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CONTENTS

List of annexes

List of symbols and abbreviations

FF	Flare Framework
GT	Gross Tonnage
NAPA	Naval Architectural Package of NAPA Oy
MVZ	Main Vertical Zone
POB	Persons On Board
WPX	FLARE Work Package X
DX.Y	FLARE Deliverable X.Y
Perm	Permeability
T0.45	Draught at 45% between minimum draught and maximum draught
T0.75	Draught at 75% between minimum draught and maximum draught
A	Attained Subdivision Index
R	Required Subdivision Index
T	Draught
WCOEF	Weight coefficient
Pfac	Probability of occurrence of the specific damage case
Sfac	SOLAS factor s_i as defined within ch.II-1, part B.
Smom	SOLAS factor $s_{mom,i}$ as defined within ch.II-1, part B.
SA	Stockholm Agreement [18]
PLL	Potential Loss of Life
FSA	Formal Safety Assessment
RCO	Risk Control Option
CL	Collision
GR-B	Bottom grounding
GR-S	Side grounding
freq	frequency of a specific hazard (collision, side grounding, bottom grounding)
TTC	Time to Capsize
TTE	Time to Evacuate

1. EXECUTIVE SUMMARY

This deliverable describes the procedure adopted for the calculation of the flooding risk according to the FLARE project proposal, as well as the results obtained on the FLARE sample ships.

1.1 Problem definition

A new framework (FF) has been proposed by FLARE in WP5 D5.1.1[6] (see Figure 1 and Figure 2). This proposal provided the general concept of the approach, but in order to apply it to the sample of ships a calculation procedure is needed, which is herein developed in Ch.2.

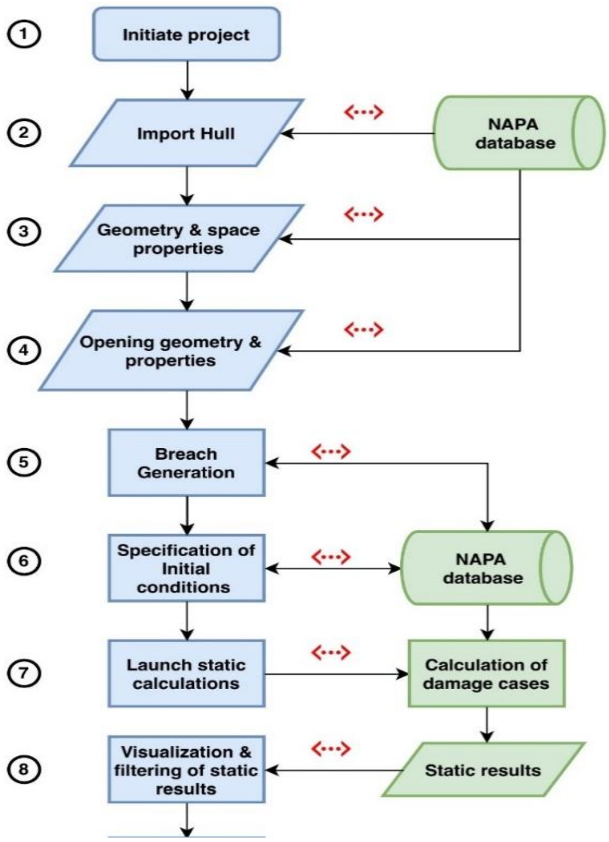

Figure 1 FLARE Framework (part 1)

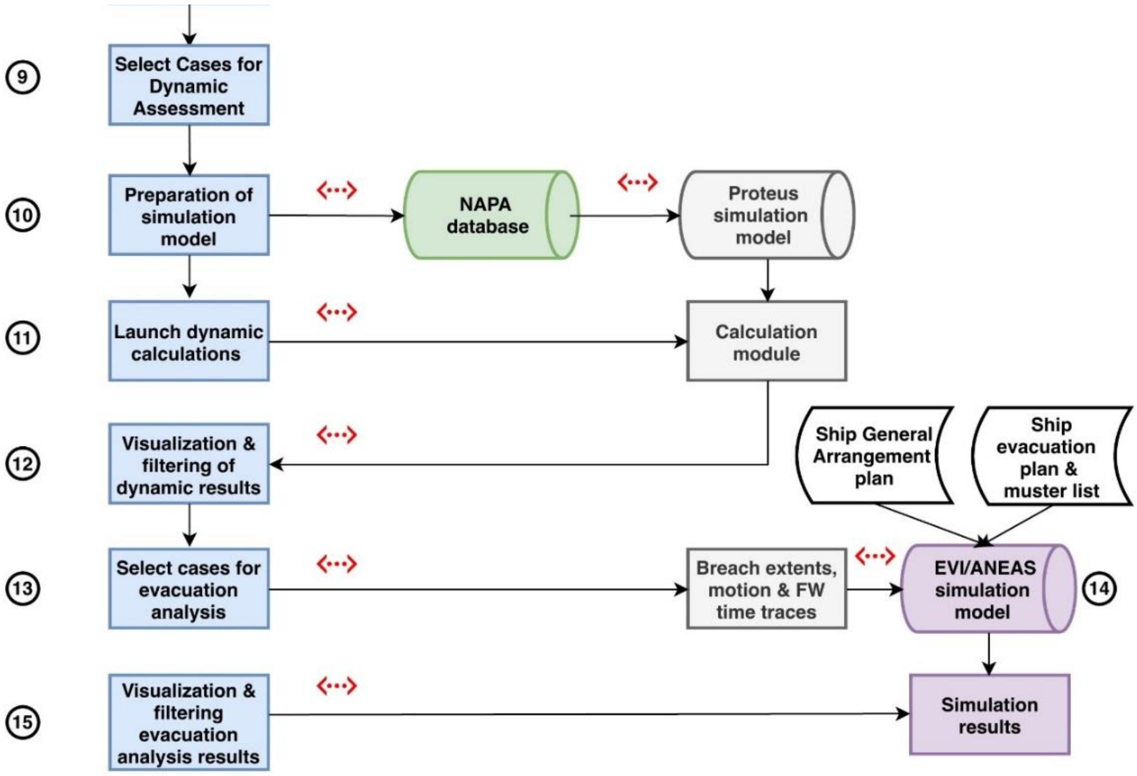

Figure 2 FLARE Framework (part 2)

Based on this framework, a calculation procedure is developed and applied to the sample ships to verify that this step-by-step process permits to calculate the flooding risk for passenger ships in a more rational, reliable and comprehensive way.

1.2Technical approach and work plan

- A procedure to calculate the flooding risk of a passenger ship has been developed based on a two-level approach.
- The sample ships D2.1 [13] calculated in WP2 (4 Cruise and 3 Ro-Pax SOLAS'20 with the addition of 1 Cruise and 1 Ro-Pax SOLAS'90) have been prepared for the implementation of the calculation procedure.
- As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.
- An interim modelling guidelines (see Annex 1) has been developed to guide the end users in the preparation of the ship models. Based on this, the ship models have been refined. In that way, a unique geometric model has been used for each ship when the flooding risk is calculated according to the two-level approach.

- On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for the A-Index and PLL, while semi-empirical methods for the remaining associated risk parameters.
- Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).
- The assumption made for the fatality rate in the calculation for level 2.1 has been validated by an evacuation analysis carried out for the selected scenarios (level 2.2).

1.3 Results

- All the details of the calculations executed, and the results obtained for the nine sample ships are included as annexes to this document (see ANNEX 3 – 11).
- The static analyses conducted on the nine sample ships show how the assumed draughts and the permeabilities influence the Attained Subdivision Index.
- For eight out of nine sample ships the Attained index obtained from the non-zonal static analysis, even for collision, is higher than the Attained Index calculated according to SOLAS [9]. This is mainly due to the lower limit for the breaches (introduced by the non-zonal collision analysis as demonstrated by the eSAFE project [2]) and to the more realistic permeabilities (calculated in the FLARE deliverable D2.3 [5]). Overall, the results for the sample ships showed that the present SOLAS is conservative, underestimating the capability of passenger ship to survive (in terms of SOLAS) in case of collision.
- The work on the risk model (D2.5 [14], D2.6 [15]) demonstrated that the grounding hazard represents a significant risk for passenger ships, therefore, to consider all pertinent risks, flooding risk assessment should take into account all relevant hazards collision and associated grounding. The Level 1 calculations showed that different design choices have a clear impact on the grounding results; e.g., long lower hold and roro car deck may increase the flooding risk in case of collision but a watertight double bottom could minimize the flooding risk in case of bottom grounding.
- The PLL calculation with a two-level approach demonstrated that the procedure is consistent. Conservative risk measures have been obtained from Level 1; however, the PLL is considerably reduced when Level 2 is calculated.
- Evacuation analysis carried out on the selected cases of two sample ships (one cruise and one Ro-Pax) demonstrated that the simplified formula used for the fatality rate in level 2.1 is conservative, i.e. lead to higher risk.
- A sensitivity analysis on the simplified fatality rate formulation has been executed which demonstrated that the PLL calculated with the approach described in Level 2.1 is reliable. It is noted that the deviation obtained for the PLL when changing the fatality rate is negligible.

- Overall, it has been demonstrated that the process to calculate flooding risk with the two-level approach is mature and practicable and may form the basis for future rules and regulations.

2. PROCEDURE FOR THE CALCULATION OF RISK

2.1 Introduction

For the analysis of human safety or risk level related to different hazards, the metric normally used is PLL (potential loss of life). This value derives from the accident frequencies (respectively dependent probabilities) in the risk model, the ship survivability rate, the fatality rate in the event of an accident and the number of persons on board (see Figure 3).

PLL = hazard-freq. * breach-freq. * (1-survivability) * fatality-rate * POB

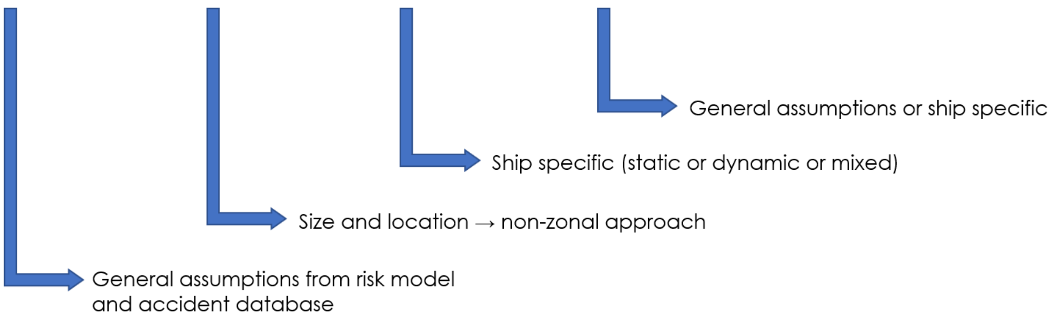

Figure 3 Concept of PLL calculation for a given scenario per ship year

This approach has already been used to define the Required Subdivision Index (R) in SOLAS2020 and it is based on an FSA carried out in the EMSA3 project [16]. However, this procedure is not clearly defining the risk level of a ship in case of flooding anymore, as only the Attained Subdivision index (A) is defined in SOLAS, which describes the quality of the subdivision of a certain ship, without taking into account the performance of this ship with regard to evacuation, e.g. effect on evacuation of the internal arrangement in modern passenger ships. Some limiting criteria (i.e. Sfac = 0 in cases of excessive heel, immersion of evacuation routes, vertical escapes, etc.) have been defined in SOLAS but these do not take into account in a proper way the performance of the ship with regard to evacuation as there is no relation between the Sfac and the Time to Evacuate (TTE).

In the EMSA3 risk model [16], which has been used to define the level of R, the estimation of fatality rates has been based on expert judgment, using representative casualties where the same applies to all ships for different or the same scenarios, i.e. did not consider the characteristics of a ship under consideration. The term (1-A) has been used to assess the survivability, because it combines the probabilities of breach size and location, operational wave heights and survivability.

To assess more in detail an individual ship, the approach needs to become modular, where individual contributors, like breach size, survivability or fatality rate, may be calculated either in a simple, generic way or by using ship specific simulations. This would also allow to consider different operational areas with different environmental conditions, multiple flooding hazards (collision, bottom and side grounding) and active or passive risk control options.

The modular setup of the concept will hence allow for a two-level approach, where the risk assessment in Level 1 is simpler and conservative, while in Level 2 is more accurate, allowing the use of alternative, more complex tools.

2.2 General concept

The concept of risk calculation follows a similar but modified approach as compared to that current used SOLAS. Instead of calculating an Attained Subdivision Index (A), which needs to be equal or higher than the Required Subdivision Index R, the potential loss of life (PLL) is the new measure of risk to be calculated.

SOLAS approach: $\boldsymbol{Attained\ Subdivision\ Index\ (A) \geq\ Required\ Subdivision\ Index\ \ (R)}$ (1)

FLARE approach: $\boldsymbol{Attained\ PLL \leq\ maximum\ allowable\ PLL}$ (2)

The Attained PLL is assumed to be the weighted sum of the PLL values for each of the initial draughts, in a similar way as the Attained Subdivision Index A, which is defined as the sum of partial indices for each draught.

The maximum allowable PLL may depend on the total number of persons on board, in a similar way as the current Required Index R. However, this is still a matter for further consideration and conclusions are to be drawn by the regulatory authorities in the future.

The maximum allowable PLL is to be assessed and determined following an FSA involving a large number of ship designs and risk control options, following the ALARP principle and the cost effectiveness of RCOs (IMO approved FSA procedure).

2.3 Combined Hazards

In the current regulatory SOLAS framework only the hazard of collision is considered directly in the Attained Subdivision Index (A), while the analysis of accident data and the risk model showed that bottom grounding and side grounding/contact play a dominant part in the reported flooding accidents frequencies (see Figure 4).

The risk due to bottom grounding is considered in SOLAS Reg. 9 following a deterministic approach, and a limited number of side breaches with insufficient extension are considered (SOLAS Reg. 8). However, this approach provides a limited level of safety due to its deterministic component, while the global flooding risk remains uncertain in the current regulatory SOLAS framework.

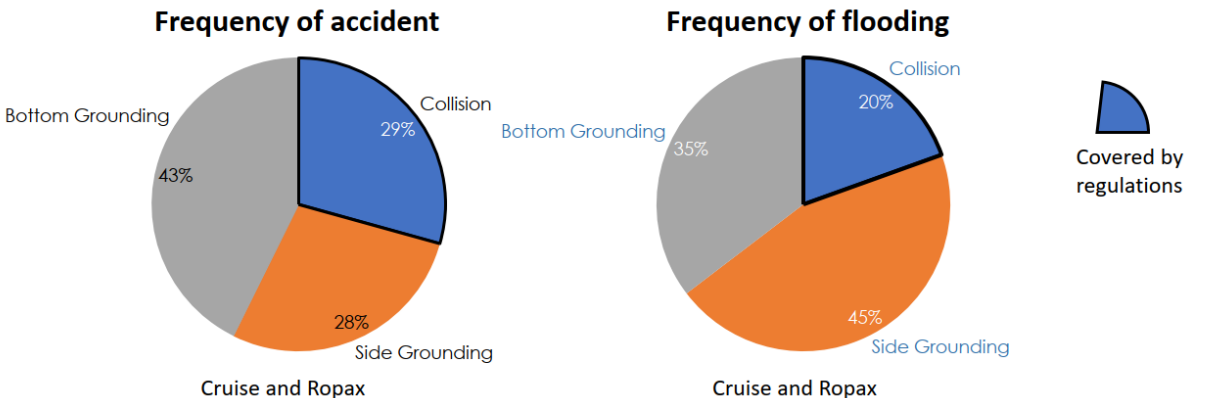

Figure 4 Frequencies of different hazards (FLARE D5.14 [8])

In order to provide a combined quantification of the risk due to different hazards, two different methods may be used (eSAFE project [2]):

• A risk-based safety metric directly related to societal risk;

• A probability-/survivability-based safety metric, making direct use of the relative frequencies of the corresponding types of accident.

