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Integrated Flooding Control and Standard for Stability and Crises Management

FLOODSTAND-deliverable:

Report on the applicability of the standard for design practice

Authors	Dimitris Spanos, Apostolos Papanikolaou
Organisation	NTUA

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Abstract: This report summarizes the research work undertaken in Task 7.3 on the testing of the approach (elaborated in WP4-6) for the risk mitigation of passengers on board as to its applicability to ship design. In this respect, the developed approach was applied within the probabilistic framework, whereas the probability distributions for the crucial parameter that of the time to capsize (TTC), was determined for two characteristic damaged ships (one RoPax and one cruise). The conducted analysis and collected experience demonstrate that the resulting capsize times are by far shorter than they were anticipated prior to the present research. And since the approach has been developed for conservative estimations of the TTC it could not dispose sensitivity in the range of short times, and its applicability could not be concluded.. The impact of some design changes on the results and TTC was evaluated too.

Acknowledgements
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CONTENTS

Page

EXECUTIVE SUMMARY

The approach[1] for the casualty mitigation as elaborated in WP4-6 is tested for ship design purposes in WP7 Task 7.3 and reported hereby.

This approach comprises of the evaluation of the risk against flooding of people onboard damaged ships on the basis of a comparison between the analytically estimated survive time of ships after damage and the required time for safe evacuation.

The proposed analytical method has been implemented and assessed on the basis of detailed results from direct numerical simulations of the ship flooding and survivability in the time domain. Probabilistic (Monte Carlo) simulations were conducted to derive probability distributions as appropriate to review the random behavior of damaged ships and to establish a basis for comparison.

The testing was carried out in the ship design stage namely assuming a generic design environment and probable damage hazards for the design life of two characteristic passenger ships, one RoPax and one cruise. Alternative watertight subdivisions were analyzed to demonstrate how the approach would respond to such modifications on the ship's layout.

Despite the initial anticipations of the outcome of this work the resulting sinking of damaged ships (when it happens) appears to be limited within very short times after the assumed damage incident. In consequence, the proposed analytical approach in WP4 appears to be inapplicable to these short time capsize/sinking scenarios.

The fast loss (which is related to damages of large extent) of the damaged ships observed in this investigation reinforces previously gained evidence that the loss of ships is a fast process and there is a much more urgent situation for the people onboard to timely evacuate the ship, compared to what was assumed to date.

A reasonable strategic objective for the passenger ship design may be formulated out of this research, namely to establish even higher survivability requirements (subdivision required indices), so that the 'non-survival' cases could be limited to a minimum, and/or to pursue, where possible, even faster evacuation and abandonment procedure.

[1] This is the 'crisis management' approach, namely one of the two approaches elaborated by FLOODSTAND. The second one, namely the 'flooding control' approach elaborated in WP1-3 and was tested for ships in operational conditions (in Task 7.2) but not for ships in design (present Task 7.3).

1 INTRODUCTION

The objective of the work undertaken in task 7.3 of WP7 was to test the effectiveness of the approach for the rating of decisions for various casualty cases, as it was introduced and elaborated in FLOODSTAND project.

Specifically the "*Crisis management*"[2] FLOODSTAND approach, elaborated in WP4-6, was tested within the ship design process and the findings provide useful feedback for modifications and further improvements of the method. This approach is one of the two approaches for the casualty mitigation investigated in this research project, the other one is the "*Flooding Control*" FLOODSTAND approach which was elaborated in WP1-3 and is not applied for the present tests in ship design.

The motivation of the FLOODSTAND research was to further investigate approaches for the ship flooding with the aim to appropriately deal with the highly variable time duration of the ship loss. Particularly, due to the gradual increase of the ship size and the number of passengers a higher associated risk emerges in cases of ship flooding.

The related concept of "*safe return to port"*, which is under discussion (at IMO) in recent years and now under implementation, aims to ensure a sufficient time either for ship evacuation or to approach nearby sheltered waters; this objective depends on the onboard capabilities to assess ship's survivability in case of flooding accidents as well as to evaluate the required and remaining time for the safe operations onboard.

The historical data for ship accidents evidence that the time takes a ship to founder may notably vary. Task 7.2 of WP7 deals with the onboard assessment of the time variation in case of specific damage events. This is here called '*operational*' problem, where *specific* damages and wave environment conditions are assumed. The distinct problem that of '*design*' is considered in task 7.3 of WP7 and the research results are reported herein. In the *design* problem the time characteristics of the damaged ship are considered at the stage of ship design for a generic random design environment which is characterized by the *wide* range of probable dangerous conditions that the ship might encounter throughout the design life.

The tested approach addresses the risk of people associated to ship flooding through the comparison between the time-to-capsize of the damaged ships and the necessary time for safe (orderly) evacuation and abandonment of the passenger and crew. Its effectiveness for ship design purposes is elaborated here, namely whether the questioned time variables can be efficiently assessed at the level of the generic design environment so that to support the design decisions, i.e. decisions relevant to the watertight subdivision of the ships.

Apart the historical data for the time to sink of various ships, the stochastic characteristics of the time variables for a particular ship are still under development and the present investigation may notably contribute to this issue too.

In the scope of the present work a case study was undertaken where the analytical approach from [5] is tested in comparison to results from detailed, first-principles

[2] "FLOODSTAND-ISTAND" has been also used as a reference name for this approach within FLOODSTAND project

numerical simulations [6], and for the specifically developed benchmark scenarios introduced in [2].

Though the tested approach is based on the comparison of the available time (time to capsize) and required time (time to abandon) [7], [8] the present research eventually concentrates on the available time (TTC) because in the course of the investigation a remarkable unbalance between the two times was detected, namely the time to evacuate and abandon the ship appears considerably longer than the TTC.

In the next sections the key elements and findings of the investigation conducted in 7.3 are reported. The analytical approach as it was here implemented is presented together with the numerical simulation approach used in parallel for the validation purposes. Additionally, information useful to the verification of the present implementation is also reported.

After the presentation of the collected results and discussion, important conclusions are drawn regarding the effectiveness of the investigated analytical approach and the characteristic properties of the damaged ships with respect to their survivability and evacuation. Apart the performance of the tested method, the findings for the capsize behavior of the damages ships may affect the future strategy in passenger ship design.

2 PROBABILITY SIMULATION FOR TIME-TO-CAPSIZE

The time-to-capsize of damage ships is a random variable depending on the random environmental conditions during a flooding accident as well as the random shape and location of the hull breaches, ship loading and local details within the flooding spaces. This random variable is the time duration form the zero time that coincides with the hull breach incident until the time the ship capsizes. When no capsize occurs then the time is indefinite, while the related variable of the survive time of ships is then infinite.

The *Monte Carlo* (MC) method can be applied to approach the probability distribution of the time to capsize. MC is robust method and combined with a fast sampling then reliable estimations for the probability can be easily obtained. The time to capsize is estimated either with the analytical formula or the time domain analysis of the ship flooding (as they are described in the following sections) and for randomly selected damage cases of a sufficient long number to achieve statistical convergence.

The damage cases are determined by the damage openings on the hull, the ship loading condition and the significant wave height of the sea waves. The dimensions of the opening and the ship weight (displacement and center of gravity) and waves follow probability distributions according to the assumed design environment, as they are presented in the next section 6. Thus each sample damage case is determined with a random vector variable (x_d, L_d, B_d, H_d, Δ, KG, H_s).

As soon as a sufficient number of cases are sampled then the statistical probability of the time to capsize can be calculated through the encountered frequencies as below.

$$F(t) = \frac{\sum[\text{cases with } (TTC < t)]}{(\text{total sampled cases})} \quad (1)$$

For the present investigation samples of 5000 damage cases considered in order to achieve a satisfactory convergence at the level of probability distributions.

3 ANALYTICAL APPROACH FOR THE CONDITIONAL PROBABILITY OF TIME TO CAPSIZE

The analytical method for the fast estimation of the probability of the time to capsize of damaged ships was introduced earlier in the research project SAFEDOR [11]; it was further refined in WP4 and is detailed presented and discussed in [5].

The essential elements of this method are summarized in this section together with a discussion of details and how it was implemented for the present investigation.

For the validation and verification purposes a set of discrete conditions was defined and is tabulated in the Annex; there, the probability of ship's capsize in 30 and 180 *min* was calculated and listed.

3.1 Conditional Probability of Time to Capsize

The tested probability model for the time to capsize is founded on the basic principle that the damaged ship may survive up to some critical wave height and, any sea state higher than the critical waves should be necessarily assumed as non-survive condition. Therefore the probability to capsize in case of some collision damage will be the probability that the encountered waves are higher than the critical waves.

Assuming this condition and following a long derivation[3] (reported in [5]) the next formula expresses the probability of time to capsize conditioned to the significant wave height H_s and dependent to the critical waves H_{scr} which is a property of the ship damage cases.

$$F(t \mid H_s) = 1 - \left[1 - \Phi\left(\frac{H_s - (H_{scr} - \varepsilon)}{0.061(H_{scr} + \varepsilon)} \right) \right]^{\frac{t}{t_o}} \qquad (2)$$

where
- F the probability function
- t the time to capsize, in (*min*)
- H_s the significant wave height, in (m)
- H_{scr} the critical wave height, in (m)
- Φ the standard normal probability function
- t_o 30 (*min*)
- ε 10^{-12}

This formulation assumes that capability of the damaged ships to withstand a damage case in presence of waves is determined by the H_{scr} parameter, which is a characteristic ship property for each ship's damage case and also dependent on ship's loading condition. The encountered waves H_s may follow some other probability model.

[3]-The method is essentially semi-empirical, noting that the essential part of the mathematical formulation is based on a regression analysis of empirical data.

The deviation assumed in this model ($0.061H_{scr}$) is notably lower than the deviations noted in earlier versions of this formulation (see ANNEX). This change represents a steeper transition between survive and non-survive wave conditions and should be one of the contributing reasons for the reduced sensitivity observed in the performance of the method, and which is being discussed in the next sections.

3.2 The Critical Waves

According to this modeling the critical wave height H_{scr} is estimated by use of the following relationship

$$H_{scr} = 4\left(\frac{GZ_{\max}}{0.25} \cdot \frac{Range}{25.0}\right) \tag{3}$$

where GZ_{max} the maximum value of righting lever GZ
$Range$ the range of positive GZ
and both variables are for the damage condition.

This is a modified formula for the critical wave height, compared to earlier versions. The original expression (which differs to the denominators of the fractions within brackets) has been also assumed for the development of SOLAS 2009 damage stability regulations. The present modified expression, introduced in [5], is the result of a regression analysis of relevant model test data; it represents a kind of *minimum (lower) envelop* for the critical waves, instead of an average value. By doing so, the estimation of the critical waves with this modified formula becomes notably more *conservative* (i.e. lower critical waves for given stability characteristics), instead of estimations with maximum likelihood of occurrence, as they were obtained with the original formulation[4].

Nevertheless the modified expression may represent a clearer boundary between survive and non-survive wave conditions. Then the damaged ship survives with highest probability all waves of significant wave heights lower than this specific boundary. Note that the original formula was assumed representing a boundary of 50% survivability.

Since the critical wave height H_{scr} represent the ability of the ship to survive in a wavy environment, *any underestimation* of H_{scr} is equivalent to assume *lower survivability for the damaged ship* and with all the consequences thereafter. The advantage of such modification for the modeling of the full decision making process remained eventually inconclusive in this research project.

[4] It is noted that in the parallel project GOALDS [12], the formula for H_{scr} was updated again.

