LARGE PASSENGER SHIP SAFETY: TIME TO SINK

Riaan van 't Veer, MARIN, The Netherlands, r.vantveer@marin.nl
Jan de Kat, MARIN, The Netherlands, j.o.dekat@marin.nl
Paul Cojeen, US Coast Guard, USA, HCojeen@comdt.uscg.mil

SUMMARY

This paper presents the first results of a study on the behaviour of a damaged Large Passenger Ship in waves. It shows how numerical tools can be applied to derive trends in relation to the time-to-sink for this type of vessel. Relevant capsize criteria have been applied to long duration motion time series, from which the time-to-sink was established as a function of sea state. The results suggest that the Large Passenger Ship considered is safe according to the criteria for waves up to 4.5 m significant wave height. In more severe waves the time-to-sink decreases rapidly from 10 hours to below 1 hour (in sea states of 6.5 m significant and higher). The criteria used for assessing safety are of major importance for determination of the time-to-sink.

1 INTRODUCTION

Recently proposed damage stability regulations follow a probabilistic approach. The probability of having damage of certain dimensions to a particular compartment or group of compartments is multiplied with the probability of surviving the damage scenario. The method provides a rational means of assessing the safety of ships, where flooding is concerned, no matter what their arrangements might be. Recently the EU-funded research project HARDER presented to IMO [1] probability distributions for damage location and size based on a large database of vessel accidents. The number of "large" ships in the database is however sparse.

This paper limits itself to a single damage size and location. The size of the damage is based on the findings in the HARDER project. The location of damage was selected based on worst case evaluation using SOLAS regulations.

In May 2001 the United States delegation at IMO identified two areas in which large passenger ship safety could be improved [2]. One of these areas was "Characterise the designed survivability of the ship to be able to link the design of the ship to the availability of SAR functions and area of operation" under the objective "to improve ship survivability in the event of grounding, collision or flooding with a view to minimising the need to abandon the ship". The reason for the last statement is that it is well accepted that, unless there will be a catastrophic sinking or capsizing failure of the ship, the safest place for passengers is to remain aboard the ship and to avoid the additional risks related to passenger evacuation and launching of survival craft.

This paper focuses on numerical prediction of the time-to-sink for a large passenger ship given a damage location and size. In theory, when the evaluations have been carried out for all possible damage scenarios an understanding can be build on the relationship between the probability factor "s" according the regulations and the time-to-sink for the ship. Such understanding can conclude that there are scenarios for which the regulations predict "no or little change to survive, $s \in [0,1\rangle$", while simulations indicate that the survival time of the ship is limited but large enough from a SAR point of view. In practice, it is expected to be extremely time consuming to simulate all scenarios in all sea states, so simplifications to the procedure are required. It is obvious that such simplifications must not violate physics and must not over-simplify the hydrodynamic problem.

2 BACKGROUND OF THE APPROACH

The motion equation for a ship sailing in waves can be solved in the frequency domain or in the time-domain. There is a direct relationship between the motion equations in the frequency and time-domain assuming linearity of the response. Solving the ship motions in the frequency domain is much more efficient than solving the time domain equations, thus when no non-linear effects are added, the frequency domain should be used since results will be identical anyway. It is clear that our approach is to exploit the time-domain approach by adding the non-linear forcing of large waves, and wind force components, manoeuvring forces, forces from flood water, etceteras. Not violating physics means that such forces should have components in all 6 degrees of freedom simply since all motion components are coupled.

From time-domain simulation results statistical values as mean roll angle or the extreme roll angles can be deduced. The random wave data used as input for the simulations can be considered as a Gaussian random data, and the output data for an intact ship can than be considered as stationary ergodic random data. It means that long-time averages on any arbitrary time-history record give results that are statistically equivalent to associated ensemble averages over a large collection or records. Thus, a single simulation of sufficient time is sufficient to obtain spectral properties of the output.

However, in case of damaged ship simulations we are concerned with transient random data. There is a clear defined beginning (the intact situation) and end (the capsize for example) to the data. This means that one must repeat the experiment over and over under similar conditions to obtain a collection of suitable records to perform reliable statistical analysis. In case of damage stability calculations, with a given damage scenario in a given sea state defined by a significant wave height Hs, a peak period Tp and a spectral shape (Jonswap spectrum, for example) the random phasing of the spectral components leads to the required variation in sea state realisations.

From model tests and numerical simulations it is found that there exist a capsize boundary for ships in damaged condition. When the wave spectrum contains too little energy the waves will not reach a height to pump large amounts of water into the ship neither do they contain enough energy to capsize the ship by imposing large capsizing moments. Part of the time record, after transient and progressive flooding is complete, might than be analysed with standard statistical tools, since the ship motions can be seen as stationary random. Above a certain significant sea state (most studies assume a fixed relationship between the significant wave height and peak period of the spectrum) each spectrum realisation will lead to capsize. The capsize boundary is defined as the range of sea states between this safe and unsafe boundary, in which it is possible to survive or to capsize depending on the realisation of the sea state.

