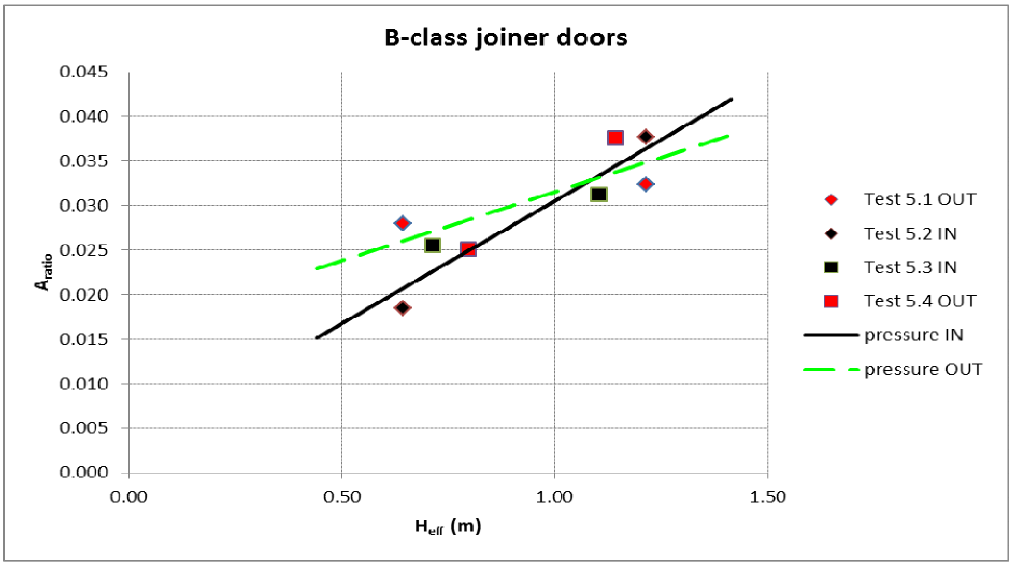

Figure 15: Calculated area ratio for all tested B-class joiner doors and linear regressions for the two pressure directions

5.4.2 B-Class Walls

B-class cabin wall with steel frames was tested for two pressure directions. In both cases, there was notable leakage through the bottom of the wall already at moderate pressure height of about 1.0 m. Most of the leakage took place through the bottom of the wall, Figure 16. Unfortunately, higher pressures were not tested. However, since the deformation of the wall is large even under a moderate water pressure, it seems likely that this kind of structures might be ignored in time-domain flooding analyses.

Both the FEM analysis for a single B-Class cabin wall panel ($H_{coll} \approx 1.12$) and the analytical solution for cabin wall element *(Naar and Vaher, 2010)* panel ($H_{coll} \approx 1.2$) are in good agreement with the CTO test results.

Figure 16: Leaking through B-class wall with steel frames

5.4.3 Conclusions on B-Class Structures

Based on the above mentioned observations from both the full-scale tests and numerical analyses on B-class joiner doors and cabin walls, it can be concluded that the failure of these structures under the pressure of floodwater cannot be modelled reliably in flooding simulation. In some cases the panels around the door can fail first. With the wall tests significant leaking occurred under small pressure heads. This implies that all walls and doors had to be modelled with high detail level.

It is believed by the authors that the exclusion of B-class boundaries in flooding simulation does not cause a very significant error in the results. However, on the decks near the sea water level this issue can be more notable. Also, it might be necessary to model e.g. large cabin areas in two parts (SB and PS side) in order to ensure that the asymmetry of the damage case is properly accounted for. These parts can be connected by large opening that starts to leak immediately when wetted.

Another aspect in the modelling of non-watertight boundaries for flooding simulation is the "free surface effect" on the stability of the ship during the flooding process. If the B-Class structures are excluded from the numerical model, the free surface effect will be over-estimated. Thus some partition of e.g. large cabin areas may be necessary.

6 GUIDELINES

If possible, experimental data for the exact door arrangement should be used. Alternatively, dedicated FEM calculations are also recommended. However, these tests and computations are very expensive and thus a more generalized data is needed.

In Table 3, rough guidelines for modelling leaking and collapsing of various non-watertight structures in flooding simulation are presented. The data is highly generalized and based on very small set of test items. If the actual item significantly differs from the tested items, a more dedicated analysis (tests or calculation) is highly recommended.

Guideline values are presented also for the B-class joiner doors, but based on the observations from the full-scale tests; it seems to be justified to exclude most of the B-class boundaries in flooding simulation models. However, some B-class boundaries may be necessary for proper treatment of free surfaces and asymmetry during the flooding process.

