FLOODSTAND Integrated Flooding Control and Standard for Stability and Crises Management

FP7-RTD- 218532

FLOODSTAND-deliverable:

Numerical simulations for characterizing Time to Capsize

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Revision	1.0
Deliverable No.	D4.3

Date	May 4, 2011

SEVENTH FRAMEWORK PROGRAMME

<table>
<tr><td colspan="2">Document identification sheet</td></tr>
<tr><td colspan="2">FLOODSTAND   Integrated Flooding Control and Standard for Stability and Crises Management   FP7-RTD- 218532</td></tr>
<tr><td>Title: Numerical simulations for characterizing Time to Capsize</td><td rowspan="2">Other report identifications:</td></tr>
<tr><td>Investigating partners: <u>NTUA</u>, SSRC, SSPA, SAS

Authors: Dimitris Spanos, Apostolos Papanikolaou

Reviewed by:</td></tr>
<tr><td>☐ Outline
☐ Draft
☒ Final
Version number: 1.0
Revision date: May 4, 2011
Next version due:
Number of pages:</td><td>☒ A deliverable
☐ Part of a deliverable
☐ Cover document for a part of a deliverable
☐ Deliverable cover document
☐ Other
Deliverable number: D4.3
Work Package: WP4
Deliverable due at month: 24</td></tr>
<tr><td rowspan="2">Accessibility:
☒ Public
☐ Restricted
☐ Confidential (consortium only)
☐ Internal (accessibility defined for the final version)</td><td>Available from: http:/floodstand.tkk.fi
Distributed to:
Discloses when restricted:</td></tr>
<tr><td>Comments:</td></tr>
<tr><td colspan="2">Abstract:
This report presents the conducted numerical simulation experiments for the exploration of the probabilistic characteristics of the Time to Capsize TTC carried out at NTUA-SDL within Task 4.3. The investigation provides a comprehensive sensitivity analysis of the main parameters affecting TTC of the damaged ship. Furthermore it provides a unique reference for the validation of the analytical modeling for TTC probabilities.</td></tr>
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Acknowledgements
The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 218532. The financial support is gratefully appreciated.

EXECUTIVE SUMMARY

Based on the description of work (DOW) of FLOODSTAND, in Task 4.3, [1], at least one comprehensive numerical model will be put forward as an alternative for modeling of the stochastic behavior of the Time to Capsize (TTC). A detailed description of the method, input information and its sensitivity to the accuracy of input information will be developed. The validation will be performed on the basis of the experimental tests performed in Task 4.1. The range of the sensitivity studies parameters must allow for quantitative uncertainty quantification to be undertaken in Task 4.5.

Responding to the above specifications, the present report describes the numerical simulation method appropriate for the estimation and probabilistic exploration of TTC as applied by NTUA-SDL for the studies for Task 4.3. The conducted systematic numerical simulation experiments are outlined, which form a comprehensive validation and sensitivity study of the main parameters affecting damaged ship's survivability in waves, and concludes on the significance of the basic design and operational parameters, affecting TTC and on the related way ahead in the project.

The reported results provide unique information for the validation of analytical modeling in Task 4.2, as the complete probability distribution for TTC was built up with statistical approach and can be used for direct comparisons.

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1. INTRODUCTION

The time to sink of damaged passenger ships is the most crucial variable in the framework of ship evacuation and the related probability of casualties. Casualties are directly correlated to the available time for an orderly evacuation. Therefore reliable estimations for the time to sink are obviously an essential component for the estimation of the casualty risk and thereby any possibility for a rational mitigation.

For a damage case which eventually sinks or capsizes, the time until such event can be reliably measured with physical tests in the tank with a ship model. However testing in tank is highly expensive method and time costly that limits this application to the generation of experimental evidences. It is not feasible to generate a complete estimation of the time for the large range of conditions that a damaged ship may encounter.

Analytical methods may provide rather useful information for the time aspects in case of ship flooding accident. The significant advantage of analytical methods is that they are fast. However this advantage should be necessary combined with reliable estimations as well. Such an analytical method is put forward and is studied in Task 4.2 of FLOODSTAND project.

Some rough validation of the analytical method can be approached on the basis of experimental evidences from tank experiments. This approach is not sufficient indeed since analytical methods are actually probabilistic whereas model tests may provide evidences only for specific and narrow set of conditions. A statistical approach of the experimental data would be the proper one, but this is limited to the few data that can be acquired with model tests.

Detailed numerical simulation method for the probabilistic analysis of the time to sink/capsize the damaged and hence flooded ship is put forward in Task 4.3. This approach may provide much more data in comparison to the tank tests hence statistical analysis of the numerical sample becomes feasible. Thereby additionally to rough experimental evidences a full picture of the time to capsize can be created and become a valuable validation case for the analytical method.

Besides the validation purposes covered, the numerical simulation tests may provide insight to the basic parameters that affect and determine the ship survivability and the related time to capsize. In the studies undertaken in this task the parametric studying of time to capsize has been an interesting outcome, as reported in the next sections, which enhances the confidence for the acquired behavior of TTC.

Independently of precise estimations for time to capsize, a fundamental question to this study is to explore for conditions that TTC may be systematically long. So far, the results suggest that long times can be encountered only for the trivial condition of lower waves.

The investigations has focused on the ship capsize mode due to flooding of upper spaces in the action of waves. ROPAX ships are mostly vulnerable to this capsize mode, however this is not limited to this ship design. Other capsize modes, like intermediate stages of flooding or progressive flooding, are not addressed here. The capsize in intermediate stages of flooding which is a rather dynamic phenomenon that is accomplished within very short times compared to the evacuation times, gains no interest for the present investigation.

It is early clarified that *Time to Capsize* TTC refers to capsize events and, it should not be mixed with survive events. For those conditions that ship survives then TTC is *indefinite*, but *not infinite*. While, the *survival time* (Time to Survive TTS) after damage may be either infinite for survive events or coincide to TTC in case of capsize. The reported work literally addresses TTC, as in context of ship evacuation the survive events are not of concern (riskless situations).

2. OBJECTIVES

The objectives of the present work are summarized below:

- The investigation of TTC in case of flooding in waves with an alternative (to analytical) numerical approach
- Parametric study for TTC and improve understanding of parameters affecting capsize time
- Data generation for the probabilistic validation of TTC with other analytical methods

3. TIME TO CAPSIZE OF ROPAX SHIPS

Beyond the specific objectives the work is also motivated by particular interest for the time dependent survivability of ships, and more specifically capsize due to flooding in waves. The massive simulations carried out shed light and provide additional evidence for the capsize characteristics of ROPAX ships, which are vulnerable to capsize due to flooding in waves.

In recent years there were remarkable efforts ([14], [15], [16]) to develop survivability criteria of damaged ships on the basis of survival time, which would establish the timeframe needed for safe evacuation and abandonment of damaged ships. These works concerned the definition of survival probability as a function of prescribed time. Then, times to capsize of long range (even 24 hours, or several days) appear to be possible for damaged ships in waves.

However in [7] pointed out that such time considerations need caution and could not be directly applicable to ROPAX ships (at least). This is because ROPAX ships may capsize after a relatively long time only in a very narrow range of wave conditions. In consequence, TTC (even of 3 hours) appeared to be remote events, and ROPAX ships behave practically binary, namely either survive or capsize rapidly. This behavior was further explored in task 4.3 where ROPAX behavior is tested in multiple conditions and above considerations could be further reviewed and evaluated.

4. NUMERICAL SIMULATION FOR SHIP MOTION AND FLOODING

The numerical simulation method for ship motion and flooding as introduced by *Spanos* [5], [8] is presently applied for the investigation of the stochastic behavior of time to capsize (*TTC*) of damaged vessels in collision damages in waves.

This is a detailed simulation approach in the time domain for the reproduction of the motion of flooded ships in waves. It has been extensively validated over the last decade, [9], [10], [11], and it may efficiently provide reliable estimations for the stochastic behavior of Time to Capsize *TTC*.

In this section the essential background information of the employed modeling is provided, while full description can be found in [5], [8].

The presently employed numerical simulation method for the motion and flooding of damaged ships is a non-linear time-domain method which is based on linear potential theory with respect to the ship hydrodynamics and considers non-linear terms like excitation by large amplitude waves, nonlinear body geometry effects like the effect of the above calm waterline body shape and its impact on the ship's restoring, and sloshing effects due to internal to the vessel or trapped on deck moving water. The method is completed with the modeling of the flooding process, namely the water ingress and egress through shell damage openings or internal openings, which is essential element for the stability of the flooded ship.

Ship motion

The ship is considered as rigid body moving in six degrees of freedom in response to incident waves. The ship motion is governed by the momentum conservation of the entire inertia system, namely ship and floodwater, under the action of external wave forces.

The wave induced forces are analyzed in the context of linear potential theory. Non-linear *Froude-Krylov* forces are calculated by pressure integration over the instantaneous wetted hull surface and incident wave elevation. Radiation and diffraction components are evaluated with the linear theory in three-dimensional frequency-domain and then are transformed in time-domain. Linear (or quadratic) roll viscous effects are taken into account with semi-empirically estimated coefficients.

The linear hydrodynamic forces (radiation, diffraction) are estimated by used of a 3D panel method, *Papanikolaou* [6]. This regards the six-degrees of freedom ship linear motion in frequency-domain on the basis of zero-speed Green function, pulsating source distribution.

Floodwater sloshing

Sloshing effects are considerable to the motion of the flooded ship, particularly when flooded spaces of large area are considered like that of car deck for ROPAX ships, which result to shallow water with large moving free surfaces. Therefore the coupled motion of ship and floodwater is modeled as well. The floodwater is assumed moving inside the flooded space due to the moving space boundary. A plane free surface of floodwater is assumed which may rotate around two axes, the longitudinal and the transverse.

Flooding process

The floodwater mass may vary over the time due to water ingress or egress through hull shell damage openings. The necessary condition for water ingress is the external water head to the opening to exceed the internal water head inside the flooded compartment. Apparently the opposite condition is necessary for water egress.

A hydraulic model based on Bernoulli equation is employed to approximate the differential flooding rate. Thereof the flow velocity at some point of damage opening is governed by the difference of water heads internally and externally to damage opening. Semi-empirical discharge coefficients are applied to account for the integral of local flow contractions.

Sea waves

Long-crested unidirectional sea waves are considered in the simulation environment. A *Longuet-Higgins* model [12] is applied to reproduce free surface elevation at the region of the floating ship on the basis of discredited spectral energy.

For the flooding process the incident (undisturbed) elevation is assumed at the region of damage opening namely omitting any swell up or diffraction effects due to the presence of ship. Therefore a Gaussian distribution for the wave elevation is considered which defines the external water head for the flow through the opening.

5. THE RANDOM VARIABLE OF TIME TO CAPSIZE

The dependence of the time to capsize to the *non-stationary* accumulation of floodwater is analyzed in order to illustrate the background complexity and eventually random character of the TTC.

Figure 1 demonstrates the establishment of water ingress/egress condition over the time. As long as the wave elevation ζ exceeds ship's freeboard f_b (the vertical distance of the lower edge and at mid-length of opening to the calm free surface) and the free surface of floodwater ζ_w then the water ingress condition is established and inflow to an open shell space (like the car-deck space of ROPAX) takes place.

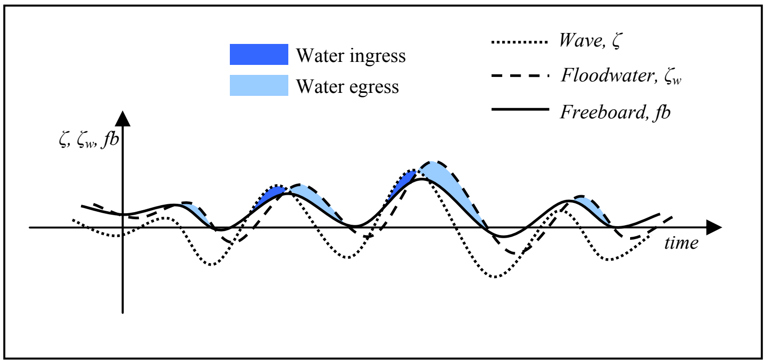

Figure 1 Water ingress condition

Apparently this is highly complex situation, determined by the combination of three irregular (non-harmonic) time series. The time series related to the actual freeboard f_b (where the motion of the ship in response to the waves is considered too) and the floodwater ζ_w free surface and that of the sea elevation ζ; their common dependence is nonlinear and necessitates their determination by a nonlinear simulation method in the time-domain.

Independently of the achieved accuracy with respect to the flooding process modeling, the accumulated floodwater on the deck is the sum of integrals of two (in and out) flooding rates. Each flooding rate is generally discontinuous over the time; however they are correlated to the size and frequencies of the random waves as modulated by ship motion and flooded space characteristics.

Next Figure 2 samples a time series for the floodwater accumulation on the car deck of the damaged ROPAX ship under investigation. In short scale the floodwater mass fluctuates over the time, because of intermediate inflow and outflow phenomena, while at long time scale the gradual accumulation of water on deck eventually results to ship capsize.

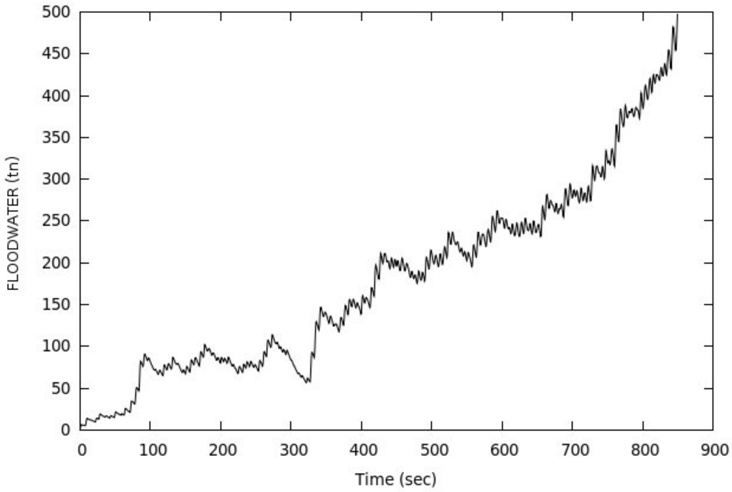

Figure 2 Floodwater accumulation on the deck

In events of capsize, like that of Figure 2, the accumulation rate is apparently a *non-stationary* process; whereas the time to capsize is the time instance when the ship either exceeds 30 degrees heeling, or exceeds 20 degrees for two minutes, whichever is met earlier (ITTC recommendations, [13]). The capsize event is directly related to the floodwater accumulation and the length of the non-stationary process until some critical amount of water on deck is exceeded.

Therefore considering the full mechanism of water accumulation as well as the definition of the capsize events then *time to capsize* TTC is actually a variable of complex dependencies that practically it should be considered as a random variable.

The probability characteristics of random TTC are not known and it is considered still early to be accurately deduced by presently available experimental evidences or state of the art numerical simulation data.

Aiming to enhance evidence and provide insight to the probability properties of TTC, the conduct of physical (in tank) model tests (T.4.1) and numerical simulation tests (T4.3) in WP4 is considered essential. The acquired experience from such tests permits the evaluation of the analytical approach introduced in T4.2 or, may provide a direction for modification and improvements.

Data from model tests in tank are generally limited mainly because of the high cost of such experiments. The conducted numerical simulation tests were designed to enhance the information from the physical tests and even complete the present picture of TTC. The numerical simulation tests are detailed in subsequent sections.

6. THE STUDIED ROPAX SHIP

The ROPAX ship *MV Estonia*, which sunk in September 1994, due to rapid loss of stability after loss of her hull integrity and ingress of sea water on the car deck through the bow ramp, selected for theoretical investigation in WP4 of FLOODSTAND and also it was tested in the model basin [3]. This vessel has a standard ROPAX subdivision with a large open (car) space above but close to ship's waterline, which is appropriate for the present research objectives.

The vessel complied with damage stability requirements of SOLAS'74 (launched in 1980), while compliance with the later SOLAS'90 is uncertain (the ship was at the time of operation treated as an *existing ship* in terms of compliance with latest regulations).

Table 1 Main Dimension of ROPAX vessel

Lpp	137.4 m
B	24.2 m
T	5.39 m
D_{DECK}	9.1 m
Displ.	12300 tn

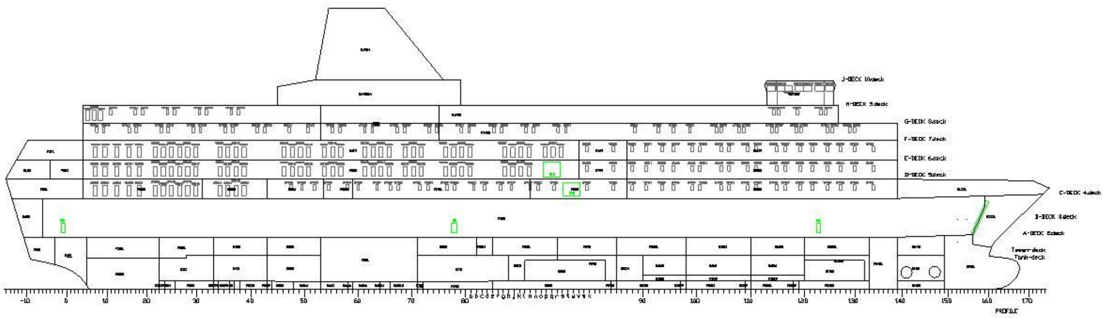

Figure 3 Profile of ROPAX vessel

Damage Case

The damage of Figure 4 is the one systematically analyzed with numerical simulation and for which experimental data were available so that direct comparisons could be achieved. The damage case considered the two shaded compartments aft amidships plus the vehicle space damaged and flooded.

