Exploring the Influence of Different Arrangements of Semi-Watertight Spaces on Survivability of a Damaged Large Passenger Ship

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SUMMARY

The transient and progressive flooding of a complex labyrinth of compartments as found on large passenger ships is studied with a numerical non-linear time domain code. Earlier papers showed that such a tool can increase the awareness of how water floods through the ship and which parameters are important for ship survivability with respect to flooding. (Van 't Veer et al, 2002, 2003) This paper presents results from a study carried out to investigate the influence of different arrangements of semi-watertight space on the survivability of a damaged (unbuilt) large passenger ship. It is shown that the location of a single down-flooding point and its kind of protection against flooding can significantly influence the intermediate flooding conditions. It is shown that survivability decreases with increasing wave height and wave steepness. Different aspects in numerical transient and progressive flooding simulations are reported.

1 INTRODUCTION

When a ship loses its watertight integrity, whether by collision, grounding or an explosion, it is subject to the risk of sinking or capsizing. The most effective way to protect the ship against progressive flooding is by internal subdivision using watertight transverse and/or longitudinal bulkheads.

The consequence for the ship when losing its watertight integrity depends not only on the subdivision itself, but also on factors such as: the actual damage extent, its location, initial GM and the sea-state. Based on statistics of past accidents one defined the probabilistic approach for damage stability. This concept was adopted by IMO resolution A.265 (VIII) in 1973. It was introduced into SOLAS regulations for passenger ships in 1978. The probabilistic method includes a set of regulations which consists of a standard and a method of calculating that standard. Recent study in the EU HARDER project has lead to a number of proposals (Ref. SLF 46 and 47 sessions at IMO) to modify the existing regulations considering up-to date collision databases and new insights in behaviour of damaged ships.

In general, the subdivision of a ship is considered sufficient if the subdivision index A is not less than the required subdivision index R. The attained subdivision index A is derived by a summation of partial indices from all damage cases using the formula: $A=\sum p_i*s_i$, where p_i accounts for the probability that only the compartment or group of compartments under consideration may be flooded, disregarding any horizontal subdivision, and s_i accounts for the probability of survival after flooding including the effect of horizontal subdivision. Within a given subdivision a watertight area can be further divided in non-watertight compartments, such as cabins. These compartment boundaries are not considered effective for the survivability of the ship and are as such not considered in traditional damage stability calculations.

This paper focuses on the probability of survival (s-factor) using time-domain flooding simulations. The proposals from SLF 47 will be used to define survivability.

Example simulations are performed using an unbuilt large passenger ship with a typical deck layout and using a three-compartment damage (beyond SOLAS). The damage reflects an imaginary striking bow-damage above the waterline and a bulbous bow penetration below the waterline. The damage length is 24 m or 0.1*Lpp, see *Figure 1*. The location and size of the damage were not varied in this study.

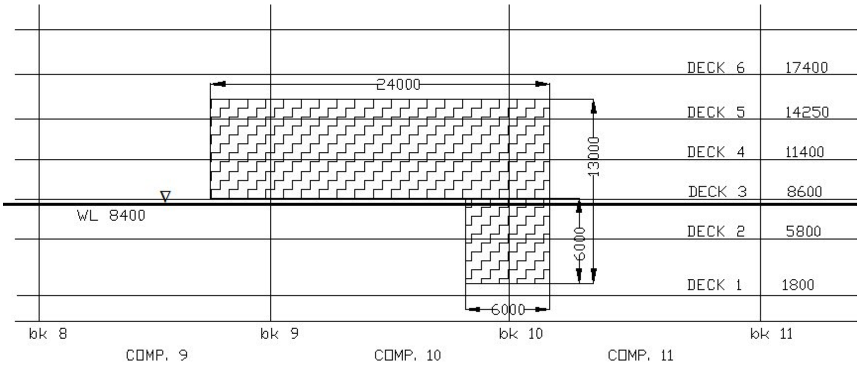

Figure 1: Imaginary three-compartment damage due to a striking bow above the waterline and a penetrating bulbous bow damage below the waterline.

1.1 Survivability

A definition of survivability is difficult, because many aspects affect the survivability of the ship after an accident that leads to flooding.

Considering the many threats for a ship with respect to flood water ingress the following aspects can be considered as limiting factors on the habitability:

- a significant final equilibrium heel;
- large intermediate heel angles, which for example prevent the use of life saving equipment, or lead to breakdown of crucial systems;
- blockage or hindering of escape routes;
- required closure of a subdivision leading to possible human life entrapment;
- breakdown of active damage control possibilities.