4 NUMERICAL APPROACH FOR THE TIME TO CAPSIZE OF SPECIFIC DAMAGE CASES

The Time to Capsize (TTC) can be also sampled from a detailed, first-principles numerical simulation approach as presented in this section. The approach comprises of a time domain analysis for the flooding of the ship and the estimation of the TTC for particular random damage cases. The random damage cases are determined by the Monte Carlo simulation process.

The TTC is generally determined both by the flooding process of the ship with water through the assumed damage opening and any possible progressive flooding of the connected spaces and, the dynamics of the flooded ship which are mainly induced by the action of sea waves. As explained in the following section 6.4, the probability of TTC can be to a great extent characterized by the calm water conditions; thereby the substance of ship's behavior can be captured by analyzing the flooding process in calm water.

Moreover such analysis is rather fast in terms of computational requirements and is suitable for the probability simulation with the Monte Carlo method.

4.1 Time Domain Analysis of the Ship Flooding

The ship's flooding in calm water can be analyzed in time domain by setting up a suitable numerical model for this purpose. There are plenty of alternative formulations for this ship flooding problem which may efficiently deliver rather accurate results. A very fundamental formulation appropriate for the scope of the present investigation is described here.

The complex of the watertight ship compartments is assumed together with several interconnecting openings. Each opening connects two adjacent compartments. Additional openings on the hull shell are assumed, the damage openings, through which the ship flooding may occur. For the present research scope all the openings are assumed *fully clear* of any obstacles, for example door openings without the presence of leaking or collapsing doors.

If the flow through all the openings is properly described as functions of time and integrate over the time then the flood water within each compartment may result at any time instance after the start of the flooding process.

Among other variables, the flooding process is notably affected by the change of ship position on the sea free surface due to the floodwater ingress. Such effect can be taken into account by describing also the slow change of the ship position over the time due to the presence of the accumulated flood water inside the flooded internal spaces.

The motion of the flooded ship (with three modes of motion heave, roll and pitch) under the action of the flood water can be analyzed over the time domain with the next non-linear differential equations.

$$m\ddot{x}(t) + b\dot{x}(t) + f_c(x(t)) + f_w(x(t)) = f_g \qquad (4)$$

Where x is any mode of motion (heave, roll, pitch), m the corresponding mass inertia, b some linear damping coefficient, f_c the non-linear restoring function, f_w the non-linear forces and moments due to flood water and f_g the gravity force.

For given ship loading condition the non-linear restoring f_c function (i.e. ship hydrostatics, GZ curves) can be described at a discrete set of the variables $x=(x_1, x_2, x_3)$, (namely heave, roll and pitch) and on some suitable resolution which covers a wide range of possible ship position. This information (tabular data) is independent of time and is characteristic for each damage case under analysis.

Similarly the flood water forces f_w for each individual compartment can be described at a discrete set of values. The hydrostatic part of these forces depend on the amount of water inside the compartments as well as the heel and trim of the compartment, i.e. $f_{w,i}= f_{w,i}(m_{w,i}, x_2, x_3)$ for some i-th compartment. Since the compartments are fixed on the ship then the heel and trim of the compartments trivially coincide to that of the ship. This information (tabular data) is also independent of time and ship loading condition and is characteristic for each compartment and each damage case under analysis.

The total flood water force is the sum of flood water forces from the individual compartments.

$$f_w = \sum_{i=1}^{N} f_{w,i} \qquad \text{where } N \text{ the number of the assumed compartments} \tag{5}$$

The mass of flood water inside each compartment is time variable and equals the sum of water flux through all the connected openings. Multiple openings can be assumed to connect a compartment with adjacent compartments and/or the surrounding sea water.

$$\dot{m}_{w,i} = \sum_{j=1}^{Ni} q_j(t) \quad \text{i=1, …, N} \tag{6}$$

where q_i the water flux through j-th opening and N_i the number of opening for the i-th compartment.

The differential flow through the opening can be efficiently estimated by use of the Bernoulli equation modified with some suitable discharge coefficient c_d.

$$dq(t) = c_d sign(H_1 - H_2)\sqrt{2g|H_1 - H_2|}dA \qquad [\text{m}^3/\text{sec}] \tag{7}$$

where H_1 and H_2 are the water heads in both sides of the assumed opening and dA the differential area of the opening.

The discharge coefficient can be taken equal to 0.65, as an average approximation for large and fully clear openings. In the past this value has been widely used for the flooding simulations with excellent results, while recent studies ([18], [19]) of FLOODSTAND project suggest a 10% lower value for fully submerged openings.

The total flow through each opening is approached with the integral of the differential flow over the assumed cross area of the opening A.

$$q(t) = \int_A dq \tag{8}$$

For the scope of the present analysis plane quadrilateral cross areas are assumed which may simplify the surface integrations.

The damping coefficients b_1, b_2 and b_3 can be set equal to some reasonable values which may decay the ship motion while simultaneously to permit the ship to follow the changes due to the flooding. For this purpose the critical damping value assumed for each motion, $b_{cr} = 2\sqrt{mc}$ where m the inertia and c the linear restoring coefficients. Such values are higher than the actual damping values for the ship motions however they well facilitate the present objective where the ship flooding is primarily concerned.

The above system of differential equations is sufficient to describe the ship flooding in calm water and to calculate the time to capsize when ship instability is encountered.

5 SUBDIVISION SCENARIOS

The subdivision scenarios for testing in '*design*' were defined in Task 7.1, [2] and they form the basis of the present investigation. Scenarios assume some modification of the original subdivision layouts for two passenger ships one RoPax and one Cruise ship.

Both scenarios are characterized by changes of the watertight subdivision above the bulkhead deck and particularly some enhancement of the subdivision there. In that way the upper subdivision would affect the later stages of the ship flooding which is sensitive to waves' action, thus suitable to study the wave dependent formulation for the TTC. However, in the course of the present investigation the effect of waves proved to be limited and these scenarios resulted not appropriate, as negligible effects on the distributions of the TTC were encountered.

It is also noted that the present scenarios do not deal with the managing of the watertight integrity which motivated the developments for the 'Crisis Management' approach, [5]. The WT integrity might be undermined through the impact of watertight doors openings and their daily operation. In this respect design modification to achieve minimum vulnerability were applied in [20]. Here the WTD are assumed always closed, with the scope to study the subdivision modifications as described below.

5.1 ROPAX vessel

A RoPax ship model of the well known *MV Estonia* was considered for the present research. This ship was studied too by FLOODSTAND participants of WP4-WP7 and it was also tested in the model basin in WP4, [4]; thus, it defined a good basis for cross collaborations, comparisons of results within the project.

Table 1 Dimensions of the ROPAX ship model

Main Dimensions	
Lpp	137.4 m
B	24.2 m
T	5.39 m
D_{DECK}	9.10 m
Displacement	12300 tn

The assumed initial watertight subdivision comprises of transverse bulkheads extended up to the bulkhead deck (the car deck, or deck No 2) and resulting to 15 watertight compartments. Compartments are extended transversely from side to side without subdivision with longitudinal bulkheads. Ship's double bottom was also considered, but not the mid deck (tween deck, or deck No 1). On the car deck, there is a central casing through which the lower compartments are connected with the upper

decks. The small rooms at both ends (poop and fore) on this deck were also assumed watertight.

The above described subdivision comprises the '*original*' layout and is depicted in Fig.1.

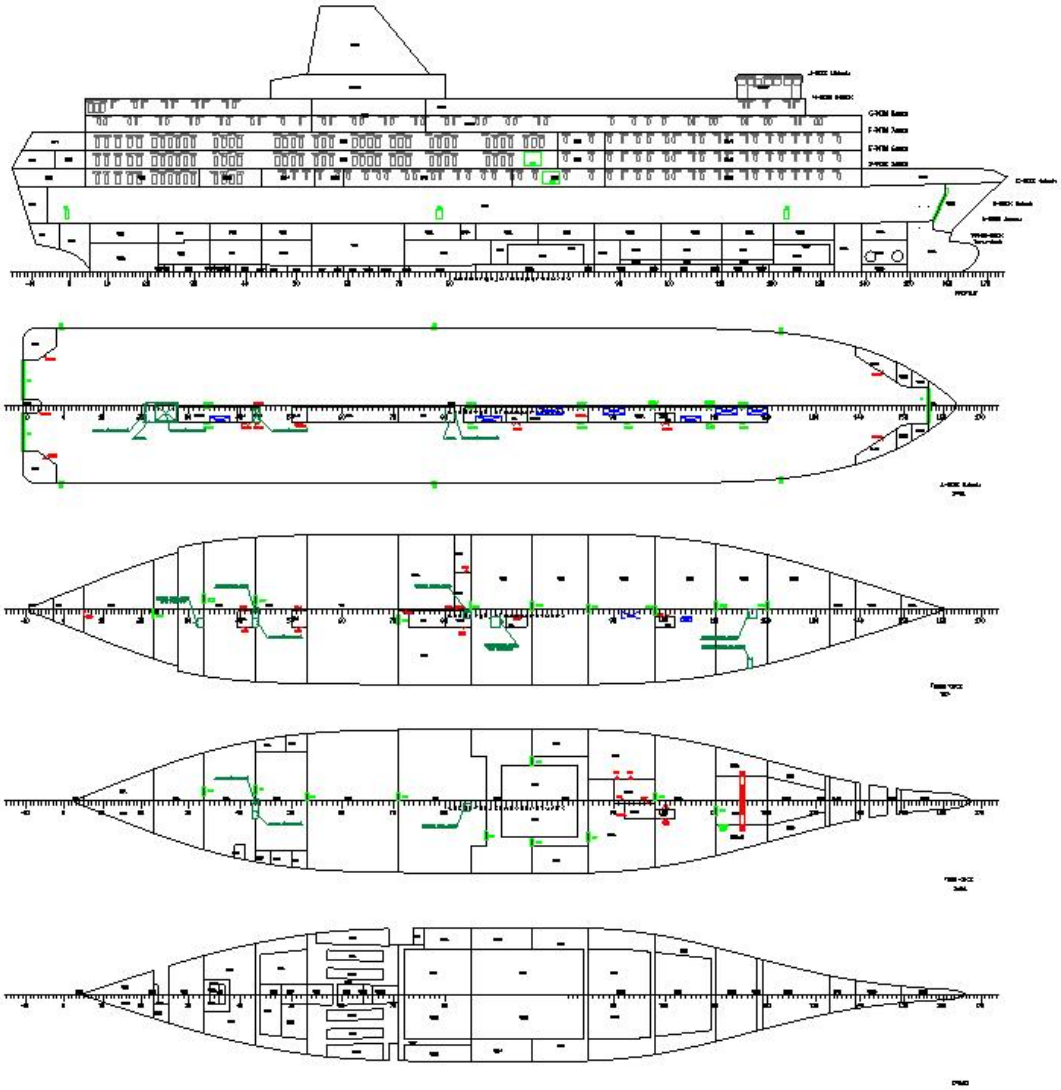

Fig.1 Original subdivision for the RoPax ship. The undivided car deck is the bulkhead deck.

According to the defined design scenario, the modification of the original layout regards the development of four watertight side casings on the car deck as shown with Fig.2.