Since the first method, so far, has been developed on basis of the EMSA III risk model that used estimated fatality rates (based on expert judgment, see Ch.2.1), the second method has been selected here and therefore the Attained PLL comprises the following components:

$$PLL = freq_{CL} \times PLL_{CL} + freq_{GR-S} \times PLL_{GR-S} + freq_{GR-B} \times PLL_{GR-B} \qquad (3)$$

Where,

CL stands for collision,

GR-S for side grounding/contact and

GR-B for bottom grounding and.

$freq_{XX}$ is the hazard frequency of each damage event (collision, bottom grounding, side-grounding/contact) from the accident database D5.14 [8].

The underlying risk model including the analysis of the accident statistics considers a taxonomy accounting for different aspects, such as:

- Type of accident: collision, bottom and side grounding/contact
- Area of operation during accident: open sea, restricted, port
- Striking / struck ship
- Aground/not aground, soft vs hard ground
- Breach/flooding

Considering the limited number of accidents recorded, in particular for cruise ships, the combined frequencies (Ro-Pax + Cruise) are used for the PLL calculation (see Table 1).

Table 1. Hazard frequencies of Ro-Pax, Cruise, and Ro-Pax + Cruise (FLARE D5.14 [8])

Hazard type	Ro-Pax		Cruise		Ro-Pax + Cruise	
	Frequency (1/ship-year)	Relative fraction	Frequency (1/ship-year)	Relative fraction	Frequency (1/ship-year)	Relative fraction
Collision	2.42E-03	0.450	3.02E-04	0.127	1.68E-03	0.388
Side grounding	1.53E-03	0.285	1.21E-03	0.509	1.42E-03	0.328
Bottom grounding	1.42E-03	0.265	8.64E-04	0.364	1.23E-03	0.284
Total	5.38E-03	1.000	2.37E-03	1.000	4.33E-03	1.000

2.4 Calculation of PLL

For each of the different PLL values the same principle of calculation applies:

$$PLL_{XXX} = \sum pfac \times (1 - sfac) \times fatality\_rate \times POB \quad (4)$$

Where,

pfac is the probability of a breach with regard to size and location following the non-zonal approach.

sfac is the probability of survival of the breach/flooding case (see below).

fatality_rate is the assumed rate of fatalities for each breach/flooding case (see below).

POB is the total number of persons on board

2.5 Survivability and fatality rate

The survivability and fatality rate for each flooding case can be calculated based on the two-level approach:

Level 1 - Static calculation

The calculation of the survivability is done using the Sfac according to SOLAS2020 (Ch.II-1, regulation 7-2) Sfac. If, at a later stage, the operational area may be considered in the assessment, an adjusted Sfac for reduced wave height for non-open sea areas may be applied. Reference is made to eSAFE [2], where formulations have been developed to calculate the Sfac as a function of the maximum significant wave height in the area of operation being considered.

To simplify the methodology and to account for the dependencies between survivability and fatality rate, it is only differentiated between survived cases (sfac = 1) and the remaining cases (Sfac < 1)

The fatality rate is depending on survivability. To simplify the application fixed fatality rates are assumed:

If Sfac < 1 then fatality_rate = 80%

If Sfac = 1 then fatality_rate = 0%

This simple and conservative approach is in line with the method used in EMSA3 for capsizing, for the development of SOLAS2020. The differentiation between fast and slow sinking, as adopted in the EMSA3 project [13], has been rejected due to large uncertainties in defining the frequencies for fast and slow sinking accordingly.

When more results from evacuation simulations after flooding will be available, the assumed fatality rates may be adjusted, accordingly.

Level 2 - Dynamic simulations

When dynamic flooding simulations are used for a selected number of breaches, the typical dynamic survival criteria are applied. Basically, the main criterion is whether ship capsizes or sinks, together with the relevant value for TTC (Time to capsize). However, due to the limited simulation time, more explicit and deterministic criteria are used, taking into account the deployment of life-saving appliances and the ITTC recommendations.

Survival criteria:

- No capsizes/sinking during the simulation time

- Steady Heel within 30 minutes ≤ 30 degrees
- No progressive flooding at the end of the simulation time

If at the end of a simulation for a specific case all the survival criteria are satisfied except for the progressive flooding criterion, the simulation is to be extended for this case (second run).

To achieve reasonable results, current state-of-the-art software tools and specifications/assumptions are used. Details about the approach for dynamic simulations are described in Annex 2. However, the following main conditions are to be assumed for the dynamic simulations:

- Heading angle of waves: 90/270 degrees
- Ship speed: 0, no current, no drift
- Wave type: JONSWAP spectrum (randomized) with a significant wave height of 4 m at the time of the accident

In the risk calculation for the FLARE sample ships summarised in this document the JONSWAP spectrum (randomized) with a significant wave height of 4 m has been used. That wave height corresponds to the 99% collision casualties in the CDF used in SOLAS, i.e. 99% of collision occurred in significant wave heights equal to or below 4 m. If at a later stage the operational area is considered, the wave spectrum may need to be adjusted. For coastal area operation, JONSWAP (randomized) with maximum height depending on operational area is used. For open sea area operation, the use of Pierson-Moskowitz spectrum is recommended.

In flooding simulations, the time to capsize TTC is an important value, which may be used to estimate the fatality rate. Again, a two-level approach is proposed, assuming pre-described fatality rates as a function of TTC in Level 2.1 and the use of evacuation simulations for a specific case as Level 2.2:

Level 2.1 - simplified fatality rate

For the simplified approach, the time to capsize is compared with the maximum allowed evacuation time as defined in MSC.1/Circ. 1533 [10].

If TTC > n then fatality_rate = 0%

Where,

n is maximum allowed evacuation time acc. MSC.1/Circ. 1533, i.e. to 80 min for cruise ships with more than 3 MVZ, 60 min for smaller cruise ships and for Ro-Pax.

If TTC ≤ 30 min then fatality_rate = 80%

Linear Interpolation between 0% and 80% for 30 min < TTC < n is applied.

$$fatality\_rate = \begin{cases} 0\%, \ \text{for } TTC > n \\ 80\% \cdot \left[1 - \frac{(TTC - 30\ min)}{n - 30\ min}\right], \ \text{for } 30\ min \leq TTC \leq n \\ 80\%, \ \text{for } TTC < 30 \text{ min} \end{cases} \quad (5)$$

Level 2.2 - Fatality rate from evacuation simulations

The Level 2.1 values proposed above for the fatality rate may be substituted with actual fatality rates from numerical evacuation simulations for those cases where the survival criteria are not met.

If the individual fatality rate for a given scenario is calculated using evacuation simulation, a number of input parameters and boundary conditions are to be followed.

It is not needed to provide here all the details of the calculation defined in MSC.1/Circ.1533 [10], to be used as reference. Only the deviations from this circular and the specific settings to consider the flooding scenarios are reported in this document.

In general, the total evacuation duration is to be calculated using the following formula:

$$\boldsymbol{Evacuation\ duration = 1.25 \times (R + T) + \frac{2}{3}(E + L)} \quad (6)$$

Where:

R, Response duration, it is the time it takes for people to react to the evolving situation;

T, Travel duration to move from where people are to the assembly station;

The multiplying factor 1.25 is an arbitrary safety margin for (R+T) defined in the MSC.1/Circ.1533 [10]

E+L, Embarkation and Launching duration, it is the time required to provide for abandonment after all persons have been assembled.

Then, considering that *E+L* may be assumed as 30 minutes (according to MSC.1/Circ.1533 ph.5.5 [10]), it can be deduced that just the values of *R* and *T* are to be calculated with the numerical simulations for each flooding scenario.

When the numerical simulations are run, the above formula permits to generate a diagram similar to that exemplified in Figure 5, where the number of persons evacuated in the specific scenario are plotted versus the time. Entering in that diagram with the TTC (obtained from the flooding simulation) it is possible to calculate the number of persons evacuated before the failing of survival criteria and related fatality rate.

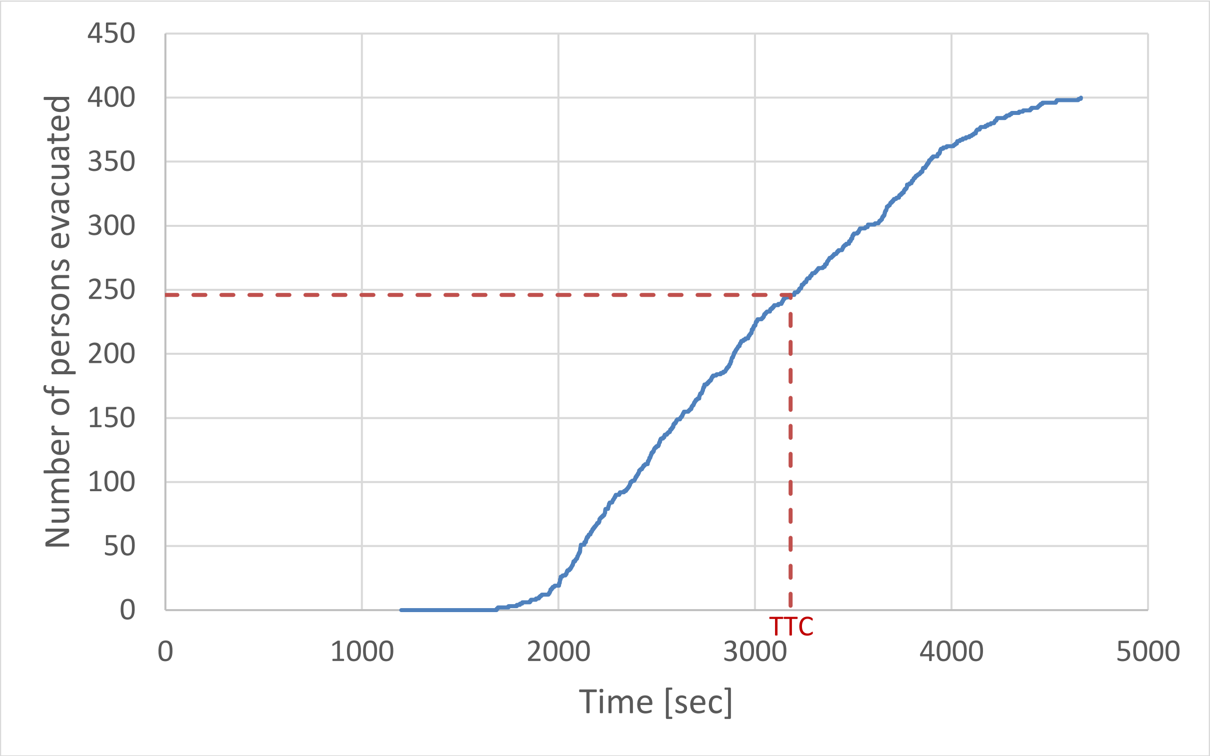

Figure 5 Example of output from evacuation analysis of a flooding scenario

With this method the actual fatality rate is calculated, anyway it has not to be assumed greater than 80% of the POB for consistency with Level 2.1.

3. APPLICATION OF RISK CALCULATION TO SAMPLE SHIPS

This chapter describes the calculation process and inputs for static analysis and case filtering used in the subsequent dynamic analysis.

3.1 Draughts and permeability

The first step of FLARE damage stability analysis starts with a static damage stability calculation in accordance with SOLAS II-1 but using new reference draughts as per deliverable D2.2 [4] and new permeabilities as per deliverable D2.3 [5].

For the sample ships, which are at a design stage, the optimal non-dimensional calculation draughts are 0.45 and 0.75 and a weighting factor of 0.5 for both draughts have been used.

GM values for the new draughts have been obtained by interpolation from the original GM limiting curve obtained by the application of SOLAS Reg. 6.1.

The FLARE GM limiting curve is obtained by keeping constant the GM below draught at 0.45 and above 0.75 (see Figure 6). This approach uses the same methodology as defined in the Explanatory Notes [11] of the current SOLAS, where also the extreme GM values are extrapolated horizontally when draughts outside the calculated draught range are needed. However, the methodology to define a GM limiting curve is the task of the regulator therefore different methodology (e.g. extrapolation) may be selected in the future without undermining the process here.

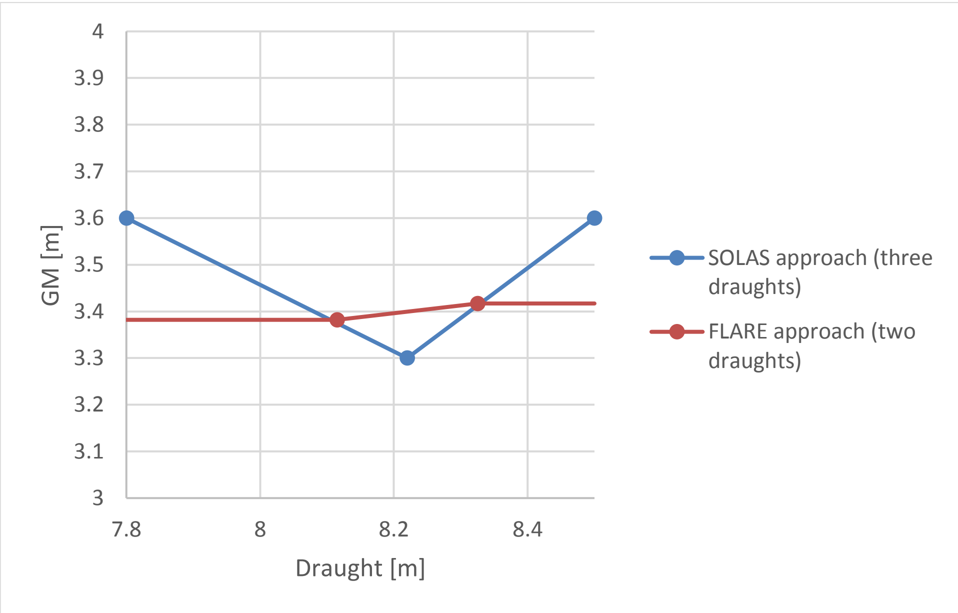

Figure 6 Example of GM limiting curve with new FLARE draughts

Considering the outcome of D.2.3 [5], the figures shown in the last two columns of the Table 2 have been used for the permeability of the cruise vessels.