It remains difficult to pinpoint specific criteria for each threat but the following are related to current regulations or proposals concerning passenger ships:

- final heel should not be larger than 7 degrees;
- intermediate heel should not exceed 15 degrees;
- people should be able to move to the mustering stations and remain safely on board until evacuation for at least 3 hours after initial damage.

A drawback of the current regulations and general applied static stability assessments is that none of them can indicate survivability in terms of time. Nor is it possible to derive realistic intermediate flooding conditions based on progressive flooding in time, or to include the wave actions imposed on the ship in a proper realistic manner.

In MSC 78/WP.14 paper performance based criteria are proposed for LPS, such that after a fire or collision:

1) The ship can return to port safely; or
2) The ship remains habitable for at least 3 hours for evacuation.

In those 3 hours the ship condition must be such that all survival craft can be launched with their full complement of persons.

In addition to the above, the following goal based criteria should be added in view of the recent revision of the SOLAS regulations, in particular Ch. II-1, Reg. 7-2;

1. Horizontal evacuation route on bulkhead deck is not allowed to immerse in final stage of flooding;
2. Any vertical escape hatch in the bulkhead deck is not allowed to immerse in intermediate of final stage of flooding.

1.2 Direct simulation approach

This paper present results of time domain simulations from which direct assessment of the time varying survivability is possible.

The ship motions are solved at each time instant accounting for the forces from flood water and waves. It is than possible to judge the results against the dynamic criteria as mentioned above.

The benefit of this approach is that, within the assumptions of the approach, realistic intermediate flooding conditions are obtained, since the behaviour of the damaged ship is simulated in time starting with an intact ship.

The flood water progress through the ship is subject to the definition of compartments and openings between them. To assess the design, it is therefore essential to capture all relevant openings and compartment boundaries which will hinder the flow in its ingress and progression. The final flooded ship condition is now affected by the intermediate flooding stages. With the traditional static naval architectural approach one cannot assess the intermediate flooding stages since the distribution of water unknown, and one can only assume that the final equilibrium condition is not influenced by it. Clearly, there will be flooding scenarios where this is very true, so that the traditional methods used provide adequate assessment of the final flooding stage for many flooding conditions.

The time domain simulations can be performed in calm water or in any sea-state to study the effect of wind and waves. Again, the traditional flooding calculations are limited to the calm water condition, neglecting possible additional flooding due to wave 'pumping'.

Where calculations for the probabilistic method only require accurate modelling of the damage zone, the direct flooding simulations, as applied in this paper, require a detailed set-up of the internal space of the ship with all relevant openings such as doors and down-flooding openings between decks. This means that full knowledge of the ship layout in all its details is needed, which is a challenging task since the large passenger ships in particular are extremely complex. It also leads to discussion which details must at least be included since in reality one lacks computing power to model the ship as it will be built with all construction details.

This paper discusses the latest findings in time domain flooding simulations and is a sequel to the initial study reported to IMO (SLF 46/INF.3). A review by experts of these first results was presented to IMO in SLF 46/8. The recommendations were followed and the results are reported in this paper.

2 BACKGROUND OF THE APPROACH

2.1 Flooding of compartments

The time domain simulation program (FREDYN) has been described in previous publications, e.g. by De Kat et al. (2000). A hydraulic flow model is used to calculate the progress of water flow between compartments. This model assumes that the flow velocity inside a compartment is zero. An empirical discharge coefficient accounts for the vena contracta of the flow through the opening between compartments, where the fluid is considered inviscid.

Air that is displaced by flood water is assumed to vent freely. A previous study (Palazzi and De Kat, 2002) has shown that air flow within flooding compartments may reduce the rate of flood water ingress. However, the incorporation of this factor requires further detailed modelling that was beyond the scope of this project.

2.2 Practical assessment of compartment boundaries

The first study report on time domain flooding (SLF 46/INF.3) showed that an accurate assessment of the flooding process requires an accurate model of internal compartments and the openings between them. Recently an assessment was published (SLF 47/INF.6) that considered the characteristics of three main categories of boundaries: 1) doors, 2) piping and 3) ventilation and windows.

To characterise an opening the following parameters are identified:

- h_L = a static pressure head at which leaking starts,
- A_L = a portion of opening area through which leaking occurs,

- h_C = a static pressure head at which the obstruction collapses, and
- A_C = the opening area after collapse of the obstruction.

The objective of the practical assessment was to define these parameters for different classes of openings. 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. The simulation program FREDYN has been modified so as to include the above effects in the internal geometry modelling.

Watertight sliding doors used under the bulkhead deck are assumed not to leak or to collapse, and as such, the watertight sliding doors below the bulkhead deck are not included in the list of openings for numerical simulations.

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. If the area is not submerged in any stage the restricting structure (door) may be of weather tight type.