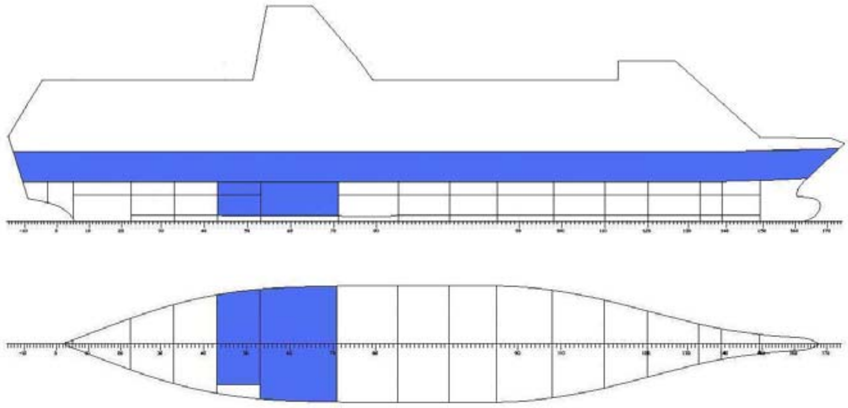

Figure 4 Main damage case investigated with tank and numerical tests

This damage case corresponds to the worst case in terms of SOLAS'90 and Stockholm Agreement provisions (even if the ship was not built in compliance with them). This is a typical damage for ROPAX ships comprising of two compartments damage, one of which is the larger compartment of engine room, and the car deck space which is the space that makes ROPAX ships vulnerable in waves.

The main engine room is the fore compartment. The double bottom is assumed to remain intact. Inside the aft compartment there is an intact side tank which causes an asymmetric damage case. The assumed damage opening is located on the port side and centered at the transverse bulkhead between the two damaged compartments. The damage length is 7.12 m (3%L + 3 m), and opening is extended upwards up to the deck over the car deck.

7. PREDICTION OF TIME TO CAPSIZE

Figure 5 presents the time to capsize for the ROPAX vessel in beam waves versus the significant height of the incident waves. The predictions for time to capsize pertain to the typical two compartments damage case as demonstrated in Figure 4.

Numerical simulation results are shown in comparison with experimental data from FLOODSTAND tank model tests [3].

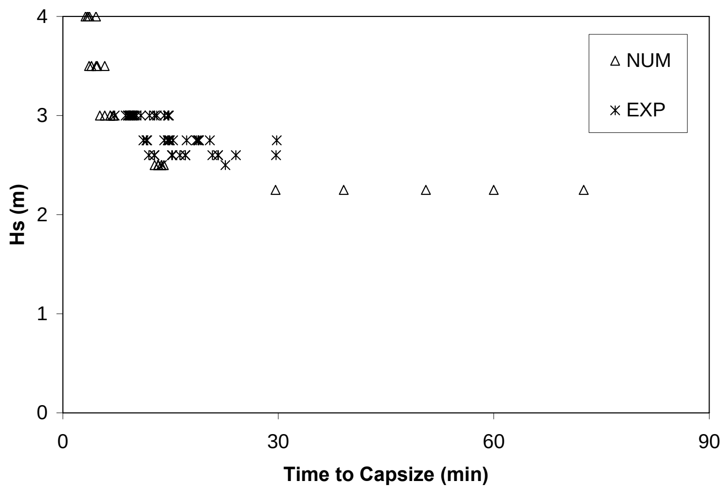

Figure 5 Prediction of Time to Capsize with numerical simulation

The numerical results correspond to genuine predictions for TTC from the first principles approach of section 4. Waves correspond to developed seas of *JONSWAP* spectrum and slope $Hs/\lambda = 0.04$.

The behavior of TTC observed in Figure 5 is characteristic for ROPAX vessels. TTC is notably spread with respect to some wave height region (here between 2.25 and 2.5 m), which is the *critical wave height* for the specific damage case. Above this height TTC is rapidly shorten and is distributed within a much narrower range. Below the critical wave height, the ship systematically survives and TTC is indefinite.

Sensitivity of TTC in the variance of the basic parameters shows that TTC maintains the characteristic behavior of Figure 5. Parameters relative to ship loading, sea state and possible damage opening may affect either the survive limit of wave heights or directly the distribution of TTC. Thereby, for different parameters the picture of Figure 5 may appear shifted vertically as well as scaled with respect to time (horizontal axis).

This is a very important property for the ship survivability and particularly for TTC as pointed out by *Spanos & Papanikolaou* [7]. According to this the damaged ROPAX may either survive for very long time after damage or will capsize within a short time; namely, in terms of TTC of ROPAX ships, a binary situation is practically encountered, rapid capsize or no capsize at all.

8. PARAMETERS FOR TIME TO CAPSIZE

Regarding the incident waves and assuming a unimodal spectral distribution, the following three parameters are considered, namely that of wave height, the wave periods and spectrum width. The spectrum width, as approached through two basic wave spectra that of *JONSWAP* and *Pierson-Moskowitz* of equal energy and peak frequencies, appears to result to only minor differences for TTC. However the wave periods may be a notably affecting parameter as shown in Figure 6 where short periods ($Hs/\lambda = 0.04$) and long periods ($Hs/\lambda = 0.018$) are assumed. In waves of longer period the critical wave height appears to be shifted by 0.5 m which consequently TTC is shifted towards longer times.

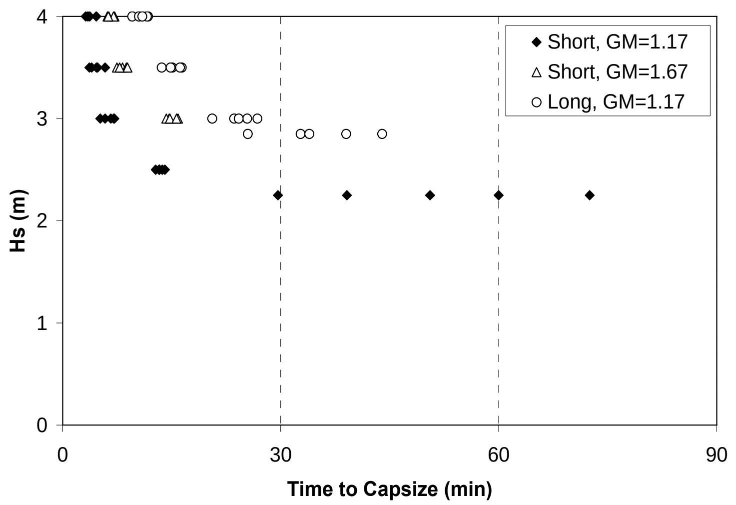

Figure 6 Effect of *GM* and wave periods on time to capsize

The ship loading condition (in terms of weight distribution) is a basic parameter affecting ship's survivability hence also TTC. The effect of *GM* on TTC is demonstrated with Figure 6 too. There, by increasing the *GM* (by 0.5 m) an increase of both the survive wave height limit (by 0.5 m) and almost double TTC results.

In summary the basic parameters that may determine the survivability of damaged ships and time to capsize TTC, and which were investigated in T4.3, are listed in Table 2.

These parameters define a large parametric space in seven dimensions, within which the behaviour of TTC is explored. When more parameters are taken into account (like the ship displacement or the shape of damage opening) the parametric space will proportionally increase. The investigation of the present space provides, however, sufficient information about the characteristics of TTC and should confirm the generic type of results of Figure 5 and Figure 6.

Table 2 Parameters for Time to Capsize

S/N	Parameter	Symbol
	SHIP LOADING	
1	Metacentric height	GM
2	Permeability	μ
3	Roll Radius of gyration	i_{xx}
	SEA WAVES	
4	Significant Wave height	H_s
5	Wave periods	T_p
6	Spectral peak enhancement parameter	γ
	DAMAGE OPENING	
7	Damage length	

9. MONTE CARLO SIMULATION

In the present investigation a *Monte Carlo Simulation* MCS[1] were conducted for the probabilistic estimation of TTC. The results of this probability simulation comprise a sound basis for validation of an analytical approach to TTC whilst simultaneously the influence of the basic parameters on TTC can be observed. Thereby the final results incorporate the effects of all parameters and the obtained distribution approaches the generic case.

Aiming to serve both above scopes, namely the estimation of probability distribution and the parametric study, the assumed probability distributions of the varying parameters was defined uniform within specific ranges. The ranges (as detailed in section 10) were rationally defined and were wide enough to capture all possible responses of the damaged ship.

For each sample of randomly selected parameters (Table 2) the ship motion in waves and ship flooding is simulated over a time period of 3 hours. During this period the damaged ship may either survive or not. For each non-survive simulation, the TTC was recorded. Thereby statistical data for TTC were generated on the basis of numerical simulation and the probability distribution of TTC is estimated on the basis of such data.

Concerning the generation of best possible numerical estimations, the numerical estimations with the genuine predictions of Figure 5 where further adjusted on the basis of available experimental data. This was achieved by trimming the discharge coefficient for the damage opening and the ship roll damping. In comparisons of Figure 5 the initial numerical estimations appear slightly conservative, i.e. shorter TTC and lower Hs. To balance these differences the discharge coefficient was lowered to C_d=0.61 (initial value 0.67) and the roll damping slightly increased. Both changes were accomplished with trials, and cannot be generalized.

Figure 7 demonstrates a characteristic simulation for a non-survive case. There the roll motion and the floodwater on the deck are plotted. The ship capsized after 1 hour and 10 min from the start time (a relatively late capsize where the different flooding phases can be visualized). At the start time the ship is assumed damaged and at equilibrium in calm water thus the compartments below water line are already flooded (with initial heel -2 deg to port).

There are three characteristic time phases. In the first, approximately 10 minutes after the assumed collision damage, the water is gradually accumulated on the deck and the ship heels towards the damaged side (port side) approximately 5 degrees. Thereafter the second phase can be observed, where an average balance takes place. The ship rolls around 5 degrees and some average water of 150 tn seems to be trapped on the deck. This condition lasts almost for 1 hour and it seems that the vessel has reached a stable and stationary condition and may survive for even longer. However, in the third phase, after 1 hour from the collision a sequence of waves has caused to further increase of floodwater on the deck and the heeling angle. When the floodwater on

[1] MC probability simulation should not be confused with the ship motion simulation

deck exceeds 250 tn, then instability conditions were developed and the ship soon capsized.

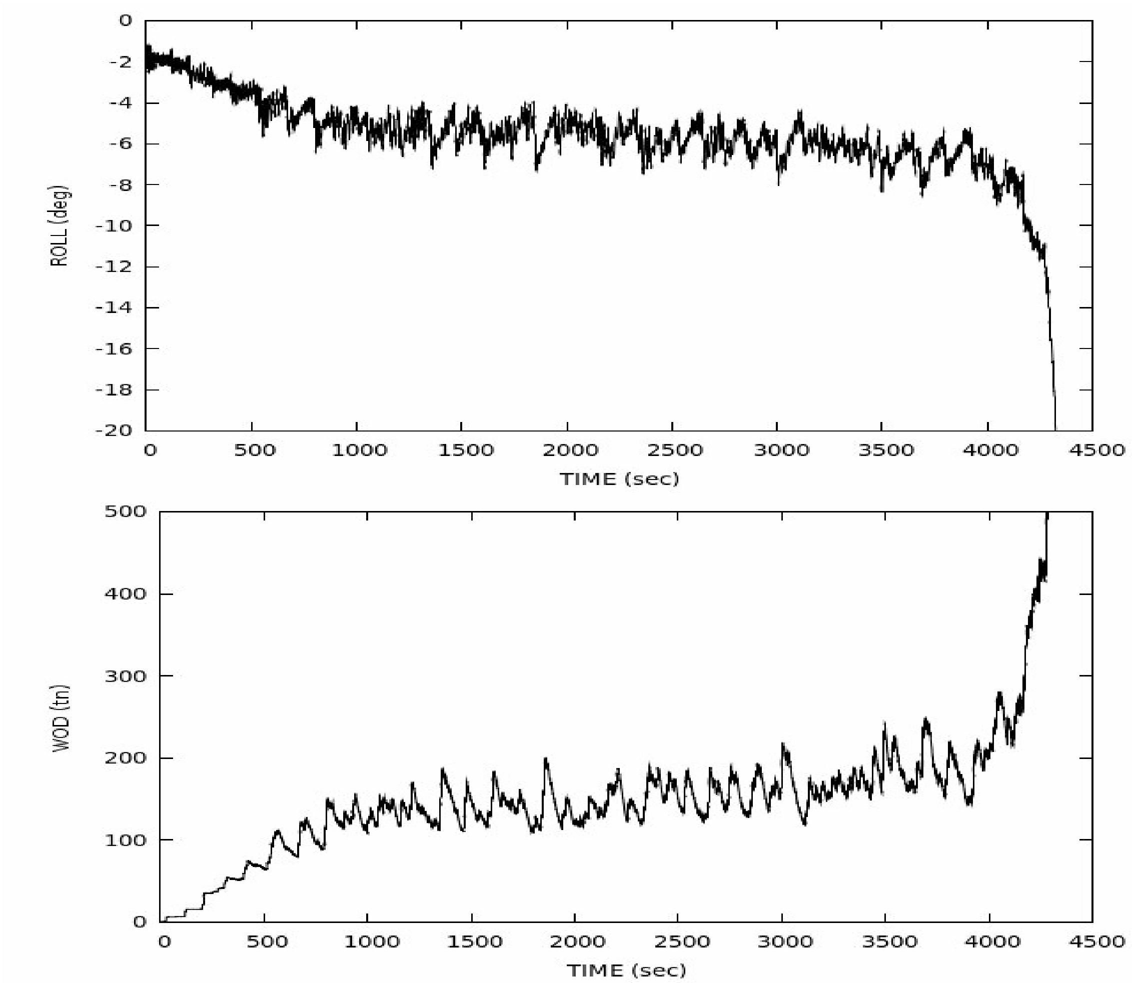

Figure 7 Numerical simulation (capsize at 1hr 10 min)

10. NUMERICAL SIMULATION TESTS

A comprehensive series of numerical simulation tests, which were carried out in T4.3, were defined as following.

Tests are designed with increasing complexity, so that the complexity of TTC can gradually built up and be interpreted.

- **Test 01** is the basic test where numerical estimations are compared with available experimental data from T4.1. All parameters are specified, while incoming waves of heights between 2.0 and 3.0 m are explored, for which the transition between survive and non-survive conditions is observed. Semi-empirical coefficients (discharge through openings, damaged ship damping) were adjusted to the experimental data to establish the best possible correlation between numerical and physical experiments (as illustrated in section 9).

- **Test 02** is a special case of Test 01, where the wave height of 2.60 m is targeted. The randomness for this test is limited to the randomness of wave realizations only. The selected height lies within the survivability transition range (observed in Test 01).

- **Test 03** regards the effect of the length of damage opening. The length is varied between 0.5 and 1.5 times the original damage length.

- **Test 04** is an extension of Test 03 where wave periods are randomized too. The periods are distributed between short waves, developed seas and up to longer waves.

- **Test 05** regards the variation of permeability over car deck. In previous tests this space assumed empty, i.e. permeability 1.0, while here a homogenous permeability is regarded up to 15% impermeable space.

- **Test 06** randomizes the roll radius of gyration. This parameter determines the roll motion in beam waves, consequently the flooding process.

- **Test 07** randomizes metacentric height GM for intact ship assuming some level of uncertainty +/-0.1 m. GM is a dominant parameter for stability of the damage ship and the flooding process.

- **Test 08** randomizes all parameters study cases tested in Tests 03 to 07 and for wave height 2.6 m. Six parameters are randomized. Thereby the probability distribution for TTC for specific wave height is approached.

- **Test 09** is similar to test 08 and randomized all parameters for a higher wave height 3.0 m. The effect of wave height on the probability of TTC is studied in comparison to Test 08.

- **Test 10** is the ultimate test, where all parameters are randomized including wave height. Parameters are extended to the maximum range and probability distribution of TTC in the wider sense is considered.