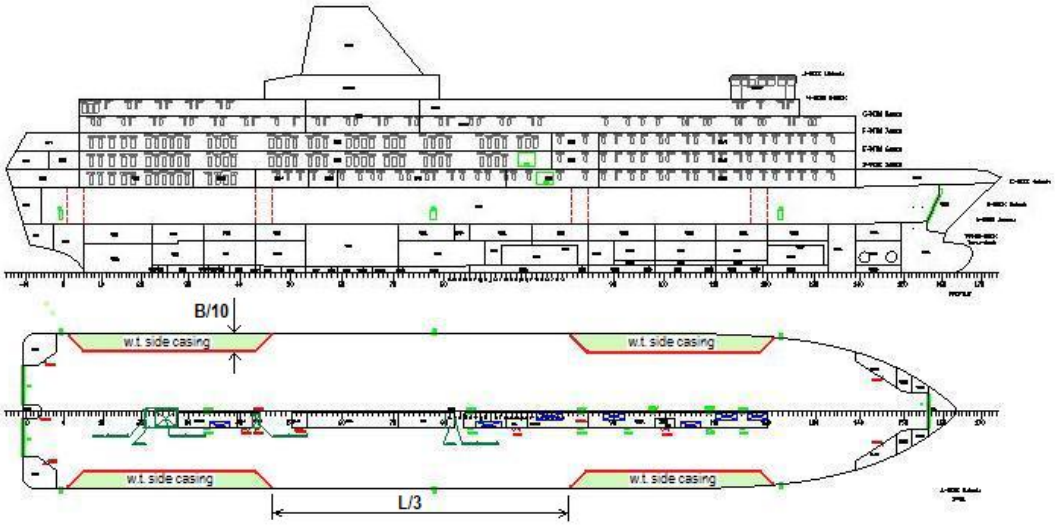

Fig.2 Modified subdivision scenario (D7.1-A3) for the RoPax vessel. Four watertight side casing are added on the car deck.

The total lateral area of the side casing equals 10% of the car deck area and the casings are separated in longitudinal distance by one third of the ship length. In that way for each damage condition only a single case could be damaged, as the damage lengths are limited below L/3.

The scenario is motivated from the impact on the damage stability, and without considerations for operational and economic implications.

5.2 CRUISE vessel

The concept design of a medium sized modern cruise vessel (63000 GT tonnage) is the second test case in this investigation. This ship design was provided to the FLOODSTAND project by the participating ship designers/yards in WP1, [3] where the design is reported in details.

Table 2 Dimensions of the CRUISE ship model

Main Dimensions	
Lpp	216.80 m
B	32.20 m
T	7.20 m
D_{DECK}	9.80 m
Displacement	35000 tn

The original subdivision layout of the cruise vessel is that shown in Fig.3. There are five main vertical zones with three watertight compartments each. Deck No 3 is the bulkhead deck.

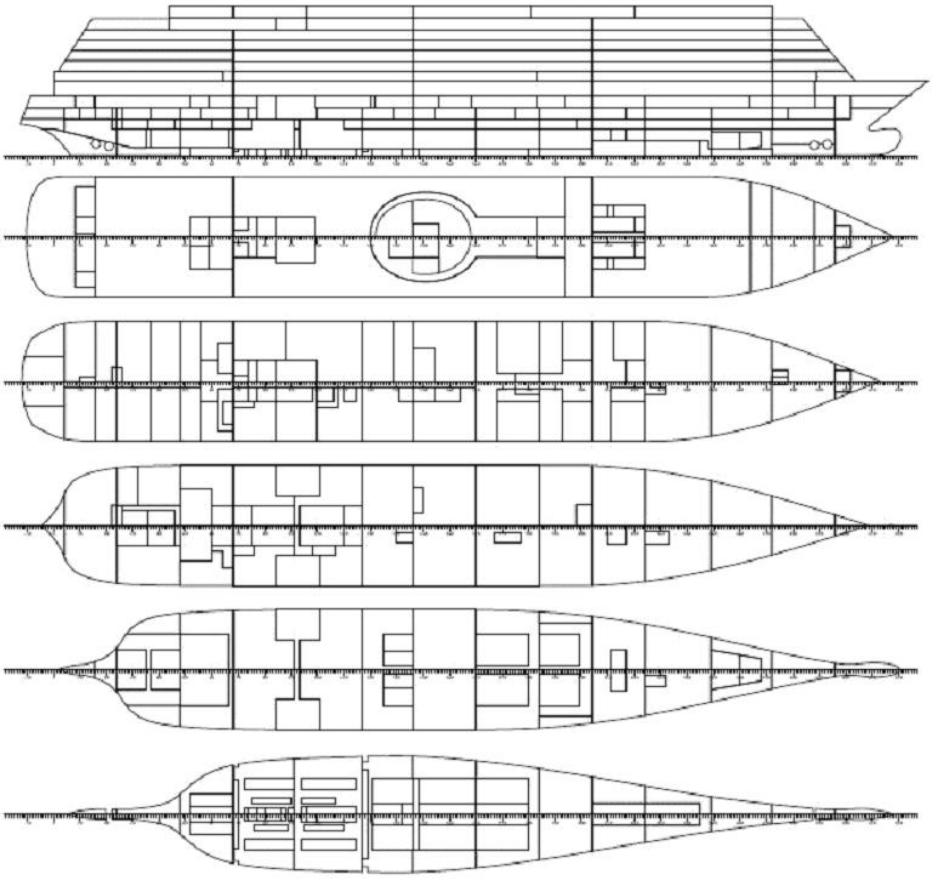

Fig.3 Original subdivision for the cruise vessel. Five (5) main vertical zones and subdivision deck the deck No 3.

The design scenario assumes the upwards extension of the zone watertight bulkheads for two decks above the subdivision deck. And since the deck 3 is already subdivided at the specified locations then the changes are limited to the above deck 4 only. Fig.4 indicates (with arrows) where the changes are applied.

The space of deck 4 is designated to public use and the additional subdivision may increase the complexity of the available room space. The present design scenario is limited to subdivision considerations without dealing with implications to operational issues.

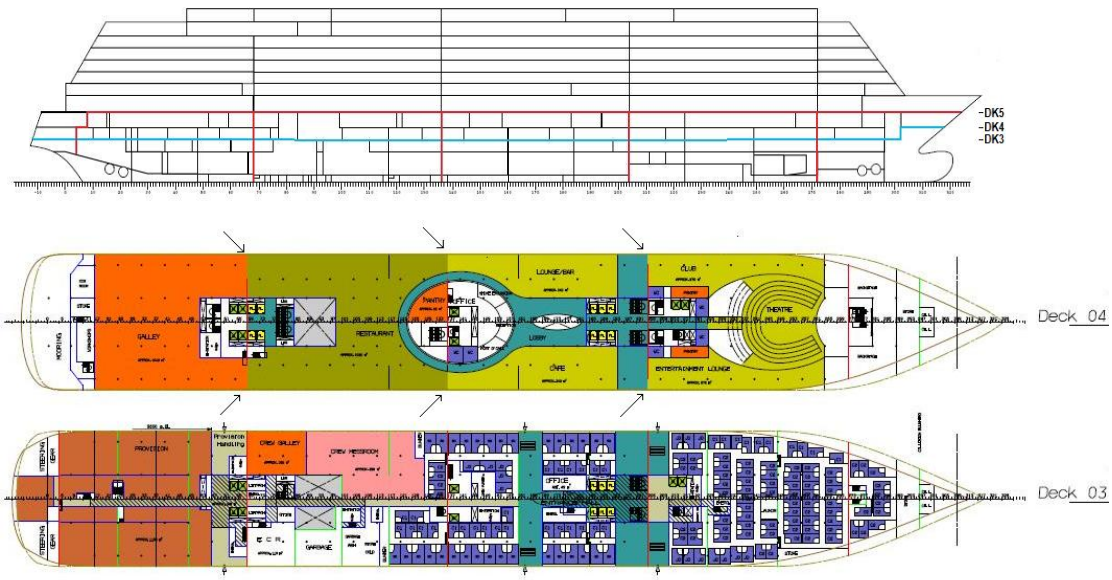

Fig.4 Modified subdivision scenario (D7.1-B3). The five main zones are extended up to Deck 5, thereby the transverse bulkhead on deck 4 (shown with arrows) are extended at full breadth.

Fig.5 highlights the internal openings considered in the subdivision modeling. Lateral openings (down flooding points) are indicated in blue color and they connect vertically the rooms within watertight compartments. The rooms themselves are assumed watertight too and they can be flooded either through the openings or through damages on the outer shell.

There are also watertight doors (yellow color) which could be assumed also open thus to alter the watertight subdivision by connecting compartments and letting progressive flooding between them to occur. However, progressive flooding through WT doors proved not necessary to be studied here.

Because of the down flooding points the full decks are not watertight. However they are *partially* watertight as watertight decks are defined locally between specific rooms. The effect of partial watertight deck gives significant impact on the ship flooding process and particularly on the intermediates stages and sequence of flooding and therefore they are considered here accordingly.

For each compartment a homogeneous permeability is assumed without considerations of local details like partial watertight boundaries with leaking and collapsing doors as investigated and reported in [16], [17] .

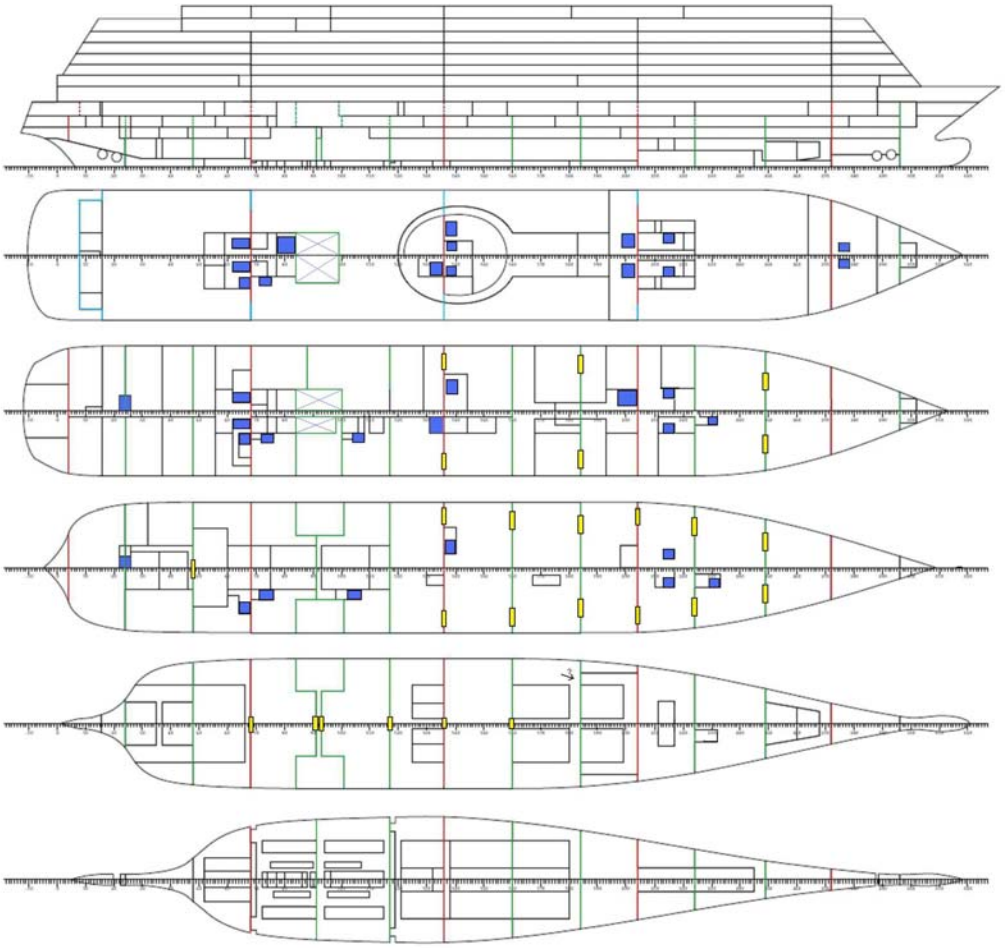

Fig.5 Assumed down flooding points (blue) and watertight doors (yellow).

6 THE DESIGN ENVIRONMENT

For the probabilistic analysis an assumed design environment should be specified first.