2.2.1 Weathertight doors

Weathertight doors do not remain watertight when a certain pressure difference over the door opening is present. Due to the lack of tested weather tight doors, the true collapse and leakage pressure are not known. But weathertight is assumed as high collapse pressure (h_C = 4 m) and low leakage when the pressure exceeds 0.3 m.

A Class Fire Doors are assumed to have zero leakage pressure, referring to the allowable gap beneath the fire door or 6 mm (resolution A.754 (18) and SOLAS regulation II-2/8.4.4.2). A moderate to high collapse pressure is assumed of 2 m.

B Class Joiner Doors are typical cabin doors. A ventilation opening is permitted in the lower portion of such doors so that the leakage pressure is again zero. The collapse pressure is assumed to be low to moderate, 1.5 m.

Table 3 summarizes the definition of openings considered in this study.

Table 3: Definition of door types in simulations.

Door type	h_L [m]	h_C [m]	A_L/A_C
Weathertight doors (hinged splashtight doors)	0.3	4.0	0.05
A Class fire doors	0.0	2.0	0.1
B Class joiner doors	0.0	1.5	0.2

2.2.2 Piping

It is assumed that all penetrations carried through subdivision watertight bulkheads below the bulkhead deck are constructed and arranged such that they remain intact. Open AC-canals, electrical cableways and grey/black water piping are assumed to not allow progressive flooding. The validity of this assumption, especially in the later flooding stages, requires further investigation and confirmation.

In general, regulation prescribes that the connections between adjacent (partial) watertight compartments shall be located on centre line side from the watertight/weather tight area.

The 'immersion limit line' determines which area of the bulkhead deck is to be made watertight

2.2.3 Port-lights and windows

It is assumed that all port-lights and windows remain intact during the simulations. Based on the required maximum allowable pressure head, and the requirement that the hull for intact stability is assumed to reach at least up to deck 6, this assumptions seems justified (see SLF 47/INF.6)

It is noted that in the final JAIC report of the 'MV Estonia' accident the impact pressures from the waves pounding on the ship was indicated as a plausible cause leading to the collapse of the windows that contributed largely to the tragically sinkage and capsize. As such, SLF 47/INF.6 recommends to perform tests to establish the leakage and collapse pressure threshold for windows and port-lights, especially those that are located in the 'intact stability hull'.

2.3 Probability of survival

The objective is to calculate time series of the ship motions, and in particular of the roll motions since criteria are based on heel. The time trace is evaluated and the probability of survival is zero (s=0) when the heel angle exceeds 15 degrees within 3 hours or when the final equilibrium is larger than 7 degrees. The latter criterion does not specifically mention that the final flooding condition should be reached within 3 hours. To limit the calculation time, simulations of 6 hours duration are performed.

The time domain simulations are performed with the FREDYN code. The motion equations are solved at each time instant using pressure integration under the actual wetted surface (non-linear force component), but with linear, 3D diffraction and radiation forces.

For simulations in irregular waves, long-crested Jonswap wave spectra were generated. Varying the random phases of the individual waves in the spectra leads to varying wave realisations with the same spectral density.

All simulations in waves were carried out in beam seas with zero forward speed.

In case of damaged ship simulations in waves we are concerned with transient random data. There is a clear defined beginning (the intact situation) and end (the final equilibrium for example) to the data. This means that one must repeat the experiment or simulation over and over again under similar (sea-state) conditions to obtain a collection of suitable records to derive the probability of survival.

In *Figure 2* a schematic view is given on the probability of survival for a particular damage condition. Below a certain sea-state the ship will not reach critical conditions and is considered survivable with s=1. Clearly, this includes the calm water result. With increasing sea-state it can be expected that survival time decreases and that at some point a criterion is exceeded and that for that particular run s=0. However, another simulation in the same sea-state but in a different sea-state realisation could have s=1. This means that the survivability of the ship in that particular sea-state is a weighted average of all runs.

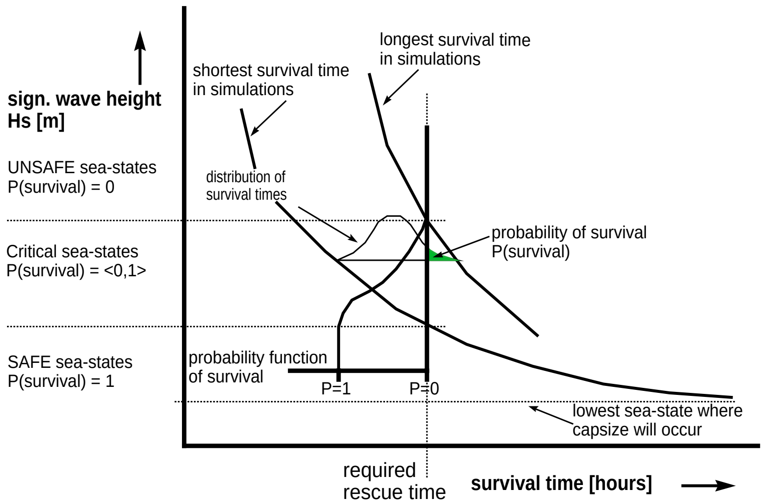

Figure 2: Probability of survival can be obtained by given rescue time and estimated distribution functions of survival time (from numerical simulations) in the critical sea state area.