TEST PARTICULARS

ROPAX Vessel *Estonia*

Midship damage case, two compartments No 5 & 6 plus car deck

Beam waves (from port side)

Unimodal JONSWAP wave spectrum

Total Tests 10

Total runs 1850

Total simulated time 12454550 sec = 3460 hrs

Table 3 Parameters of numerical tests

TEST	Hs (m)	Tp/ Sqrt(Hs)	γ	GM (m)	ixx/B	perm	Ld (m)
01	2.0÷3.5	4.0	3.3	1.20	0.37	1.0	7.12
02	2.6	4.0	3.3	1.20	0.37	1.0	7.12
03	2.6	4.0	3.3	1.20	0.37	1.0	3.56÷10.68
04	2.6	3.6÷6.0	3.3	1.20	0.37	1.0	3.56÷10.68
05	2.6	4.0	3.3	1.20	0.37	0.85÷1.0	7.12
06	2.6	4.0	3.3	1.20	0.35÷0.45	1.0	7.12
07	2.6	4.0	3.3	1.1÷1.3	0.37	1.0	7.12
08	2.6	3.6÷5.0	1.0÷4.0	1.1÷1.3	0.35÷0.45	0.85÷1.0	3.56÷10.68
09	3.0	3.6÷5.0	1.0÷4.0	1.1÷1.3	0.35÷0.45	0.85÷1.0	3.56÷10.68
10	2.0÷4.0	3.6÷6.0	1.0÷4.0	1.0÷2.0	0.35÷0.45	0.85÷1.0	3.56÷10.68

11. TEST01 (varying Hs + specific all other parameters)

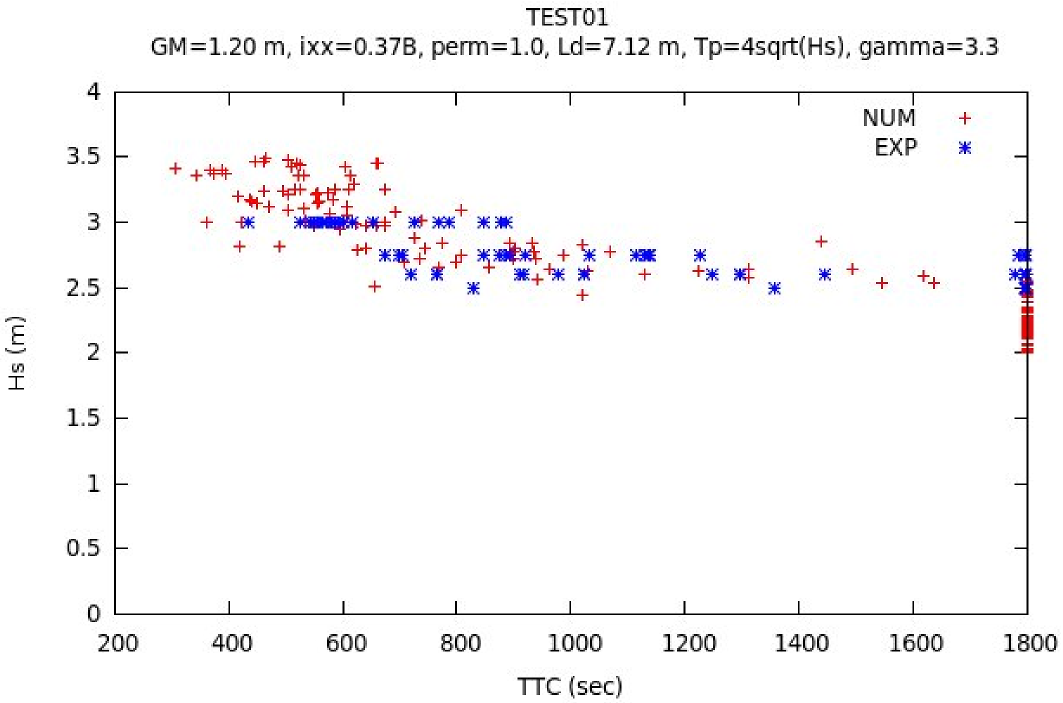

Figure 8 Test01, Time to Capsize TTC over significant wave height for the basic damage scenario

<u>TEST 01</u>

- All parameters are fixed and correspond to those of tank model tests. The significant wave height is randomly distributed between 2.0 and 3.5 m.
- Both numerical and experimental tests are stopped at 1800 sec (30 min).
- A critical wave height appears between 2.25 and 2.50 m. For heights below that height no capsizes occur, whereas approaching this height from above the TTC increasingly spreads, with the maximum spread at critical height.
- The region of scattered data defines the transition range between survive conditions and non-survive conditions within 30 min. The transition range shrinks over the time and it becomes less than 0.5 m at 30 min.
- Although the direct prediction of TTC by the employed numerical simulation method is rather successful, as shown in Figure 5, the numerical simulation was further adjusted to the experimental data in order to establish the best possible estimations of the effect of the change of the various on TTC in the frame of this parametric investigation.

12. TEST02 (specific Hs = 2.60 m)

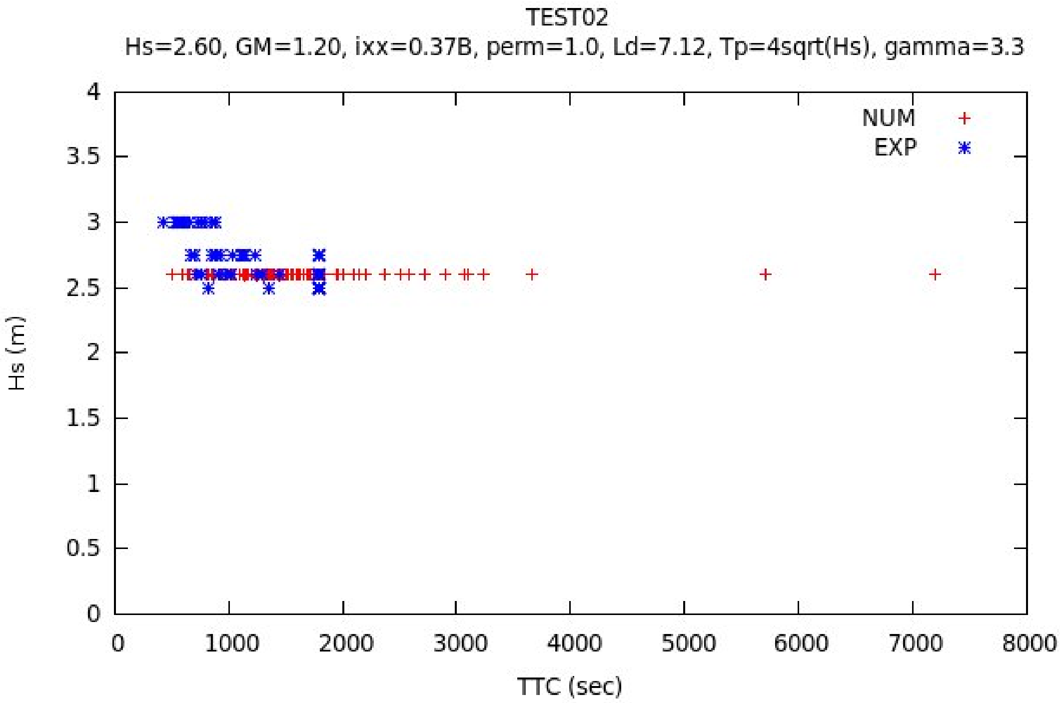

Figure 9 Distribution of Time to Capsize *TTC* for Hs=2.60 m (red symbols)

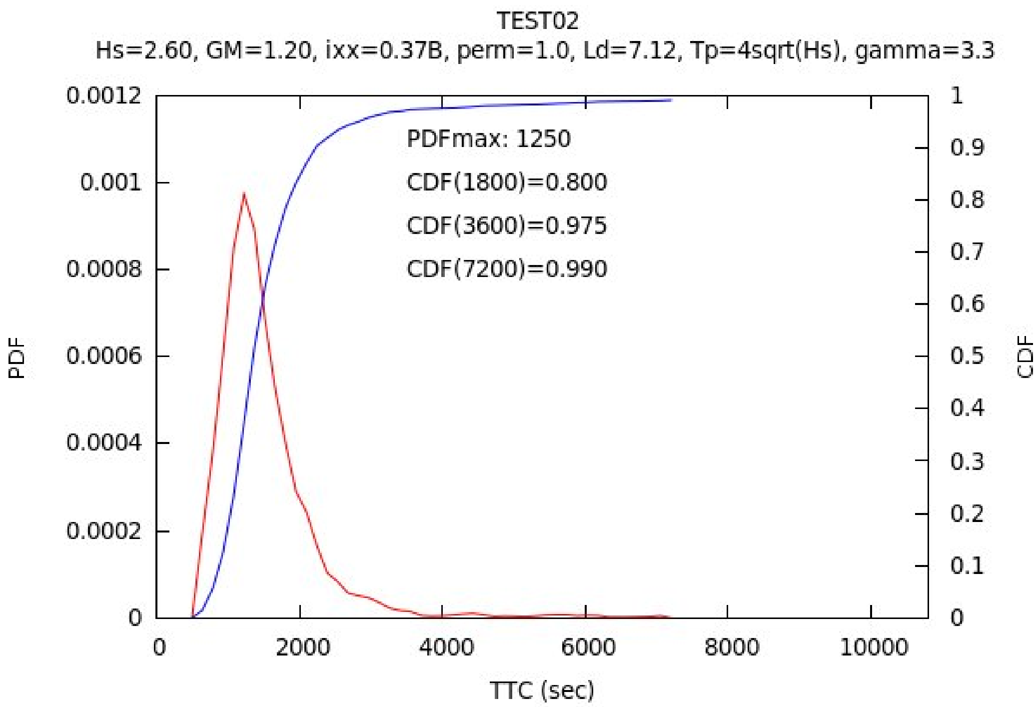

Figure 10 Probability functions

TEST 02

- Testing conditions are concentrated at wave height of 2.60 m. This height is within the transition band with a remarkable spread of TTC.
- Tank experiments were stopped at 1800 sec (30 min), while numerical tests at 7200 sec (120 min).
- Unimodal probability distribution is estimated with a peak around 20 min. TTC decays fast above that peak. TTC longer than 1 hour appears a quite remote event. No capsizes occur for very short times as a consequence of the time required to accumulate some critical floodwater mass on deck.
- The spread of TTC is due to the randomness of waves. Thus waves may cause a difference in TTC up to 1 hour. This long difference is because the specific wave height is close to critical height.
- The probability to capsize within 30 min is 0.80. From tank tests [3] this probability was roughly estimated at 0.65 on the basis of 20 trials.

13. TEST03 (specific Hs = 2.60 m + varying damage opening)

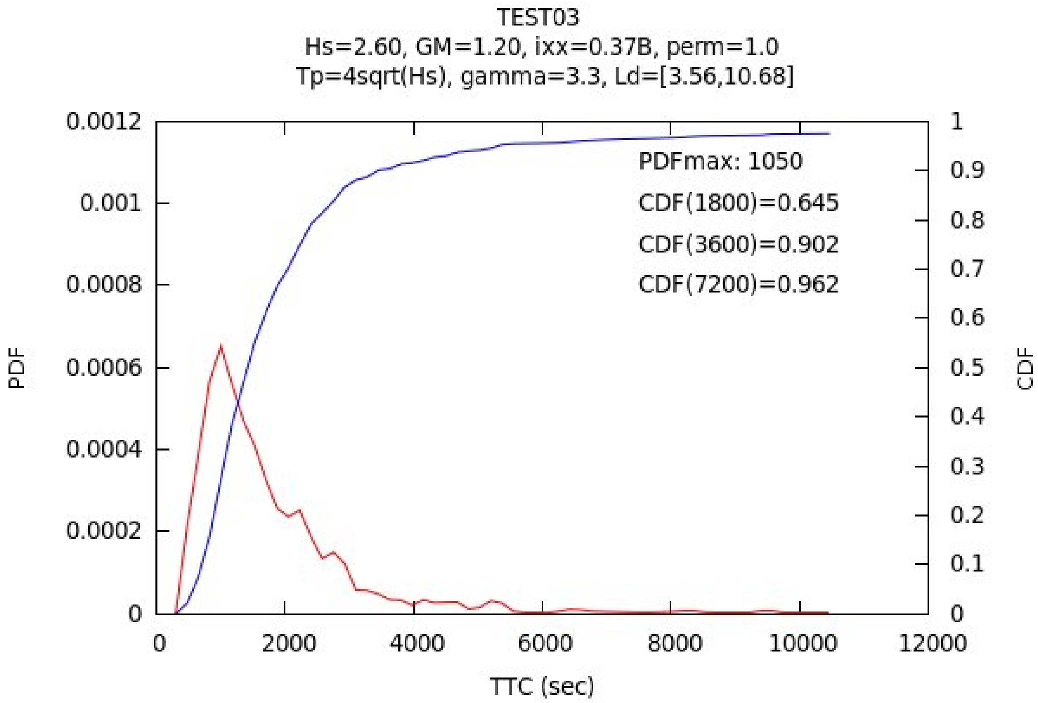

Figure 11 Probability functions

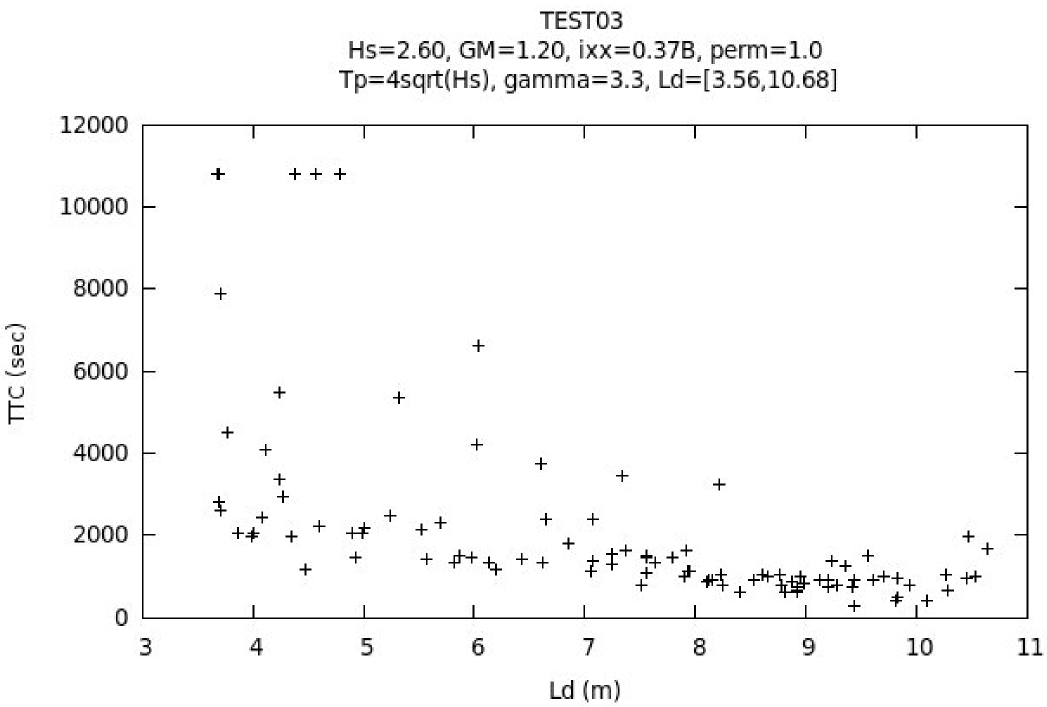

Figure 12 Length of damage opening *Ld* and Time to Capsize *TTC*

TEST 03

- Numerical tests were stopped at 10800 sec (3 hours).
- The damage length of 7.12 m assumed in previous tests (and tank tests) corresponds to 5.2% of ship length. The presently tested range corresponds to 2.6% ÷ 7.8% of the ship length.
- The probability for TTC remains unimodal with a peak still close to 20 min, while some higher spread is observed.
- Figure 12 analyzes TTC over the damage length. Lower sizes of damage opening may cause considerable spread on TTC.
- Although the main percentage of probability is below 1 hour, there is still some widely spread probability above 1 hour. This is related to lower damage openings.