The design environment may comprise of a set of parameters and variables, either of specific (value) and/or of pure random nature. While the associated uncertainty for any constant parameter may be considered as a random variable too. Here the random variables assumed are the sea waves prevailing during a ship flooding event, the ship loading condition, the size and the location of the collision damage openings.

Specific probability models can be assigned to each random variable as determined below. Then, the variables are sampled from such distributions to define random damage cases.

6.1 Wave Environment

Following the results of the research project HARDER [10] the prevailing wave height in case of collision damages is distributed as shown in Fig.6. This distribution was determined on the basis of historical data and for any ship type. The probability is limited practically to below 4 m significant wave height, while a notable percentage of *40%* regards *calm water* conditions[5]. This distribution was also the basis for the development of the current SOLAS 2009 stability regulations.

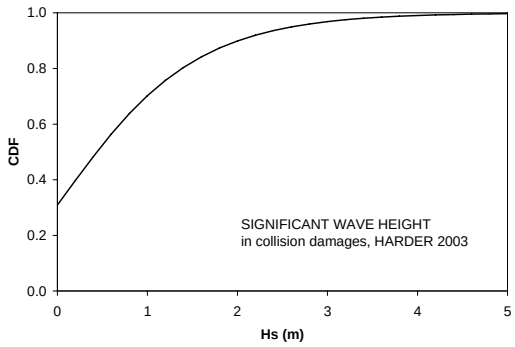

Fig.6 Probability of wave height in collision accidents

6.2 Collision Damages

The dimensions of the surrounding box of the damage opening, because of some collision accident, are assumed to follow the probability distributions of Fig.7

The damage location is evenly distributed along the ship length. The damage length linearly decreases up to 15% of ship's length plus some additional lower probability for lengths up to 30% of the ship length. Since the distribution is almost of triangular shape, the *average damage length is apparently close to 5% of the ship length*. A

[5] Note: More recent investigations [12] suggest that collisions of *passenger* ships in calm water happen at even higher probability (reaching to 70%).

difference of this distribution with respect to the one adopted distribution by SOLAS 2009 is that the maximum damage lengths are limited up to 60 m, which affects ship larger than 200 m. The present cruise ship size (216 m) is close to this boundary therefore the differences are limited.

The damage penetration is also linearly decreasing up to half breadth of the ship. While the damage height is extended upwards above the waterline according to the shown double step function and is limited below 12.50 m from waterline.

These dimensions were here assumed to be generally independent; however, combinations of very deep penetrations together with very small damage area on the shell should be discarded as non-realistic events.

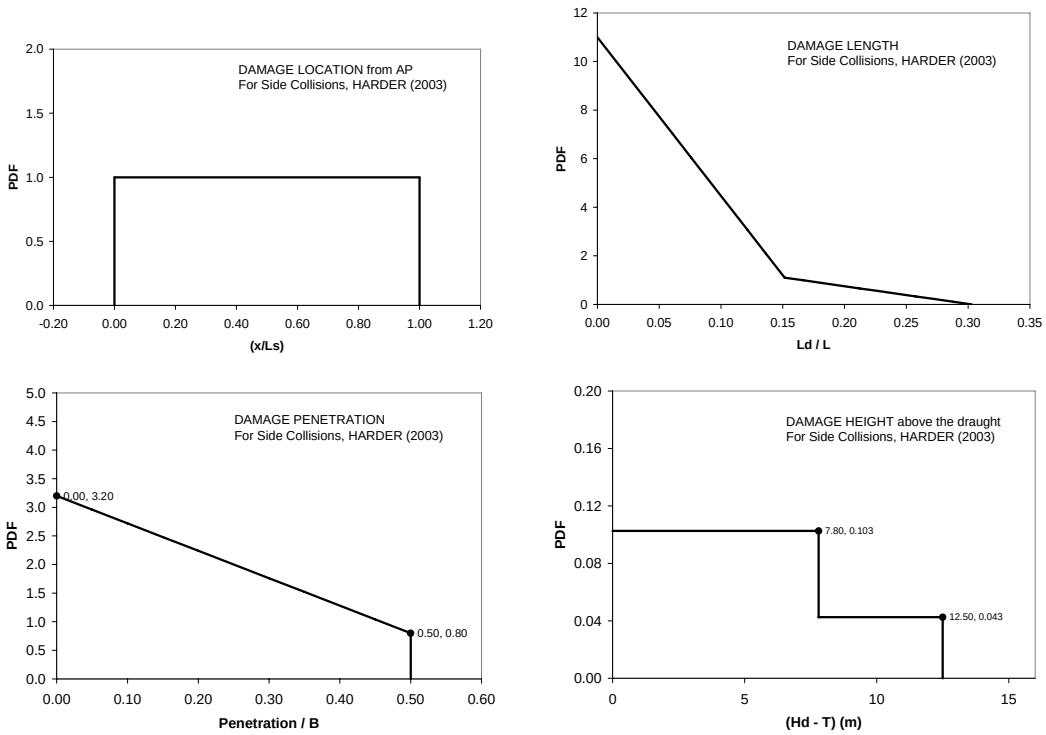

Fig.7 Location and dimensions of collision damage openings acc. to HARDER [10]

6.3 Ship Loading Conditions

The probability of ship displacement was distributed between three discrete loading conditions in line with the SOLAS 2009 regulation. The probabilities for the full and the partial draught equals 40% and for the light draught condition 20 %, Fig.8.

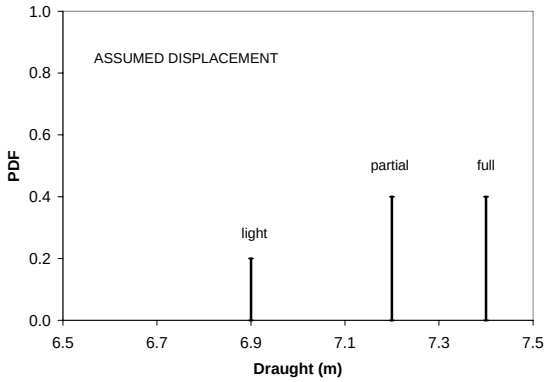

Fig.8 Assumed probability distribution for the ship loading conditions

The vertical distance of the center of gravity for the intact ship condition is assumed distributed as shown with the Fig.9.

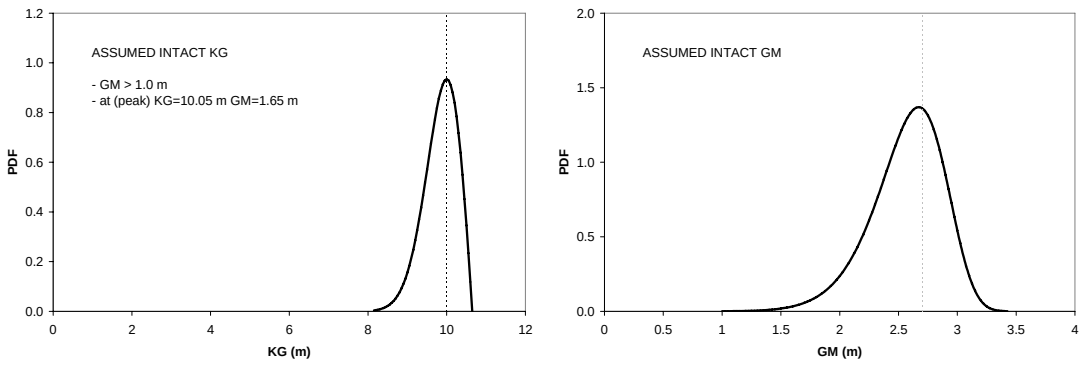

Fig.9 The assumed probability distribution for the vertical center of gravity for the RoPax ship (left) and cruise ship (right).

Both distributions are single peak models with a peak equal the nominal (design) value (for ROPAX ship higher *GM* was assumed in order to cover the range of 1.0 m < GM < 2.6 m) and with some variation included which may cover the operational range of loading conditions and also some extreme situations with lower probability. Thus these variations are a bit wider with the aim to capture probable extremes during the investigation. However because of the nature of the problem (discussed below) the increased variance, and GM for the RoPax ship, had not notable impact on the findings.

The intact ship can be assumed always even keel. Then the distribution of the longitudinal center of gravity can be determined by the longitudinal center of buoyancy.

The displacement Δ (or the draught T) and the center of gravity (KG or GM) are assumed independent variables, omitting any interdependence for more realistic

loading conditions. This proved eventually of less importance after reviewing the test results, thus this assumption was kept unchanged throughout the present investigation.

6.4 Stability of the Damaged Ships

The stability properties of the damaged vessels, represented with the GZ_{max} distributions, as they result after the probability simulation and in reference to the design environment described above are shown in next Fig.10. While Fig.11 shows detailed results around the zero stability range.

The modified design scenarios (blue lines) demonstrate improved stability after damage, having the probability distributions shifted towards higher values. It is recalled that this design variant was purposely developed within the selected design scenarios in order to test the sensitivity of analytical approach with respect to the time to capsize. As the estimation of the time to capsize with the analytical approach is actually a function of the damage stability, the sensitivity and the effective response of the approach would be thoroughly surveyed for such intended differences on the stability, and validation evidences would be collected.

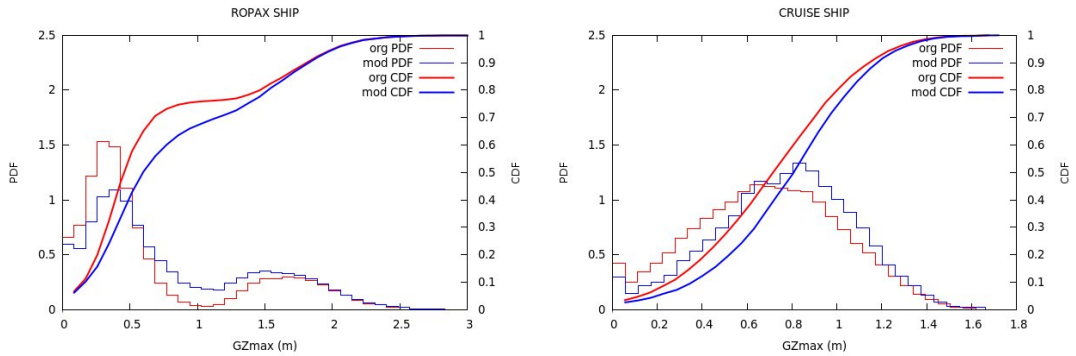

Fig.10 Distribution of GZ_{max} for the damaged RoPax ship (left) and for the damaged Cruise ship (right) in calm water, (original and modified subdivision scenarios)

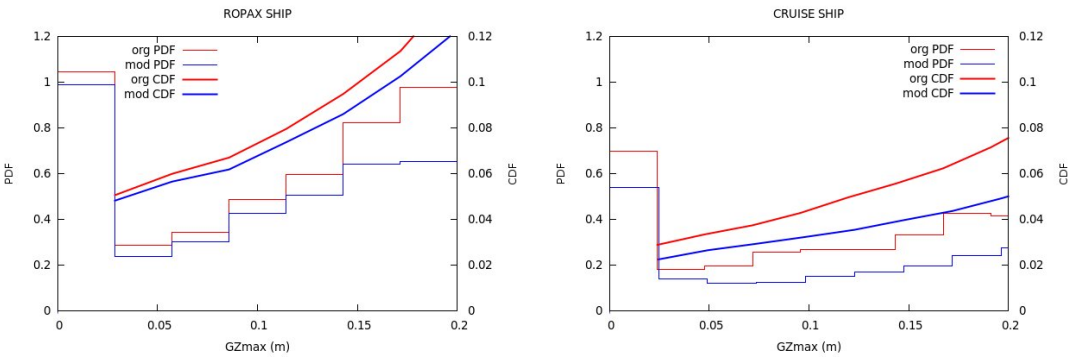

Fig.11 Distribution of lower values GZ_{max} for the damaged RoPax ship (left) and for the damaged Cruise ship (right) in calm water, (original and modified subdivision scenarios)

The two tested ships demonstrate characteristically different stability distributions after damage. Apart of the main range of the distribution from 0.0 m up to 1.0 m or 1.5 m for each ship, in case of the RoPax ship a second apparent hump extends the GZ_{max} towards higher values of 2.5 m. This is the result of how the space above the

car deck (vehicle space) contributes to the damage stability. When the assumed damage openings are limited to below the car deck, thus the space above remains intact, and then the large intact volume above the bulkhead deck contributes with large buoyancy and restoring which results to double as high righting levers.