For sea states inside the capsize boundary it is of interest to estimate the probability function of time-to-sink. In lower sea-sate the probability for survival is simply 1.0, and in higher sea states it will be zero. All probability results should be linked to a wave scatter diagram, determining the probability of occurrence of the sea state, to perform the operability. In the safe low sea state conditions the ship will never capsize and in principle no simulations have to be carried out in this region. The main difficulty immediately seen is to find efficiently the capsize boundaries and the probability distribution for rescuing the ship. In particular the lower boundary will be hard to estimate since in these conditions long duration simulations will be required. On the other hand, a required rescue time can be defined after which we are in principle not concerned anymore, or less, with what happens to the ship since all passenger and crew are save. This will provide an upper time limit to the calculations. Figure 1 gives a sketch of the critical area to survive and the overall probability function to estimate. The shortest survival time boundary will have an asymptotic behaviour near the low sea states.

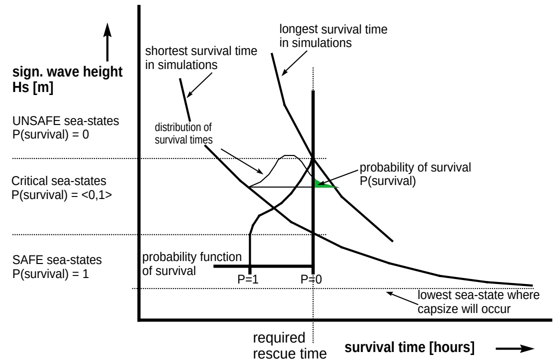

Figure 1: Probability of survival can be obtained by given rescue time and estimated distribution functions of survival time(from numerical simulations) in the critical sea state area.

2.1 CRITERIA FOR 'CAPSIZING'

The term capsize refers typically to a 90 degree roll angle situation from which the ship can not recover. Keeping in mind that the capsizing of a Ro-Ro ferry is likely to be different than a Large Passenger Ship, the following aspects need to be considered when assessing safety following damage:

- Mustering and evacuation of large numbers of untrained passengers;
- Time required for keeping the ship afloat with passengers and crew onboard until rescue teams have arrived;
- Preventing breakdown of crucial systems to maintain possibility to proceed to port or sheltered waters, or to start damage control plan.

The issues mentioned above indicate that smaller roll angles than 90 degree are already a danger for the ship and crew. Thus it is better to talk about time-to-reach a criterion when safety is concerned than to associate the term time-to-sink with it, although sinkage is still a topic to be considered.

In this respect, a 'capsize' run according to the recently updated 'Stockholm' model testing procedure for ro-ro ferries [3] is a (model test) simulation with dynamic roll angles of more then 30 degrees, or a steady heel greater than 20 degrees for more than 3 minutes full-scale, even if a stationary list angle is reached. According to the SOLAS regulations [4], it must be possible to launch survival craft up to 20 degrees list, which seems in agreement with the model test procedure. Chapter II in the SOLAS regulations [4] refers to the final condition of the ship after damage as not to exceed a static 12 degrees list (regulation 6), and refers to a maximum angle of heel after flooding before equalisation which shall not exceed 15 degrees.

Since a qualitative judgement on the above-mentioned criteria is beyond this paper, the above mentioned criteria will be applied without further discussion.

2.2 TIME-DOMAIN SIMULATION TOOL

The time domain simulations are performed with the program FREDYN. This program is a 6 degree of freedom non-linear time domain simulation. The inflow and outflow of water to compartments is based on a quasi stationary hydraulic flow model that accounts for the pressure difference over the defined openings. At each time step the forces and moments from the waves acting on the wetted part of the ship are calculated. The forces and moments (including inertia effects) from the flood water in the damaged compartments are updated at each time step using a pre-calculated database. Retardation functions for all 36-hydrodynamic coefficients are taken into account. For this project the memory functions were based on hydrodynamic coefficients obtained from a 3D panel code. The program FREDYN has been validated with model tests of dynamic flooding of Ro-Ro ferries and naval ships, as presented in for example [5].

2.3 SIMULATION PARAMETERS

For simulations in irregular waves, long-crested Jonswap wave spectra were generated using 50 wave components. With each wave realisation different random phases were used so that each wave realisation leads to a different time series of wave elevation.

Constant wind velocity of 3.45 + 1.823*Hs was used, where Hs is the significant wave height of the sea state. The wind direction was parallel to the wave direction. The wind force acting on the ship is calculated at each time step using the formulations given in [6].