Since long-duration time domain flooding simulations are still quite time consuming for complex ships such as a large passenger ship, calculation speed is about 2.5 times faster than real time, it is essential to limit the number of runs.

Therefore, the scenarios under investigation were limited to sea states of 3.5 m significant wave height and less. This is in agreement with statistical data that most flooding accidents occur in these sea states. The test conditions are based on the wave scatter diagram from the North Atlantic Annual Bales data, given in *Figure 3*. To limit the number of simulations further, first a set of calculations was performed using the steepest waves with Hs ≤ 3.5 m.

From this the most critical condition was selected and 10 simulations were executed for this scatter diagram entry. Based on the statistics of these runs the probability of survival could be calculated in that particular sea state.

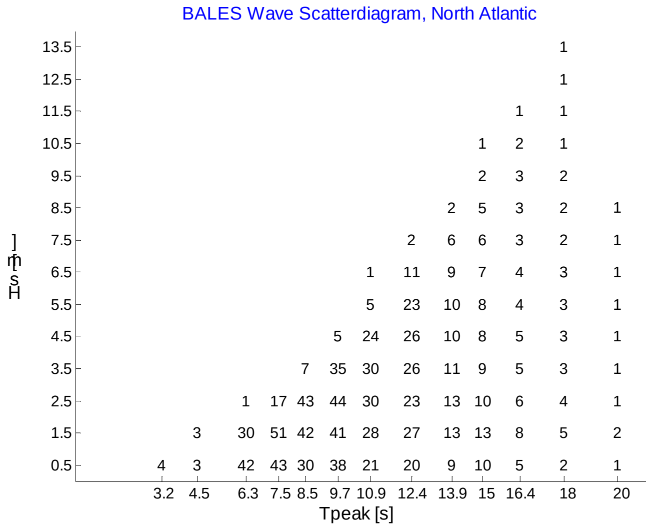

Figure3: Bales Wave Scatterdiagram for the North-Atlantic.

3 LARGE PASSENGER SHIP DETAILS

A noted shipbuilder of large passenger cruise ships provided the general arrangement drawings of a large unbuilt passenger ship useful for studying dynamic flooding. Support was given to understand the complexity of the ship in all its relevant details.

The main particulars can be found in Table 4 and a small body plan is given in *Figure 4*.

Table 4: Large passenger ship main particulars and intact loading condition

SHIP PARTICULARS	VALUE
Length overall	289.605 m
Length between perpendiculars	242.280 m
Breadth moulded (deck 9)	40.20 m
Breadth moulded (deck 8 and below)	36.00 m
Bulkhead deck (deck 4)	11.40 m
Summer load draft (moulded)	8.45 m
Intact LOADING condition	
Draft	8.40 m
Displacement	53010 tons
Trim	0.0 m
GM transverse	2.10 m

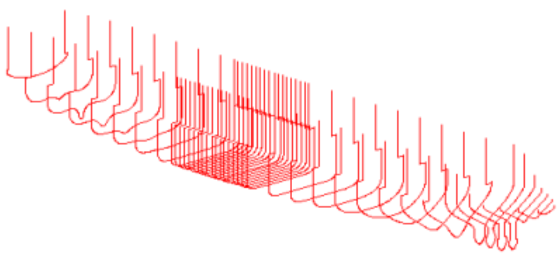

Figure4: 3D hull lines of the LPS. The knuckle point in the side is at deck level 7 (20.0 m). Lines extend up to deck 15 (40.0 m). Significantly more stations around the damage location.

3.1 Loading condition for three compartment damage

For the three-compartment damage, an intact GM condition of 2.10 m was defined by the ship designer. According to the proposed regulation from the document SLF 47/3/1 for SLF 47, Ch II-1 Part B Reg. 7.2 (3.1), the survivability factor for final flooding is:

$$s_{final} = K \cdot \left[\frac{GZ_{\max}}{12} \cdot \frac{Range}{16} \right]^{1/4}$$

where *Range* is not to be taken as more than 16 degrees and GZmax is not taken as more than 0.12 m. The factor K equals 1.0 when the equilibrium heel angle is less than 7 degrees as zero when greater than 15 degrees, and varies between zero and unity for intermediate heel angles.