The next Fig.12 demonstrates the samplings for the GZ_{max} and the height of the upper end of the damage openings, where for the RoPax ship the effect of the intact vehicle space is apparent.

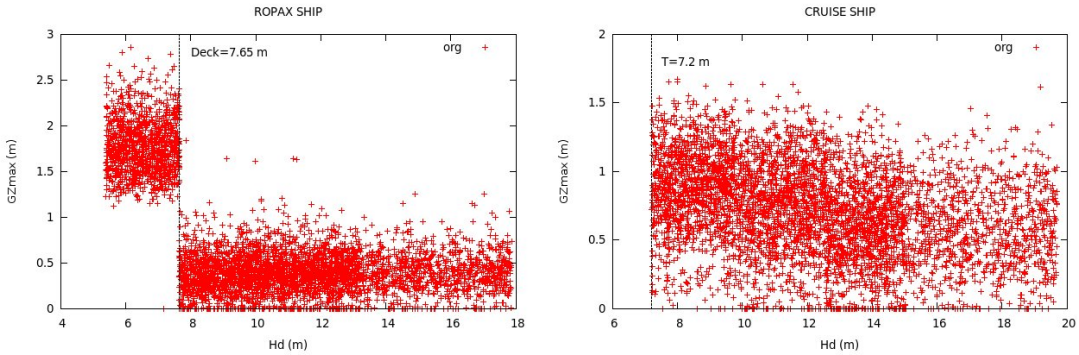

Fig.12 Distribution of GZ_{max} vs H_d (height of damage opening) for the damaged RoPax ship (left) and Cruise ship (right) in calm water (original subdivision scenario)

For the probability simulation the length of the sampling was determined through the statistical convergence of the random variables. Fig.13 demonstrates the evolution of the mean values for the location and length of the damage opening for the cases that result to capsize in calm water. *The average damage length seems convergent to 19% and 18% of the ship length for RoPax and Cruise respectively*. While the modified scenarios give no remarkable impact on these numerical statistics.

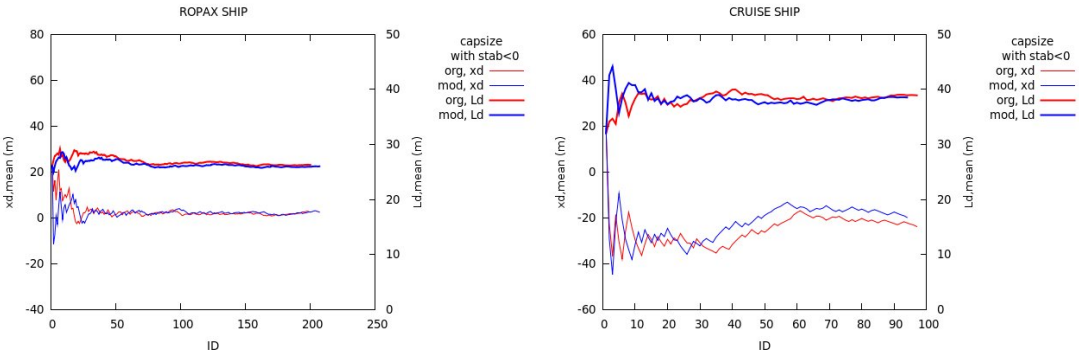

Fig.13 Mean location (x_d) and length (L_d) of the damage opening for the damaged RoPax ship (left) and Cruise ship (right) in calm water, (original and modified subdivision scenarios), *ID* the number of capsize tests

For samplings of 5000 in extent, the observed (Fig.13) number of capsize cases per ship is 200 for the tested RoPax and 100 for the cruise. Thus the average capsize rate in calm water can be approximated to be 4% and 2% for RoPax and cruise ship respectively. These values should be also assumed with some rough uncertainty of 10% (i.e. ±0.4 % and ±0.2%), which is the expected general level of accuracy of Monte Carlo simulations.

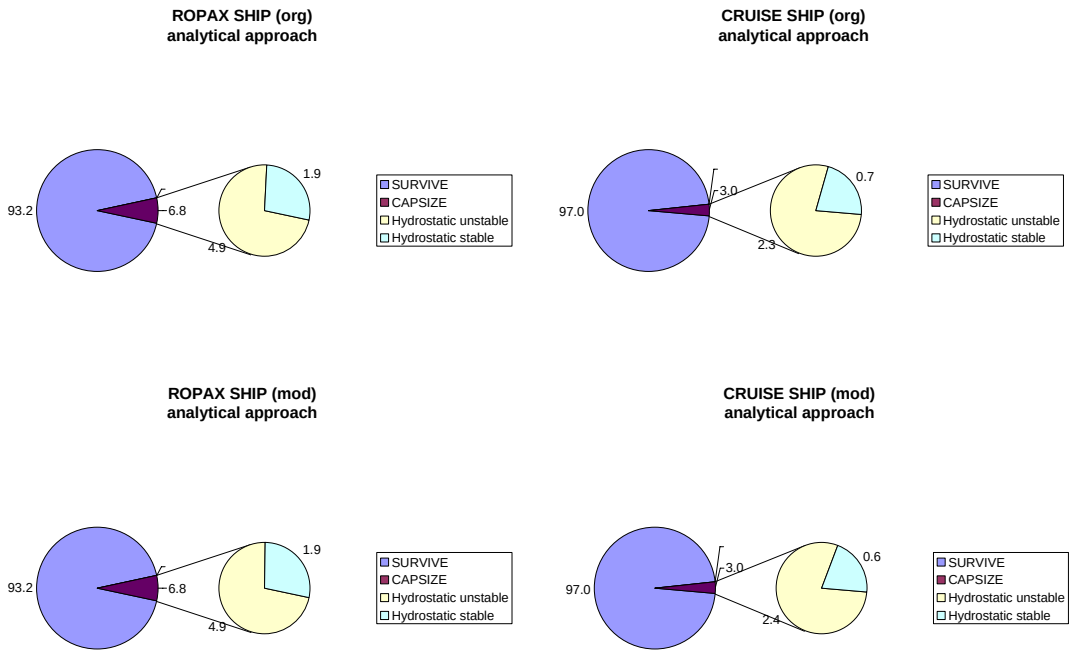

Fig.14 Percentages of capsize analyzed to unstable and stable conditions in calm water (i.e. prior to the wave effects) with the analytical approach

These capsize probabilities are further analyzed as shown with Fig.14 above, where the larger part of capsize events seems to occur because of instability in calm water. The stable conditions in calm water would need some additional cause to get a ship to capsize, like the impact of sea waves, but these cases are limited to the low percentages of 1.9% for the RoPax and 0.7% for the cruise ship.

The effect of the subdivision modifications on the percentages of Fig.14 is negligible as the particular modifications do not affect the zero stability conditions. For both ships, the original and modified scenarios are convergent each other at the limit of zero stability (GZ_{max}=0.0) as observed in Fig.11.

Thus for the larger percentage of the non-survive cases the *two* ship*s* would capsize even without the presence of waves. Consequently, the probability distribution of the *Time to Capsize appears to be dominated by the hydrostatically unstable conditions*.

The above percentages *were estimated with the analytical approach* and were used as guidance for the subsequent comparisons. Similar data are presented with independent studies in [5].

7 PROBABILISTIC RESULTS AND COMPARISONS

The probability distribution of the time to capsize for the two tested prototype ships and for the two selected design scenarios was estimated with the two alternative approaches, namely the *analytical* one (of sec. 3) and the *numerical simulation* one (of sec. 4). The comparative results are summarized and discussed in this section.

For the time domain numerical simulation approach the damage cases were tested up to 3 hours full scale time length; however, the capsize events (when they occurred) were limited within the first hour from the assumed start time which is the time the assumed damage incident happens. Here capsize events are conventionally detected as any case for which the ship exceeds 45 degrees of heeling.

7.1 Time to Capsize

The estimated probability of Time to Capsize within 3 hours and assuming the design environment of section 6 is depicted in Fig.15. The results demonstrate that capsize generally occurs within the first hour of time and only some sparse capsize events may occur between 2 and 3 hours.

The probability of capsize converges to the limits of 6.8% and 3.0%, respectively, for the two tested ships, which is the probability a capsize event to occur within 3 hours. These limits can be also considered as the ultimate limits of corresponding probabilities, as the distributions are almost flat in the range of time over 2 hours; therefore the probability to capsize later than 3 hours can be inferred to be negligible with high confidence.

The results for the tested two different design scenarios remarkably coincide (blue lines overlap red lines in Fig.15), thus there is no recorded effect from the changed parameters in the defined design scenarios. This is because no late capsizes could be encountered, where the impact of the modified subdivisions had been planned for.

Furthermore, there is not a notable effect due to the different ship types and related subdivision. The distributions are quite similar, in terms of the range of distribution, for both vessels.

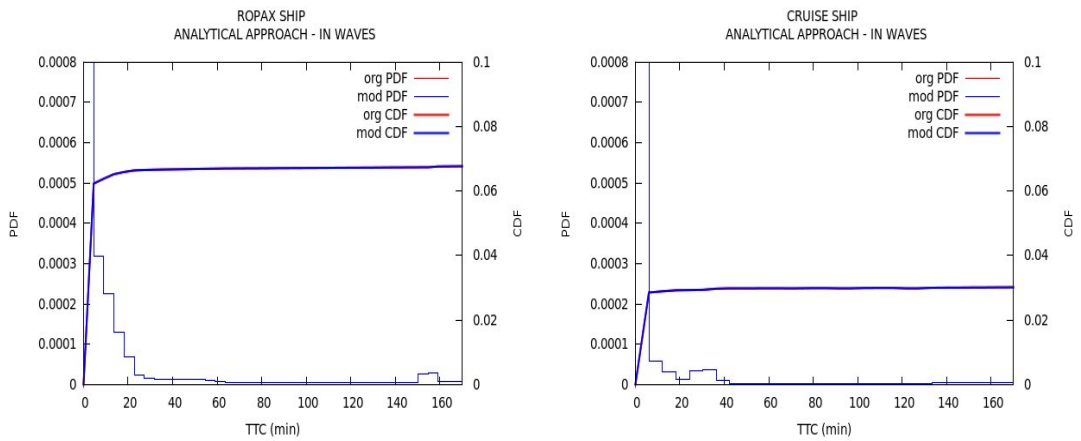

Fig.15 Probability of the Time to Capsize for the damaged ships (waves including), RoPax (left) and cruise (right), analytical approach (original and modified subdivision scenarios)

In the calm water the probability of Time to Capsize for the capsizing conditions are depicted in Fig.16 and Fig.18 for RoPax and cruise ship respectively; the same applied to Fig.17 and Fig.19, where the results are limited up to 30 *min*. Only *capsize conditions* are herein processed, consequently the probability functions converge to one.