All simulations were carried out in beam seas, zero speed. At zero speed the rudder is obviously not able to maintain heading, thus the balance between the wave and wind force can lead to a different heading after some time. Since the damage is slightly aft of station 10, it is expected that the ship turns its bow into the waves.

All simulations were carried out using a time step of 0.25 seconds. This leads on a 1000 MHz computer to about 20 to 30 minutes simulation time for 1 hour full scale.

3 LARGE PASSENGER SHIP DETAILS

Fincantieri provided the large passenger ship details used in the analysis, including the damage location. The main particulars can be found in Table 1 and a small body plan is given in Figure 2. The intact GM condition of 1.576 m was set by Fincantieri,0.1 m above the minimum required GM to comply with all SOLAS requirements for the given damage. The calculated heel angle for the specified damage was 1.7 degrees with a positive GZ range of 20.2 degrees.

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	1.579 m

Table 1: LPS main particulars.

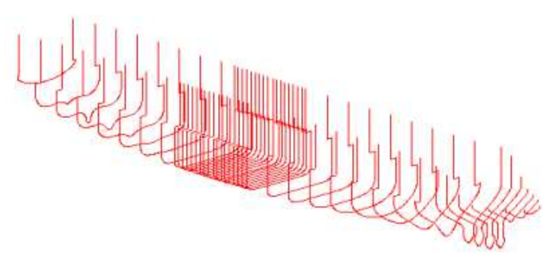

Figure 2: 3D hull lines of the LPS. The knuckle point in the side is at deck level 7 (20.0 m). Lines extend up to deck 15 (40.0 m). Significant more sections around the damage location.

The hull definition was included up to deck 15, which is located 41 m above the keel. This is the highest deck in the large superstructure of the ship. The bulkhead deck 4 is located 11.40 m above the keel. At even keel draught of 7.40 m the waterline is located between deck 2 and 3.

A side view of a sister ship of the one used in the calculations is given in Figure 3.

The damage is on port side at frame 148, 18.77 m aft of midship. Using the findings from the HARDER project, the length of the damage is 0.033% of LPP, which is 8.0 m. The damage starts 3.6 m under the waterline (4.8 m from base) and extends 5.85 m above the waterline, which is just below deck 5. The damage extends herewith to deck levels 1, 2, 3 and 4. The penetration depth of the damage is B/5.

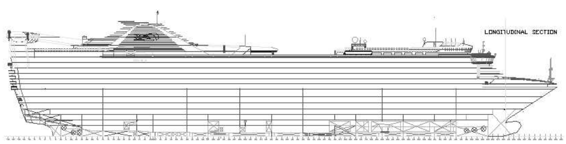

Figure 3: Longitudinal view of the LPS (sister) ship.

3.1 INTERNAL LAYOUT

The internal layout of the large passenger ship consists of a large number of small compartments throughout the different decks. Especially on deck 3 and 4 a large number of crew cabins are located in the area which would be exposed to flooding. The details must be modelled accurately, since significant volumes of water during the simulations are expected on these decks.

Deck 3 is located 5.6 m above the keel line, thus compartments in the damage zone on deck 1 and 2 will be 100% flooded. Due to confidentiality the layout of these decks is not given, but the flooded compartments typically look like engine rooms. Above the bulkhead deck 4 large open spaces exist; deck 5 contains dining rooms and other large compartment areas. On deck 5 partial bulkheads exist to restrict the flow of water along the deck when the ship is in heeled damage condition. These bulkheads are all included in the compartmentation set-up.

The crew cabins on deck 3 have a typical size of 2.1 by 3.0 m. The door to each cabin is 60 cm wide and 2.2 m height. Very often two cabins shear the same wet-area so those two cabins are in fact connected with each other. It is clear that the cabin bulkheads are not watertight due to their construction, and due to for example required piping work. Such openings are not considered in the simulations presented here.

A typical part of deck 3, to be modelled for simulations is, given in Figure 4. Deck 3 is below the bulkhead deck, thus the bulkheads at frame 124, 148 and 172 are watertight. The bulkhead 172 does not continue to the side-shell of the ship as can be seen, but the whole bulkhead in itself remains watertight.

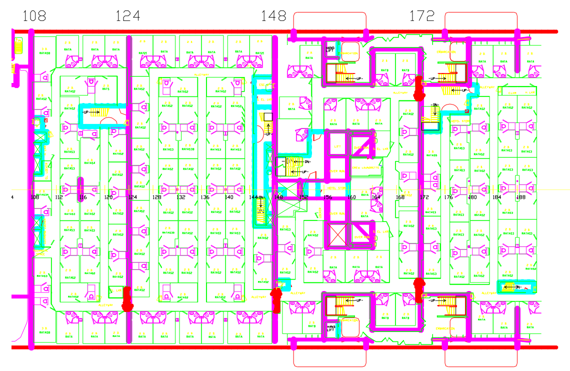

Figure 4: Typical cabin area on deck 3 in the damaged area. Damage is on bulkhead 148.