14. TEST04(specific Hs = 2.60 m + varying damage opening + varying wave periods)

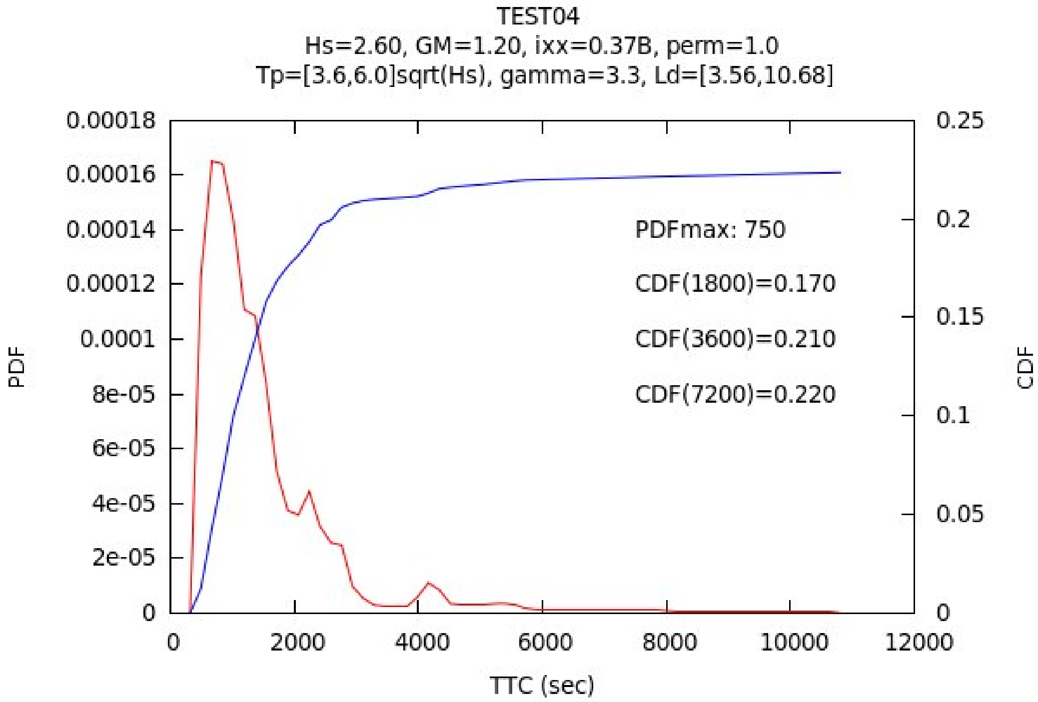

Figure 13 Probability functions

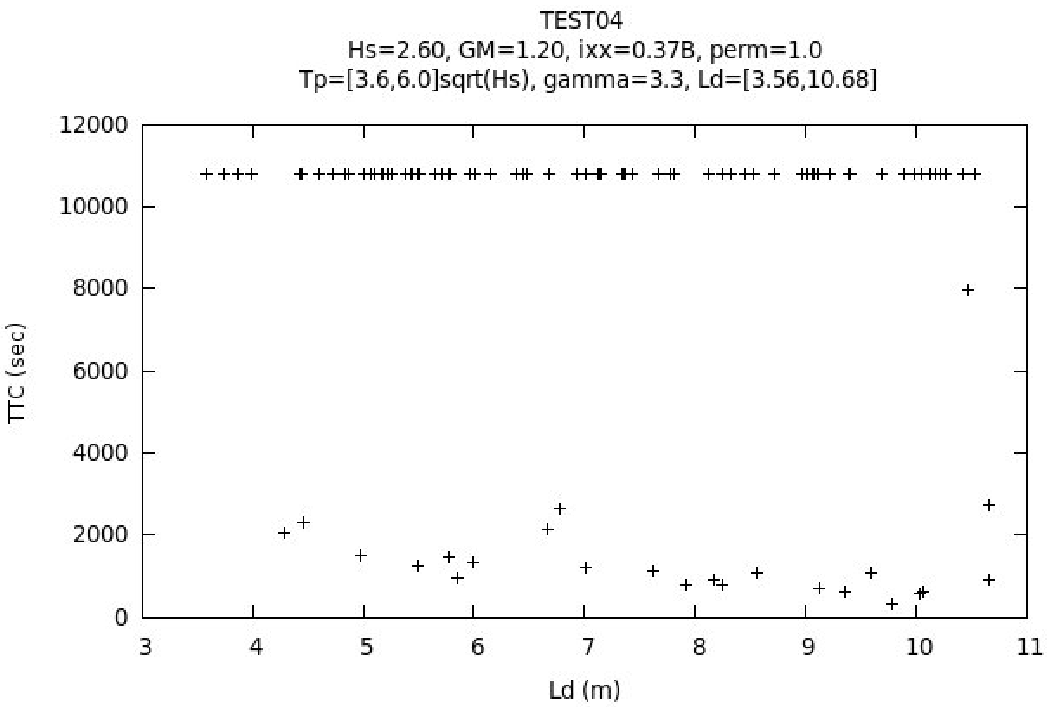

Figure 14 Length of damage opening *Ld* and Time to Capsize *TTC*

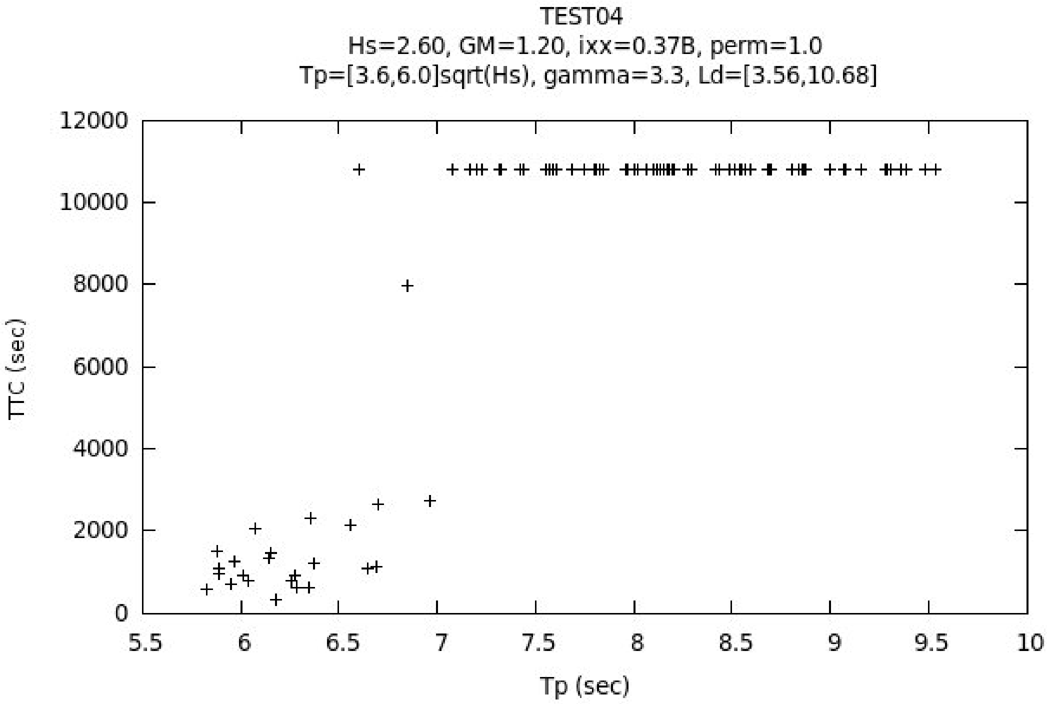

Figure 15 Spectrum peak period *Tp* and Time to Capsize *TTC*

<u>TEST 04</u>

- Numerical tests were stopped at 10800 sec (3 hours).
- Shorter periods approach fully developed sea waves (wave breaking) that correspond to this wave height. The peak period for previous tests equals 6.5 sec.
- Wave period is a rather significant parameter, Figure 15. A dramatic increase of the critical wave height appears for longer waves and in consequence no capsize events may be encountered anymore at the wave height of 2.6 m.
- Some evidence of long TTC is encountered for larger damage openings, Figure 12. This is a combined result of large opening with long waves, as Figure 12 illustrates that large openings are not correlated to long TTC.
- The probability for TTC demonstrates a peak around 12 min, while the spread is still up to 1 hour. The probability limits at 22.5% for long TTC. Considering the convergence of probability, TTC later than 1 hour is still a rare event. Therefore almost 78% of tests should be expected to survive infinite.

15. TEST05 (specific Hs = 2.60 m + varying permeability of car space)

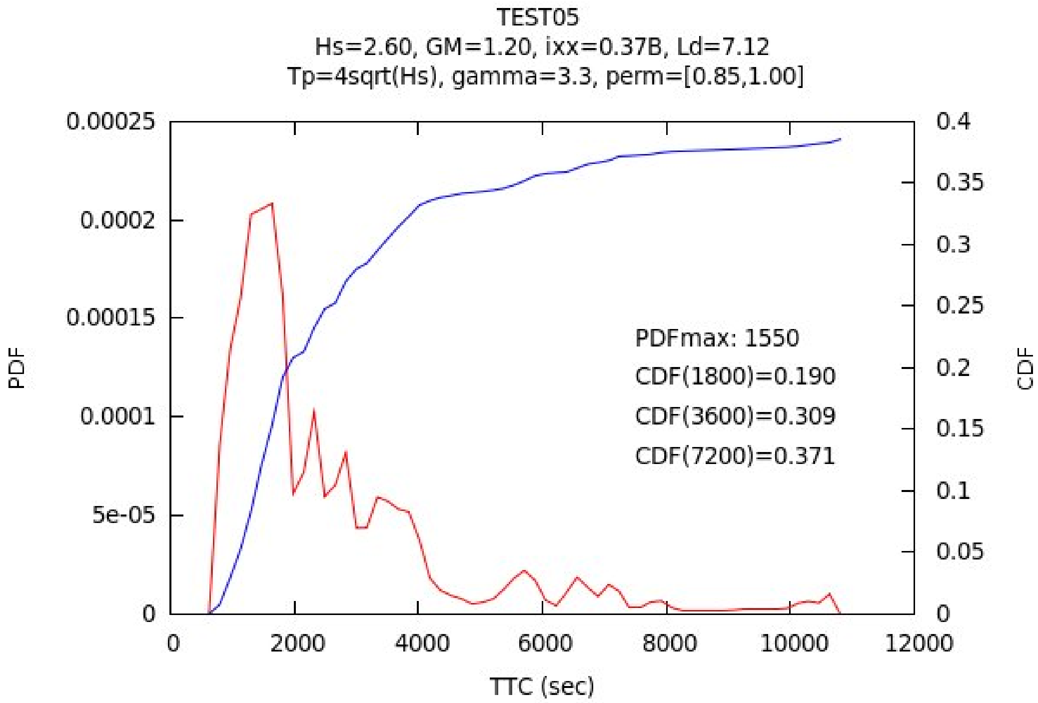

Figure 16 Probability functions

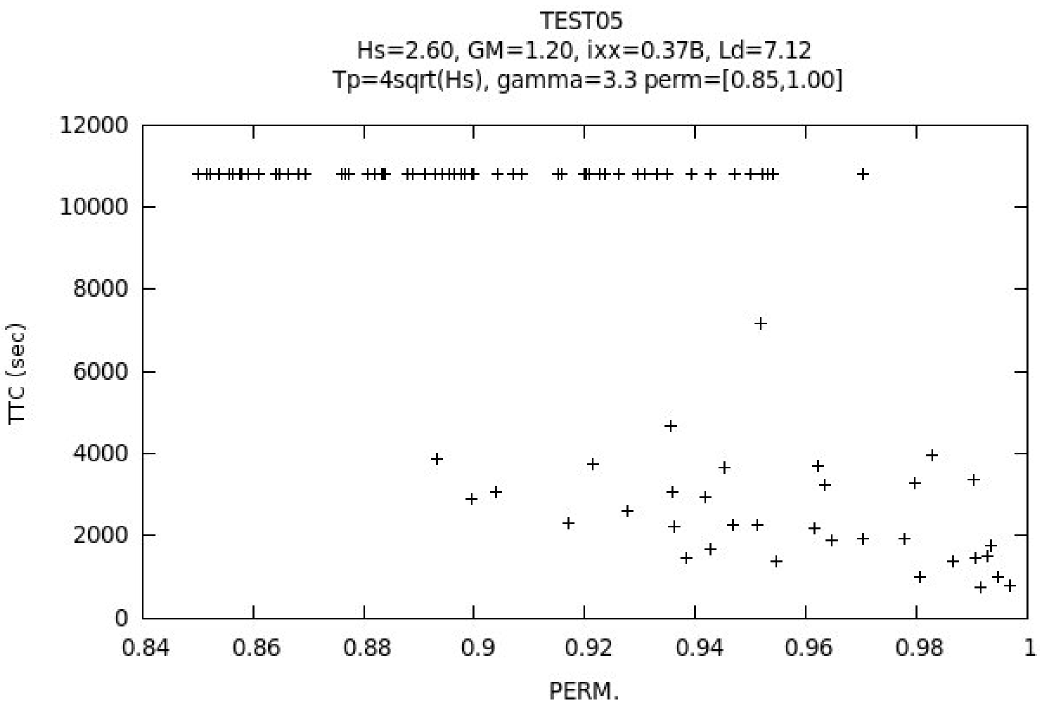

Figure 17 Permeability of car space and Time to Capsize *TTC*

TEST 05

- Numerical tests were stopped at 10800 sec (3 hours).
- Homogenous permeability of car deck space between 0.85 and 1.00 assumed, namely no cargo details considered.
- Permeability appears a rather significant parameter too. Ship systematically survives 3 hours for permeability below 0.90. A dual behavior is observed in the range of 0.90 and 0.95, which is of most practical interest. There the ship either capsizes within 1 hour or survives 3 hours.
- Probability for TTC between 1 and 3 hours appears again limited and decreasing, consequently a percentage of 60% can be assumed as probability to survive.
- The peak of probability distribution has been shifted to 25 min. This 5 min difference from Test 02 is due to one side spread of permeability with respect to Tests 02 which was 1.0.

16. TEST06 (specific Hs = 2.60 m + varying roll radius of gyration)

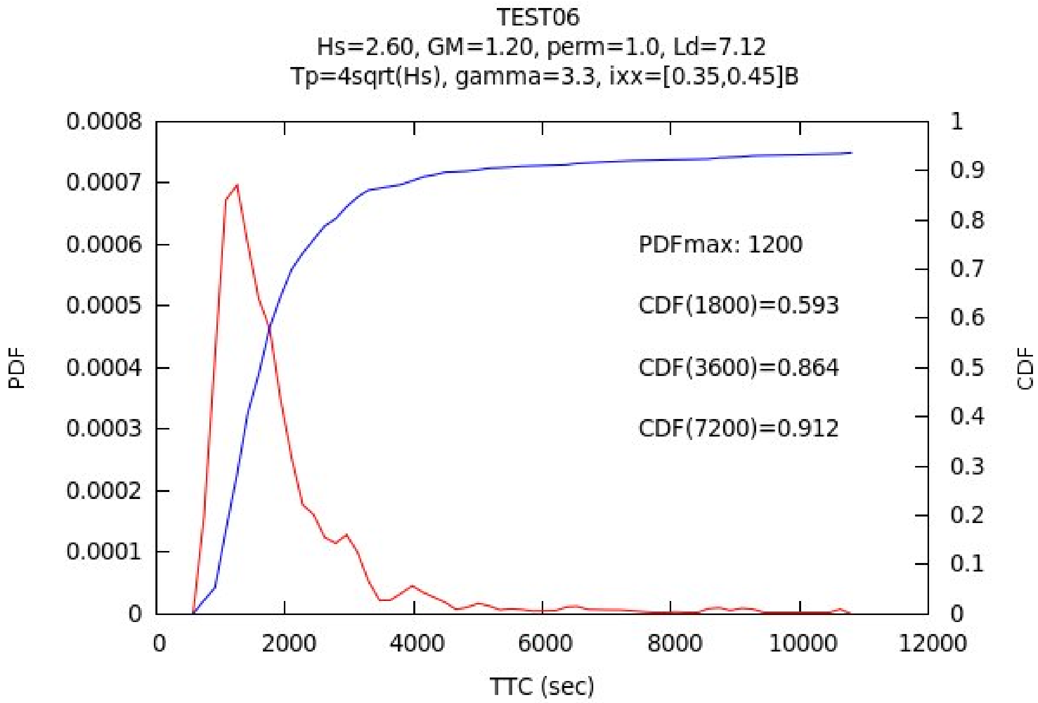

Figure 18 Probability functions

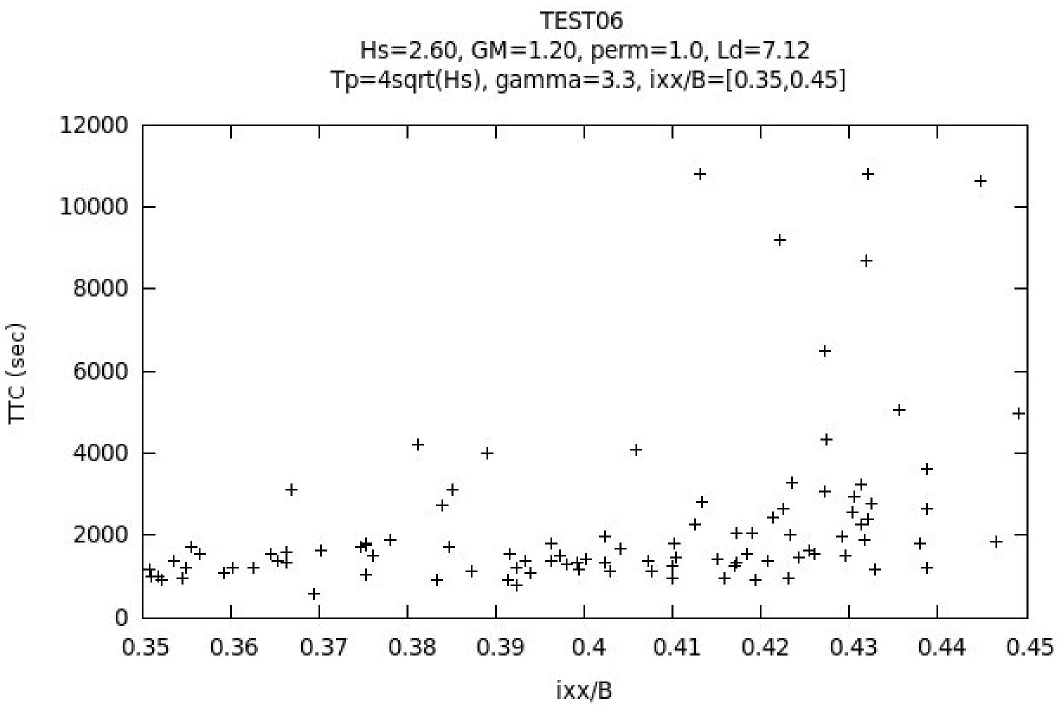

Figure 19 Roll radius of gyration *ixx* and Time to Capsize *TTC*

TEST 06

- Numerical tests were stopped at 10800 sec (3 hours).
- Roll radius of gyration appears here favorable to ship survive, namely increasing its value leads in general to longer TTC. For larger values of TTC some increasing spread of up to 3 hours is observed, Figure 19.
- The peak period is still around 20 min. While because of the slow convergence of the probability at larger TTC the ultimate limit cannot be safely estimated, therefore the probability of roughly 5% to survive 3 hour cannot be assumed as survive probability (namely survive infinite time).