Table 2 Permeability of cruise ships acc. to SOLAS and FLARE

Rooms	**SOLAS perm.**	**FLARE perm. T0.45**	**FLARE perm. T0.75**
Engine rooms	0.85	0.90	0.90
Auxiliary machinery spaces	0.95	0.90	0.90
Stores	0.60	0.90	0.90
Accommodation (cabin areas, galleys, offices, workshops etc)	0.95	0.90	0.90
Public spaces, crew mess, corridors, staircases	0.95	0.95	0.95
Fuel Oil, LNG, Marine Gas Oil, Lube Oil, Potable Water, Waste Water, Technical water, Water ballast, Misc.	0.95	0.541	0.508
Heeling tanks	0.95	0.51	0.51
Void Spaces	0.95	0.95	0.95

For Ro-Pax ships, the SOLAS figures have been used with the exception of heeling tanks where 0.51 has been used (Table 3).

Table 3 Permeability of Ro-Pax ships acc. to SOLAS and FLARE

Rooms	SOLAS perm.	FLARE perm. T0.45	FLARE perm. T0.75
Engine rooms	0.85	0.90	0.90
Auxiliary machinery spaces	0.95	0.90	0.90
Stores	0.60	0.90	0.90
Accommodation (cabin areas, galleys, offices, workshops etc)	0.95	0.90	0.90
Public spaces, crew mess, corridors, staircases	0.95	0.95	0.95
Fuel Oil, LNG, Marine Gas Oil, Lube Oil, Potable Water, Waste Water, Technical water, Water ballast, Misc.	0.95	0.95	0.95
Heeling tanks	0.95	0.51	0.51
Void Spaces	0.95	0.95	0.95
Ro-ro spaces	0.95-0.90	0.9125	0.90

3.2 Non-zonal static calculations with refined FLARE model

Subsequently, the geometry models used for calculations have been updated according to the FLARE modelling guidelines (Annex 1).

The refined FLARE models reflect as close as possible the geometry of the physical ships and their designs; the following items have been refined or added (see Annexes 3 - 11):

- Weathertight hull
- Cabin areas
- Staircases and lifts
- U-shaped compartments above double bottom
- U-shaped void spaces within the DB.

Once a geometrical model has been updated according to the modelling guidelines, static damage stability has been calculated again with the aim to evaluate the impact of the refined model on the Attained Subdivision Index.

Then, with the new model, the *non-zonal approach* has been used to calculate the attained indices A_i for collision, bottom grounding and side grounding/contact.

The *non-zonal approach*, in contrast to the *zonal* subdivision approach in present SOLAS, for grounding damages has been developed in GOALDS and EMSA3 [1], and for collision in the eSAFE project [2].

Many tests have been done to verify the minimum number of breaches needed to achieve stable results. These runs permitted to show that 10,000 breaches for each type of damage and each draught are sufficient to minimize the confidence interval of the results (achieve satisfactory convergence).

Thus 10,000 breaches have been generated using a tool within the naval architectural software package NAPA [17] (*Non zonal analysis*) using the Monte Carlo method. Then the frequencies and damage cases to be calculated were obtained by grouping breaches leading to the same sets of flooded rooms.

3.3 PLL level 1

Using the results from the static analysis, the PLL level 1 has been calculated according to the procedure explained in chapter 2. Next, is a summary of the settings for the PLL calculations:

- Draughts as per deliverable D2.2 [4] and permeability as per deliverable D2.3 [5];
- Non-zonal approach [3];
- 10k breaches generated for each type of damage and for each draught;
- EMSA3 breach distribution used for Side Grounding/contact and Bottom grounding [1];
- SOLAS breach distribution used for collision [2];
- Calculations by software NAPA rel.2020.2 [17];
- SOLAS Sfac (i.e. no differentiation for the area of operation);
- Hazard frequency for Ro-Pax+Cruise (see Table 1)

In Table 4 the PLL level 1 values for each sample ship are reported. It has to be noted that ships 1 to 8 are designs fulfilling SOLAS 2020, while Ship 9 and Ship 10 are existing ships built according to SOLAS'90 requirements (deterministic approach) therefore the SOLAS Attained Subdivision Index is lower than the SOLAS 2020 Required Subdivision Index.

Table 4 PLL level 1 overall results for 10 Cruise/Ro-Pax sample ships

Ship	**Ship 1**	**Ship 2**	**Ship 3**	**Ship 5**	**Ship 6**	**Ship 7**	**Ship 8**	**Ship 9**	**Ship 10**
Type/SOLAS standard	Cruise S2020	Cruise S2020	Cruise S2020	Cruise S2020	Ro-Pax S2020	Ro-Pax S2020	Ro-Pax S2020	Cruise S90	Ro-Pax S90+SA
POB	10000	4940	3750	478	2000	3500	2800	2800	2400
SOLAS 2020 R Index	0.9173	0.8935	0.8835	0.7323	0.8611	0.8811	0.8730	0.8730	0.8675
SOLAS A Index	0.9185	0.9067	0.8938	0.7436	0.8892	0.8948	0.8825	0.7691	0.8142
FLARE A_{CL}	0.9583	0.9508	0.9296	0.8043	0.9178	0.9144	0.8612	0.7781	0.8942
FLARE $A_{GR\text{-}S}$	0.9042	0.9309	0.8744	0.8681	0.9180	0.9768	0.9074	0.8683	0.9412
FLARE $A_{GR\text{-}B}$	0.9298	0.9394	0.9461	0.8978	0.9351	0.9656	0.9082	0.9396	0.9849
FLARE Combined Index	0.9324	0.9410	0.9162	0.8518	0.9228	0.9494	0.8897	0.8536	0.9354
FLARE PLL Level 1 (1/ship year)	**2.340**	**1.0091**	**1.0888**	**0.2454**	**0.5348**	**0.6132**	**1.0698**	**1.4204**	**0.5372**

The FLARE Combined Index has been calculated just for information by using the relative frequency (see Table 1) for each hazard (i.e., collision, side grounding and bottom grounding), with the following formula:

$$FLARE\ Combined\ Index = 0.388\ A_{CL} + 0.328 A_{GR-S} + 0.284 A_{GR-B} \qquad (7)$$

Where,

A_{CL} is the FLARE Attained Index for collision;

$A_{GR\text{-}S}$ is the FLARE Attained Index for side grounding;

$A_{GR\text{-}B}$ is the FLARE Attained Index for bottom grounding.

In Figure 7 such combined index versus the Persons on Board (POB) is reported. In that figure it may be noted that ships with similar number of persons and comparable Attained Subdivision Index, such as ship 7 and ship 8 (Ro-Pax ships both, SOLAS2020 compliant), have very different results when using the FLARE approach for the static analysis. This means that two ships with similar SOLAS Attained Subdivision Index do not have the same flooding risk, in fact ship 7 has a FLARE combined index of about 0.95 while ship 8 has a FLARE combined index that is about 6% lower (for comparison: SOLAS2020 A-Index of ship 8 is 1.3% lower than for ship 7). This highlighted the impact of considering grounding (bottom and side) flooding and demonstrated that current SOLAS leads to deviating risk levels for comparable ships.

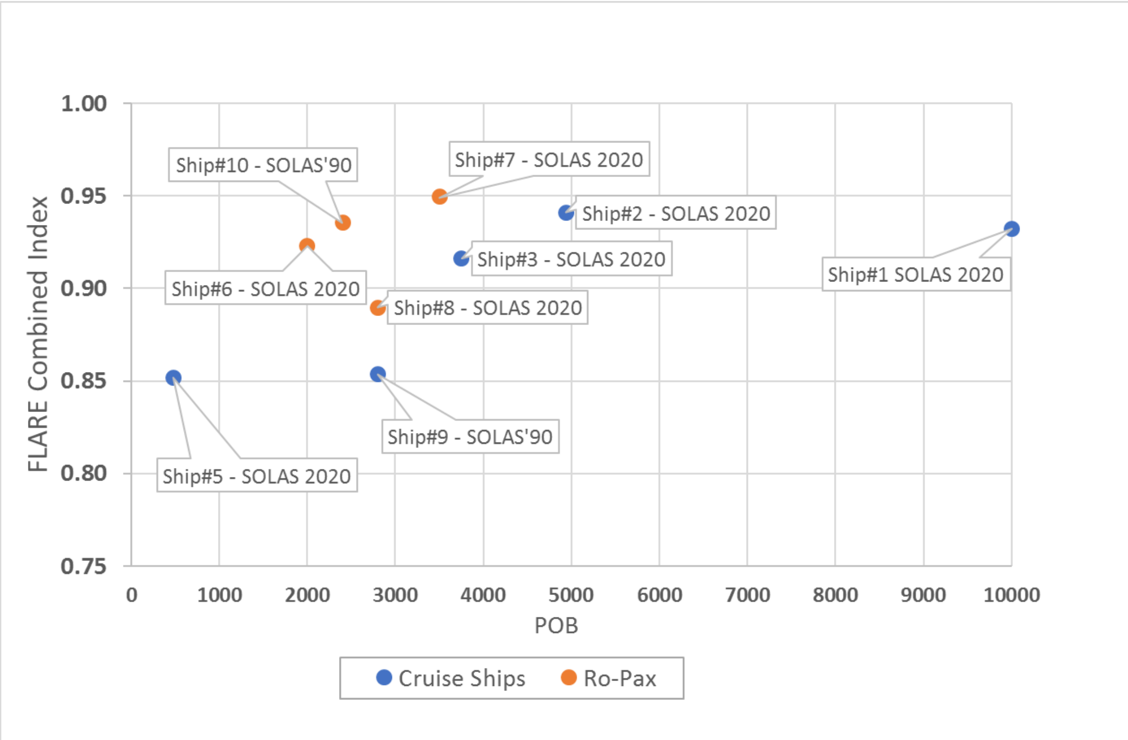

Figure 7 FLARE Combined Damage Stability Index vs POB

This is also showed by Figure 8 and Figure 9 where the PLL level 1 and the FLARE Combined Index are plotted versus the SOLAS Attained Subdivision Index.

Again, the results obtained from the static analysis on the FLARE sample ships showed that there is no correlation between SOLAS A Index and the Risk calculated by FLARE approach, the PLL Level 1 for ship 2 is approx. 1.0 while for ship 1 it is more than doubled (approx. 2.4), nevertheless those ships had a comparable SOLAS Attained Subdivision Index (0.91 vs 0.92).

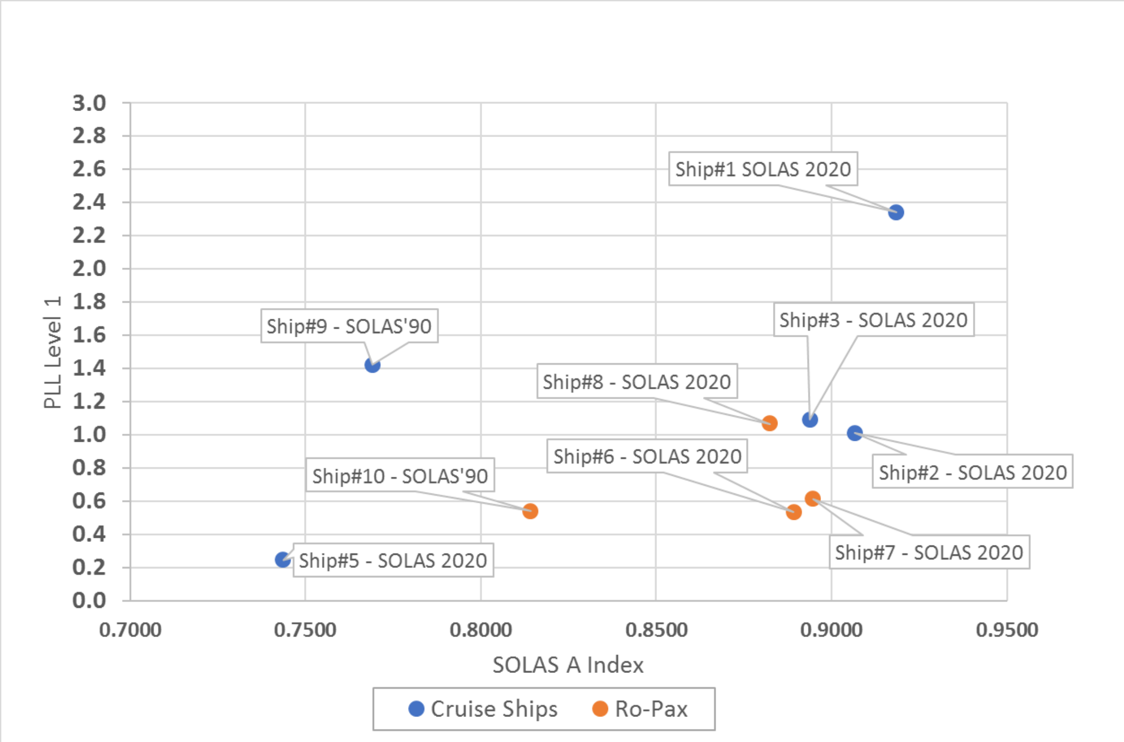

Figure 8 PLL Level 1 vs SOLAS Attained Index

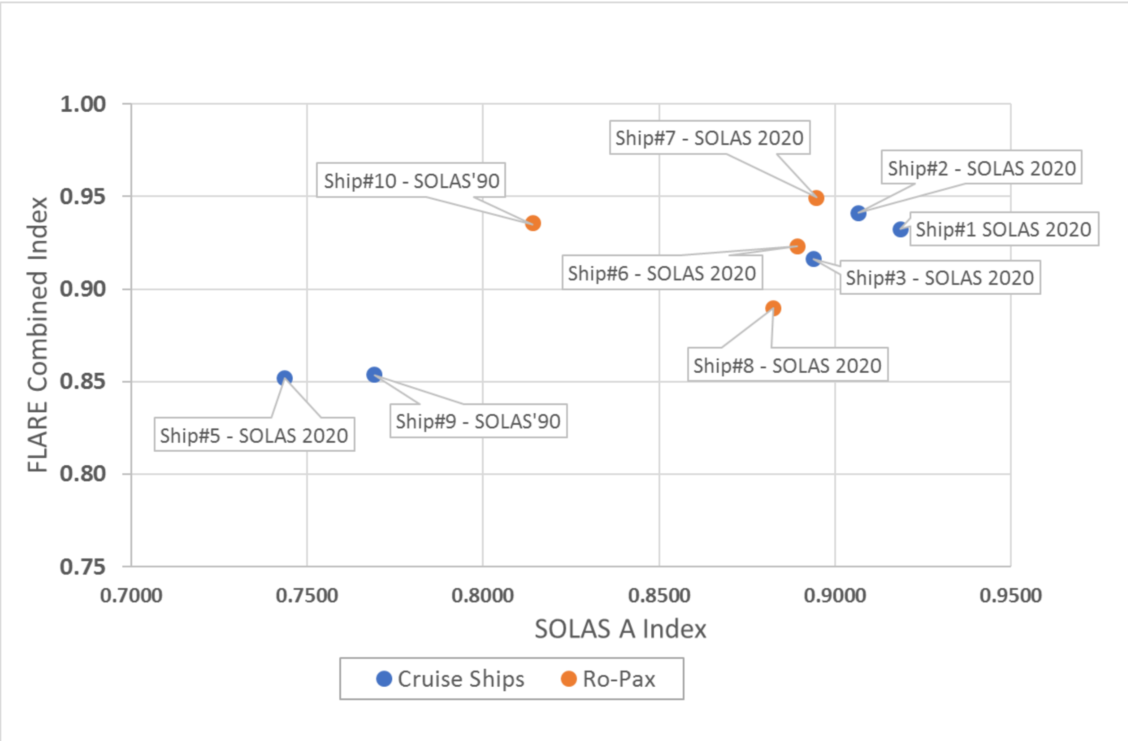

Figure 9 FLARE Combined Index vs SOLAS Attained Index

It could be understood that the differences found in the comparison between SOLAS Attained Subdivision Index and FLARE Combined Index (Figure 9) are due to the inclusion of the grounding in the FLARE framework. This is true but not sufficient to justify the differences found between SOLAS Attained Subdivision Index and FLARE Combined Index. In fact, even isolating the results obtained for collision, we see that there is no clear correlation between FLARE Collision Index and SOLAS Attained Index (see Figure 10). The FLARE collision index, indeed, for ships 6 and 7 is much higher than the value obtained for ship 8.