When defining the compartment boundaries for flooding calculations we simplified the complex deck layout. Although in principle it would be possible to model all cabins separately, it leads to a complex flooding model and with each defined compartment calculation time will increase. In view of the long duration runs envisaged (simulation of several hours for the ship in damaged condition are expected) it was decided to simplify the layout to some extent. Simplifications were based on experience in earlier validation work.

For deck 3 this leads to the modelling given in Figure 5. The main bulkheads at frame 108, 124, 148 and 172 are modelled as watertight boundaries. Between 124 and 148 the cabins are grouped, keeping in mind that the damage is on frame 148 and located on port side. Water that floods into the ship on deck 3 at frame 148 will not directly flood towards frame 124, since the compartments near the side-shell of the ship prevent this. Therefore compartment 3407 is considered necessary. When the ship rolls to starboard side water will have mainly three small corridors to flood to starboard side and most likely will only enter the mid compartments when there is sufficient time (that is when the roll angle changes slowly). Most of the water is expected to rush through the corridors to the lower part of the ship.

Therefore six compartments (3431 through 3436) are considered, each in size of 4 crew cabins in that area, and with openings equal to about 4 door openings. Near frame 148 a protected area is seen on the drawings connecting deck 3 with deck 4 (down flooding point on deck 4). This is obviously an important area to model as correctly as possible.

Similar arguments hold to defend the compartmentation between bulkhead 108-124 and 148-172. All boundaries are watertight except for the openings which are 2.2 m in height when it represents a door (8.6 to 10.8 m) or extend up to deck 4 (11.4 m) when the opening represent a corridor passage.

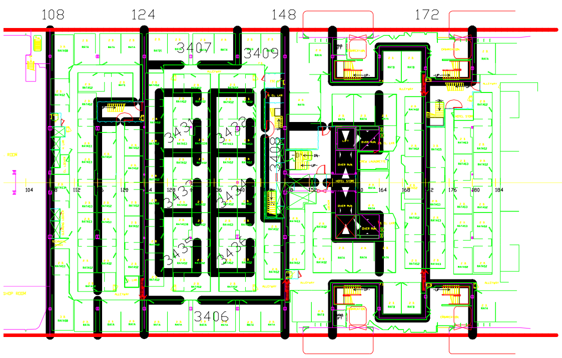

Figure 5: FREDYN compartment definition for deck 3.

Bulkheads on deck 1, 2 and 3 are watertight and are modelled as such. Above the bulkhead deck 4 openings are allowed in the bulkheads in a certain area which will not be exposed to flood water when the ship is heeled to the maximum angles according to the regulations. It was decided that these openings are small in general and located near the top of deck 4. For that reason they are not included in the present model. This means that progressive flooding across watertight bulkheads, which might take place in the ship in severe conditions, is not accounted for in the calculations.

All stair case openings between deck 1, 2, 3, 4 and 5 have been modelled when relevant for flooding. The compartments on deck 5 have been included in the compartmentation, since they can be flooded through stair case openings from deck 4.

4 SIMULATION RESULTS

4.1 NORTH-ATLANTIC WAVES

The wave scatter diagram from the North Atlantic Annual Bales data is given in Figure 6. This scatter diagram was used to select the steepest wave conditions for simulation, which are given by the circles in the diagram. Wave conditions from Hs = 2.5 to Hs = 15.5 m were selected. Higher sea states are recorded and when an operability analysis is carried out the whole scatter diagram should be used. But in this phase of the project we are interested in trends and we are interested in realistic wave conditions for damage stability calculations. In the EU HARDER project all damages in the damage-statistic table were reported to occur in sea states below Hs = 4 m. The largest ships in this database are 300 m, so that the Large Passenger ships are 'just' included, in principle, but hardly any data points exist for large ships. In general collision accidents are thought to occur in crowed waterways as they can be found near the shore. In such waterways significant sea states of Hs = 15 m are not likely. Still, when concerned with safety issues one should not restrict simulations in sea states where past accidents occurred only.

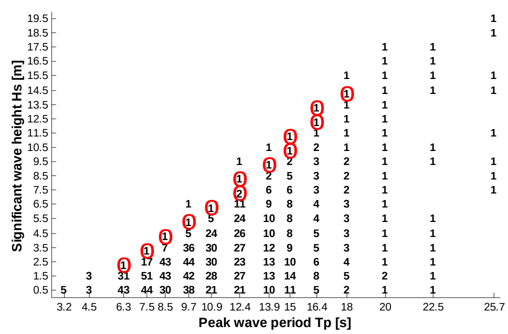

Figure 6: North Atlantic Annual Bales wave scatter diagram.