For the three-compartment damage, the designer provided the following damage stability parameters:

$$\left.\begin{array}{ll} \theta_e = 2.658 & [\text{deg}] \\ Range = 13.031 & [\text{deg}] \\ GZ_{\max} = 0.134 & [\text{deg}] \end{array}\right\} \Rightarrow s_{final} = 0.95$$

When during intermediate flooding the heel angle exceeds 15 degrees the s_i factor from this damage will reduce to zero, otherwise the maximum is to be taken from the s_{final} and $s_{\text{intermediate}}$, where the intermediate survivability factor is obtained from the proposed formula in regulation 7.2 (2):

$$s_{intermediate} = \left[\frac{GZ_{\max}}{0.05} \cdot \frac{Range}{7}\right]^{1/4}$$

The above approach requires calculating the GZ curve for the damage ship for all intermediate flooding stages, and as such, is based on a quasi-static approach which does not allow easy comparison with dynamic simulation results.

3.2 Compartment details

All compartments are modelled with permeability according to SOLAS regulation:

- Permeability = 0.95 for spaces occupied by accommodation
- Permeability = 0.85 for spaces occupied by machinery

The watertight bulkheads define the subdivision. They extend up to deck 4, which is located 3.0 m above the calm water plane. The watertight doors in these bulkheads are assumed closed and intact during the simulations.

3.2.1 Downflooding points

There are no connections on deck level 1, 2 or 3 between the subdivisions 9, 10 and 11, apart from watertight doors which remain intact by flooding. To escape from deck 1 in case of emergency, one or two vertical escape openings to deck 2 exist in each subdivision 9, 10 and 11, and similar number of escape openings connect deck 2 and 3. Such openings act as downflooding points between the decks, and as such, the location is very important for progressive flooding. Other than these defined openings between decks, the decks are assumed to be watertight.

The escape points are all protected by a small compartment and it will be shown that it is important to model these compartments and their protection (fire-doors) properly. As an example the escape point in subdivision 9 between deck 2 and 1 is shown, see *Figure 5*. An opening (stairs) to deck 3 is seen as well, which is located near the escape point to deck 1, but watertight boundaries restrict direct flooding between the openings in deck 2 and 3. All such boundaries need to be taken into account throughout the ship. The direction of the hinged doors might influence the flow behaviour as well, but this level of modelling has not been considered yet.

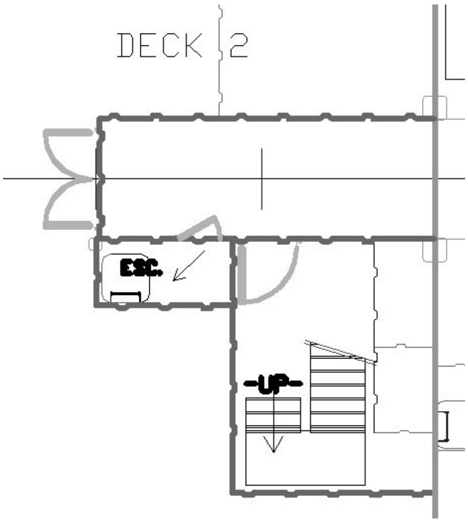

Figure 5: Deck 2 detail near the centreline in subdivision 9. A protected downflooding point (ESC) to deck 1 is seen as well as a protected upflooding (UP, stairs) to deck 3. The small compartments and their protection need to be modelled.

3.2.2 Longitudinal bulkheads

In several large compartments longitudinal bulkheads are present as seen in the drawings. Such boundaries limit the flood water flow between port and starboard extreme ends of the ship and it is important to include them in the set-up. It is important to recognize that many flow obstruction items (such as machinery equipment) will reduce the flow velocity in a large compartment. The hydraulic model assumes a zero flow velocity in a compartment and an instantaneous flood water distribution with always horizontal surface.

Typical cabin areas consist of many bulkheads with openings between them, defining a large number of non-watertight cabins. The philosophy in this study was to group a number of cabins into a larger area and to create an opening reflecting the total area of all connections. An example is shown in *Figure 6*.

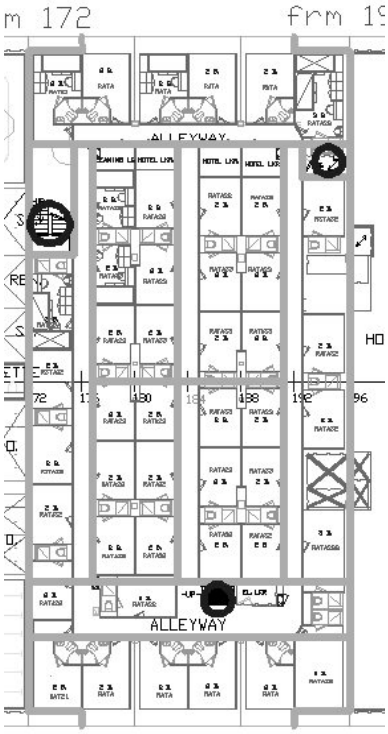

Figure 6: Typical example of watertight boundaries in a cabin area (deck 3). The openings between the area are not given. The circles represent down flooding points.