The same poor correlation was obtained for FLARE Combined Index.

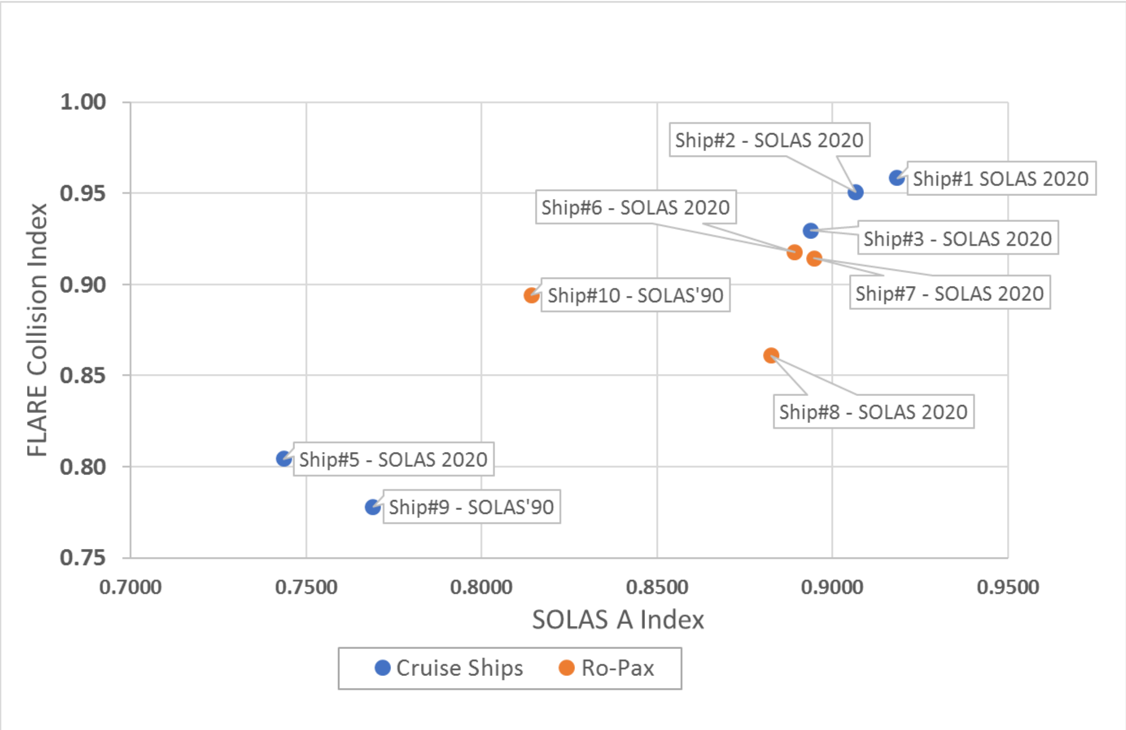

Figure 10 FLARE Collision Index vs SOLAS Attained Index

In the Figure 11 the SOLAS 2020 [9] Required Subdivision Index (R) is plotted as well, and it may be observed that ship 8 and ship 9 are below the required index. This result was expected for ship 9 as it is a SOLAS'90 ship, but it would be not expected for the ship 8 which is designed according to SOLAS 2020. This is caused by the different values introduced by FLARE WP2 for the draughts and the permeability, and by the non-zonal approach which takes into account the lower limit of the breach for the collision as well. These aspects, which are not included into SOLAS, lead to a different result for the collision index.

Therefore, that figure provides additional evidence that the present SOLAS does not provide a holistic approach to evaluate the flooding risk of a vessel.

Figure 11 FLARE Collision Index vs SOLAS Required Index

Furthermore, it may be observed that ship 10 is above the required Index despite being built according to SOLAS'90. This is partly justified by the fact that the ship is compliant with *Stockholm Agreement* [18] and SOLAS 2009 [19] requirements as well.

With the reference to the values obtained for the PLL Level 1 on the sample ships, it can be observed that, despite the number of people on board POB, which is one of the fundamental parameters for calculating the PLL, there is not a strong correlation between PLL level 1 and POB (see Figure 12). It can be observed that there are some ships with a very different PLL despite a similar POB (e.g. Ship 6 vs Ship 8). This is due to different grounding performance essentially.

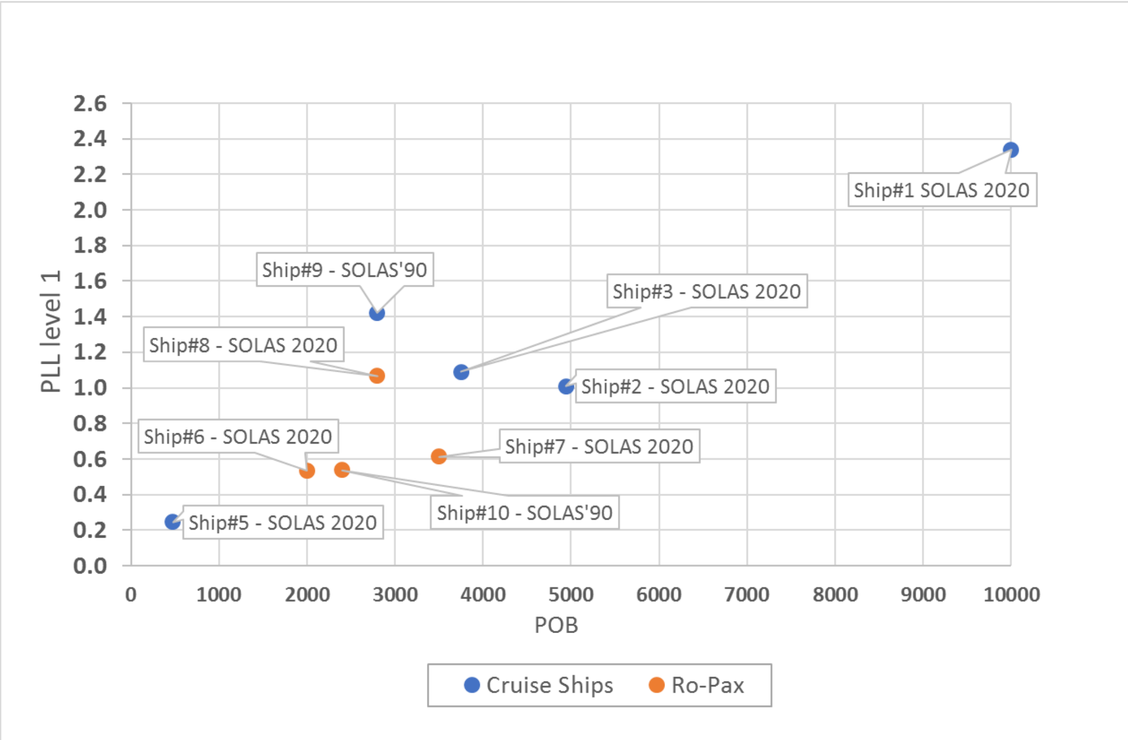

Figure 12 PLL Level 1 vs POB

That outcome is confirmed when normalizing the PLL Level 1 by POB also (see Figure 13).

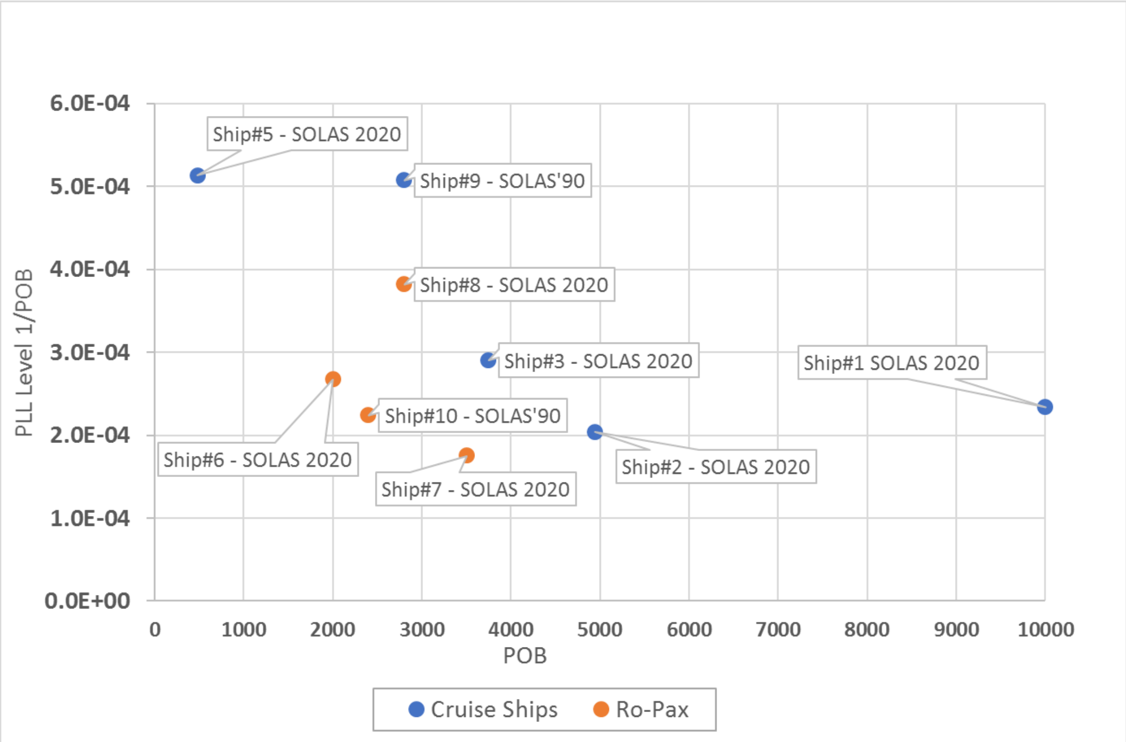

Figure 13 Normalized PLL vs POB

3.4 Filtering breaches for dynamic analysis

Before filtering breaches for the dynamic simulation, some tests have been carried out on Ship 5 to verify that the SOLAS Sfac is a trustable parameter to filter breaches with capsize potential. For that purpose, 3000 collision breaches have been generated, corresponding to 1478 unique damage cases in the static analysis. Those 1478 cases have been simulated for 30 min (assuming a seaway with significant wave height of 4 m). From the simulations result it has been observed that:

- 1300 cases of 1478 did not resulted into a capsize even if the corresponding SOLAS Sfac was lower than 0.5 for 210 cases;
- 142 cases of 1478 resulted into a transient capsize (TTC ≤ 3 min), the corresponding SOLAS Sfac for these cases was zero (for all of them);
- 36 cases of 1478 resulted into a non-transient capsize (TTC > 3 min), the corresponding SOLAS Sfac for 33 of these cases was zero, the remaining 3 cases had the Sfac between zero and one.

Hence, in general the tests confirmed that static calculations are conservative when determining the capsize probability and the SOLAS Sfac is a trustable parameter to filter breaches with potential capsize.

Considering that the dynamic simulations are very time consuming, there is the need to filter damage cases to perform dynamic simulations only for those cases where survival is not already guaranteed by static calculations. Therefore, static vulnerability screening is needed and applied.

For that purpose, damage cases with s < 1 have been sorted by the product *haz.freq*pfac*(1-s)* in order to filter only damage cases with greater potential for PLL reduction in case of survival after dynamic simulation.

Then, a sensitivity analysis has been carried out in order to select the suitable number of breaches. The results of this sensitivity analysis are summarized in the Figure 14 by a diagram showing the potential delta PLL over delta number of breaches versus the number of breaches to be simulated and for each ship.

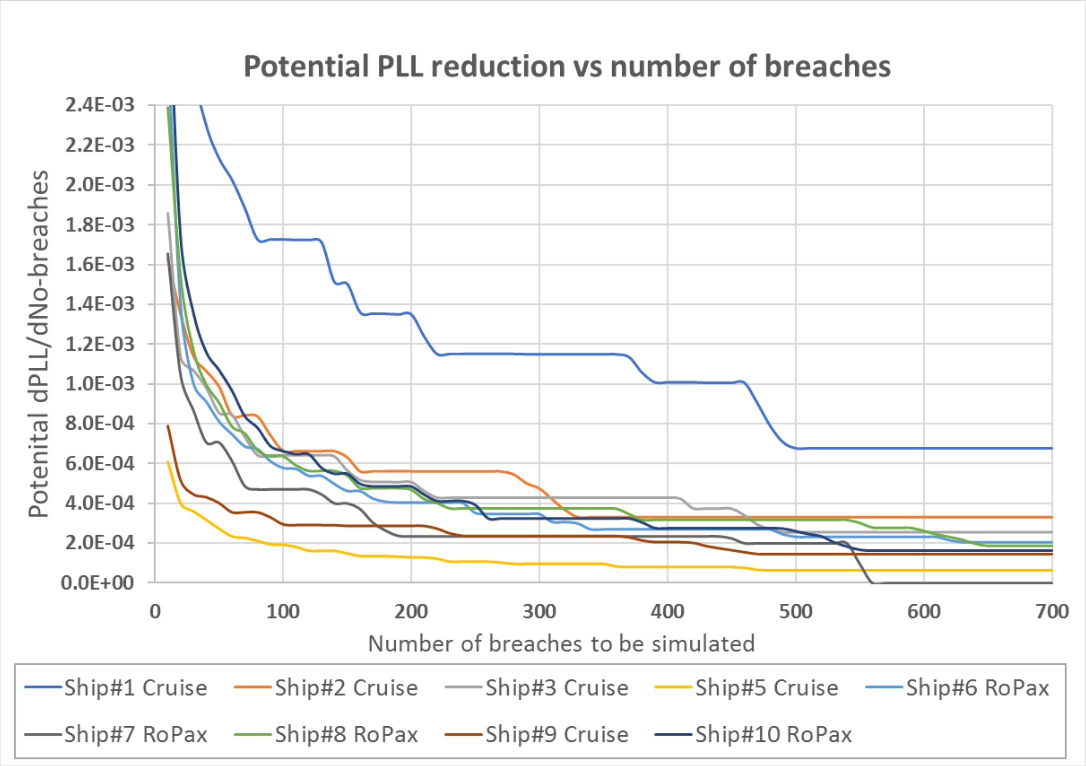

Figure 14 Potential PLL reduction versus Number of breaches to be simulated (FLARE sample ships)

In the Figure 15 the potential increase of FLARE Combined Index over delta number of breaches versus the number of breaches to be simulated has been plotted for each ship. These diagrams both (Figure 14 and Figure 15) are generated by assuming that the selected breaches are going to survive in the flooding simulations.