The trends in mean roll motion for a single 6 hour simulation are given in Figure 7, for the sea states up to a significant wave height of 9.5 m. The corresponding peak periods of each run can be found Figure 6. The results indicate a very clear trend. All runs show a large roll angle towards the damage when the damage is created. Since the actual roll angle signal was put through a low-pass filter to obtain the mean angle shown in Figure 7 (where periods less than 20 seconds were filtered out) this maximum angle is not reliable and should be disregarded. The issue of maximum transient roll angles immediately following damage is not dwelled on in this paper.

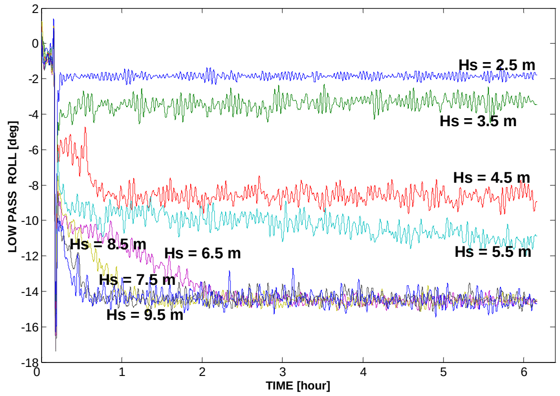

Figure 7: 6 hour simulations in different wave spectra.

For the two lowest sea states (Hs = 2.5 and 3.5 m) the final mean roll angle after 6 hours is identical to the mean roll angle reached at about 10 minutes after damage. Basically when the ship has recovered from the first roll, the mean angle does not change significantly anymore. In these sea states no capsize will occur in any realisation.

In all other runs performed no capsize of 90 degrees roll angle occurred, so that a pure capsize run condition for this ship seems unlikely. However, other conditions might be reached that impede ship evacuation, for example. The limiting roll angle in rescue operations can be much smaller, for 12 degrees due to impossible operation of the life-saving appliances.

When a mean roll angle of 12 degrees is set as criterion associated with a time-to-sink of at least one hour, this condition is met in sea states of 6.5 m significant and above. With this criteria these runs can be seen as capsize runs. Interesting is that the maximum mean roll angle in all runs is identical, close to 15 degrees. When the real roll-signal is plotted, larger roll angles occur, as we will discuss later on.

The runs in sea state with 4.5 and 5.5 m waves show some 'intermediate' behaviour. The trend in 5.5 m waves is that after 6 hours the mean roll is still increasing. At 4.5 m significant wave height the roll angle shows a 'jump' after about 45 minutes of simulation after which the mean roll angle becomes constant around 8 degrees. When 12 degrees mean roll angle was is set as criterion, the runs in Hs = 4.5 and 5.5 m are in the so-called capsizing boundary, or critical sea states.

The behaviour of the ship in extreme sea states is given in Figure 8. Here the results of the low-pass roll motions in sea states with Hs between 10.5 m and Hs = 15.5 m are presented.

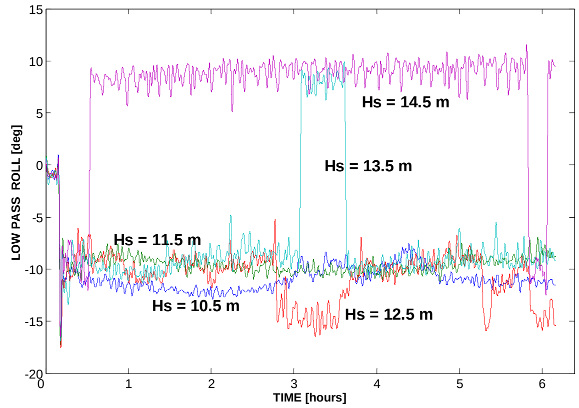

Figure 8: 6 hour simulations in different (extreme) wave spectra.

The results in Hs = 10.5 m and 11.5 m look realistic, but in higher sea state the ship seems to 'swap' between a mean angle to port and to starboard. Apparently the wave forces contain enough energy to push the ship to the other side, which means that a large volume of water has to 'swap' sides as well. To which extent such behaviour is influenced by the internal layout of the ship is not clear, but this behaviour does not seem very realistic.

The unfiltered roll motions for a single case, sea state of Hs = 9.5 m is given in Figure 9. It is seen that the roll angle maxima are about -25 degrees and -5 degrees, so the vessel roll motion amplitude is about 10 degrees with a mean of about –15 degrees. This is significantly larger than for the intact condition, which shows about 5 degrees roll amplitude. The heave motions and the calculated mean heave are given in Figure 10 showing that the sinkage becomes constant in time similarly as the mean list angle in Figure 9.