Table 3: Rough guidelines for modelling doors and boundaries for flooding simulation, the values marked with an asterix (*) are estimations that are not based on experimental or FEM results

Type	direction	H_{leak} (m)	A_{ratio}	H_{coll} (m)	Notes
LWT	into	–	–	8.0*	minimal leaking at lower pressures, full collapse likely for H > 8 m; note that only direction "out" was tested
	out	–	–	8.0	
A-class sliding	into	0.0	0.025	1.0	almost constant leakage area ratio
	out	0.0	0.025	1.0	
A-class hinged	into	0.0	$0.02 \cdot H_{eff}$	2.5	A_{ratio} depends on the gap size
	out	0.0	$0.03 \cdot H_{eff}$	2.5	A_{ratio} depends on the gap size
A-class double leaf	into	0.0*	0.025*	2.0*	**Not tested!** Assumed to be independent on direction
	out	0.0	0.025	2.0	Collapsing could not be tested due to high leaking, value based on FEM
Cold room sliding door	into	0.0	$0.01 \cdot H_{eff}$	3.5	Only one direction tested; collapsing pressure height assessed with numerical methods
	out	0.0*	$0.01 \cdot H_{eff}$*	3.5*	
B-class joiner door	into	0.0	$0.03 \cdot H_{eff}$	1.5	panels around the door will fail first, A_{ratio} expression is very approximate
	out	0.0	0.03	1.5	door is distorted, A_{ratio} increases slowly
Windows	–	–	–	> 18	can be excluded in simulations

7 CONCLUSIONS

The guidelines, presented in chapter 6, are based on the experimental and numerical research in the WP2 of the project FLOODSTAND. It should be noted that the set of tested items was rather limited, and consequently the presented guidelines are highly generalized, and to some extent, still based on assumptions and simplifications. This fact should be taken into account when using the presented values in time-domain flooding analyses. If newer or more reliable data is available, it should be used instead of these guidelines.

A systematic sensitivity analysis will also be carried out within the FLOODSTAND project (Deliverable D2.6 is scheduled to October 2011). That study is expected to highlight the effects of small (and very likely) variation in the actual leakage and collapsing behaviour of non-watertight structures in flooded compartments. The previous research, such as *van't Veer et al. (2004)*, indicates that there are certain critical openings, such as fire doors to staircases. The applied input parameters for pressure losses and leaking for these openings can have a very notable effect on the simulation results.

Further research on leakage and collapse of different kinds of typical non-watertight structures in ships is still needed. This should include more full scale tests. Especially, repetition tests are needed in order to find out the possible statistical variations. The performed tests with hinged A-Class doors showed that in some cases a very notable variation is possible. Thus special attention should be paid on different A-class fire doors and cold room doors/walls since these structures were found out to notably affect the flooding progression.

The present study is limited to flow conditions, where the leaking water through the structure discharges freely into air. In real flooding case also a situation, where the leaking structure is partly or even fully submerged is also likely. Therefore, further studies on the effect of flow condition on leakage and collapsing is also highly recommended.

Finally, it is noteworthy that all the tested Category B structures (A-class doors, B-class walls and doors, cold room doors, etc.) were found out to collapse or become significantly damaged under rather low pressure heights. This implies that on lower decks of the ship these structures have only a small effect on the progress of flooding within the damaged watertight compartment. However, up-flooding through staircases and flooding on the decks near the waterline are more complicated.

8 REFERENCES

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APPENDIX A: IMPLEMENTATION IN NAPA SOFTWARE

The proposed method for modelling leakage through non-watertight structures has been implemented in the time-domain flooding simulation tool of the NAPA software (forthcoming release 2011.1). The principles of the simulation tool are described in *Ruponen (2007)*. The modelling of leakage comprises of three different input parameters for each door:

- HLEAK: critical pressure head for leaking (m)
- HCOLL: critical pressure head for collapsing (m)
- ARATIO: leakage area ratio (-)

It is possible to give different parameters for different directions of the pressure. Based on the experiments, the direction of the pressure can have a very significant effect on the leakage rate, especially for hinged doors.

Originally, the leakage area ratio was assumed to be constant. However, based on the observations from the tests at CTO, this feature was enhanced to evaluate the effective leakage area ratio from the effective pressure head at each time step by using the predefined mathematical expression.