17. TEST07 (specific Hs = 2.60 m + varying metacentric height)

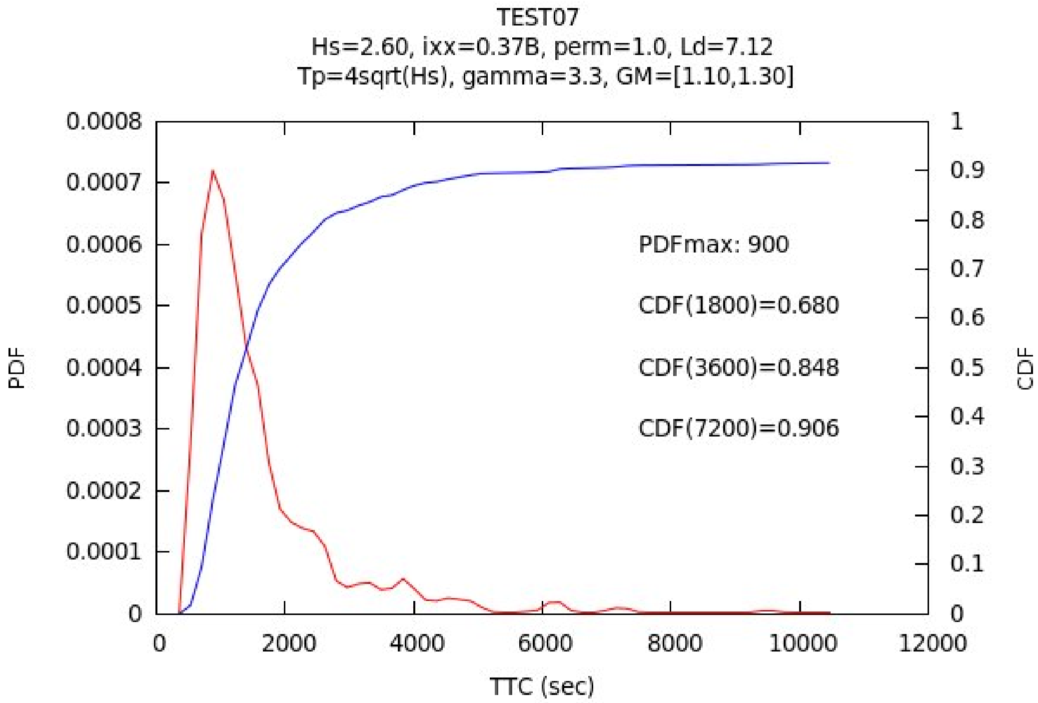

Figure 20 Probability functions

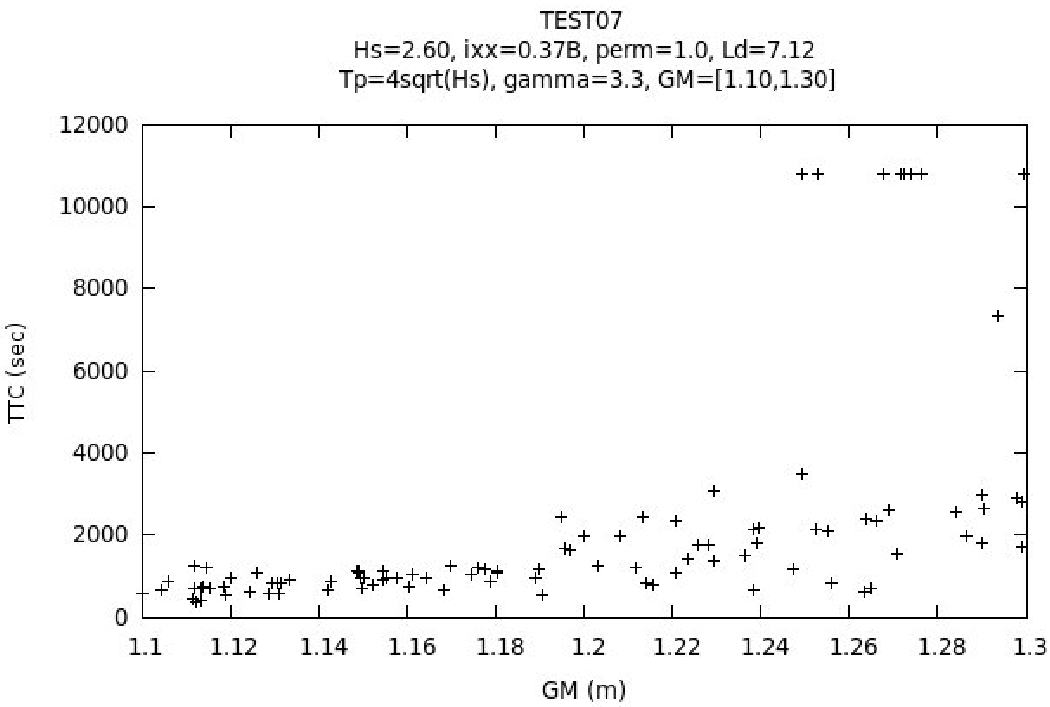

Figure 21 Metacentric height *GM* and Time to Capsize *TTC*

TEST 07

- Numerical tests were stopped at 10800 sec (3 hours).
- An uncertainty of +/- 0.1 m for *GM* is assumed here, namely around intact ship *GM*=1.2 m.
- The significant effect of *GM* on *TTC* is apparent in Figure 21. An increase of *GM* by 10 cm establishes a remarkable percentage of 10% survive in 3 hours. At this range of GM, the ship either capsizes within 1 hour or survives 3 hours.
- Test 06 demonstrated that larger i_{xx} may result to longer *TTC*. In the present Test 07, larger *GM* may result to longer *TTC* as well. Both parameters affect ship's roll motion (namely via ship's roll natural period) however inversely. Therefore the effect of *GM* is presumably related to an increase of residual stability and to a lesser degree to roll motion.