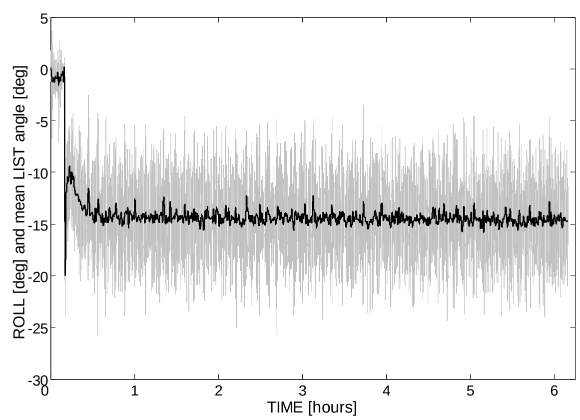

Figure 9: Roll angle and mean list [deg], Hs = 9.5 m.

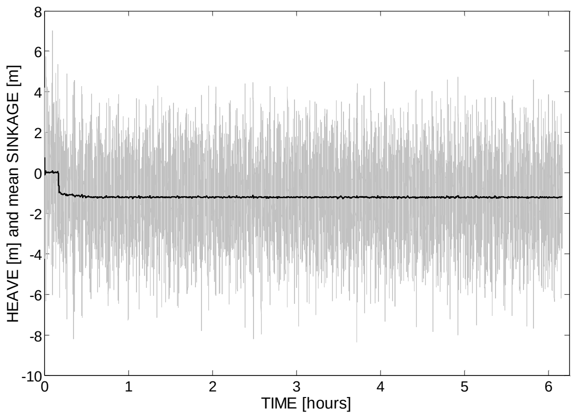

Figure 10: Heave and mean sinkage [m], Hs = 9.5 m

4.2 TIME-TO-SINK CRITERIA

The outcome of time-to-sink probabilities will depend heavily on the applied criteria. Apart from regulations, the ship operator might have more specific or perhaps even higher standards concerning ship safety. In case of numerical simulations any criterion can be applied and evaluated using the time series of the simulations.

As mentioned before, the time-to-sink simulations are assessed using the following criteria:

(a) The maximum roll angle should not exceed 30 degrees,

(b) the mean roll angle should not exceed 20 degrees for a period of more than 3 minutes,

(c) the mean roll angle (taken over 15 minutes interval) after damage should not exceed 12 degrees

Criteria (a) and (b) are based on a revised proposal for SOLAS resolution 14 [3], criteria (c) is based on SOLAS Chapter II-1, regulation 8 [4].

In [3] at least 10 experiments are proposed to prove if the vessel will be save. The model shall have reached a steady state, and the experiment shall not be less than 30 minutes. A complication is obviously that a towing tank has limited length so that the capsize or time-to-criteria for a Large Passenger Ship might not have been reached before the model has reached the end of the tank. For progressive flooding long duration runs might be required, which will be especially visible near the lower boundary of the critical sea states. Numerical calculations can be done for unlimited time in principle.

In deriving a time-to-sink the variation in time-to-criteria, which is in theory a continuous random variable, should be determined, as indicated in Figure 1. When it is assumed that the time-to-criteria follows a normal distribution, with unknown mean μ and standard deviation *s*, the confidence interval with 99% confidence level ($(1-\alpha)=0.99$), using n simulations can than be calculated using:

$$\Delta = 2t_{\alpha/2}(n-1)\cdot s\cdot n^{-0.5}\ .$$

In this paper the number of simulations per sea state is defined to $n=25$; tables for $t_{\alpha}(\nu)$ can be found in the literature. When the mean $\overline{x}$ is determined using all n simulations, and the 99% confidence interval is then: $\overline{x}-\Delta/2<\mu<\overline{x}+\Delta/2$. A somewhat different procedure could be followed, using the formulations above, to determine the required number of simulation n given a confidence interval Δ. The number of simulations was fixed in this paper to evaluate the variation in time-to-criteria with a large enough number of simulations.

4.2.1 Results of time-to-criteria (a), (b) and (c)

Figure 9 presents the roll motion time trace as obtained for a simulation in Hs = 9.5 m. As can be seen, the mean roll angle in this run is close to 15 degrees and does not exceed the 20 degrees, the ship is safe according to criterion (b). The mean roll angle taken over 15 minutes intervals is however larger than 12 degrees, so the ship would be unsafe according to criterion (c) and the time-to-criteria is less than 1 hour. The maximum roll angle in this runs was -25.76 degrees, which is just below 30 degrees, thus the ship is also safe according to criterion (a).

Based on the results of Figure 7 and the procedure defined in paragraph 4.2, 25 simulations were performed in each sea state with the following duration: 12-hours in Hs = 5.5 m, 9-hours in Hs = 6.5 and 7.5 m, and 4-hour simulations in Hs = 8.5 and 9.5 m.