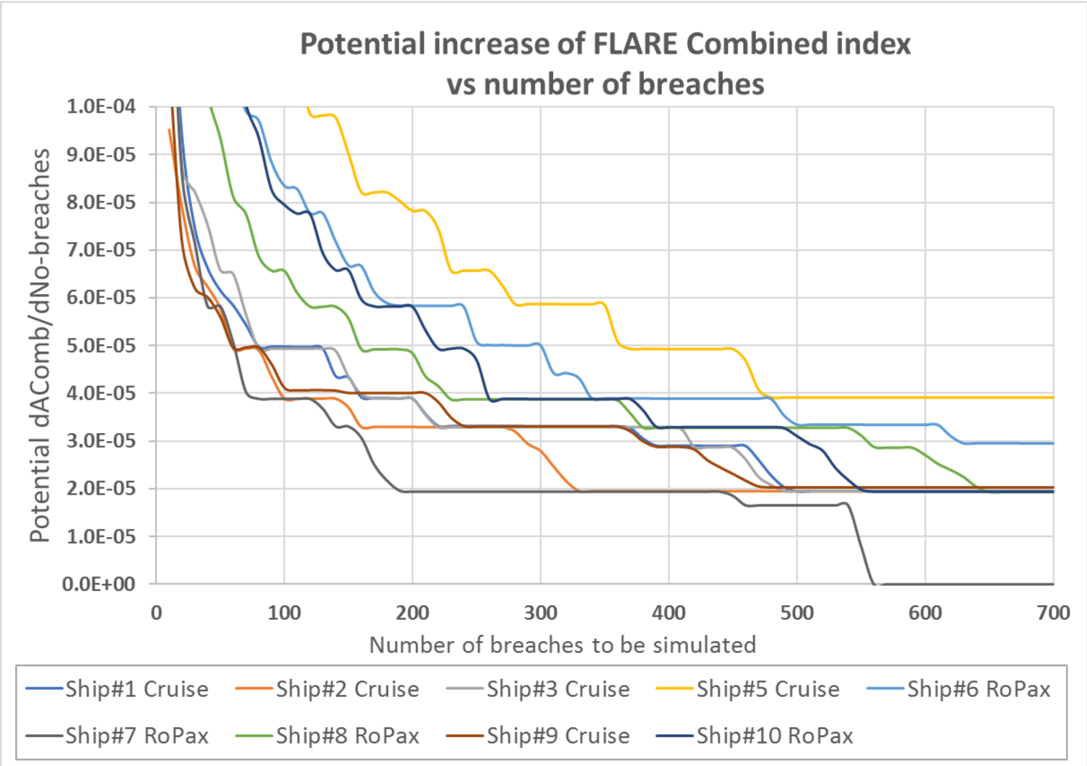

Figure 15 Potential increase of the FLARE Combined Index versus Number of breaches to be simulated

The intention of these diagrams is to see where the risk reduction by simulating breaches starts to marginalize. In both diagrams (Figure 14 and Figure 15) a step down is observed in correspondence of approx. 500 breaches. Furthermore Figure 14 shows that, for eight ships over nine, selecting more than 500 breaches the potential contribution to PLL reduction by each breach would be less than 4E-4, this means that the breaches corresponding to the right side of the diagram are characterized by a low Pfac because of a very long extension, it is therefore foreseeable that such cases would result in the sinking/capsize of the ship also in the dynamic simulation and hence no reduction of the PLL consequently. Based on the above considerations, it has been decided to simulate 500 breaches for the Level 2.

In the method presented above all the breaches have been collected in one data set and the selection of cases is driven by the most effective improvement of the overall PLL. This approach ignores the different character of scenarios due to different hazards, which may result into a design, where scenarios of a certain hazard, e.g. bottom grounding, are not considered due to the fact, that more collision or side grounding cases may contribute to PLL in a higher degree. Although this approach is very efficient some measures have to be taken to ensure that all hazards are considered properly according to accident statistics and to ensure that whilst the risk may be higher for a given hazard the risk control option might be more cost-effective for the hazard filtered out based on the risk value alone. In particular it is possible to filter breaches, separating them by hazard or to define separate PLL requirements for the three hazards; collision, bottom grounding and side contact/grounding.

The applied approach permits to filter damage cases from static results, but for a dynamic simulation a breach corresponding to each case is needed. It is obvious that there may be more than one breach leading to the same extent of flooded spaces in a damage case and it could result in a different outcome when dynamic simulations are executed. Anyway, in this process the objective of the dynamic simulations is not to simulate all possible breaches but just to evaluate the outcome of dynamic simulation for those cases, which show a failure based on the static analysis (Sfac < 1). Therefore, the corresponding breach with the maximum area of damage has been selected for each case, which is assumed to reflect a conservative approach and combining several breaches into one.

3.5 Preparation of the dynamic simulation model

The ship flooding process needs to be analysed also by means of dynamic simulation tools. Proteus® software [12] has been used to simulate ship flooding in regular waves and irregular seaways. For such purpose, the preparation of the simulation model has been done by using the Proteus Manager [12].

All the process to prepare the simulation model with Proteus Manager is described in Annex 2, with the basic assumptions for dynamic flooding simulations being:

- Time to open the breach: 20 sec
- Simulation time (first run): 30 min
- Simulation time (second run): not less than 80 min for cruise ships with more than 3 MVZ and 60 min for smaller cruise and Ro-Pax (see MSC.1/Circ. 1533 [10]).
- Recommended number of runs per case: 5 but for the FLARE project, where the intention is not to calculate the PLL with high precision but just demonstrate the process, one run is considered sufficient. In fact, some tests executed on the small cruise demonstrated that the simulations results are stable enough as the roll angle limit has not been included in the survival criteria (see Figure 16 and Figure 17).

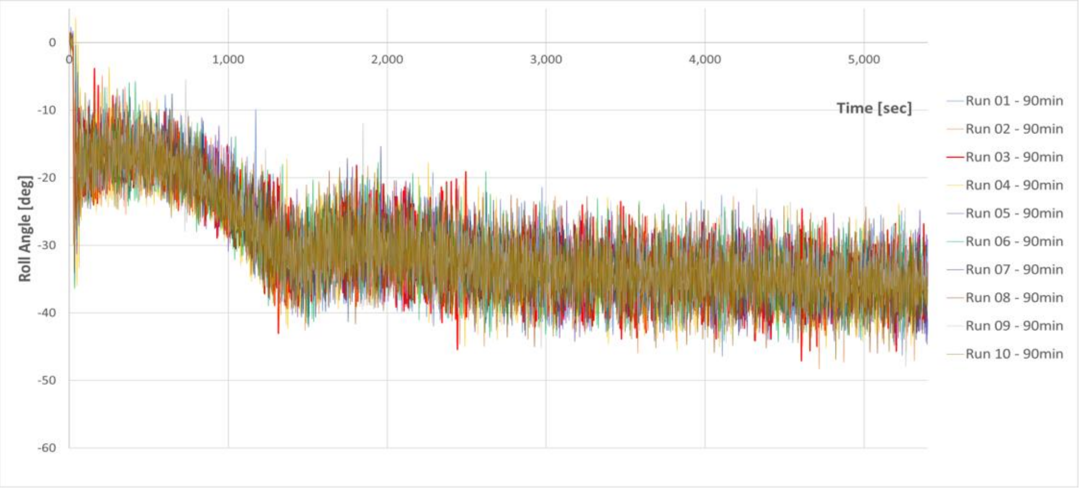

Figure 16 Result of multi-run test for a flooding scenario of the small cruise (ship#5) – Roll angle

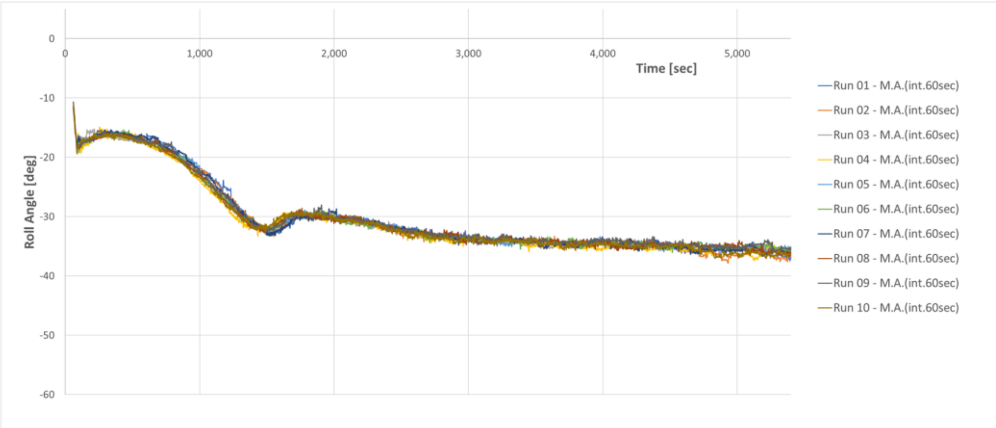

Figure 17 Result of multi-run test for a flooding scenario of the small cruise (ship#5) – Moving average of the roll angle calculated with an interval of 60 seconds.

3.6 Capsize probability and Time to capsize

The capsize probability and the time to capsize (TTC) are obtained as main results of the flooding simulations.

When more than one run is executed, the capsize probability of the case may be calculated with the following formula:

$$Capsize\_probability = Nc/Nr \quad (8)$$

Where

Nr is the total number of runs

Nc is the number of runs where one survival criterion, at least, is not satisfied.

From each run TTC may be defined as the lowest time at which one or more survival criteria fail. If the progressive flooding criteria (annex 2, Ch.3.1) is not satisfied after the second simulation run, TTC is to be assumed equivalent to the simulation time.

Then for each case the time to capsize (TTC) may be calculated as the average of TTC_i for all non-survival cases:

$$TTC = \sum_{i=1}^{Nc} TTC_i \ /Nc \quad (9)$$

Since for the purpose of this work package only one run per case has been executed for the FLARE sample ships, the capsize probability is:

- 0, when the ship is found to survive at the end of simulation or

- 1, when at least one survival criterion fails; in that case the TTC is directly obtained from the first criterion, which has been found to fail earliest.

In Figure 18, Figure 19 and Figure 20 the global results for collision, side grounding and bottom grounding respectively are reported for the simulations executed on the filtered breaches of the sample ships.

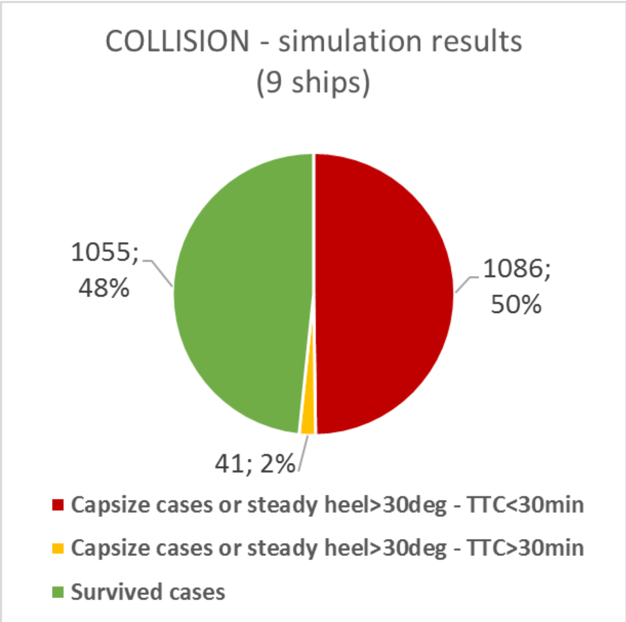

Figure 18 – Collision simulation results for the filtered breaches (nine sample ships)

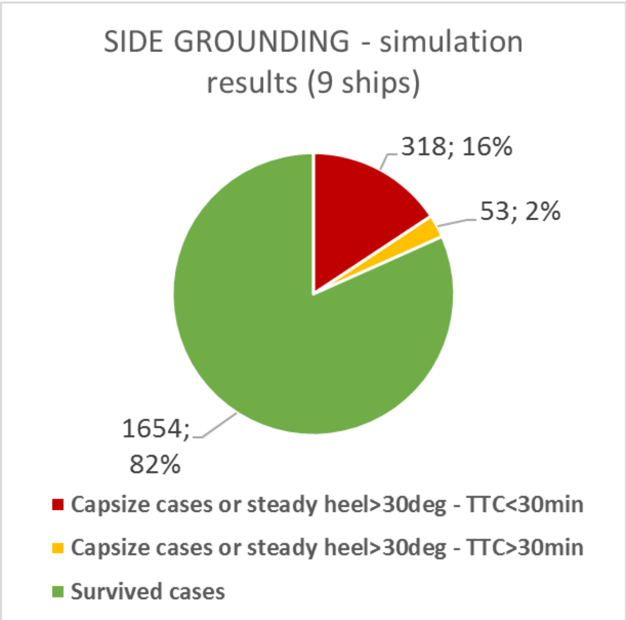

Figure 19 – Side Grounding simulation results for the filtered breaches (nine sample ships)

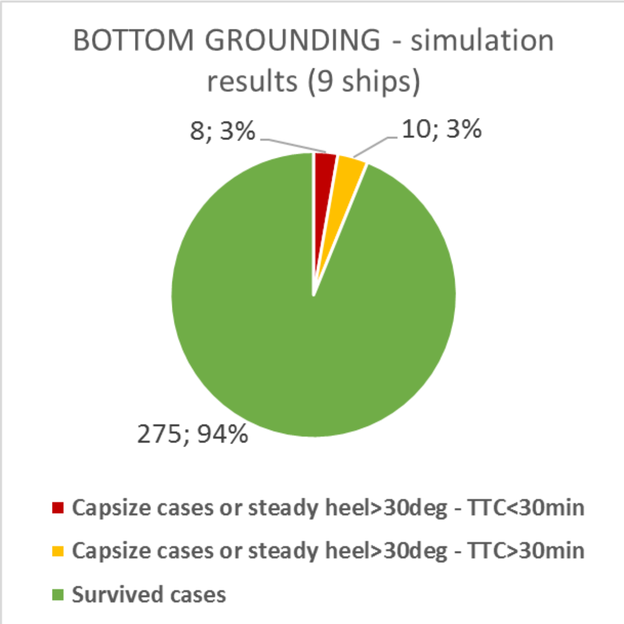

Figure 20 – Bottom grounding simulation results for the filtered breaches (nine sample ships)

It may be observed that for the side and bottom grounding a great majority of the simulated cases did not result into a capsize while for collision the 50% of the simulated cases resulted into a capsize. Furthermore, in Figure 21 the global results of the simulations, including the three hazards, have been shown. From that diagram it is evident that the cases resulted into a slow capsize (TTC > 30 min) are few, 2% only. This implies that the evacuation analysis would have a negligible impact on the PLL as it would affect just this very limited number of cases.