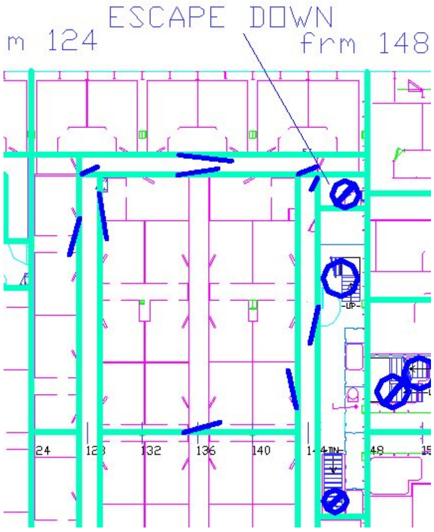

Figure 7: Two downflooding points near frame 148 in compartment 9 (between frame 124-148) are presented by the circles. The solid lines are compartment boundaries. The door openings are schematically given. The protection of the one near the damage side (marked escape down) has been varied.

4 SIMULATION RESULTS

4.1 Effect of a single downflooding point in calm water and in waves

The effect of the type of protection of a single down flooding point can make a large difference in intermediate flooding condition. An example is given in *Figure 8*. The protection of the down flooding point (escape area) was modelled as open, closed by a fire door, closed by a cabin door, and watertight. The drawing shows fire door protections near all escape areas, and this modelling was used in all other simulations. The down flooding point under consideration connects deck 3 and 2 and is located about 6 m from the damage in the shell at portside. It is the first down flooding point the water reaches on this deck in this compartment. When the flooding continues in time one other down flooding point, located around centreline, is reached, see *Figure 7*.

The simulation results suggest a strong effect on the intermediate flooding conditions in calm water, but not so much on the final flooding stage. See *Figure 8*. When the opening remains closed, downflooding to the lower deck can only take place after a considerable amount of flood water has entered ship and the downflooding through centreline openings occurs. The lower the collapse pressure of the door, the sooner deck 2 will be flooded which decreases the roll angle since the compartment on deck 2 extends from port to starboard. The difference between a fire door protection and the open door modelling was marginal.

An interesting observation is that the maximum roll angle towards the damage is not so much changed (from 10 to 12 degrees) but that the time event of this maximum heel is very different (from half an hour to one and a half hours). All simulations show a first roll peak only a few minutes after damage, and a decreasing roll towards 2 degrees within 15 minutes. As soon as downflooding starts the list angle increases which can be explained by the fact that the water will flood to the lower corner of the compartment. Only when the filling grade of the lower compartment increases the flood water mass will bring the ship back to a smaller list angle.

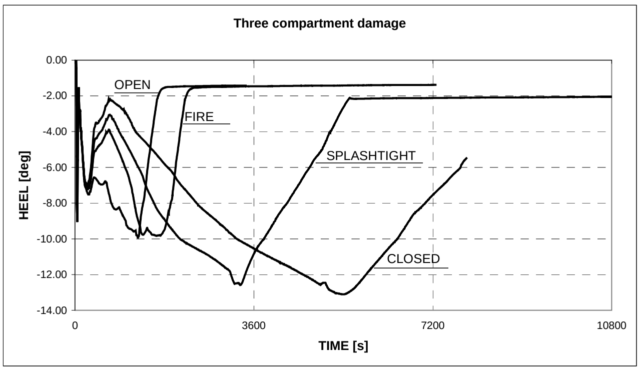

Figure 8: Effect of the protection of a single down flooding point on intermediate flooding conditions in calm water.