The results of time-to-criteria for all simulations can be found in Table 2. A graphical representation (mean and simulation boundaries) is given in Figure 11. The distribution of the time-to-criteria results are presented in Figure 12, using bins of 10 minutes to group the results.

SUMMARY TABLE for TIME-TO-CRITERIA					
	SEA STATE, significant wave height				
CRITERION A					
Simulations	5.5 m	6.5 m	7.5 m	8.5 m	9.5 m
1 to 25	safe	safe	safe	safe	safe
CRITERION B					
Simulations	5.5 m	6.5 m	7.5 m	8.5 m	9.5 m
1 to 25	safe	safe	safe	safe	safe
CRITERION C					
Simulation	5.5 m	6.5 m	7.5 m	8.5 m	9.5 m
1	10.64	1.83	0.81	0.53	0.46
2	11.71	1.68	0.78	0.49	2.29
3	10.63	1.94	0.81	0.54	0.63
4	11.63	1.98	0.86	0.54	0.48
5	11.28	2.01	0.73	0.56	1.44
6	9.66	1.63	0.78	0.51	0.46
7	8.39	2.11	0.81	0.59	0.48
8	11.19	2.06	0.81	0.58	0.51
9	10.78	1.71	0.79	0.54	0.46
10	11.68	1.93	0.86	0.58	0.73
11	10.59	1.98	0.68	0.53	0.51
12	10.34	1.71	0.81	0.54	0.69
13	10.71	2.03	0.88	0.54	1.08
14	10.38	1.96	0.76	0.51	0.46
15	9.38	2.34	0.69	0.49	0.48
16	11.01	2.09	0.71	0.51	0.46
17	10.61	1.84	0.76	0.58	0.48
18	10.48	1.98	0.63	0.54	0.48
19	10.18	2.06	0.89	0.53	0.44
20	11.81	2.04	0.84	0.59	0.51
21	9.54	1.66	0.76	0.53	0.49
22	10.58	1.91	0.94	3.34	0.44
23	10.59	2.03	0.66	0.53	0.59
24	9.81	1.58	0.74	0.63	0.36
25	10.96	2.09	0.99	0.48	0.43
Mean	10.58	1.93	0.79	0.65	0.63
Standard deviation	0.80	0.18	0.09	0.56	0.42
99% boundaries	10.11	1.82	0.74	0.32	0.39
	11.06	2.04	0.84	0.99	0.88
Simulation boundaries	8.39	1.58	0.63	0.48	0.36
	11.81	2.34	0.99	3.34	2.29

Table 2: Summary table of time-to-criteria in hours (format 10.6 hours = 10 hours 35 minutes)

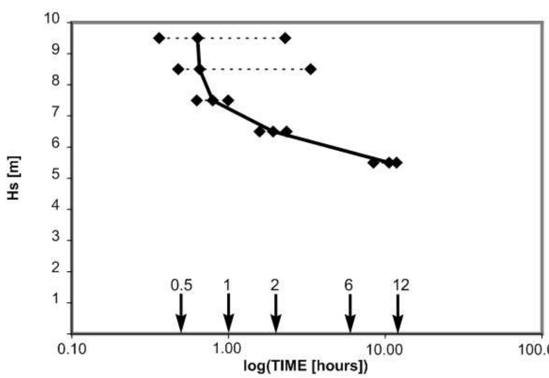

Figure 11: Mean value of time-to-criteria (c) with boundaries from 25 simulation results.
Below sea state of 5.5 m waves all simulations were safe according criteria (c).

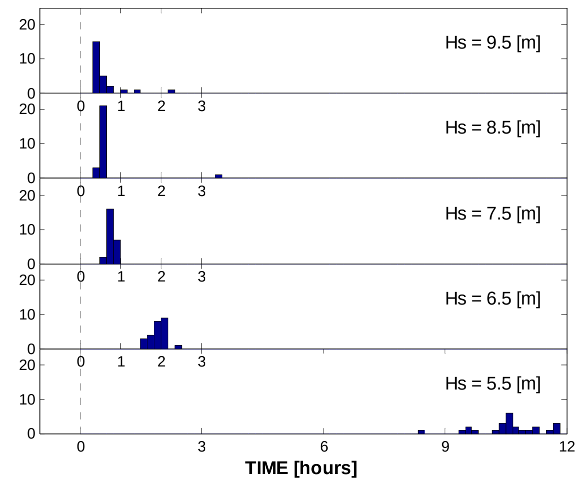

Figure 12: Distribution of time-to-criteria values in 10 minutes bins.