18. TEST08 (specific Hs = 2.60 m + varying all other parameters)

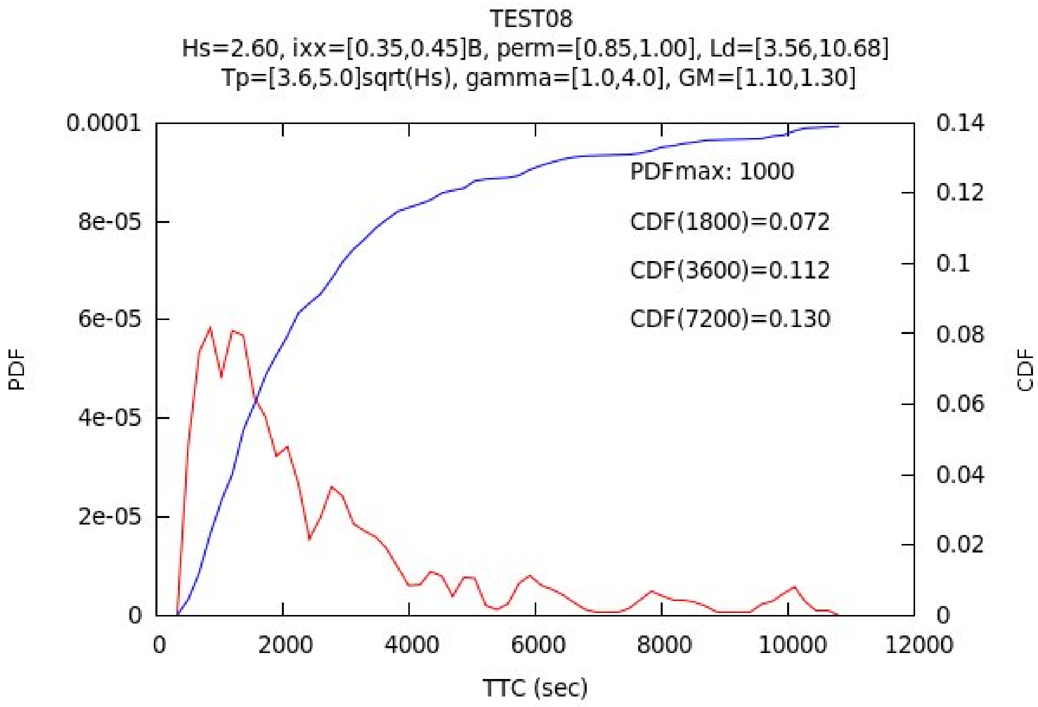

Figure 22 Probability functions

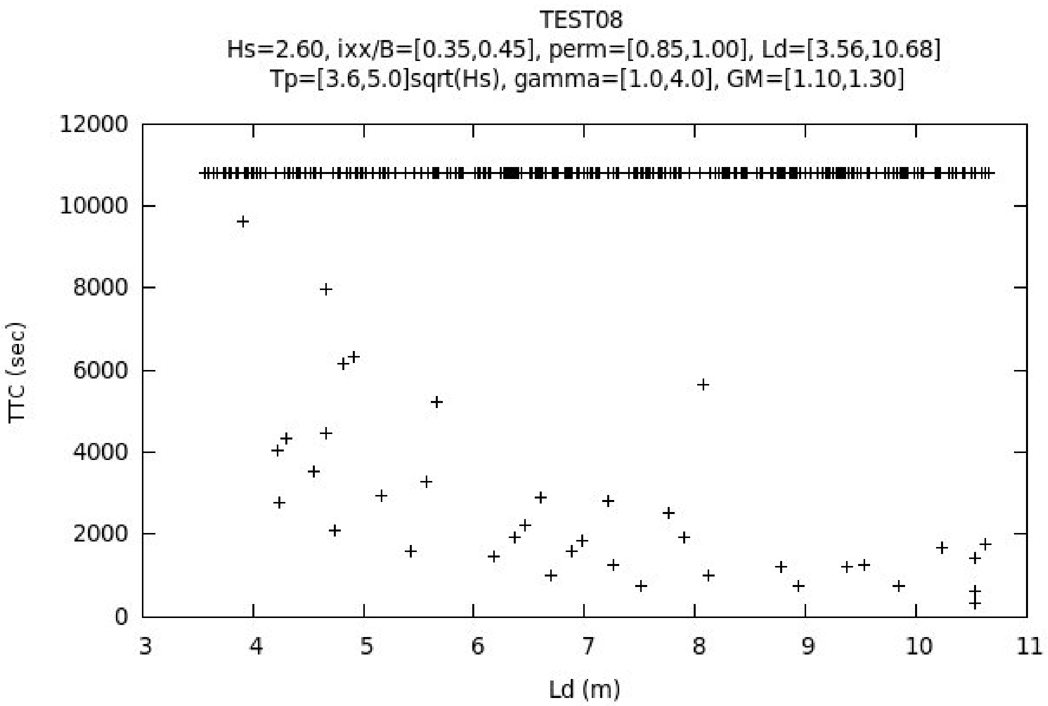

Figure 23 Length of damage opening *Ld* and Time to Capsize *TTC*

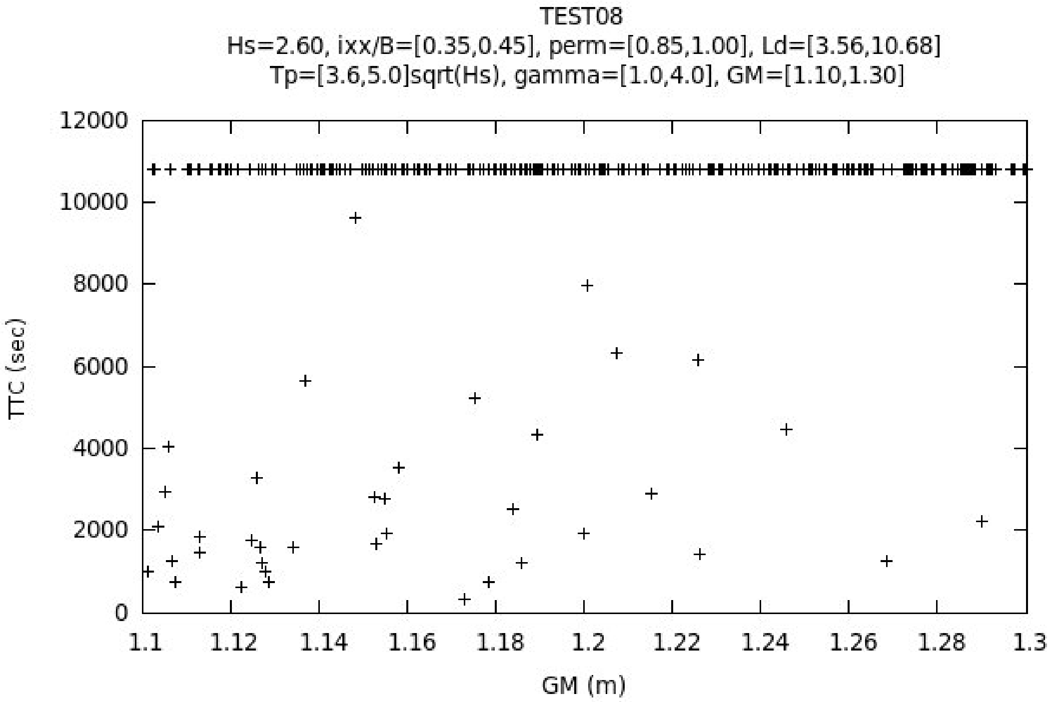

Figure 24 Metacentric height *GM* and Time to Capsize *TTC*

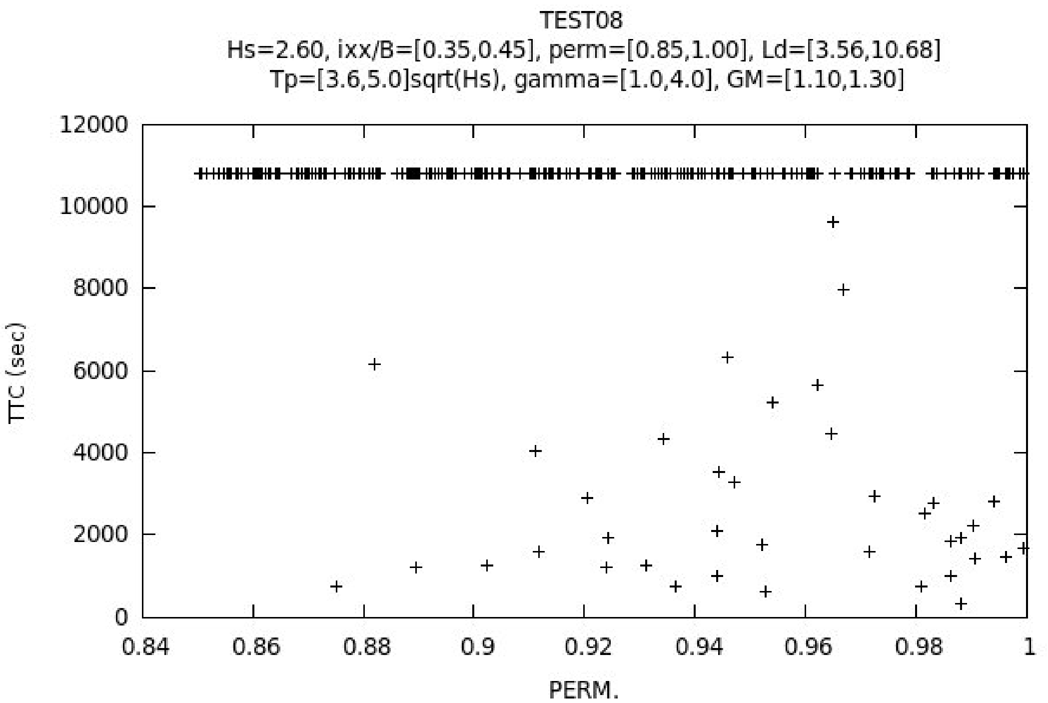

Figure 25 Permeability of car space and Time to Capsize *TTC*

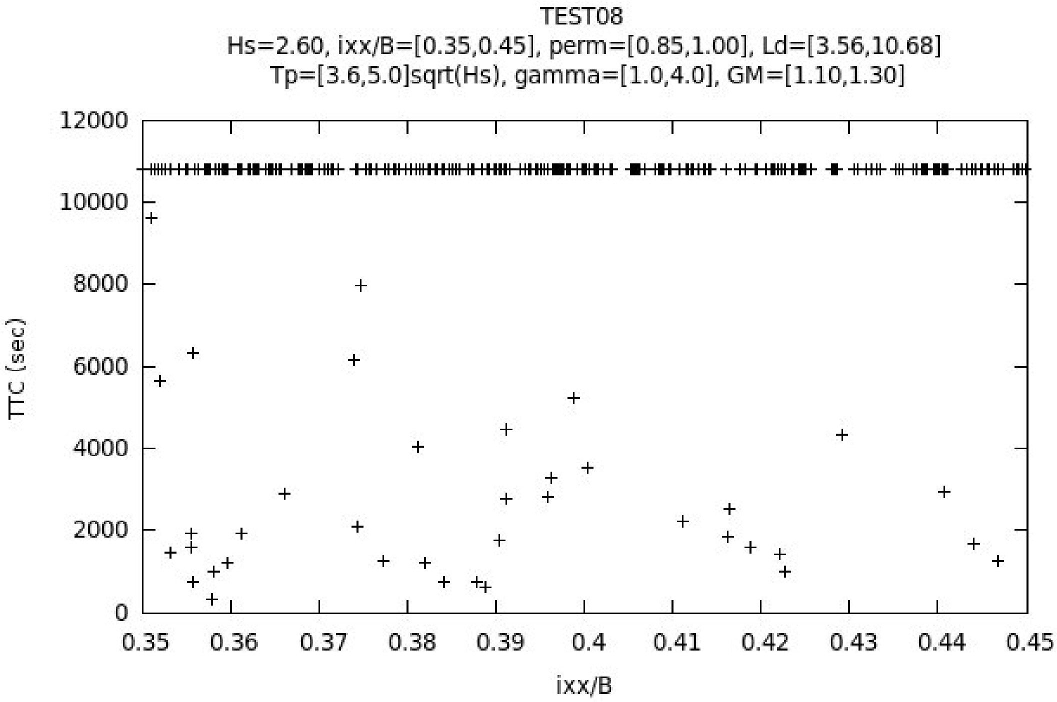

Figure 26 Roll radius of gyration *ixx* and Time to Capsize *TTC*

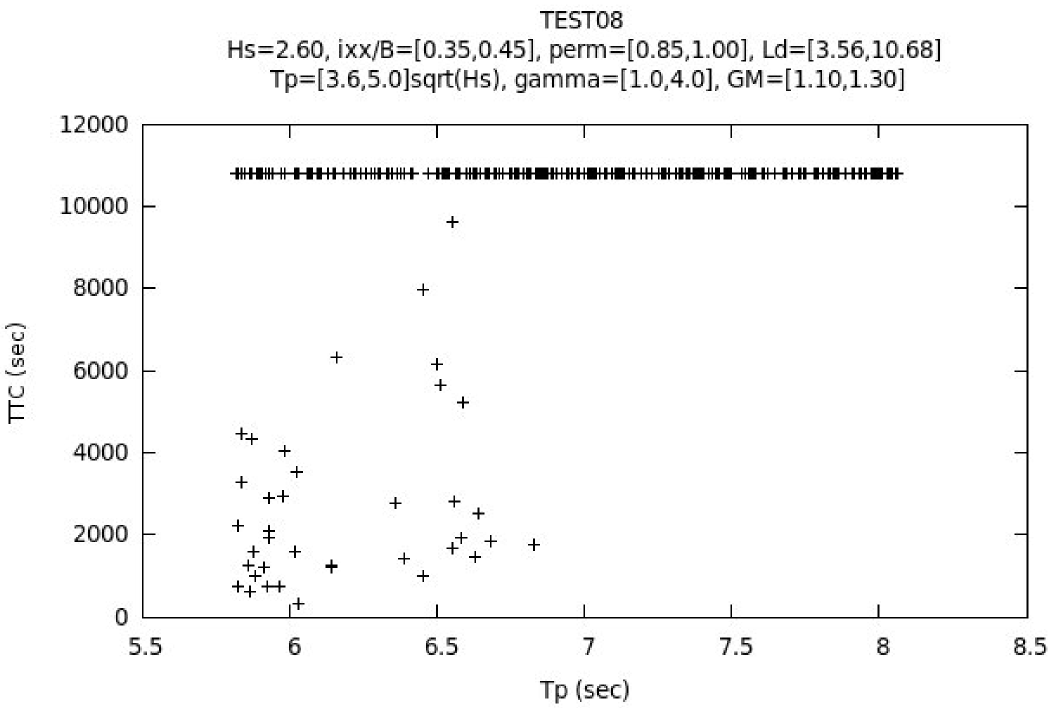

Figure 27 Spectrum peak period *Tp* and Time to Capsize *TTC*

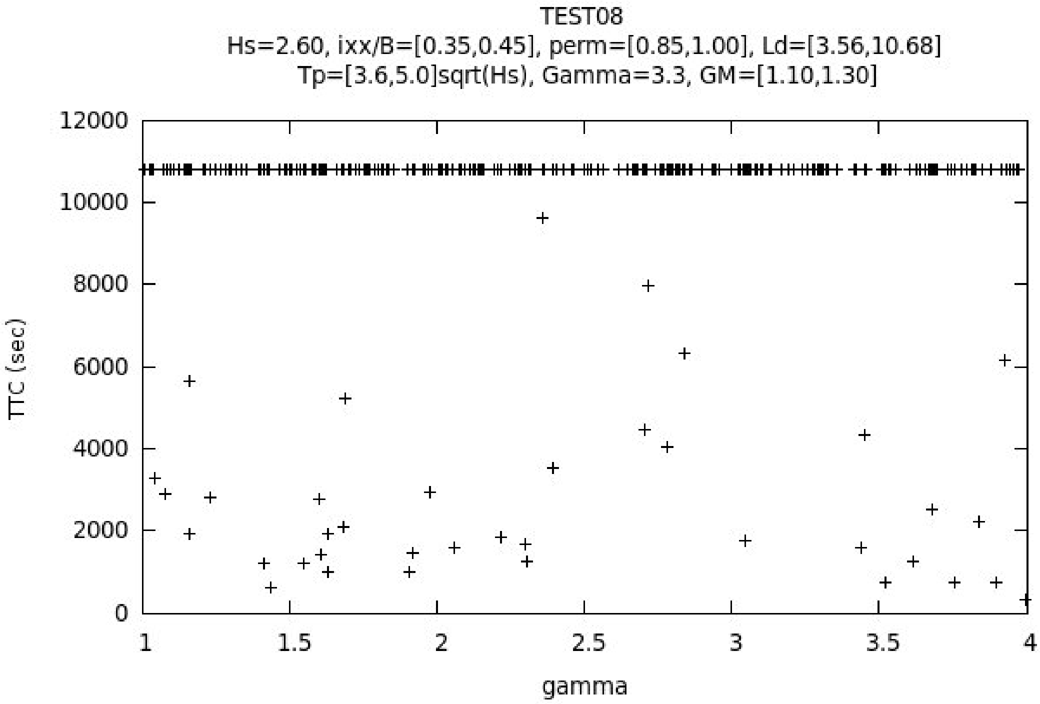

Figure 28 Peak enhancement parameter γ and Time to Capsize *TTC*

TEST 08

- Numerical tests were stopped at 10800 sec (3 hours).
- Significant wave height is fixed at 2.60 m, whereas all other parameters are randomized.
- TTC is distributed around 15 min Figure 22. Considerable probability for TTC throughout 3 hours can be observed.
- A probability of 85% to survive longer 3 hour can be roughly estimated from Figure 22. Survive events may occur along full ranges of the investigated parameters. However *GM* and *Tp* are the most affecting parameters (Figure 24 and Figure 27) and to a lesser degree damage opening and roll radius of gyration (Figure 23 and Figure 26).