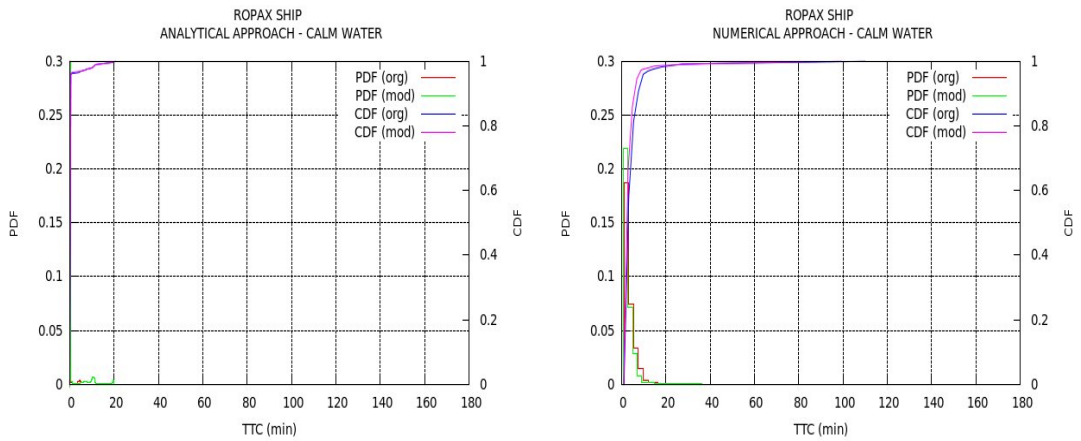

Fig.16 Probability of the Time to Capsize for the damaged ROPAX vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios)

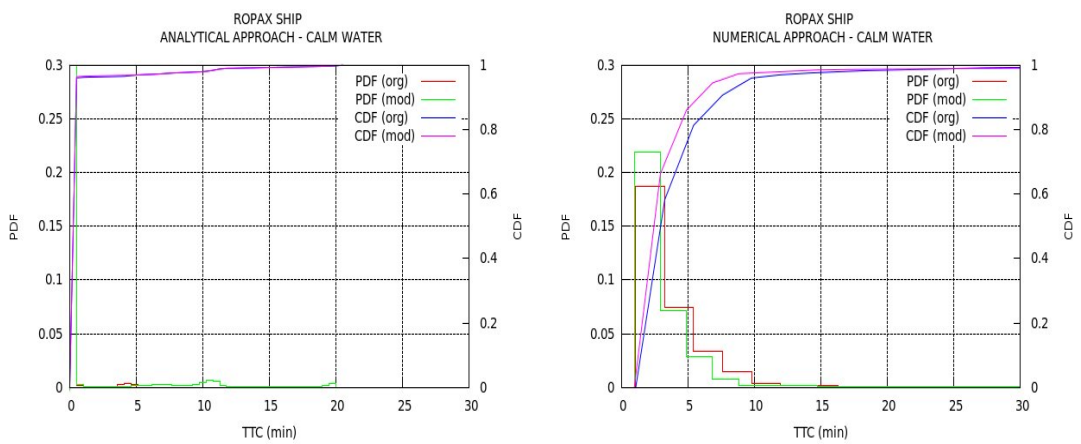

Fig.17 Probability of the Time to Capsize for the damaged ROPAX vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios), time range up to 30 min.

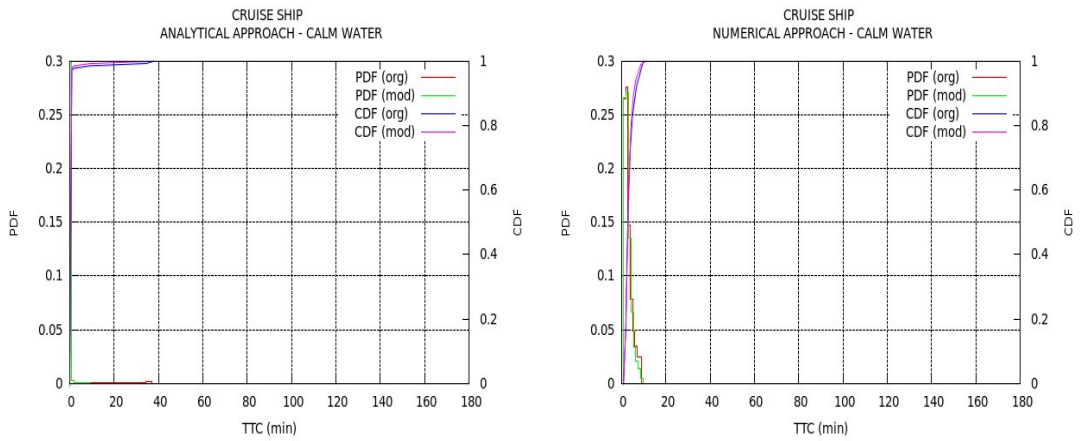

Fig.18 Probability of the Time to Capsize for the damaged Cruise vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios)

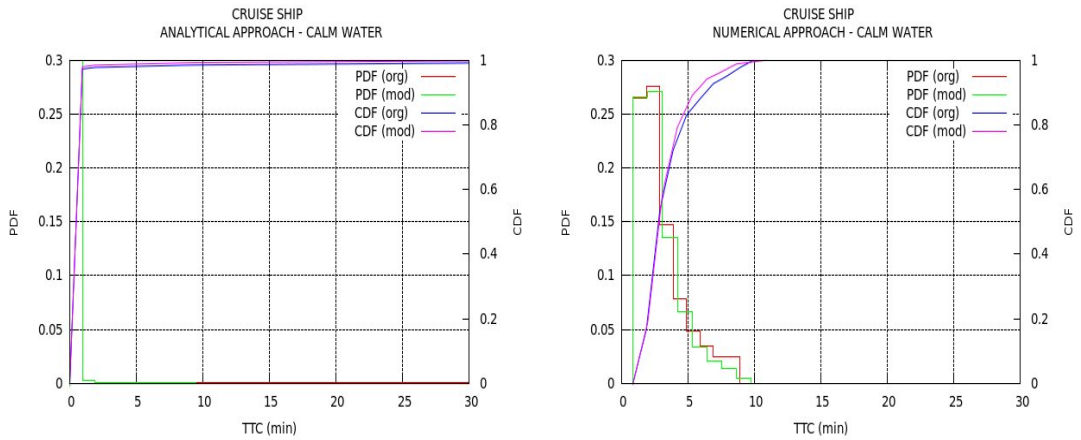

Fig.19 Probability of the Time to Capsize for the damaged Cruise vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios), time range up to 30 min.

Apparently for both approaches TTC is distributed well below 30 *min*. Nevertheless, the analytical approach seems practically insensitive to capture the design changes, Fig.17 and Fig.19. However, in view of the assumptions and scope of application of the analytical approach, scenarios with short times to capsize, like herein, should be assumed out of the application domain of this approach; namely, at the set level of accuracy for this approach, capsize events happening within few minutes are reproduced as zero time capsize events.

The above distributions are also far away of the set limit of 3 hours, which so far has been considered as a rational mean time necessary for the safe operation, mustering and orderly abandonment of ship. However, when damaged ships capsize they appear to capsize very fast and this is confirmed by the scarce historical data. As yet such behavior was observed and was thoroughly analyzed for RoPax ships in waves, for which flooding of the car deck occurred [6]. The present results suggest that fast capsize may be the most probable event for cruise ships as well.

The effect of design changes on ship's damage stability, as defined in the modified scenarios, remains of low importance as the range of capsize times is quite short and

limited. Some longer times, due to modifications, are consistently observed only when assessing the results by the numerical simulation approach.

7.2 Residual stability after damage

The next Fig.20 and Fig.21 detail the stability characteristics of the capsize cases. It can be observed that instability in calm water is trivially connected with very low residual stability damage conditions. Approximately 80% of the cases are fully unstable, while for the rest of them the GZ_{max} is limited to below 0.10 m. This limit is straightly comparable to the current limits of 0.05 m and 0.12 m which are used by SOLAS 2009 for the assessment of ship's survivability. Therefore, the particular limit seems to effectively characterize the damage survivability and this observation can be considered as an additional verification of the regulations currently in force.

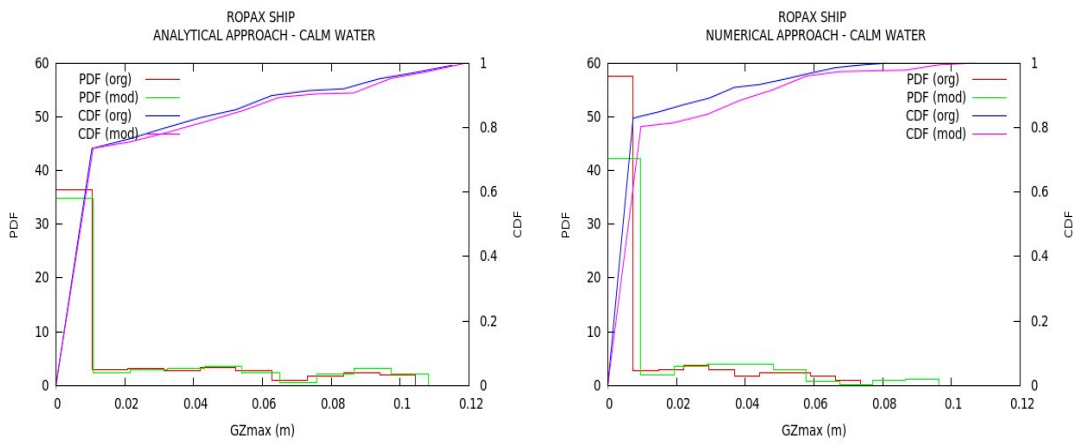

Fig.20 Probability of the GZmax for the damaged RoPax vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios)

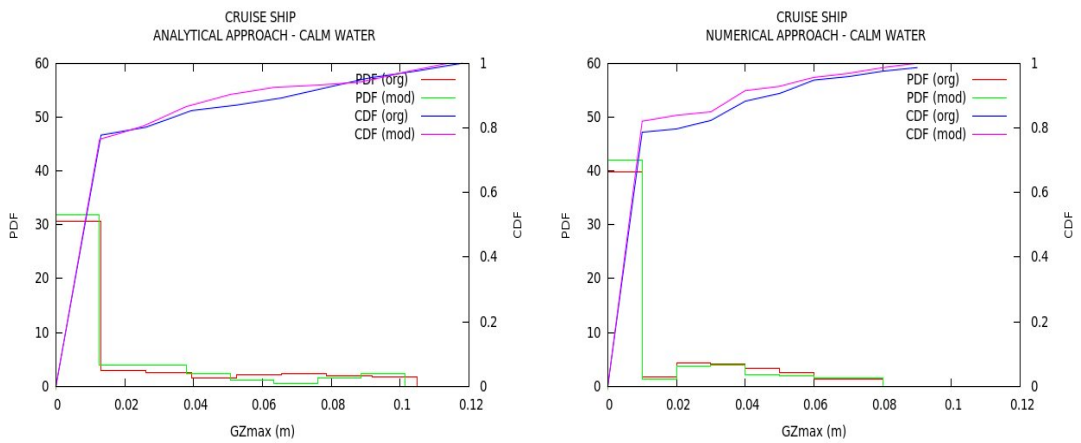

Fig.21 Probability of the GZmax for the damaged Cruise vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios)

Nevertheless it should be noted that so far in this investigation there are no full considerations for the dynamics that may affect the survivability of the ships. The above observed limit value should be enhanced in order to approach some more rational criterion that captures all possible damage conditions, including the dynamic effect of waves; then, some increased value should be expected, which bounds capsizes in waves too.