An example of opening definition is shown below and in Figure 17.

```
OPEN, D.A.14_STAIRS-R140203, 'A-CLASS FIRE DOOR TO STAIRCASE'
GEOM, DOORTUBE_D2_214/Y=0
CON,  R140STAIRS, R140203
WRC,  0.6, 0.6
HCOL, 2.5, 2.5
HLEA, 0, 0
ARAT, 0.03*HEFF, 0.02*HEFF
```

	ID	DES	ARATIO	HLEAK	HCOLL
1	D.A.14_STAIRS-R140203	A-CLASS FIRE DOOR TO STAIRCASE	'0.03*HEFF' '0.02*HEFF'	0.0 0.0	2.5 2.5
2	D.A.14_STAIRS-R140201	A-CLASS FIRE DOOR TO STAIRCASE	'0.03*HEFF' '0.02*HEFF'	0.0 0.0	2.5 2.5
3	D.A.14_STAIRS-R140101_1	A-CLASS FIRE DOOR TO STAIRCASE	'0.03*HEFF' '0.02*HEFF'	0.0 0.0	2.5 2.5
4	D.A.14_STAIRS-R140101_2	A-CLASS FIRE DOOR TO STAIRCASE	'0.03*HEFF' '0.02*HEFF'	0.0 0.0	2.5 2.5
5	D.A.15_STAIRS-R150201_1	A-CLASS FIRE DOOR TO STAIRCASE	'0.03*HEFF' '0.02*HEFF'	0.0 0.0	2.5 2.5
6	D.A.15_STAIRS-R150201_2	A-CLASS FIRE DOOR TO STAIRCASE	'0.03*HEFF' '0.02*HEFF'	0.0 0.0	2.5 2.5
12					

Figure 17: Modelling leaking and collapsing in NAPA Flooding Simulation

APPENDIX B: SLF47/INF.6

ANNEX

SURVIVABILITY INVESTIGATIONS OF LARGE PASSENGER SHIP

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

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:

$$Q = C_d * A * (g * h)^{1/2}$$

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").

$h_l > 1.0$ m and $h_c > 3.0$ m
$A_l/A_c < 0.2$

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

$h_l > 0.3$ m and $h_c > 4.0$ m
$A_l/A_c = 0.05$

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

$h_l = 0$ m and $h_c > 2.0$ m
$A_l/A_c = 0.1$

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

$h_l = 0$ m and $h_c > 1.5$ m
$A_l/A_c = 0.2$

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

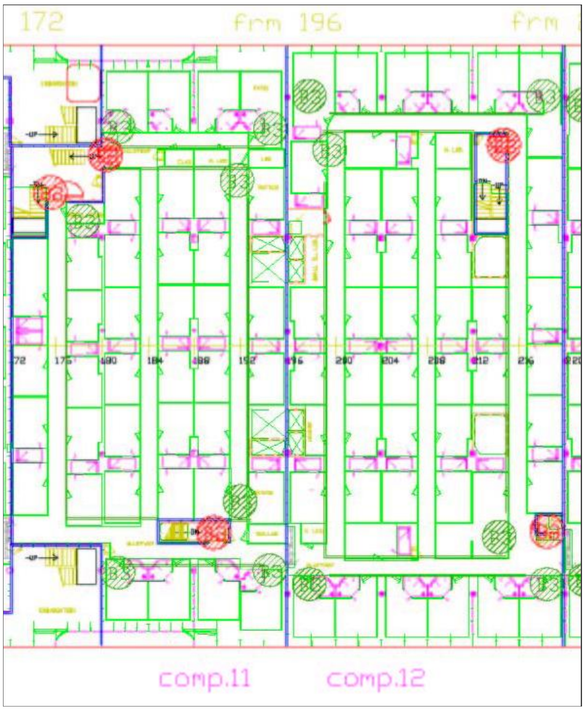
An accurate assessment of flooding process requires an accurate model of the internal compartments. But how accurate? To determine all cabins and doors to cabins in the cabin area would be a of waste time and the size of the model would become too large.

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 is it 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 deck 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.