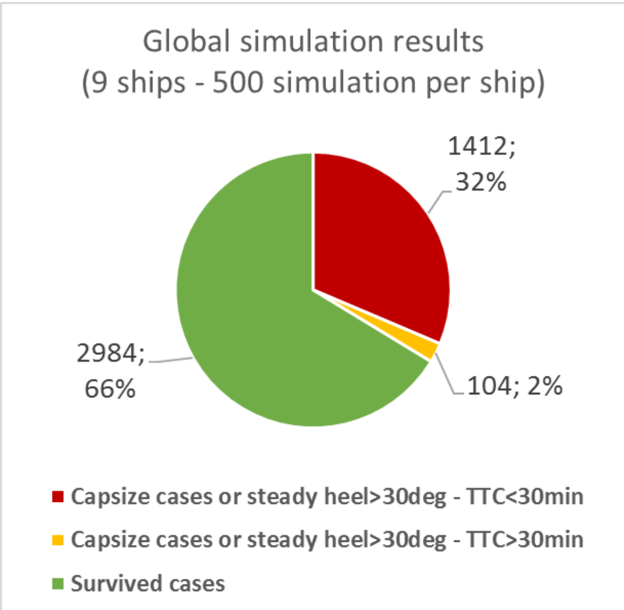

Figure 21 – Global simulation results for the filtered breaches (9 sample ships)

Furthermore, Figure 22 shows that the fast/slow rate of the capsize cases, found by the flooding simulation on the sample ships, is very far from the percentages assumed in the EMSA3 risk model [16] for which only 18% fast capsize rate on cruise ships and 50% on Ro-Pax ships was assumed.

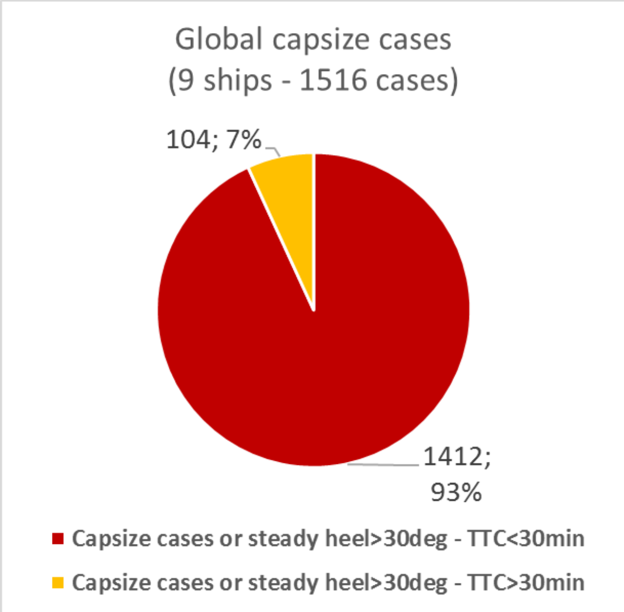

Figure 22 –Capsize cases found by the flooding simulations on the sample ships

3.7 PLL level 2.1

The simplified fatality rate may be estimated with the formula described in Ch. 2.5 (equation 5). In Figure 23 a diagram of the fatality rate, expressed as percentage of the POB, versus the TTC is reported for the Ro-Pax or small cruise ships and medium/large cruise ships.

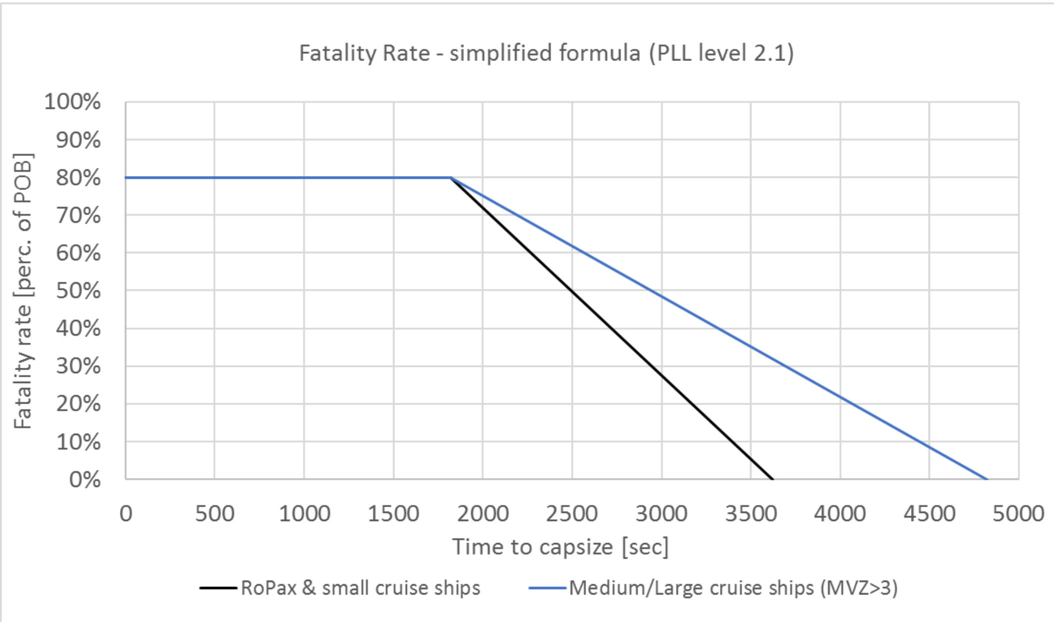

Figure 23 – Simplified formula for the fatality rate and impact of ship's size

The capsize probability and fatality rate calculated by the flooding simulations permit now to obtain the PLL level 2.1 for the sample ships.

Table 5 PLL level 2.1 overall results

Ship	**Ship 1**	**Ship 2**	**Ship 3**	**Ship 5**	**Ship 6**	**Ship 7**	**Ship 8**	**Ship 9**	**Ship 10**
Type/SOLAS standard	Cruise S2020	Cruise S2020	Cruise S2020	Cruise S2020	Ro-Pax S2020	Ro-Pax S2020	Ro-Pax S2020	Cruise S90	Ro-Pax S90+SA
POB	10000	4940	3750	478	2000	3500	2800	2800	2400
FLARE PLL Level 1 (1/ship year)	2.340	1.0091	1.0888	0.2454	0.5348	0.6132	1.0698	1.4204	0.5372
FLARE PLL Level 2.1 (1/ship year)	**1.773**	**0.7840**	**0.8334**	**0.1955**	**0.3649**	**0.6154**	**0.9313**	**1.2542**	**0.4677**
Difference	**-0.5670**	**-0.2251**	**-0.2554**	**-0.0499**	**-0.1699**	**+0.0022**	**-0.1385**	**-0.1662**	**-0.0695**
PLL L2.1 vs L1 (variation percentage)	**-24.2%**	**-22.3%**	**-23.5%**	**-20.3%**	**-31.8%**	**+0.4%**	**-12.9%**	**-11.7%**	**-12.9%**

It may be observed that the dynamic analysis for Ship 7 did not produce any benefit for the PLL as the large majority of the simulations resulted into a sink/capsize of the ship. For the other sample ships designed according the SOLAS2020 requirements the reduction of the PLL obtained by the flooding simulations is about 20% or higher, while for the two existing ships (ship 9 and ship 10), built according to SOLAS'90 the reduction of the PLL is approximately 12%. In general this is due to the fact that SOLAS'90 ships have a lower GM (For ship 9 the GM at T0.45 is approx. 2 m while for Ship 3 it is approx. 2.8 m) therefore the flooding simulations result in higher number of capsize cases.

The values of the PLL Level 2.1 of the sample ships and the comparison between Level 1 and Level 2.1 are shown in the Figure 24 and Figure 25 respectively.

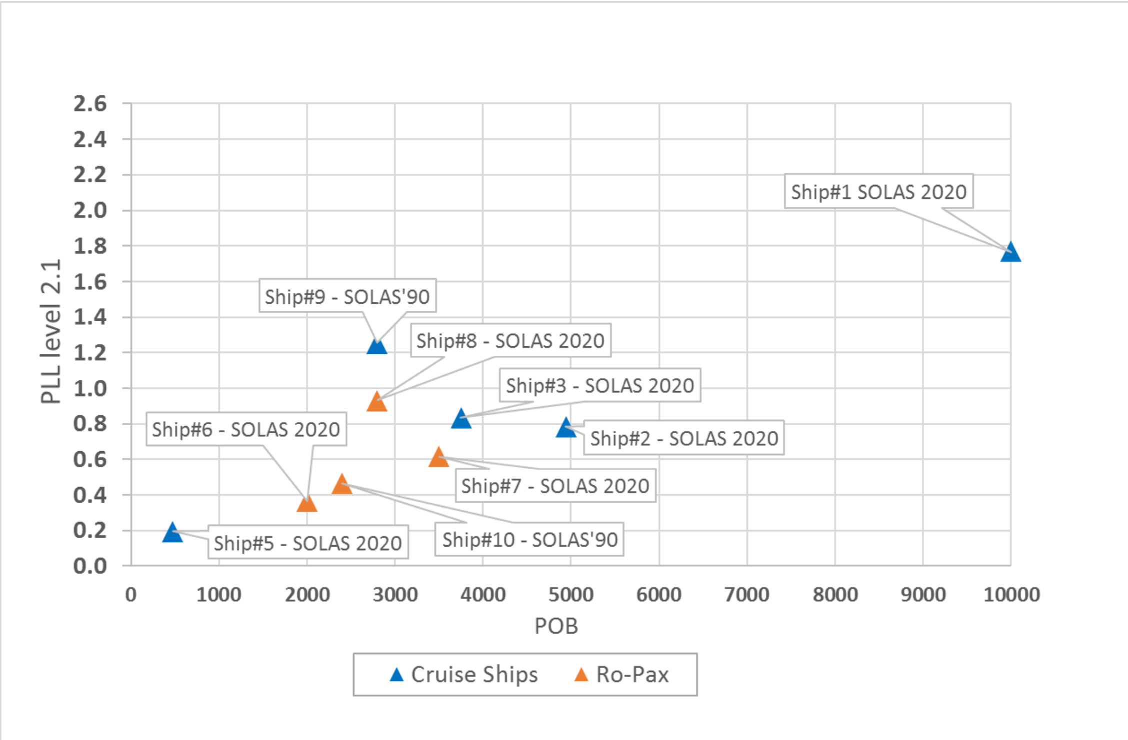

Figure 24 PLL Level 2.1 vs POB

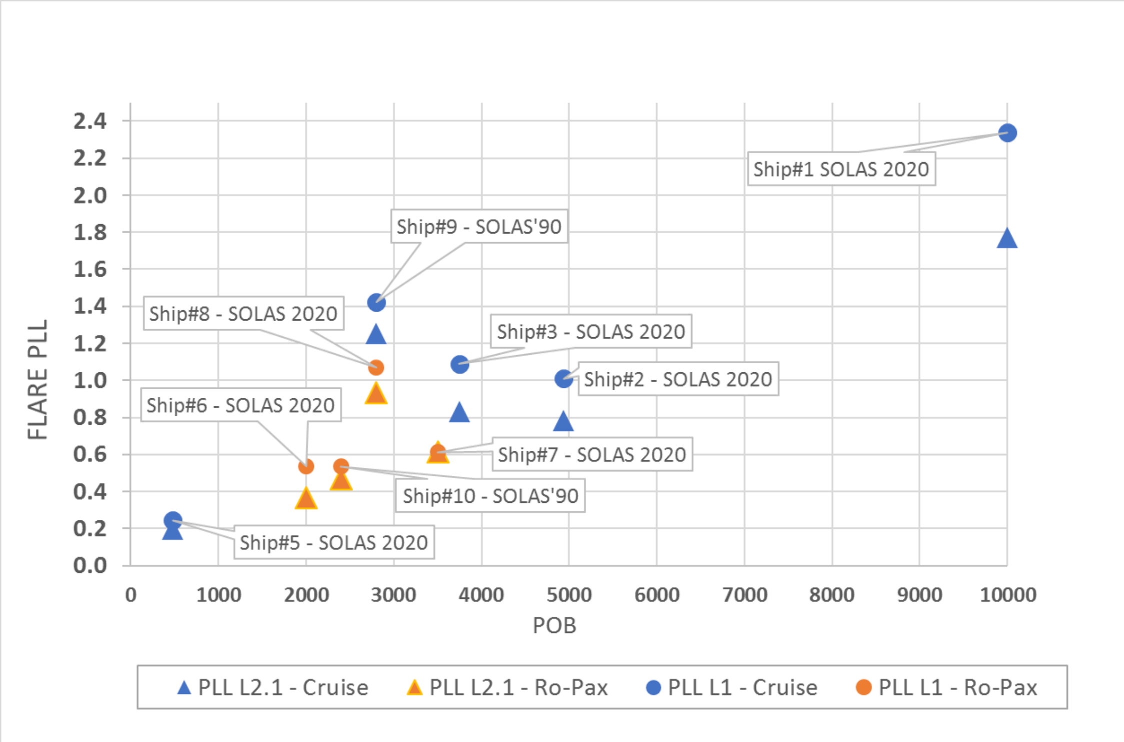

Figure 25 Comparison between PLL Level 1 and Level 2.1

It may be observed that the results of PLL Level 2.1, obtained through the flooding simulation, confirm that there is no strict correlation between the persons on board (POB) and the PLL of the sample ships.

3.8 Sensitivity analysis on the simplified fatality rate

The simplified formula for the fatality rate used in the calculation of the PLL level 2.1 could generate some doubt on the reliability of the PLL values obtained; therefore, a sensitivity analysis has been carried out for each sample ship. Hence a fatality rate deviation of ± 30% of the POB (for the transition between 80% and 0%) has been examined and the impact on the PLL has been calculated.

In the Figure 26 and Figure 27 the deviations of the fatality rate assumed in the sensitivity analysis are shown for Ro-Pax or small cruise ships (with maximum three main fire vertical zones) and for medium/large cruise ships (with more than three main fire vertical zones) respectively.