19. TEST09 (specific Hs = 3.00 m + varying all other parameters)

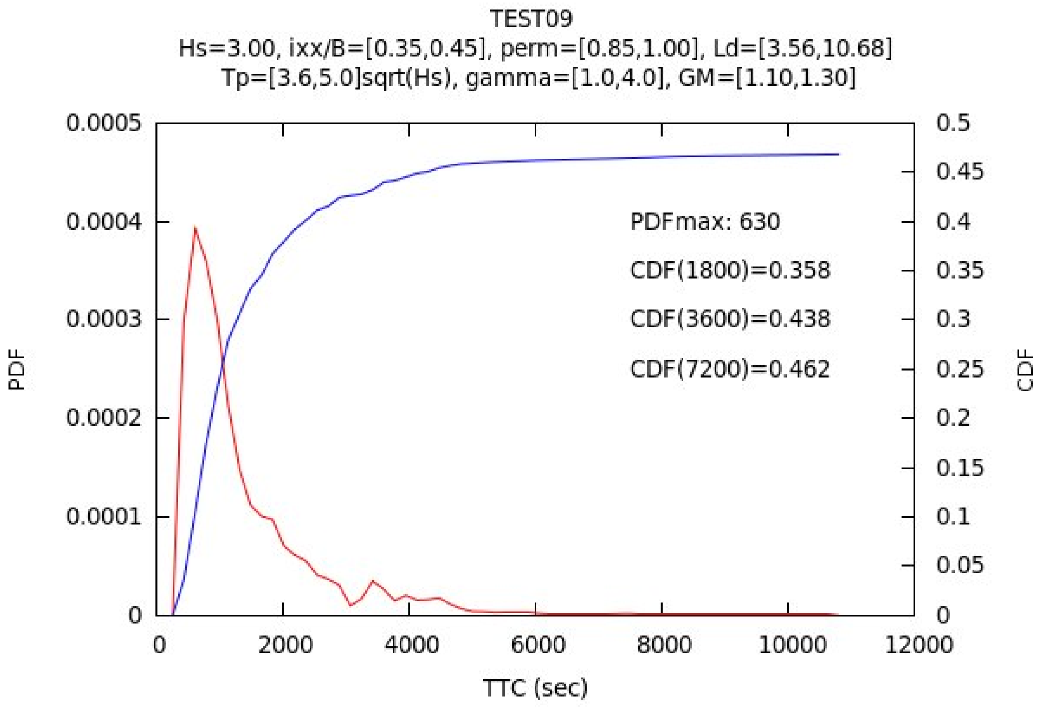

Figure 29 Probability functions

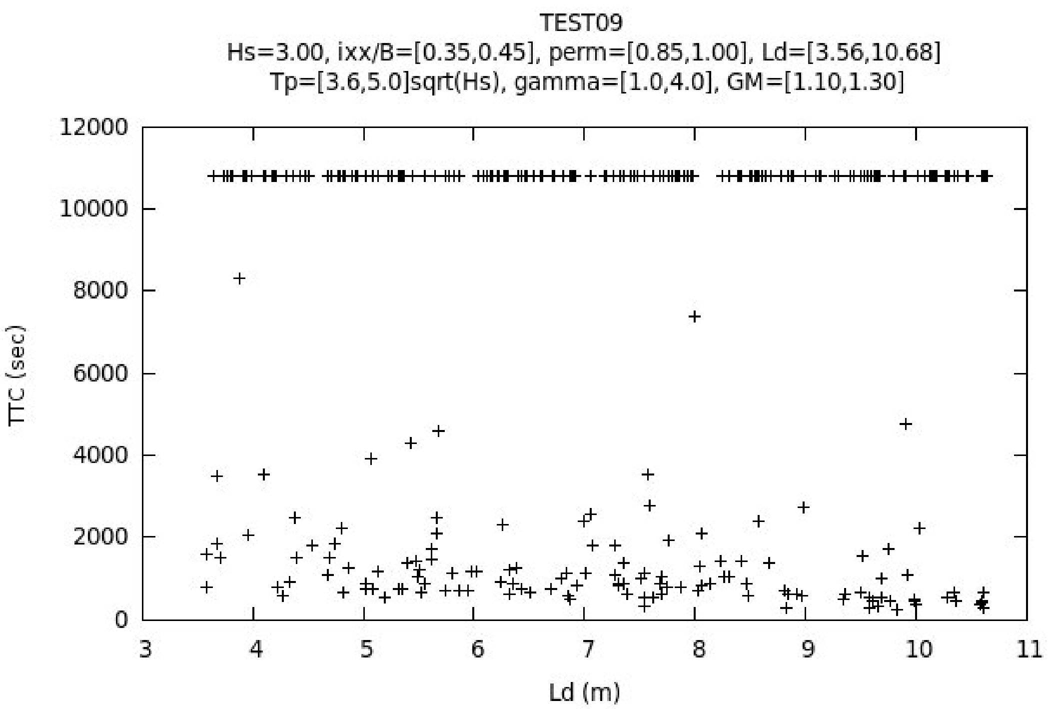

Figure 30 Length of damage opening *Ld* and Time to Capsize *TTC*

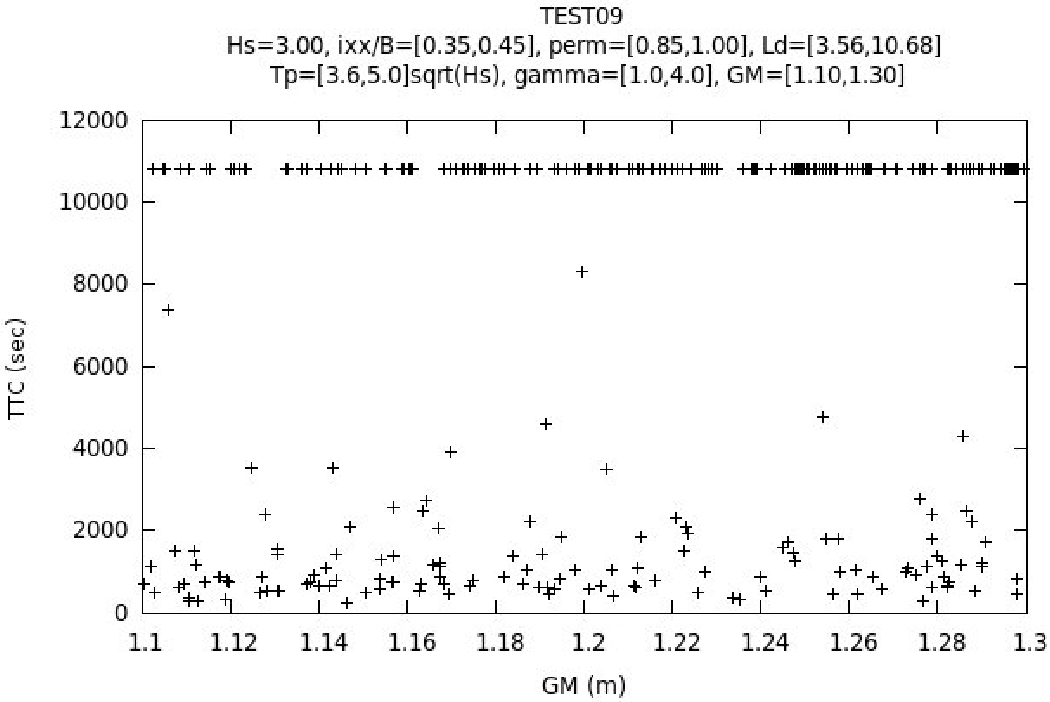

Figure 31 Metacentric height *GM* and Time to Capsize *TTC*

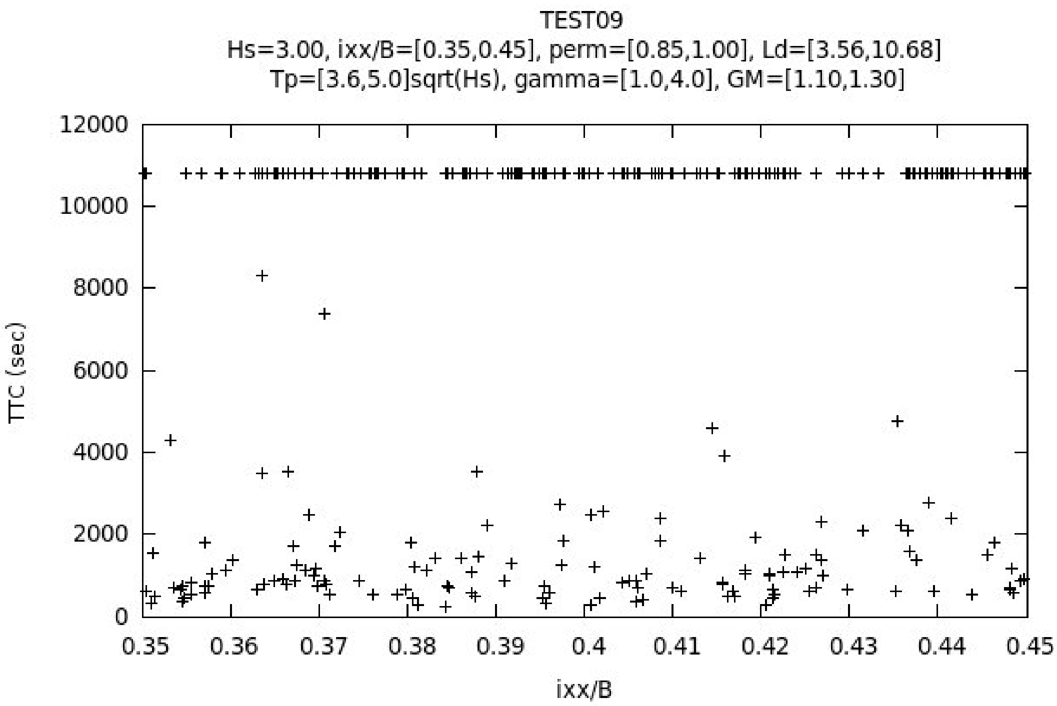

Figure 32 Roll radius of gyration *ixx* and Time to Capsize *TTC*

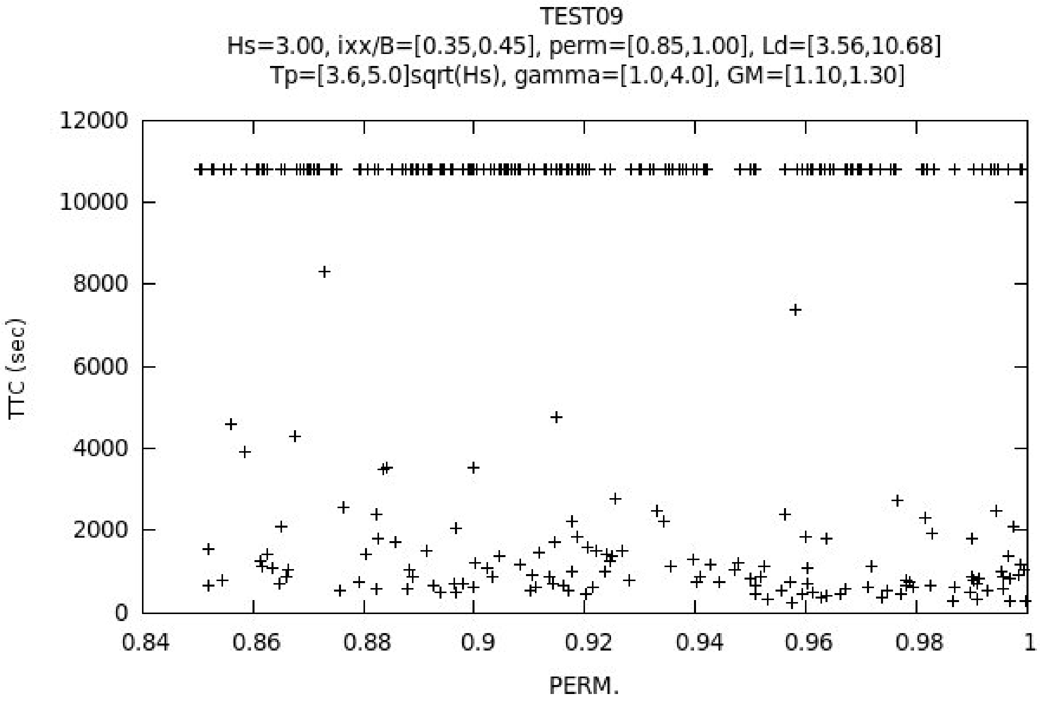

Figure 33 Permeability of car space and Time to Capsize *TTC*

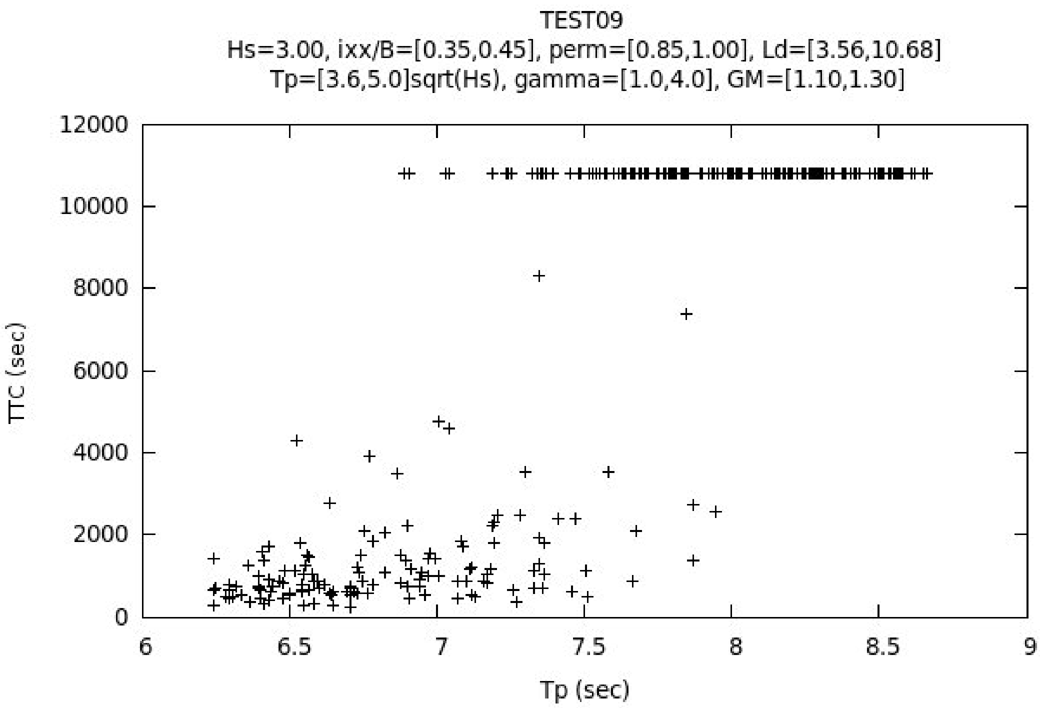

Figure 34 Spectrum peak period *Tp* and Time to Capsize *TTC*

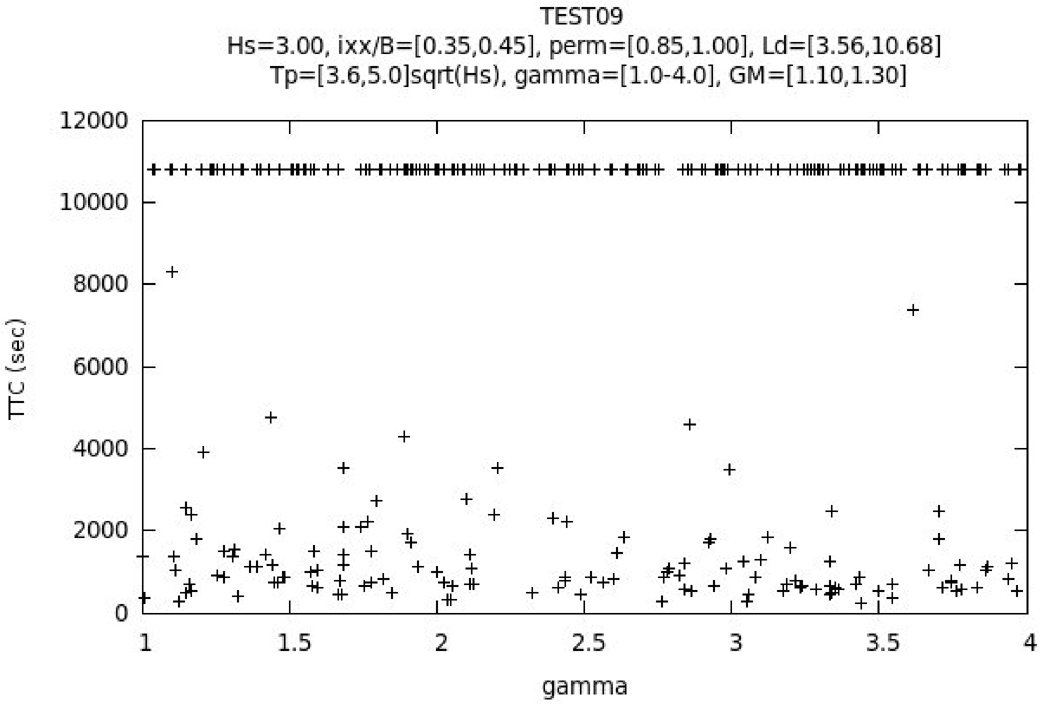

Figure 35 Peak enhancement parameter γ and Time to Capsize *TTC*

TEST 09

- Numerical tests were stopped at 10800 sec (3 hours).
- The difference to Test 08 is that the significant wave height is here fixed to 3.00 m, whereas still all other parameters are randomized.
- A consequence of increasing wave height is that TTC has been shifted towards shorter times with a peak at 15 min and much less events of survive 3 hours, limiting the probability to survive 3 hours to 52%.
- For this range of conditions, TTC is mostly affected by wave periods Figure 34, whereas the effect of other parameters is difficult to be observed in the scattered data.