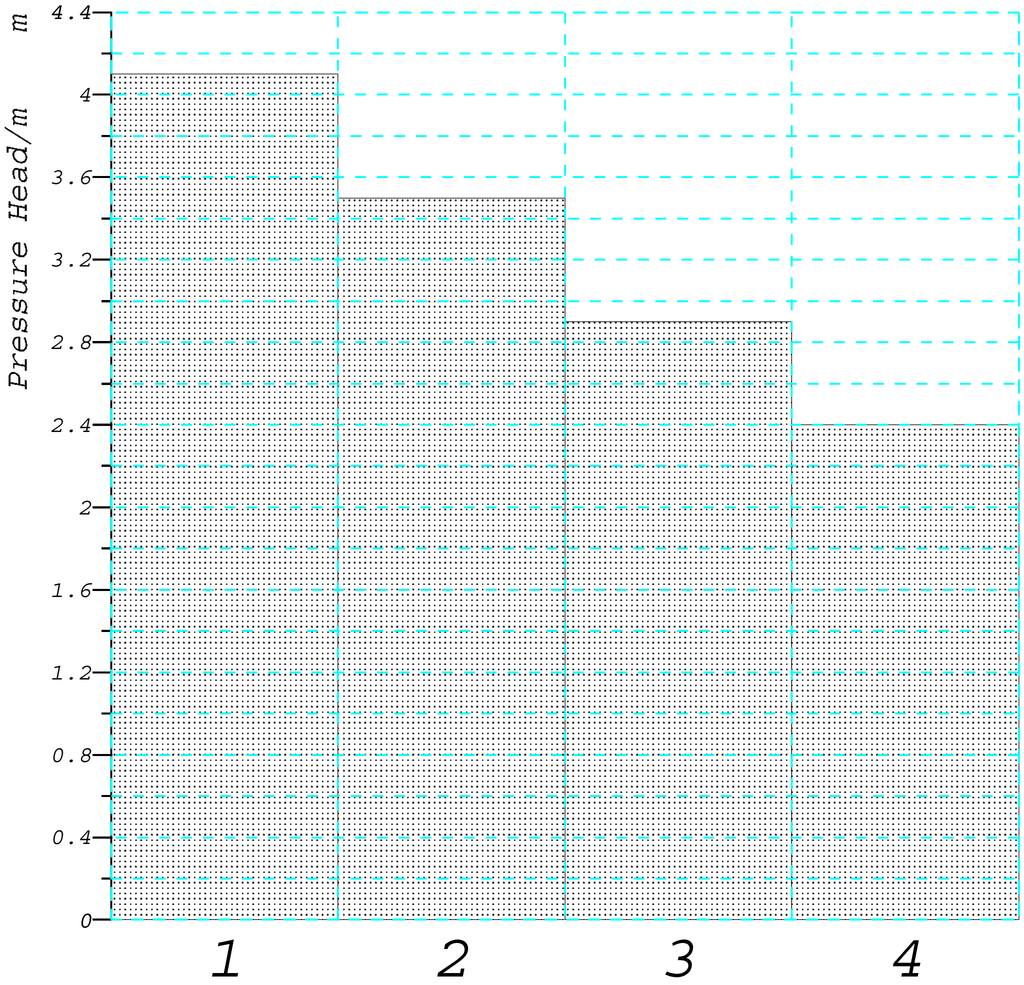
Secondly, the flow of water through any other openings except doors has been studied. The finding was, that the effect of smaller openings, e.g. open piping or cable penetrations, are of minor importance in a short time frame. While in the long time frame, the flooding through these types of openings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

***

Kvaerner Masa-Yards Turku	WATERTIGHTNESS TESTS A60-FIRE/SWT-SLIDING DOORS	DATE 03-10-31 PAGE 1(2)



Door Number	Clear opening width mm	Pressure Head m	Door height mm
1	900	4.10	2000
2	1500	3.50	2000
3	1600	2.90	2000
4	2300	2.40	2000

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.

APPENDIX 2

POS.	CLEAR LIGHT	DECK	FRAME	DISTANCE X FROM #7	THE DESING PRESSURE	MAXIMUM ALLOWABLE PRESSURE	CHOSEN GLASS THICKNESS
2	ø 350	1	107	87.8 m	168 kPa	241 kPa	15 mm
2	ø 350	1	196	167.0 m	175 kPa	241 kPa	15 mm
2	ø 350	1	265	228.0 m	237 kPa	241 kPa	15 mm
1	ø 350	1	281	242.0 m	258 kPa	392 kPa	19 mm
4	ø 450	2	12	4.0 m	159 kPa	238 kPa	19 mm
3	ø 450	2	28	17.5 m	145 kPa	146 kPa	15 mm
3	ø 450	2	55	42.8 m	123 kPa	146 kPa	15 mm
6	2*(525*1100)	2	59	45.8 m	128 kPa	149 kPa	25 mm
9	2*(525*1100)	2	65	50.8 m	125 kPa	149 kPa	25 mm
6	2*(525*1100)	2	106	87.3 m	105 kPa	149 kPa	25 mm
6	2*(525*1100)	2	186	158.3 m	108 kPa	149 kPa	25 mm
6	2*(525*1100)	2	243	208.5 m	150 kPa	149 kPa	25 mm
5	ø 450	3	2	1.8 m	96 kPa	146 kPa	15 mm
11	2*(845*1740)	3	62	48.5 m	71 kPa	83 kPa	25 mm
11	2*(845*1740)	3	102	84.1 m	52 kPa	83 kPa	25 mm
8	ø 1100	3	117	96.8 m	38 kPa	40 kPa	19 mm
8	ø 1100	3	149	125.5 m	35 kPa	40 kPa	19 mm
12	2*(695*1440)	3	121	100.4 m	45 kPa	49 kPa	19 mm
12	2*(695*1440)	3	186	158.3 m	51 kPa	49 kPa	19 mm
7	ø 1100	3	200	170.0 m	45 kPa	69 kPa	25 mm
7	ø 1100	3	243	208.5 m	68 kPa	69 kPa	25 mm