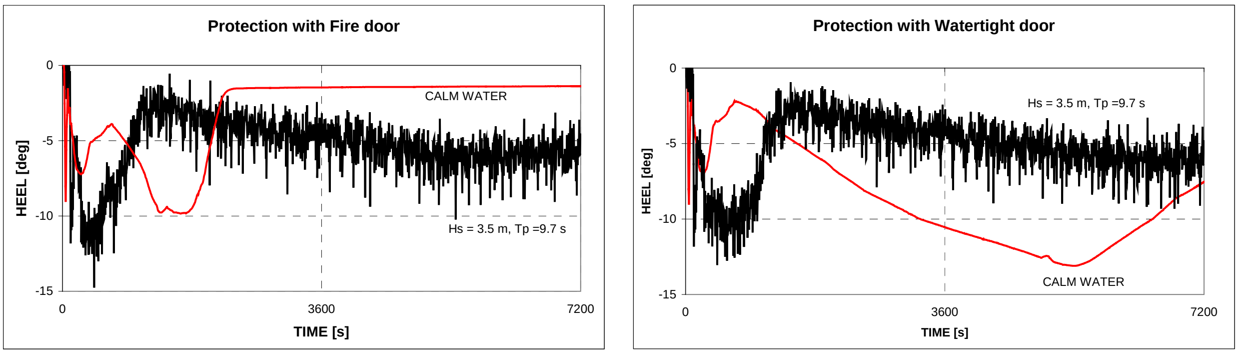

Figure 9: Response of the ship in calm water and in waves with two different protections of a single down flooding point (fire door and watertight door).

The effect of the type of protection of this single downflooding point in waves is presented in *Figure 9*. It is clearly seen that in this sea state the effect of the protection of the downflooding point on the roll behaviour is very different than in calm water. The response of the ship is in fact very comparable in both simulations. This indicates that in (more extreme) waves the simulations in calm water are not a good measure for the response of the ship. The progressive flood water spills through the other downflooding point in compartment area 9 in a much earlier stage. This is an effect of the water being pumped into the ship by the higher waves.

4.2 Effect of longitudinal boundaries in lower compartments

The drawings of the unbuilt design show a number of longitudinal semi-watertight boundaries. These have been modelled to represent the ship, but simplifications were made to obtain a useful numerical model. The methodology has been explained in chapter 3.

The physical models used to validate the hydraulic flow model over the past years all had a simplified internal compartmentation with a limited number of compartments since a complex model as studied here is extremely difficult to realize for model testing purposes. A complex physical model such as the one made numerically for the present study has not been constructed or tested so far.

The modelling of (non-watertight) longitudinal and transverse bulkheads and other major objects is important in damaged areas open to the sea. When neglecting such obstructions, the water will flood much faster into the ship leading to a different roll response. This is especially true for symmetrical, large compartments extending from port to starboard. The hydraulic flow model instantaneously ‘distributes’ the water between port and starboard shell and hence no roll moment will be present. The results in *Figure 10* can be compared with those in *Figure 9* and the difference in response is found to be very significant. The survivability in waves is decreasing while the ship in calm water lacks the large intermediate heel angles.

The results suggest that a correct modelling of all boundaries and the openings in those bulkheads is very important. Large machinery spaces which are open to the sea need to be modelled correctly.

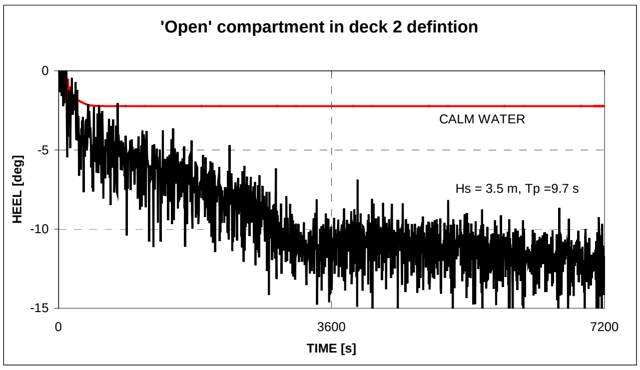

Figure10: Effect of removing a single longitudinal boundary in the machine engine room. The results should be compared with those in Figure 9, which include the longitudinal boundary.

4.3 Effect of wave steepness

The shorter the wave period, the steeper the waves will be. In FREDYN long-crested waves are used and the spectrum is created by linear superposition. Thus, non-linear waves are not considered in this study. This would increase the local wave steepness in the wave crests.

Figure 11 shows results of simulations in different sea states of 2.5 m significant wave height. In *Figure 12* the results are shown for a number of sea states with a significant wave height of 3.5 m.

Both figures suggest that the roll response is affected and that the steeper waves lead to, in general, a larger list after some time. The roll response of the damaged ship is detuned from the peak period of the waves so that vertical relative motions are the driving phenomenon for pumping water into the ship. The steeper the waves the more critical wave crests are experienced in the same amount of time and the greater tendency that the roll period will be detuned from the wave period.