20. TEST10 (varying all parameters)

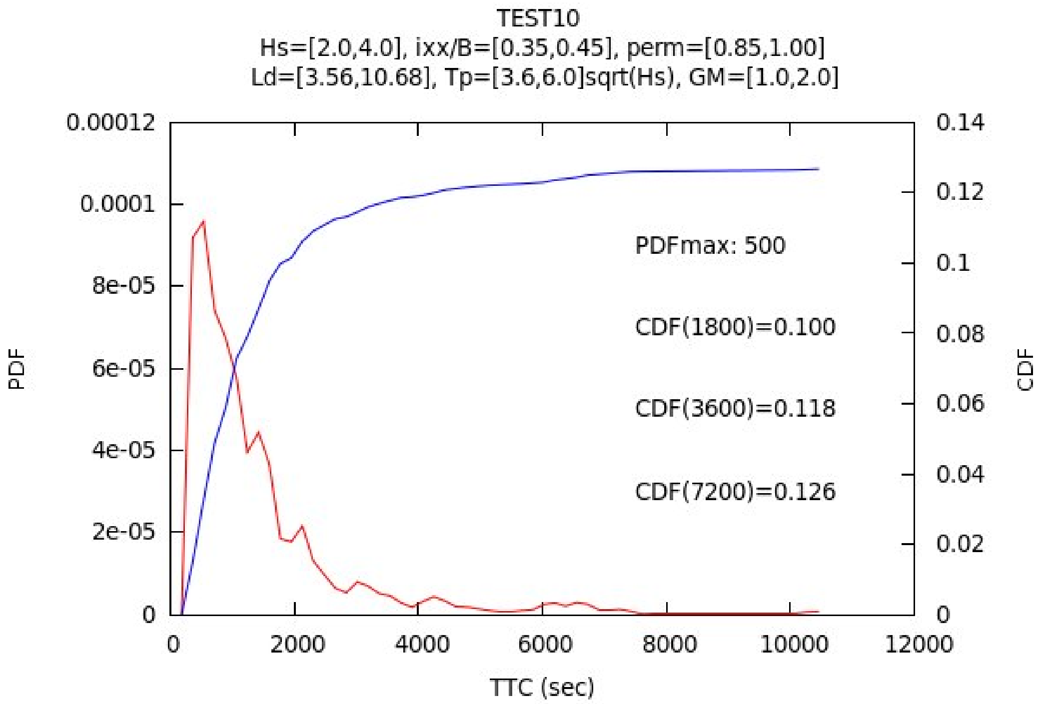

Figure 36 Probability functions

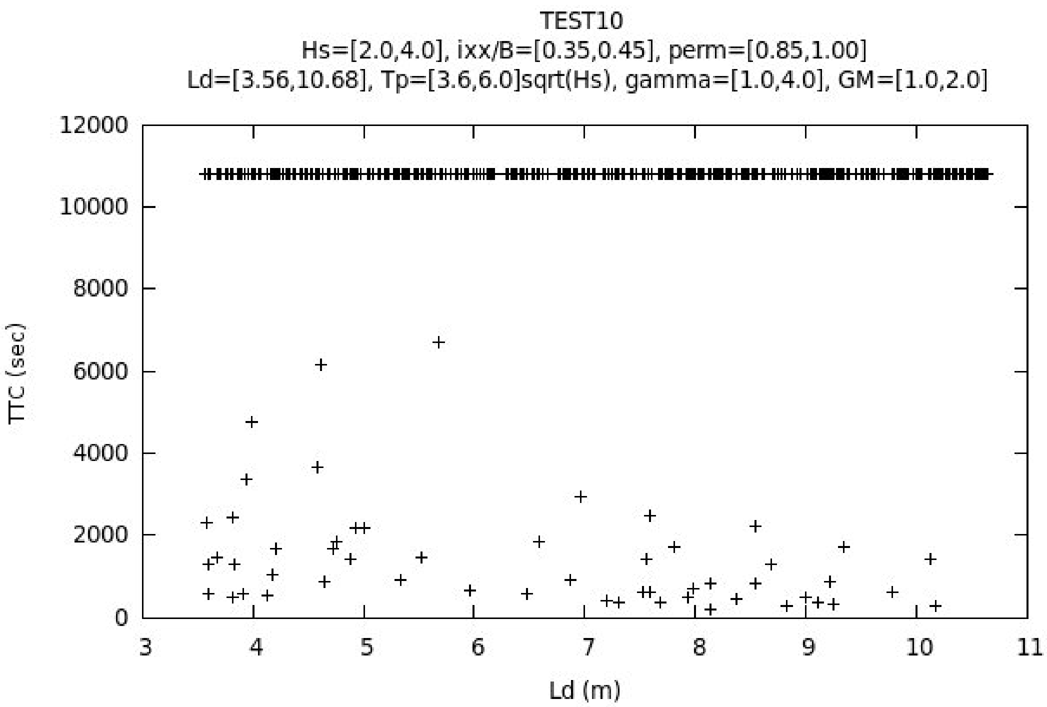

Figure 37 Length of damage opening *Ld* and Time to Capsize *TTC*

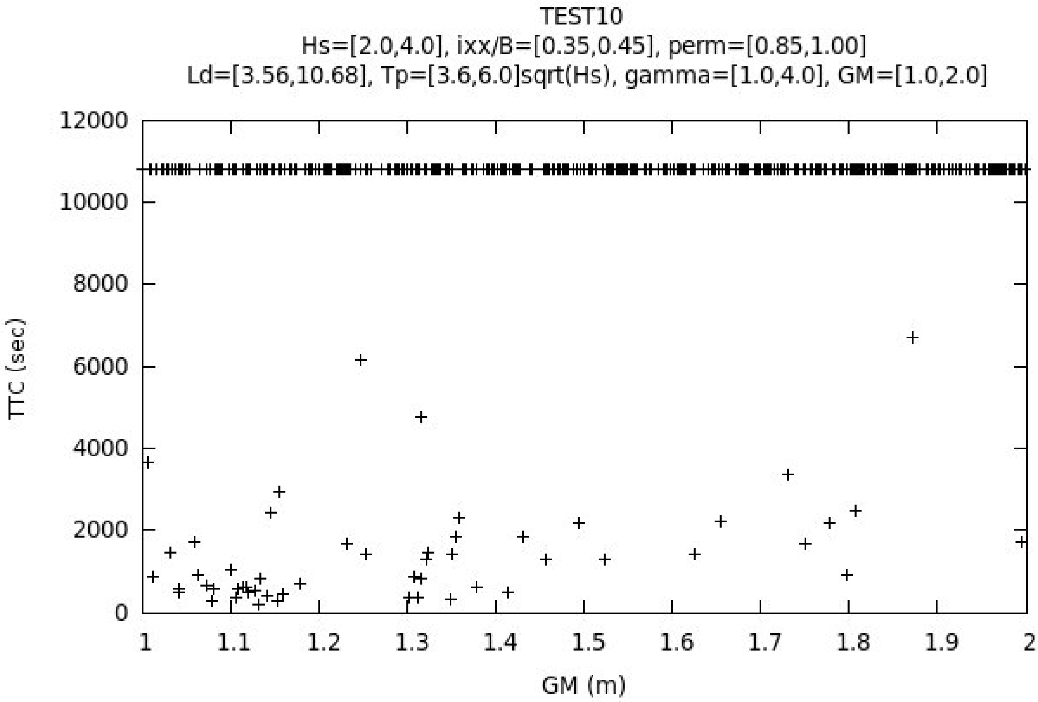

Figure 38 Metacentric height *GM* and Time to Capsize *TTC*

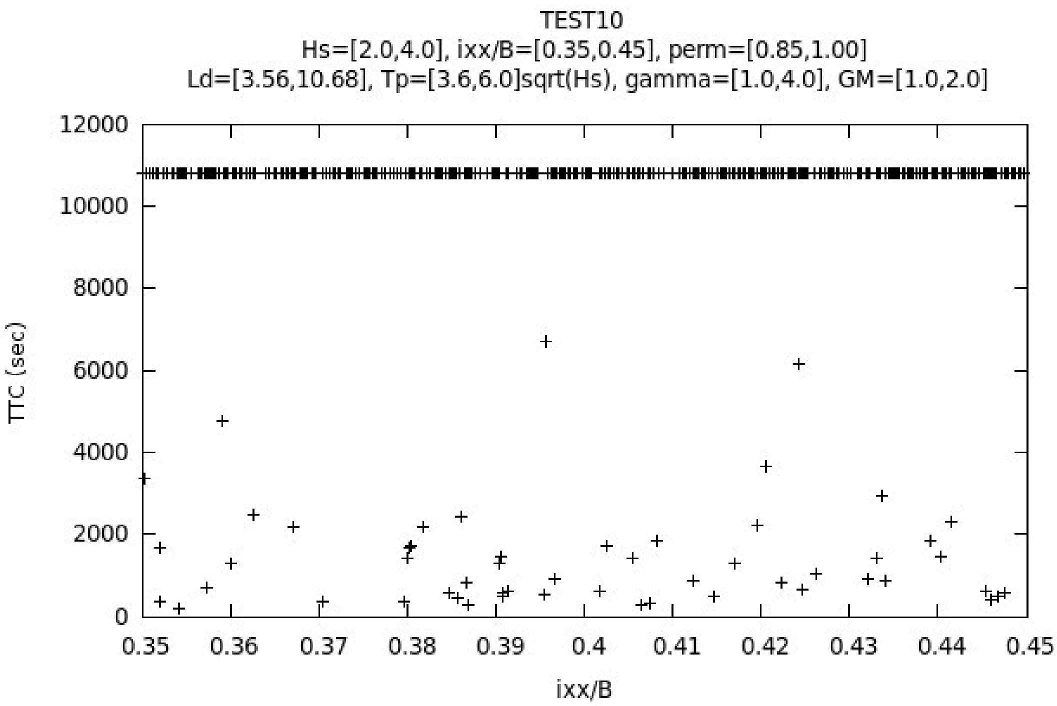

Figure 39 Roll radius of gyration *ixx* and Time to Capsize *TTC*

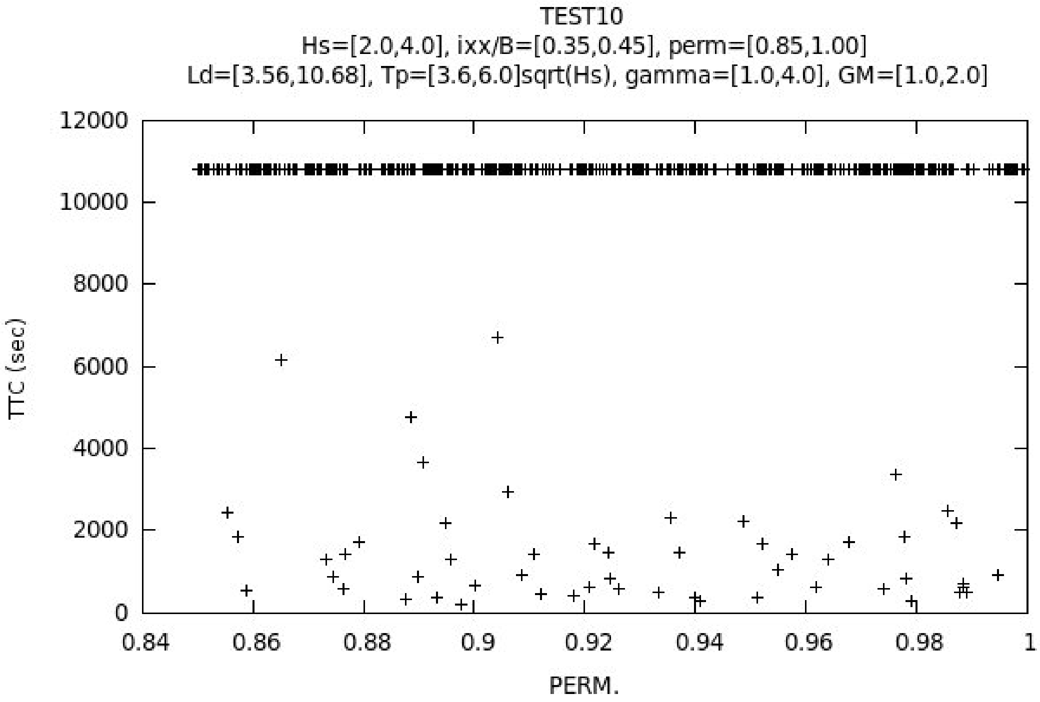

Figure 40 Permeability of car space and Time to Capsize *TTC*

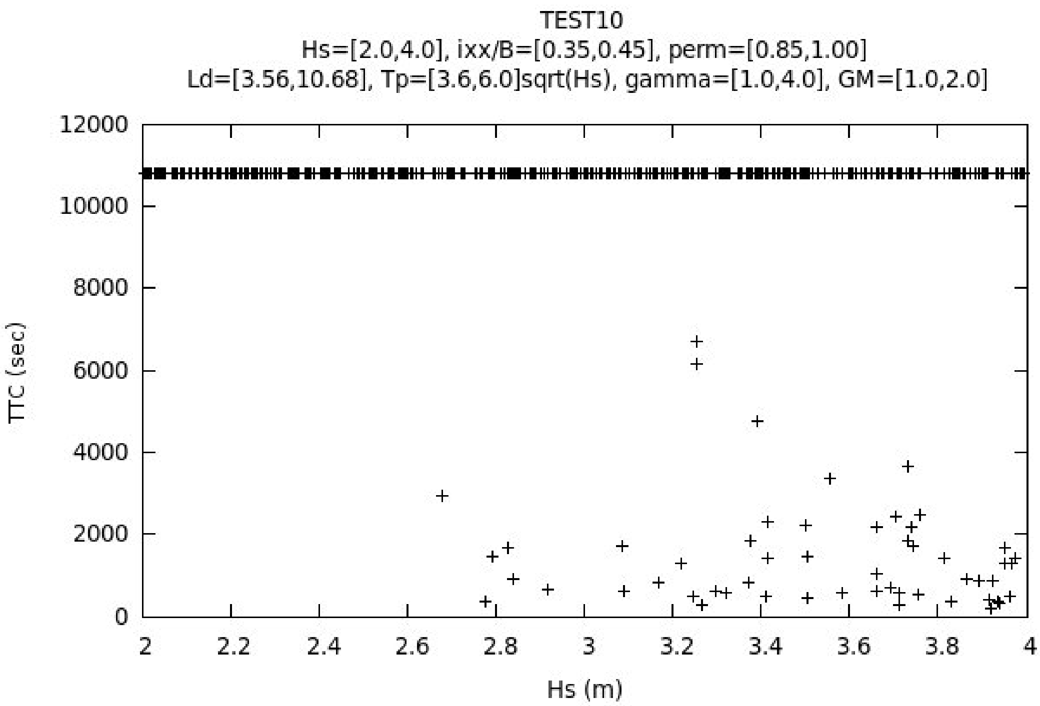

Figure 41 Significant wave height *Hs* and Time to Capsize *TTC*

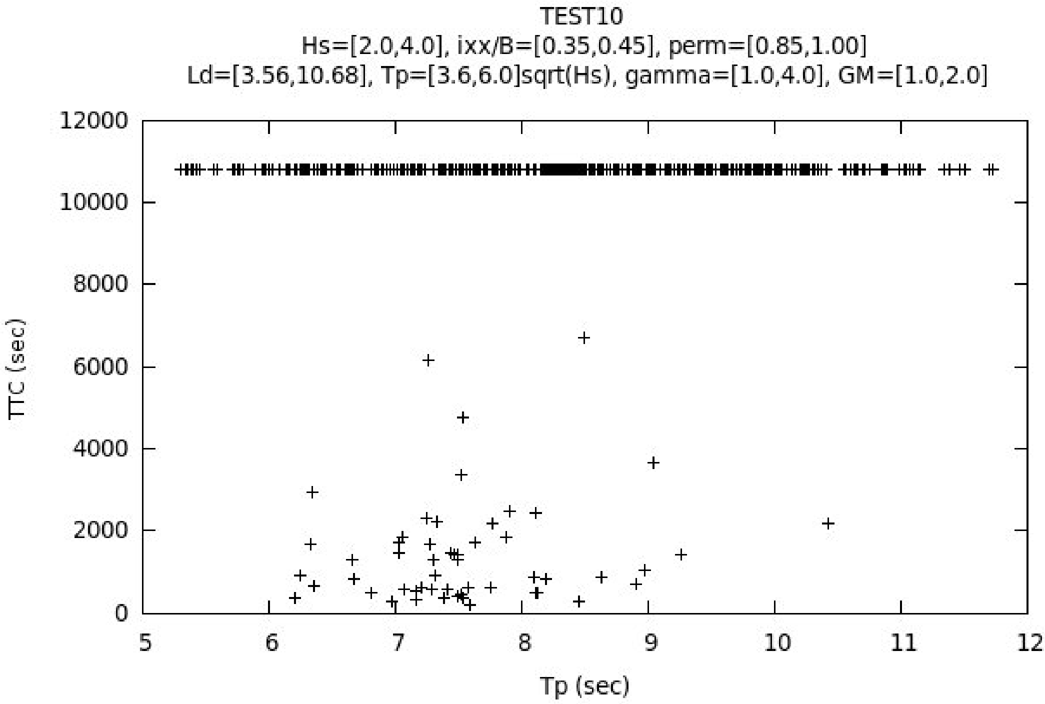

Figure 42 Spectrum peak period *Tp* and Time to Capsize *TTC*

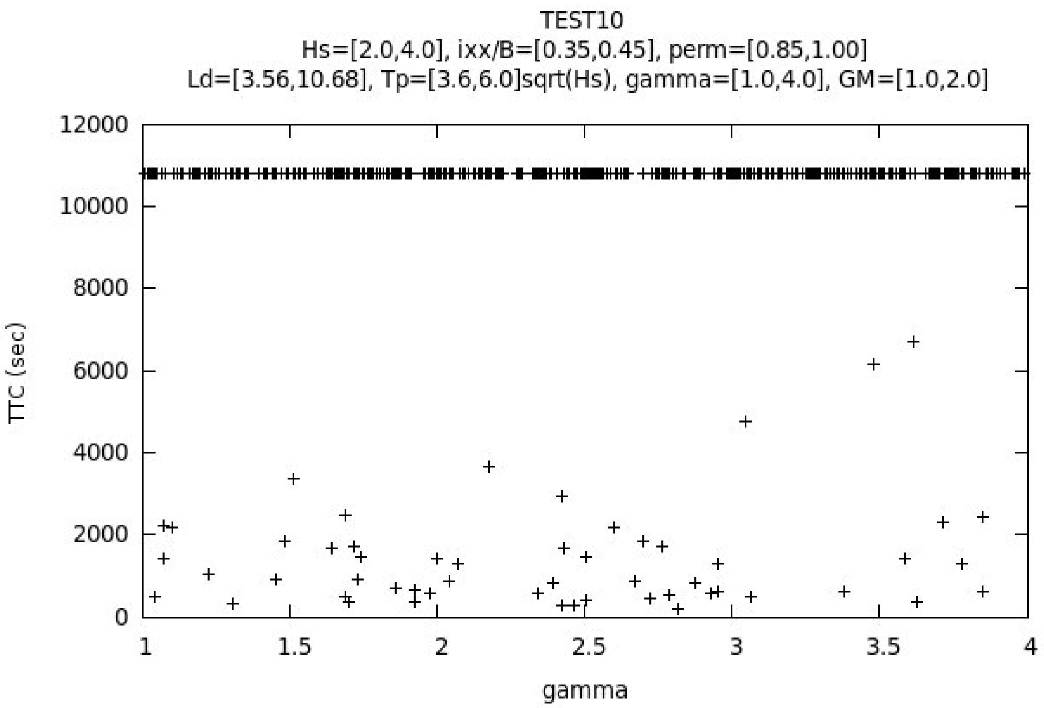

Figure 43 Peak enhancement parameter γ and Time to Capsize *TTC*

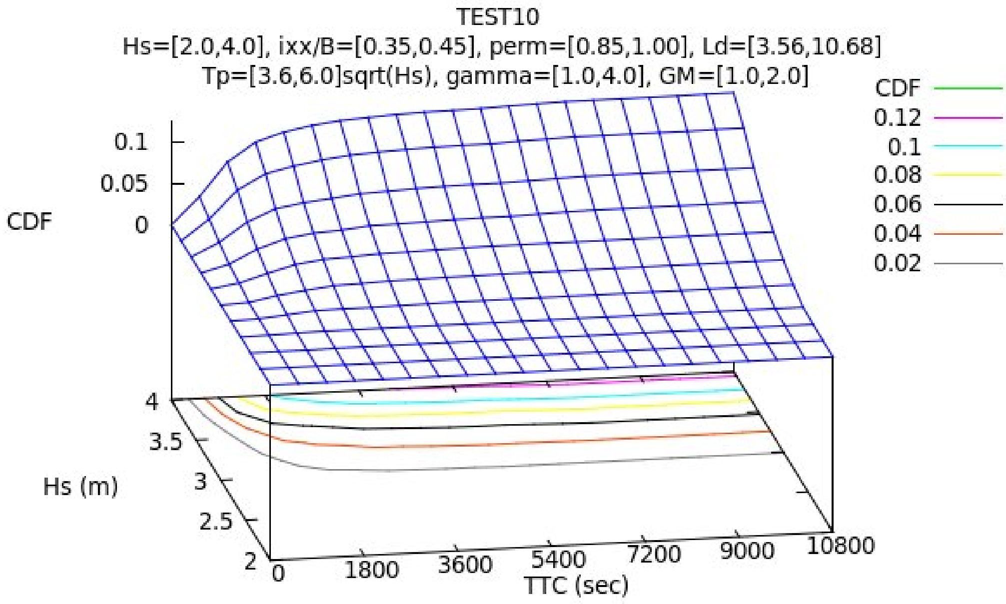

Figure 44 Joint probability distribution of Time to Capsize *TTC* and significant wave height *Hs*

<u>TEST 10</u>

- Numerical tests were stopped at 10800 sec (3 hours).
- In the last Test 10 all parameters were randomized and the largest scatter of results is encountered.
- The estimated probability for TTC is still unimodal with a peak around 10 min.
- The probability to capsize within 3 hour is close to 13%. However only 1% appears to capsize between 1 and 3 hours. This percentage corresponds to 7.5% of the capsize events.
- The sea waves mostly affect the TTC as observed in Figure 41 and Figure 42. Damage opening appears a less influencing factor Figure 37. This factor directly determines the area of opening and may proportionally lengthen or shorten the TTC, whereas the wave parameters are related directly to the critical wave height, which has a more drastic effect on ship survivability.
- The estimated joint cumulative probability of TTC and significant wave height H_s is shown in Figure 44. The concentration of probability below 1 hour can be observed with the contour lines which become almost parallel above 1 hour. Capsize events are notable above H_s=3.0 m, where the probability to capsize increases by 2% every 0.20 m increase in H_s.

21. TTC FOR ROPAX SHIPS

Taking into account the results of the systematic studies presented in the previous sections, the Time to Capsize (TTC) of ROPAX ships can be evaluated here.

The subtle distinction between capsize and survive events is crucial for the time considerations. The *Time to Capsize* TTC and the *Survival Time* ST after damage are interrelated variables, but strictly they do not coincide. They are equal for the non-survive (capsize) events, whereas for the survive events ST is infinite and TTC is indefinite. In the context of evacuation only, TTC should be of prime interest, as in cases of survive events the evacuation is actually not necessary.

For the TTC of ROPAX vessels, namely capsize due to flooding of upper large[2] spaces caused by the waves' action, the model depicted in Figure 45 is nowadays generally accepted. There exists some critical wave height over which capsize events occur. While longer TTC can be encountered only within a very *narrow* range of wave heights close to and above the critical height (see, [7] for detailed discussion). This model was once more confirmed with the present studies with respect to the ample range of parametric space investigated herein. And it can be assumed as the basic systematic behavior for all relevant damage cases (one or more compartment damages).

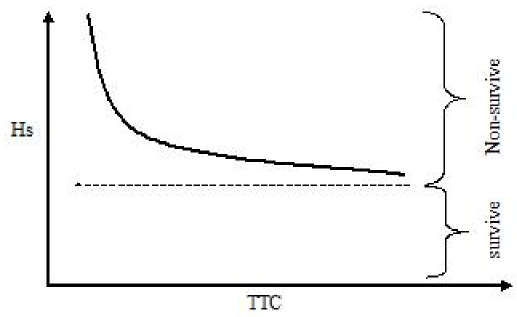

Figure 45 TTC model for ROPAX ships

The above model for TTC is encountered for specific damage conditions, namely for specific ship loading, damage as well as wave properties. When the overall survival perspective for ROPAX in case of collision damage is contemplated, namely when considering a range of probable damages, ship loading conditions and waves (or even their associated uncertainty) then the ensemble distribution for TTC is derived by integration of the individual specific cases. And since for the specific conditions TTC systematically follows the model of Figure 45, then it can be easily inferred that the probability for longer TTC will be necessarily proportionally small for the ensemble general case too ([4] for more discussion).

For the assessment of a specific flooding accident, when the damage conditions become quite specific and might happen to be close to the corresponding critical wave, then some longer TTC could be probable. In such cases, there is always the

[2] With the meaning that the size of potentially flooded spaces is enough for the accumulation of critical floodwater mass and development of instability

practical problem of determining the actual conditions and control the uncertainty; therefore a more generic consideration for TTC remains still inevitable.

Nevertheless TTC of ROPAX ships is evaluated on the basis of the more generic conditions and regardless the behavior in very specific conditions. On this basis the reported work further confirms that capsize of ROPAX ships occur in short times after damage.

In any case *short times should NOT be confused or necessarily related with a low survivability for the damaged vessels. Survivability may be high independently to time.*

22. CONCLUSIONS

A systematic series of numerical simulation tests for the *Time to Capsize TTC* of a damaged ROPAX ship in waves was carried out with the aim to explore the probabilistic characteristics of TTC as well as to generate a full study case matrix appropriate for validation of the theoretical developments in WP4.

TTC is literally considered to account for capsize events, and should not be mixed with the time of survive events, for which TTC is *indefinite*. The distribution of TTC was studied and regardless the survivability of the damaged ship.

In this course the following conclusions can be drawn as documented in the main text of the report.

- The present results confirm earlier conducted similar studies that the time to capsize of ROPAX ships (in case they capsize, what will be in general the case of flooding of large spaces above waterline in presence of waves) is short and will be in general in the range of up to 1 hour after the damage incident, with the maximum likelihood around 20 min.
- Sea wave characteristics (wave height and peak period) are the most determining parameters for the *TTC*. Waves may result to significant spread of *TTC*, when their significant wave height is close to the critical wave height that corresponds to the damage case. Therefore capsize times later than 1 hour are rare events and may occur for wave heights very close to the critical wave height.
- For specific wave heights *TTC* is distributed around a mean value. In consequence, it shows a unimodal probability distribution of some variance. Thereby TTC appears bounded, which is a very important property for the evaluation of the time aspects after damage.
- The size (length) of damage opening appears a factor of less influence on the TTC, considering the studied range of (2.6% ÷ 7.8%)L.
- In consequence of the short TTC, there appears, actually, no time available for an orderly evacuation of (non-surviving) ROPAX ships, when the damage events occur in presence of rough waves and the damage scenario involves the flooding of

their car deck. If otherwise the ship does not eventually capsize for the specific accident conditions, then the evacuation itself becomes questionable and dependent on the confidence for the estimated probability to survive.

- It is noted that the present investigation and findings regarded time to capsize due to accumulation of water in large spaces above waterline due to the action of waves. Other capsize modes, like loss of stability in calm water, or progressive flooding, are herein not considered. Similar investigations for such modes of capsize should be conducted in order to complete the picture for *TTC*.
- The above conclusions, which are based on a large number of systematic numerical tests, maybe regarded with high confidence with respect to the observed characteristics of *TTC*. They are in general supported by results of similar case studies conducted for other sample ships by the same authors [7] and others, so that a generalization of the conclusions for the TTC of ROPAX ships appears straightforward.

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