According to criteria (a) and (b) the ship is safe in this damage condition in all sea states up to Hs = 9.5 m. Results of Figure 8 indicate that this might even be true in all sea states for the wave scatter-diagram, but this has to be proven by calculations in principle.

According to criterion (c) the ship *can be unsafe* depending on the required survival time. For a sea state lower than 5.5 m significant wave height no time-to-criteria was found; the ship is *always* safe in these sea states following criterion (c). In Hs = 5.5 m the time-to-criteria is about 10.5 hours, but the safety of the ship drops down dramatically to 2 hours when the sea state becomes 6.5 m significant. In 7.5 m to 9.5 m criterion (c) is reached within 1 hour after damage.

The standard deviation in the series of simulations is rather small, about 25 to 45 minutes. The first three sea states in the table give an expected and logical trend, a longer time-to-criteria gives a larger standard deviation in the results, that is the spreading found in the simulation results is larger when the time-to-criteria becomes larger. In this respect it was expected that the standard deviation in 8.5 and 9.5 m waves would of the same order, but when looking through Table 2 it is found that the results in these sea state occasionally significant larger time-to-criteria occur (simulation 22 in 8.5 m waves for example). Apparently it is possible to find a sea state realisation (in relation with the time of damage occurring) in which the waves are favourably for the ship. Since in higher sea states the wave forces become more and more important with respect to the forces from the flooded water in the ship, a larger spreading in the time-to-criteria might be realistic. Figure 8 indicates similar trends. The mean roll angle found in the extreme sea states are in many cases lower than the final equilibrium list angle for sea states 8.5 and 9.5 m, seen in

Figure 7! This requires further study, but it seems that in extreme seas, most likely due to the wave actions and the fact that the ship simply follows the wave slope, the time-to-criteria may increase.

Figure 12 demonstrates that the distribution of time-to-criteria is a dense function around the mean value. In the lowest sea state the distribution shows a larger spreading than in higher sea states, but there is still a dominant number of runs with time-to-criteria close to the mean value.

5 CONCLUSIONS

Numerical calculations of time-to-sink or time-to-criteria have been carried out with a Large Passenger Ship. The internal layout of the ship comprises a large number of small compartments, which have been grouped in larger blocks to accommodate feasible simulation times. Still, a large number of simulations are required to cover a complete scatter diagram. The results in this paper limit itself to the steepest waves occurring in the North Atlantic, so that about 125 simulations were sufficient. Still this required about 800 simulation hours which equals about 400 CPU hours, close to 2 days on a cluster of PC's. Extrapolation would lead to about 1 week calculations for one single damage configuration.

Three different criteria were used based on existing regulations to assess the time-to-criteria for the ship. For the current damage size and location, the ship is safe following the probabilistic regulations (criteria (a) and (b)). Using a static approach according SOLAS regulations leads however to time-to-sink of under 1 hour in the more severe sea states of 6.5 m significant wave height and higher. In 5.5 m significant waves the time-to-sink increases to 10 hours, and in lower sea state the ship is safe according criterion (c). This suggests a sharp and well-defined boundary, similar to the 'capsize boundary' found for Ro-Ro ships.

It is clear that many assumptions had to be made concerning watertight bulkheads and openings between compartments above the bulkhead deck. The assumptions were made based on detailed assessment of the drawings. This was a time consuming process, but necessary to obtain realistic simulation results.

The results found so far suggest that a numerical simulation tool, such as FREDYN, can be used to assess time-to-sink efficiently for a Large Passenger Ship.

6 ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Mr. A. Serra from Fincantieri, who provided all data for the Large Passenger Ship. The research is sponsored by the US Coast Guard (DTCG40-02-Q-6CA015).

7 REFERENCES

[1] SLF 45/3/5, April 2002, *Investigations and proposed formulations for the factors "p", "r", and "v": the probability of damage to a particular compartment or compartments.*

[2] SLF 45/INF.2, March 2002, *Large passenger ship safety,* with Annex: *Damage stability "Time to Sink" Feasibility Study* by Herbert Engineering Corp., USA.

[3] SLF 45/10/1, April 2002, *Revision of the model test method specified in the 1995 SOLAS conference resolution 14.*

[4] SOLAS edition 2001, Chapter II-Part B, *Subdivision and stability;* Chapter III-Part B, *Requirements for ships and life-saving appliances*

[5] Kat, J.O., Kanerva, M., Van 't Veer, R. and Mikkonen, I.: *Damage survivability of a new Ro-Ro Ferry,* Proc. 7th Int. conference on Stability for Ships and Ocean Vehicles, STAB 2000, Launceston, Tasmania, Feb. 2000.

[6] Blendermann, W. (1996): *Wind Loading of Ships – Collected data from wind tunnel tests in uniform flow,* Bericht Nr 574, Institut für Schiffbau, University of Hamburg