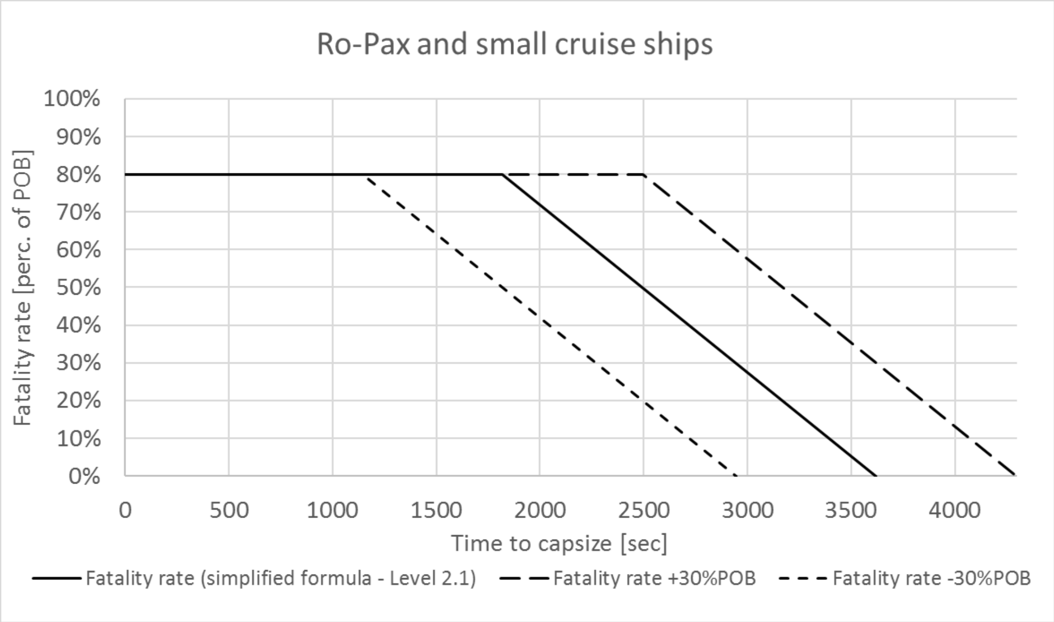

Figure 26 Sensitivity analysis of the fatality for Ro-Pax and small cruise ship

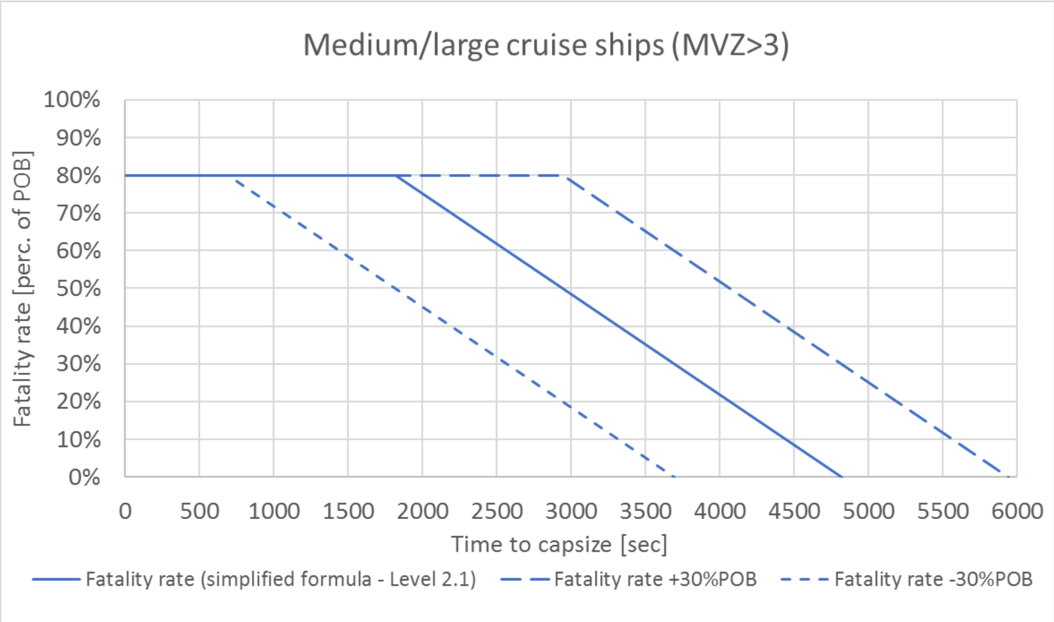

Figure 27 Sensitivity analysis of the fatality for medium/large cruise ship

The results of the sensitivity analysis on the simplified fatality rate are reported in the Table 6. In the last two lines the impact of the PLL is shown and it can be concluded that the PLL calculated with the approach described in Level 2.1 is reliable as the deviation expected for the PLL is not more than 1% even with a deviation of the fatality rate by 30% of the POB.

Table 6 Results of the sensitivity analysis on the simplified fatality rate

Ship	**Ship 1**	**Ship 2**	**Ship 3**	**Ship 5**	**Ship 6**	**Ship 7**	**Ship 8**	**Ship 9**	**Ship 10**
Type/SOLAS standard	Cruise S2020	Cruise S2020	Cruise S2020	Cruise S2020	Ro-Pax S2020	Ro-Pax S2020	Ro-Pax S2020	Cruise S90	Ro-Pax S90+SA
POB	10000	4940	3750	478	2000	3500	2800	2800	2400
FLARE PLL Level 2.1 (1/ship year)	1.7730	0.7840	0.8334	0.1955	0.3649	0.6154	0.9313	1.2542	0.4677
PLL L2.1 with fatality rate +30%POB	1.7950	0.7841	0.8390	0.1976	0.3651	0.6190	0.9379	1.2636	0.4690
PLL L2.1 with fatality rate -30%POB	1.7482	0.7839	0.8332	0.1945	0.3647	0.6151	0.9313	1.2532	0.4677
Impact on PLL (percentage) with fatality rate +30%POB	1.23%	0.01%	0.67%	1.06%	0.05%	0.58%	0.70%	0.74%	0.28%
Impact on PLL (percentage) with fatality rate -30%POB	-1.40%	-0.01%	-0.02%	-0.51%	-0.05%	-0.05%	0.00%	-0.08%	0.00%

3.9 Evacuation analysis

With the results obtained from the sensitivity analysis of the simplified fatality rate it is evident that an evacuation analysis, for the calculation of the fatality rate with more precision, is not needed for the FLARE sample ships, as its impact on the PLL would be negligible. Furthermore, the preparation of an evacuation model and the execution of the advanced evacuation analysis is a very time-consuming activity; therefore, it should be executed only when the expected impact on the PLL is relevant for the analysis.

However, in order to demonstrate the FLARE procedure, such analysis has been conducted for one cruise ship (ship 5) and one Ro-Pax Ship (ship 10).

The description of the process to prepare the model for the evacuation analysis will be not part of this deliverable as it is based on the normal procedure followed for the evacuation analysis executed by each yard.

For the selected two ships the EVI® software has been used, but the AENEAS® tool may be also used for that purpose.

In general, the model preparation and the simulations are based on the prescriptions of the MSC.1/Circ.1533 [10]. The general approach for the fatality rate calculation is described in the Ch. 2.5 and the specific settings are reported in the annex 6 (ship 5) and annex 11 (ship 10).

From the results obtained on the two selected ships it can be concluded that the simplified approach for the fatality rate calculated as a linear function of the TTC (Level 2.1) is conservative (leads to higher fatality rates than obtained by evacuation analysis).

In Figure 28 the comparison of the fatality rates obtained from the numerical simulations and the values calculated with the simplified formula is reported for Ship #5 and Ship #10.

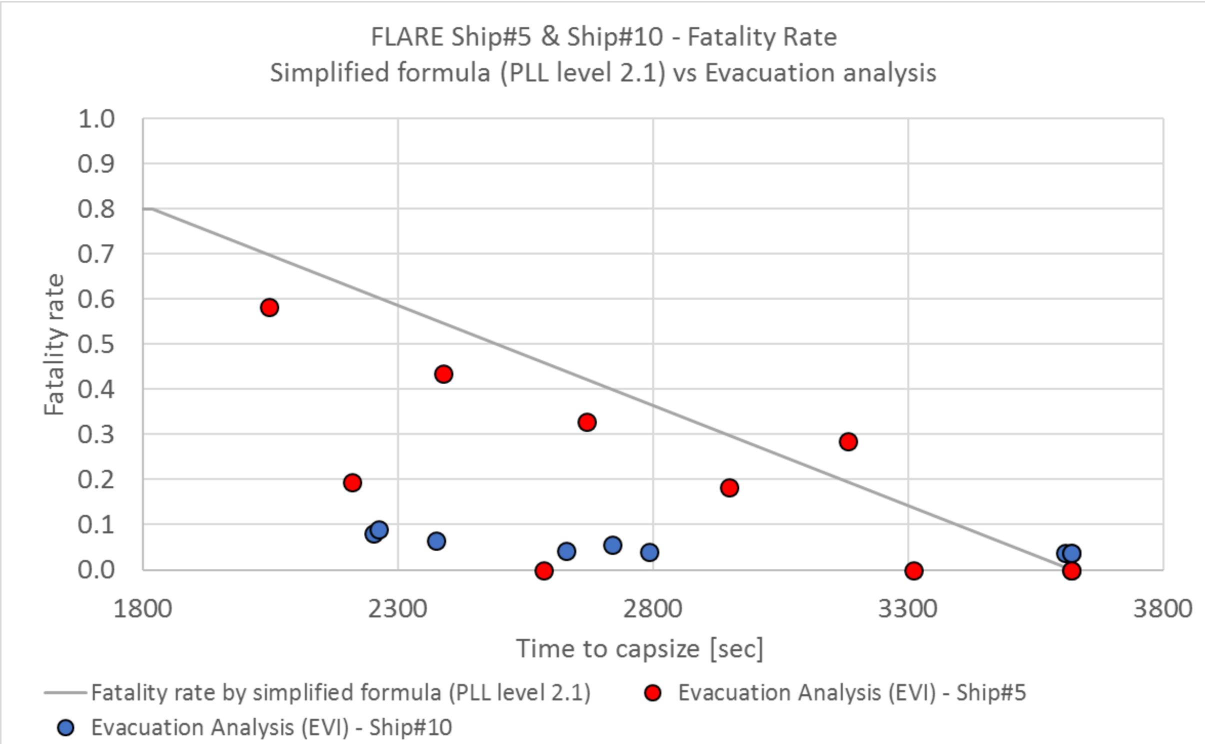

Figure 28 Comparison of evacuation analysis vs simplified formula – Ship #5

4. CONCLUSIONS

- The procedure for PLL calculation described in Ch.2 has been applied to nine FLARE sample ships and the results demonstrated that the procedure is coherent with the two-level approach.
- The PLL Level 1 seems conservative, but it appears more realistic than PLL calculated by EMSA3 Risk Model, as the fast/slow sinking node has not been used here.
- Dynamic analysis in level 2.1 showed that the PLL could be reduced by more than 20%, for the majority of sample ships designed according to SOLAS 2020, with the simulation of 500 breaches.
- For the SOLAS'90 ships, a lower reduction (approx. 12%) of the PLL has been obtained by the dynamic analysis. In general this is due to the fact that SOLAS'90 ships have a lower GM therefore the flooding simulations result in higher number of capsize cases.
- The results of dynamic simulations showed that most of the cases (approximately 66%) selected from the static cases, showed survival while the static results showed non-survival.
- A large majority of the cases, which are not survived in dynamic simulations, showed to sink/capsize within 30 minutes (approximately 93% of the non-surviving cases). This implies that an orderly evacuation is not feasible and confirms that the assumptions in the EMSA3 risk model made regarding the probability of sink/capsize are not realistic.
- The process to calculate the PLL level 2 has shown to be mature; however, it is not user friendly as only some rudimentary tools have been applied (i.e. Microsoft Excel macros) for the time being. It is expected that the whole process will be more user-friendly, when the FLARE framework software will be delivered to the end users.
- For demonstration purposes an evacuation analysis (Level 2.2) has been carried out on two ships and it is confirmed that the simplified fatality rate (Level 2.1) is conservative
- With the aim to check the reliability of the employed simplified formula for the fatality rate in the calculation of the PLL level 2.1, a sensitivity analysis has been carried out. The results obtained demonstrated that the impact on the PLL is negligible, even by large deviation of the fatality rate. The use of the simplified formula (PLL Level 2.1) is more cost-effective than the advanced evacuation analysis (PLL Level 2.2) because of the preparation of the evacuation model that requires high resources.

5. REFERENCES

[1] George Zaraphonitis et al., EMSA/OP/10/2013 – *Evaluation of risk raking damages due to grounding*, Final report - 2015

[2] Henning Luhmann et al., eSAFE - A joint industry project on Damage Stability for Cruise Ships - *Executive Summary*, Oslo 2018

[3] Gabriele Bulian et al., *Considering collision, bottom grounding and side grounding/contact in a common non-zonal framework*, Proceedings of the 17th International Ship Stability Workshop, Helsinki 2019

[4] Donald Paterson et al. - *Database of operational data and statistical analysis*, D2.2 FLARE Deliverable, October 2019

[5] Henning Luhmann et al. - *Analysis of Permeabilities*, D2.3 FLARE Deliverable, November 2019

[6] Donald Paterson et al. - *First Description of Framework for life-cycle flooding risk*, D5.1.1 FLARE Deliverable, May 2020

[7] Sotiris Skoupas et al. - *Report outlining the vulnerability process and results for the two test ships and a comparative assessment between static and dynamic vulnerability*, D5.7 FLARE Deliverable, February 2021

[8] Dracos Vassalos, Mujeeb Ahmed M.P. – *Flooding Risk Model*, D5.14FLARE Deliverable, 2021

[9] IMO, 2020. International Convention for the Safety of Life at Sea - *SOLAS. Consolidated edition as of 2020*.

[10] IMO, 2016, MSC.1/Circ.1533 - *Revised guidelines on evacuation analysis for new and existing passenger ships*, June 2016

[11] IMO, 2017 Resolution MSC.429(98) - *Revised explanatory notes to the SOLAS chapter II-1 subdivision damage stability regulations*

[12] Safety-At-Sea, 2021 *Proteus Manager* - beta version for research purpose released on 13th October 2021

[13] Henning Luhmann et al. - *Sample Ships - Overview*, D2.1 FLARE Deliverable, October 2019

[14] Rainer Hamann et al. - *Revised event tree and recommendations for improvements*, D2.5 FLARE Deliverable, November 2019

[15] Mujeeb Ahmed Mughadar Palliparambil et al. - *Accident database*, D2.6 FLARE Deliverable, November 2020

[16] Dimitris Konovessis et al., EMSA/OP/10/2013 – *Risk Acceptance Criteria and Risk Based Damage Stability, Final Report, part 2: Formal Safety Assessment*- June 2015

[17] Napa Ltd, *NAPA Release B30 2020.2 x64/WNT* - December 2020

[18] European Parliament, 2003 - Directive 2003/25/EC on specific stability requirements for ro-ro passenger ships (called "Stockholm Agreement") - April 2003

[19] IMO, 2009 International Convention for the Safety of Life at Sea - *SOLAS. Consolidated edition as of 2009*.

ANNEX 1 – Modelling Guidelines for Ship Flooding Simulations

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

List of symbols and abbreviations

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GT	Gross Tonnage
NAPA	Naval Architectural Package
eSAFE	JIP enhanced Safety after a Flooding event
c_d	discharge coefficient
H_{leak}	Leakage height
H_{coll}	Collapse height

1 EXECUTIVE SUMMARY

This document provides a unified interim guideline how to set up a geometrical model for ship flooding simulations.

As a uniform modelling is essential to achieve comparable results of simulations done by different users it is highly recommended to follow this guideline.

2 INTRODUCTION

The assumptions made during the creation of the model to be used for flooding calculations/simulations may have a significant impact on the results. This document provides the agreed approach for the models which are to be created within the FLARE project.

This document represents the actual state of agreement, with the objective to find a reasonable balance between accuracy expectation, modelling effort, constraints of the simulation tools and the physical representation of the ship. As validation work is still ongoing these guidelines are to be seen as an interim solution only.