The present investigation illustrates that an additional increase of the GZ_{max} (over 0.12 m) limit value would improve the damage stability and be sufficient to deal with the percentage of 1-2% likely capsizes in waves, shown with Fig.14 above. Currently parallel investigations regarding possible suggestions for a revision of the damage stability regulation currently (SOLAS 2009) is being conducted by the research project GOALDS [12] which is expected to be completed in October 2012.

7.3 Damage openings

The distribution of the length of the damage openings and for capsize events is plotted in Fig.22 for RoPax ship and Fig.23 for the cruise ship. The observed differences between the analytical and numerical simulation approach occur because each approach may evaluate differently each damage case, i.e. some cases might be evaluated as capsizes by the analytical method, while the numerical simulation approach evaluates them as survives and vice versa.

In particular, these differences regard mostly the lower end of the distributions. The analytical approach evaluates some damage cases *with lower lengths as capsize*, whereas with the numerical simulation *the capsize events may occur only for larger damage lengths*. This is a rather reasonable difference as the analytical approach sees only the general stability characteristics of the cases, but not the actual flooding details.

For capsize events, the average damage length is approximately 20% of the ship length (overall average incident damage length 5%, sec. 6.2) as already commented with Fig.13 above. Such lengths correspond to multiple damaged compartments, namely three or more watertight compartments.

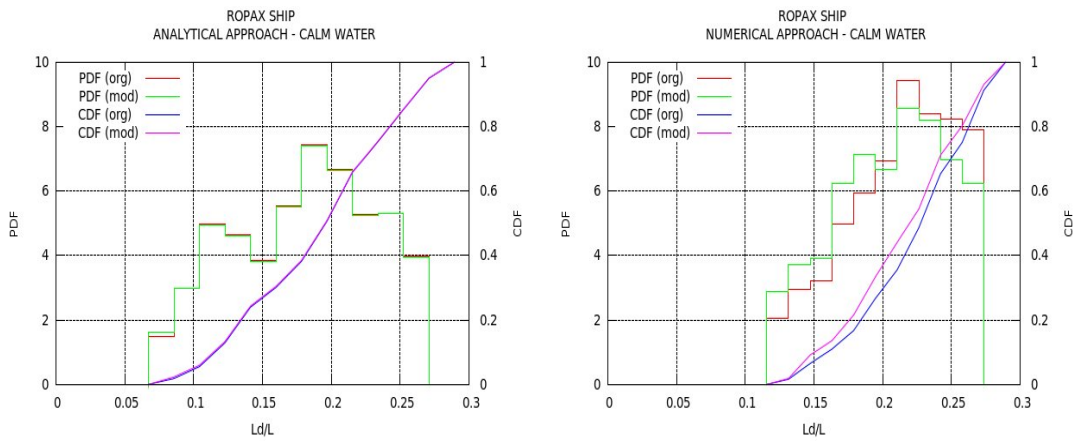

Fig.22 Probability of the Length of the damage opening for the damaged RoPax vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios)

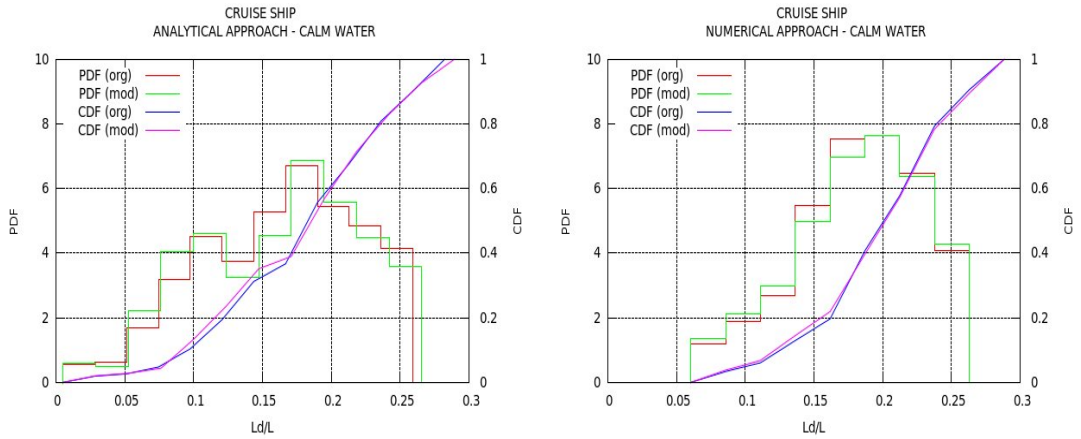

Fig.23 Probability of the Length of the damage opening for the damaged Cruise vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios)

7.4 Flood Water

The distributions for the accumulated flood water inside the flooded compartments are shown with Fig.24. This is the total water mass at the time when ship heeling exceeds 45 deg, namely the time when the ship is assumed lost.

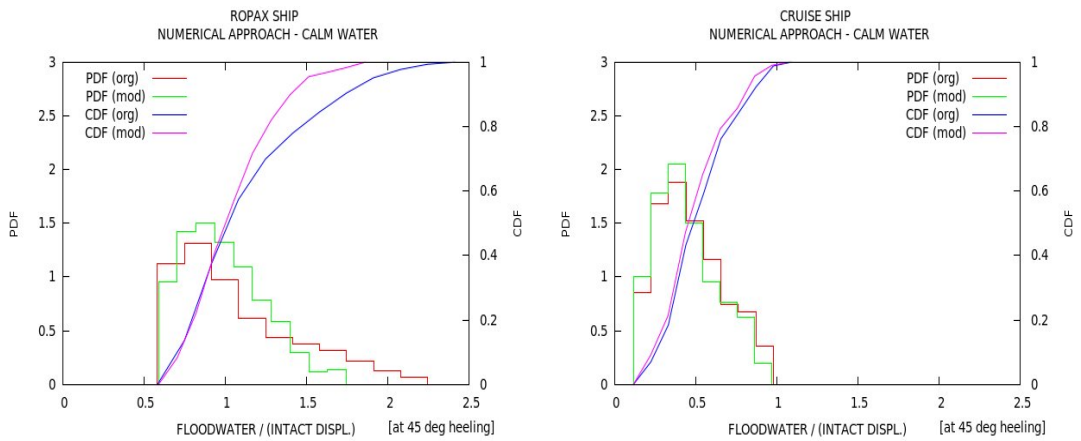

Fig.24 Probability of the Floodwater into the damaged RoPax vessel when capsizes in calm water, analytical (left) and numerical (right) approach (original and modified subdivision scenarios)

While for the cruise ship the floodwater ranges up to the ship's weight (intact displacement) differently for the RoPax the water ranges up to the double of the ship weight. This is the effect of the space above the car deck. In the numerical approach this space is assumed as an additional compartment of large volume (14500 m^3 for the vehicle space) located at a notable height.

Obviously when this space remains intact after the damage, this contributes with large buoyancy and restoring moments so that ship is not possible to capsize. The vessel may only capsize when this particular compartment gets flooded too. Nevertheless, this difference observed between the two ships has not practical impact on the time to capsize because the total amount of floodwater is comparable for both ships, as the cruise ship is three times larger with respect to the displacement.

Though the effect of the ship size on the time to capsize is not systematically studied here, it could be presumed that present qualitative observations could not be altered by the size of ships.

8 TIME DEMAND FOR SAFE OPERATIONS

The FLOODSTAND approach for "*Crisis Management*" is not limited to the assessment of the time to capsize, which was discussed in the previous sections, but is complemented by the assessment of the necessary time to carry out the safe operations of ship abandonment by passengers and crew on board. The comparative assessment of the two variables (i.e. time to capsize and time to abandon) suggests a rational criterion for the evaluation of the risk of people in cases of ship flooding.

The abandonment of the ship, when required, comprises two discrete phases that of the people mustering towards the muster stations and then the ordered abandonment of the ship. Though the abandonment comes after the mustering the two phases are not strictly sequential procedures as abandonment may well start before the full completion of the mustering. These procedures were analyzed in WP5 and reported with [6] and [8].

Another discrete phase that of the rescue of the people when at sea was also elaborated [9] and might be taken into account at a higher level of the decision making for the safety of people. However, only the duration of the mustering and abandonment determine the time demand for the safety of people and which depends on the ship survivability and evacuation characteristics. Rescue is part of a wider safety framework.

Some evidence of the mustering durations was reported in [6] for the RoPax ship *Estonia* (approx. 1000 persons on board) and one cruise liner (approx. 3400 persons on board) of size larger than the cruise ship analyzed in the present investigation (approx. 2600 persons on board), however still comparable. For the indicative scenarios worked out in the FLOODSTAND project the RoPax vessel requires roughly 20 *min* for the mustering. The mustering time remarkably increases for the larger heeling angles of the flooded ship where it may even get tripled in the duration. For the cruise liner the mustering time is roughly 40 *min*, which can be prolonged to 1 *hr* for operations in the night and which still notably varies in dependence on the ship heeling (similarly tripled time durations for large inclinations).

The time related to the abandonment procedure results to be quite comparative to the mustering times, as analyzed in [8]. Given these evidences, a conservative approximation of the total time demands for the safe operations can be assumed to be about 40 *min* for the RoPax and 1 *hr* 20 *min* for the cruise liner.

Both times are reasonably *lower* limits and, when a considerable probability exists for the sinking ship to survive longer than these limits then safe operations can be proportionally ensured for this probability. However, as shown with Fig.15 to Fig.19, the generic (design stage) time to capsize resulted to be characteristically much

shorter. Thus, in view of these theoretical evidences, the orderly abandonment of the sinking ship appears to remain *uncompleted*.

In emergency conditions, like after a real accident, the safe orderly evacuation of the ship in full extent seems to be not feasible and could be only partially ensured; then unordered (at least partially) evacuation with fast and hastily reactions of the people on board seems unavoidable.

Moreover, the discussed analysis assumes that the survivability of the damaged ship is *assessable* soon after the hull breach incident. Though this is feasible at the stage of ship design, when considering some particular damage incident then the survivability onboard assessment remains still a challenge as reported in [13] and [14]. The onboard assessment of the survivability suffers by remarkable uncertainty, namely the survive time for the ship might be short as discussed here or even the ship does not sink and the vessel stays afloat and upright for long. Under this uncertainty and mixing non-survive with survive damage conditions the time to capsize might be considered to spread over a wider range, and then faulty, it seems to correspond to higher probability for the ship to survive and available time to carry out the orderly abandonment.

It should be also borne in mind that the present discussion concerns side collision damages. For other hull damages, like groundings, the analysis should be repeated accordingly. However, the findings for the fast capsize of ships are not expected to change.

The herein raised perspective, where the time demand for the safe operations cannot be supported by the investigated subdivisions, points towards revisiting present regulations, systems and procedures for the mustering and ship abandonment in order to achieve significant time reductions and enhanced passenger ship safety.

9 CONCLUSIONS

Aiming to investigate the developed approach for the time to capsize of damaged ships due to flooding two alternative passenger ship basic subdivision arrangements, namely that of one RoPax and one cruise ship, and two subdivision modification scenarios were analyzed in the ship design stage. The main findings and conclusions out of the present investigation are summarized here below.

- The capsize events in collision damages appear to occur in short time after damage, namely within 30 *min,* for both investigated ships. This is a very short time compared to the 3 *hours* which is currently a reference time for safe operations of passenger ship after damage (*safe return to port* procedures).
- For the studied design environment the probability for late capsizes is negligible, whereas the investigated *analytical* approach appears insensitive in the range of short times. The above suggests that the studied analytical approach is not appropriate for this range of short times where the sinking of ships systematically occurs.
- Because the times to capsize are shorter than the times for orderly abandonment, the analyzed problem can be assumed practically independent of time and rather an immiscible survivability problem (binary problem: survive or non-survive). This unfavorable situation of the time shortage for safe evacuation requires even higher confidence for the ship master to take decisions on the basis of a survivability assessment.
- No effects due to the implemented different design scenarios could be detected as a consequence of negligible number of late capsizes.