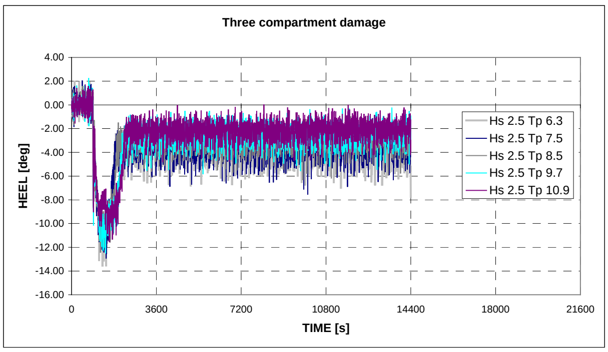

Figure11: Effect of wave steepness on the roll response in Hs = 2.5 m

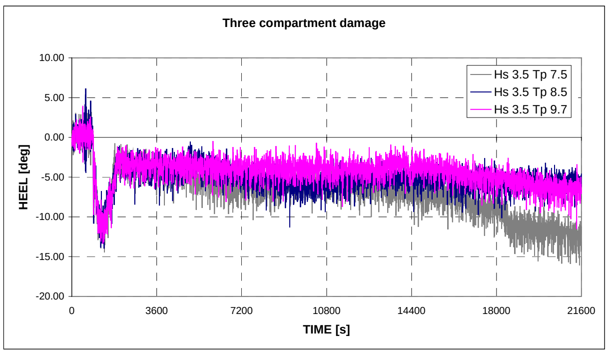

Figure 12: Effect of wave steepness on the roll response in Hs = 3.5 m

4.4 Effect of sea state realisation

A sea state is constructed from superposition of a number of wave components with different wave amplitude and random phase, such that the spectral density defines the spectrum. Variation in the phases introduce different sea state realisation and in critical conditions the behaviour of the ship in time will be different leading to variations in time to flood.

In *Figure 13* a number of time domain simulation results are given in different sea state realisations. The roll response is filtered and only the mean roll response is shown. Two criteria lines are given; 7 degrees heel and 15 degrees heel. As can be seen, in four realisations the mean heel remains below 7 degrees, while in two other realisations the mean heel is significant larger than 7 degrees after 6 hours of progressive flooding. The difference in the first heel towards the damage is marginal. The maximum heel remains below 15 degrees in all simulations within 6 hour time span, but as can be seen there is not always an equilibrium roll angle reached.

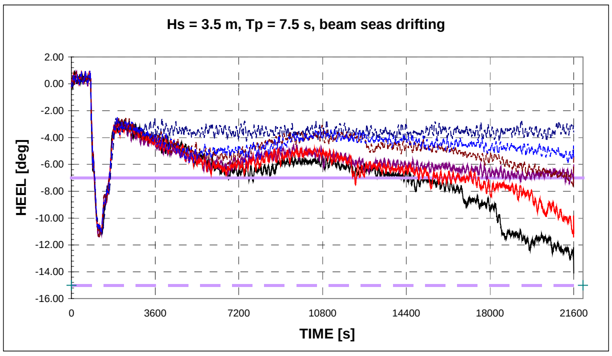

Figure13: Effect of seastate on the heel of the ship during flooding in beam seas condition.

4.5 Survivability

A large number of simulations should be carried out to investigate properly the survivability of the unbuilt large passenger ship in waves. The framework has been outlined in this paper.

The results so far suggest that the first roll response of the ship after damage is significant. But it should be kept in mind that many uncertainties as for example the effect of the striking ship have not been included. Depending on initial conditions and in terms of survivability this first transient heel may be neglected.

In all simulations the ship heel reduced to a few degrees (around 4 deg) within half an hour. Depending on the significant wave height the ship remains at this list (Hs = 2.5 m) or increases slowly in time (Hs = 3.5 m). The variation in roll response between different sea state realisations increases with increasing wave height, as was expected.

The time-to-flood or time-to-criteria can be summarised as follows, using:

s = number of runs that comply / number of runs

- Mean list below 7 degrees:
  Hs = 2.5 m   all simulations comply, s=1
  Hs = 3.5 m   s = 4 / 6 = 0.67
- Time-to-criteria of 7 degrees list:
  Hs = 2.5 m   T > 6 hours
  Hs = 3.5 m   T = 4 hours (minimum)
- Maximum heel below 15 degrees
  Hs = 2.5 m   s = 1
  Hs = 3.5 m   s = 1

5 CONCLUSIONS

The results in this paper suggest that the unbuilt large passenger ship design considered complies with damage stability criteria when subjected to a large three-compartment damage.

The simulation results imply that accurate modelling of longitudinal and transverse bulkheads is important, as well as the proper modelling of the protection of downflooding points. However, the results in waves suggest that the ship, in more extreme conditions, is less sensitive to the modelling of the door type of a single downflooding point than in calm water.

The scatter in the time-to-criteria increases with increasing wave height. More simulations are required to perform full insight in the survivability boundary with respect to the defined criteria.
A time domain simulation model is a useful tool investigate the behaviour of a damaged passenger ship in waves and to investigate critical points in the design for damage control options.

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