In view of the above findings the problem of a passenger ship's sinking due to flooding is notably bounded within short times; consequently, the related concept of *safe return to port*, which is currently under implementation, needs reconsideration.

The 30 *min* ship survive time after damage, which is assumed in the background of the development of passenger ship damage stability regulations, is *further confirmed with the present results*. However for the larger ships, with larger number of passengers on board and longer time demands for safe operations, the problem of sufficient survive time remains still an open challenge and calls for further enhancement of subdivision requirements and abandonment procedures.

Closing this report it should be stressed that since the capsize events are short time bounded any projections for the survive time after damage (which determines the evacuation decisions too) needs to account for the associated uncertainty of the survivability of the ship, and not for the duration of the ship loss process. If this uncertainty could be minimized then the survive time would be either short or infinite, namely the ships either capsize or not.

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ANNEX

In the course of development of the analytical model there were two models considered which differ with respect to the variance of the assumed critical wave height. The final and preliminary analytical models for the probability of time to capsize are compared together and with the corresponding results from numerical approach.

As shown with the following diagrams the results of the final model fit better to the data from the numerical approach however it is less sensitive and behaves more like a binary mode instead of continuous.

Final Analytical Model, [5]:

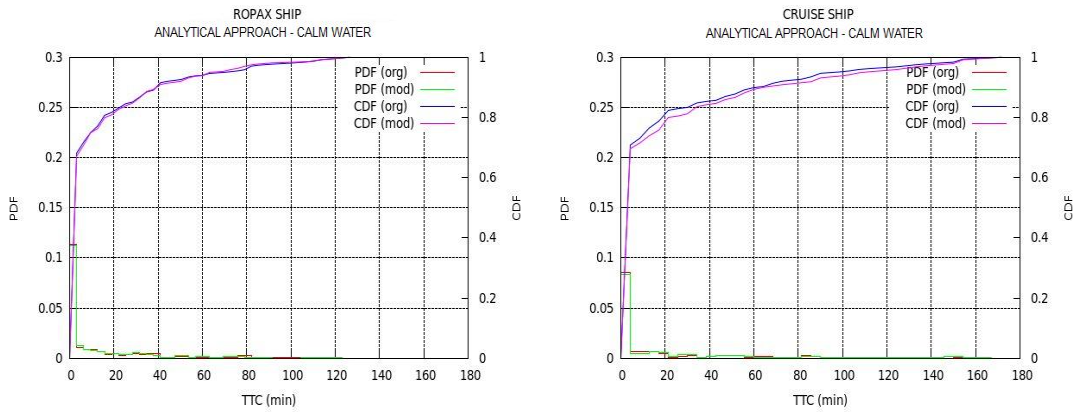
$$F(t \mid H_s) = 1 - \left[1 - \Phi\left(\frac{H_s - (H_{scr} - \varepsilon)}{0.061(H_{scr} + \varepsilon)} \right) \right]^{\frac{t}{30}}$$

Initial Analytical Model [15], ([11]):

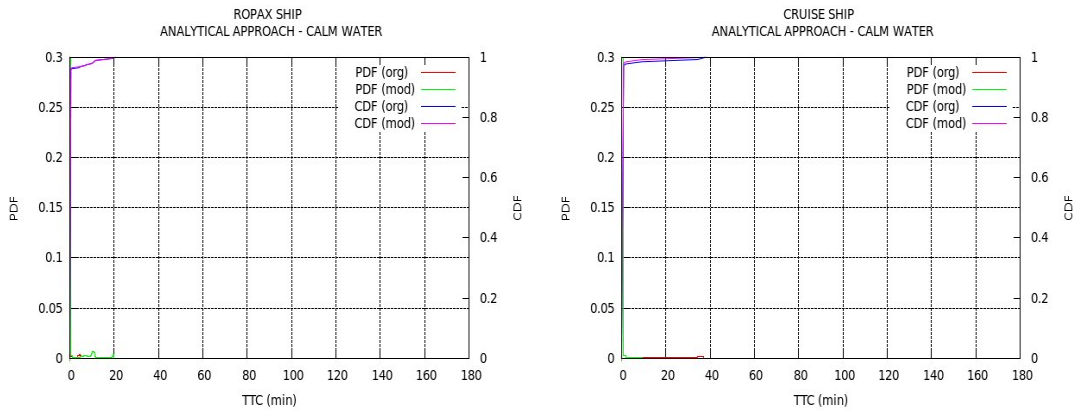
$$F(t \mid H_s) = 1 - \left[1 - \Phi\left(\frac{H_s - H_{scr}}{0.039 H_{scr} + 0.049} \right) \right]^{\frac{t}{30}}$$

ROPAX VESSEL CRUISE VESSEL

Initial Analytical:



Final Analytical:



Numerical approach:

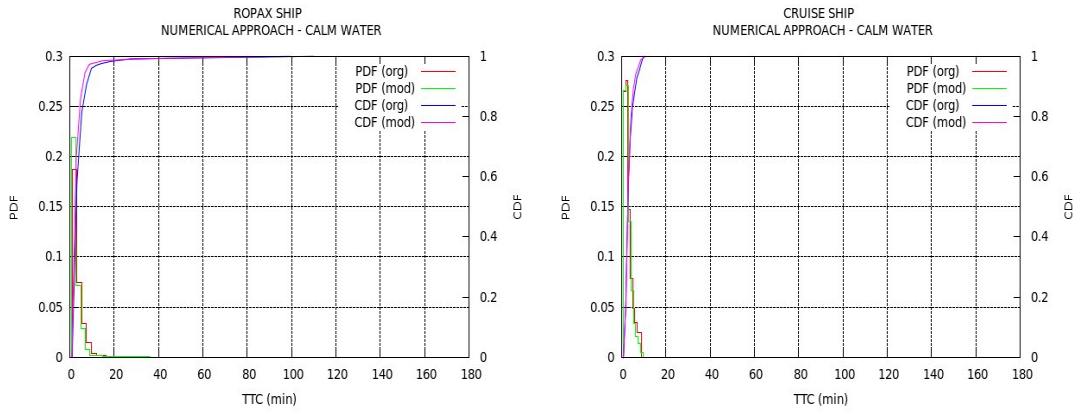


Fig.25 Probability of Time to Capsize estimated with three alternative approaches.

Table 3 collects a set of discrete values of the probability to capsize at 30 *min* and 180 *min*. The Fig.26 plots the probability over full range 0-180 *min* for the test cases defined in Table 3.

Table 3 Discrete values of probability for TTC with (final) analytical approach

TEST	GZmax m	Range deg	Hs m	PROBABILITY TTC CDF 30min	CDF 180min
1	0.07	16.0	0.75	0.776	1.000
2	0.07	16.0	0.70	0.350	0.925
3	0.07	16.0	0.65	0.063	0.324
4	0.12	16.0	1.30	0.829	1.000
5	0.12	16.0	1.20	0.350	0.925
6	0.12	16.0	1.10	0.043	0.231
7	0.20	16.0	2.10	0.661	0.998
8	0.20	16.0	2.00	0.350	0.925
9	0.20	16.0	1.90	0.118	0.529
10	0.07	12.0	0.55	0.647	0.998
11	0.07	12.0	0.50	0.126	0.554
12	0.07	12.0	0.45	0.004	0.022
13	0.12	12.0	1.00	0.918	1.000
14	0.12	12.0	0.90	0.350	0.925
15	0.12	12.0	0.80	0.015	0.088
16	0.20	12.0	1.60	0.753	1.000
17	0.20	12.0	1.50	0.350	0.925
18	0.20	12.0	1.40	0.073	0.367

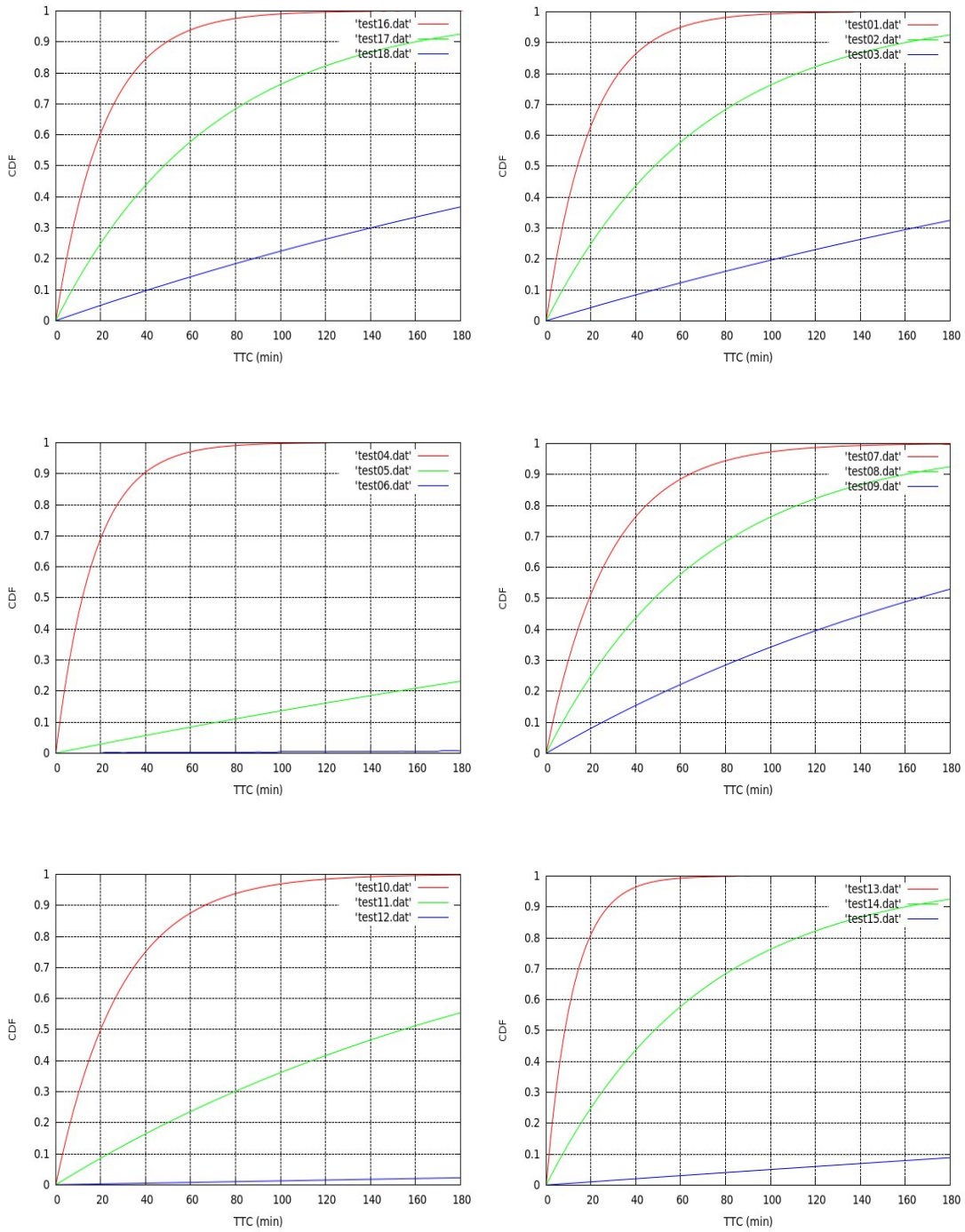


Fig.26 Probability of Time to Capsize that corresponds to the test cases of Table 3.