During the preparation of the data models of the sample ships and their use for numerical simulations/calculations in dynamic/static analyses, respectively, questions have been identified, for which a common approach has been defined, pertaining to the following topics:

- General geometry and arrangement
- Hull forms
- Common parameters for different door types
- Opening status of doors
- Cabin areas
- Cold room (refrigerated) areas
- Staircases, lifts and other vertical trunks
- U-shaped compartments
- Equipment spaces / compartments containing machinery
- Spaces on decks above the bulkhead deck
- Windows and weather tight doors
- Modelling of (non-watertight)A-class fire boundaries without doors
- Downfloodng arrangements
- Other non-watertight steel structure

3 Guidelines

In general, the model should as close as possible reflect the geometry of the physical ship or the anticipated ship design in question. Hence, simplifications should only be made where a negligible effect on the simulation results is evident or if constrains of the simulation software requires such approach.

3.1 *General geometry*

Preferably the real physical geometry should be modelled, i.e., dividing compartments where steel structures are located, which may influence the flooding process significantly.

In general, the same detailed definition of the model should be used for static index calculations and quasi-static or dynamic time-domain flooding simulations. Usually, the input for static calculations should be provided as being a subset of the more detailed input for dynamic assessments

At all times, the aim should be to maintain the significant layouts, which may impact the flooding scenario.

The following geometry should be modelled:

- Watertight bulkheads and decks
- Tanks
- A-class fire rated bulkheads and decks
- Lifts and staircases
- Main structural HVAC ducts
- Downflooding and horizontal ducts and hatches

Where compartments are to be divided to reflect the flooding process, the division should follow the location and arrangement of the existing steel structures

As a guidance on how much detailed the model should be, an approximate value of 4 m^2 may be applied to identify those A-class spaces which may be disregarded. However, if smaller spaces, e.g. horizontal or vertical ducts, would impact the flooding, such spaces are worth to be modelled.

3.2 Hull

For the use in numerical simulations the whole weather tight buoyant hull is to be modelled, including the spaces above the watertight subdivision within the boundaries of the weather tight hull.

3.3 *Openings / Doors*

Doors, hatches or portholes which should collapse in a flooding event, as well as other openings, form an essential part of the geometric model.

Typical approach to be followed:

All openings connecting modelled spaces are to be defined with their correct location and dimensions. Typical kind of openings are fire screen doors, semi- or light watertight doors, AC ducts, open hatches in decks, end of partial bulkheads, or virtual free openings to reflect the connection of open spaces.

For different types of doors, the characteristics as presented in FLARE WP4 D4.1 Annex G with parameters based solely on the FLOODSTAND results, see Figure 1, are to be used.

Vent pipes from tanks are not to be modelled in general. For forensic analysis of a specific flooding case a more accurate modelling of the vent pipes may be needed if significant counter pressure from locked air is to be expected.

For hinged doors the different parameters for the flooding direction are to be used.

The discharge coefficient is in general to set to c_d=0.6

Table 1 Summary of the FLOODSTAND recommendations for different door types, Jalonen et al. (2017)

Door type	Pressure direction	H_{leak} [m]	$a_{ratio} = \alpha + \beta H_{eff}$		H_{coll} [m]	Note
			α [-]	β [1/m]		
A-class hinged (single leaf)	into	0.0	0.0	0.02	2.5	Doors with a hose port can have larger leakage at lower pressure heads, but for simplicity, the same guideline values can be used.
	out	0.0	0.0	0.03	2.5	
A-class double leaf	out	0.0	0.025	0.0	2.0	Collapsing pressure head based on FE analysis
A-class sliding	into	0.0	0.025	0.0	1.0	
	out	0.0	0.025	0.0	1.0	
Cold room sliding door	into	0.0	0.0	0.03	3.5	Collapsing pressure head based on FE analysis
B-class joiner door	into	0.0	0.0	0.03	1.5	Panels around the door will fail first, thus leakage area is very approximate
	out	0.0	0.03	0.0	1.5	

For pipes and structural ducts, the flooding parameters as described in MSC.362(92) are to be used.

3.4 Opening Status of doors

Recommended approach

All doors (watertight doors, A-class and B-class fire screen doors) are assumed to be closed. If some openings are by purpose normally left open their status should be reflected accordingly.

Typical examples could be fire screen doors in the service corridor or semi-watertight doors on the bulkhead deck.

3.5 Cabin Areas

Although cabins are not watertight, it is essential to agree on a common approach, as cabins may have an effect in delaying the flooding of the whole cabin area on a given deck/MVZ.

Recommended Approach:

- Cabin spaces are to be modelled as blocks (groups of cabins with corresponding collapse height and openings)
- All cabins (regardless of the cabin type) that are only separated by B-class boundaries are to be modelled as one block, unless there is a corridor in between. C-class boundaries (e.g., C-class door of the toilet unit inside the cabin, C-class cabin ceilings, etc.) are to be neglected
- Cabins that are separated by steel structures or corridors are to be modelled as different blocks.
- Each block of cabins is to be modelled with combined openings. The total area of all combined openings of one block is to correspond to the sum of all cabin door areas in this block.
- The corridors that surround the cabins are to be combined to form a large separate compartment, which is reduced by the blocks of cabins in order to minimize the number of modelled rooms.

  The parameters used for a single cabin door are to be defined as basis for dimensioning the combined openings of the relevant cabin blocks

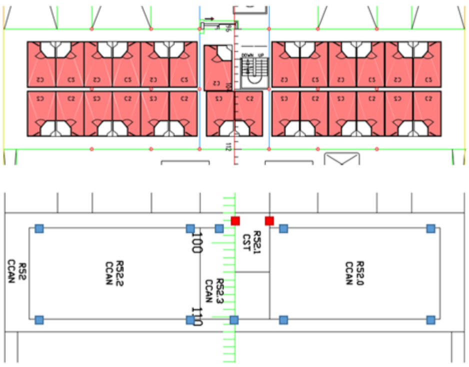


Figure 1 Example of approach for modelling cabin spaces as blocks

3.6 Cold room areas

Recommended Approach:

- Cold rooms (refrigerated spaces) are to be modelled as separate spaces.
- Steel divisions inside cold rooms are to be modelled with free opening(s)

- Main service corridors and staircases in between cold rooms are to be modelled separately considering the A-class boundaries.
- Cold room doors (hinged or sliding) are to be modelled using the FLOODSTAND parameters.
- Cold room boundaries are assumed to be watertight, although the cold room doors have a limited collapse height of 3m.

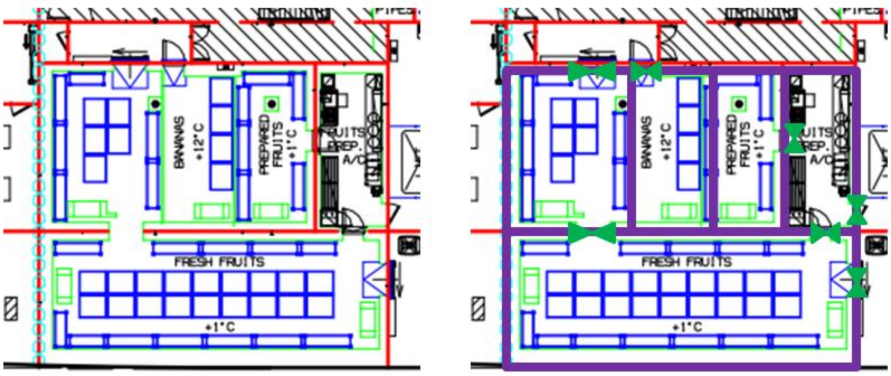


Figure 2 Example of cold room modeling

3.7 Dry stores

Recommended Approach:

- Dry stores are to be modelled as separate spaces as they usually are surrounded by A-class boundaries.
- The doors into such stores are to be modelled as any other fire screen door

3.8 Staircases and lifts

Recommended approach

Staircases and lifts are to be modelled as one space spanning over several decks. Openings are to be defined at each deck level.

3.9 U-shaped compartments

Recommended approach

- U-tanks below the double bottom are to be divided into two parts at the centre line
- U-shaped compartments above double bottom, which contain central tanks are to be divided into 3 parts at the beginning of the duct (ideally, only in way of steel structures).

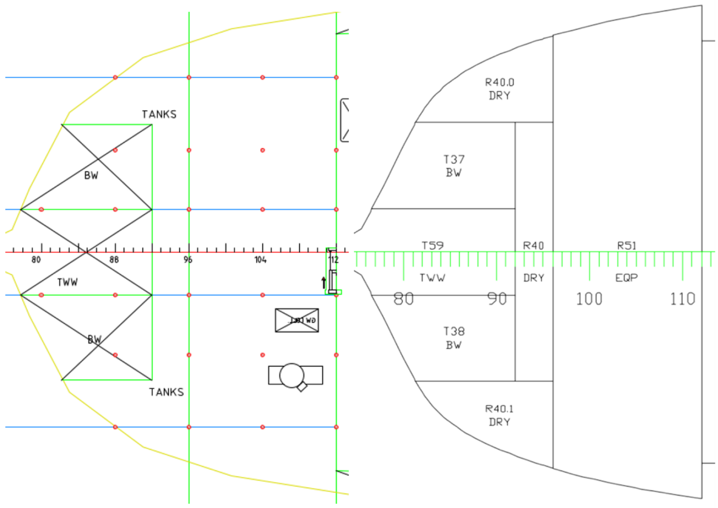


Figure 3 Example of U-shaped voids

Spaces forming a vertical U are to be modelled as two separate spaces connected via a free opening (see below)

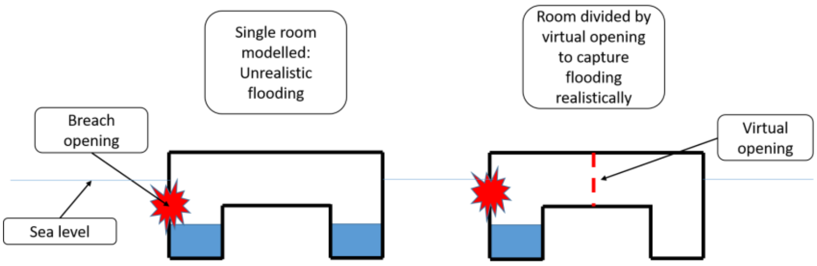


Figure 4 Example of vertical U-shaped spaces

3.10 Equipment spaces / compartments containing machinery

Recommended approach

Such spaces are to be modelled as one space when there are no obvious obstructions preventing free flooding. Perforated decks and bulkheads are to be disregarded in general, based on the user's experience.

3.11 Spaces on decks above the bulkhead deck (partial bulkheads)

Recommended approach

Spaces between partial bulkheads are to be modelled as separate rooms connected via free openings at the end of the bulkhead. In addition, spaces surrounded by A-class boundaries, e.g., staircases, stores or refrigerated rooms are to be modelled. Long corridors are to be split in way of fire doors.

Figure 5 Example for modeling partial bulkheads

Spaces between partial bulkheads should be at least modelled as shown above. Other recommendations for modelling are to be applied as well (e.g. A-class boundaries, fire-doors or cabin blocks) as previously specified

For free openings in way of the corridor a C_D=1.0 is to be applied

3.12 Windows

Recommended approach

Normal windows within the buoyant hull need not to be modelled as they usually sustain water pressure of up to 18m.

If large glass structures or balcony doors are located within the buoyant hull they should be modelled as openings, using the design collapse pressure

3.13 Modelling of A-class boundaries without doors

A-class spaces are usually connected via fire screen doors, which are to be modelled based on an agreed standard.

There might also be situations, where adjacent A-class spaces are not connected by a door, but the A-class boundary is not watertight.

Recommended approach

In this case no openings are to be modelled.

3.14 Other non-watertight steel structure

Structural elements which do not significantly delay the flow of water (e.g. structures perforated by a large number of holes and openings) need not to be modelled.

Recommended approach

It is proposed that these steel structures are not used as a boundary for a flooding space, unless differently considered by the experience of the designer.

3.15 Permeability

The permeability of spaces has a significant impact on the outcome of the flooding event.

SOLAS II-1/7.3 defines default values to be used for permeability. However, the work in FLARE WP2.3 has shown that these values may not be appropriate for passenger ships.

Recommended approach

The following values for permeability are to be used during design stage:

Table 2 Values for Permeability

	SOLAS	New proposal
Engine rooms	0.85	0.90
Stores	0.60	0.90
Accommodation (cabin areas, galleys, offices, workshops etc)	0.95	0.9
Public spaces, crew mess, corridors, stair cases	0.95	0.95
RoRo cargo holds	0.90 – 0.95	0.90 – 0.95
Tanks	0 or 0.95	$Tperm = 0.59 - 0.11 \frac{T - T_{min}}{T_{max} - T_{min}}$
Heeling tanks	0 or 0.95	0.51

For forensic analysis or for the use of dynamic simulations in operation, the actual loading condition and filling of tanks may be used instead

For spaces above the bulkhead deck the same values for permeability are to be used.

4 Acknowledgments

This work has been based on a trustful collaboration of the team of FLARE. Thanks are going to Wiebke Römhild initiating this document and Anna-Lea Routi (MT), Mike Cardinale (FC), Rodolphe Bertin (CdA), Luis Guarin (BB Safety at Sea), Pekka Ruponen (NAPA), Donald Paterson, Francesco Mauro, Dracos Vassalos (MSRC)for the open discussion and the valuable input.

5 REFERENCES

[1] H. Luhmann et.al.: eSAFE guidelines for modelling eSAFE D4.3.1 Annex 2

[2] D. Paterson et.al: FLARE deliverable D5.1.1: "Initial Flare Framework Report and Users Guidelines"

[3] S. Sotiris et.al: FLARE deliverable D5.2.1: "Static Assessment of Ship Vulnerability to Flooding"

[4] L. Guarin et.al: FLARE deliverable D5.2.2: "Dynamic Assessment of Ship Vulnerability to Flooding"

[5] FLARE WP4 D4.1 Annex G

ANNEX 2 – Preparation and running dynamic simulations

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

1 INTRODUCTION

FLARE is the first project where all the yards participating in the project have used the flooding simulations in waves to assess stability. When new tools are used it is essential that guidelines is provided to guide the end users in the preparation of the model, tool setting, running the simulation and getting the results.

The intention of this annex is to collect the actions taken for the execution of the dynamic simulations with software PROTEUS [1] step by step on each ship.

2 PROTEUS MODEL PREPARATION

2.1 Importing geometry

To create a Proteus Project the refined NAPA [3] database has been used. The software needed some definitions, such as:

- HULL
- DAMHULL (watertight/weathertight hull used for static calculation)
- FORCES_HULL simplified hull (without positive and negative appendages) needed for forces calculations within Proteus
- Arrangement
- Loading conditions
- Setup

After all the definitions were provided to Proteus via the User Interface, the Proteus manager generated a NAPA macro to be run in the NAPA database. This method guarantees the correct data export from NAPA Database to a new Proteus project.

In order to define the correct value of permeability, two arrangements were created, one for each draft value. To each of them corresponds a different loading condition, based on a different lightship value. Doing so, the correct values of permeability are related to the non-dimensional calculation drafts T0.45 and T0.75.

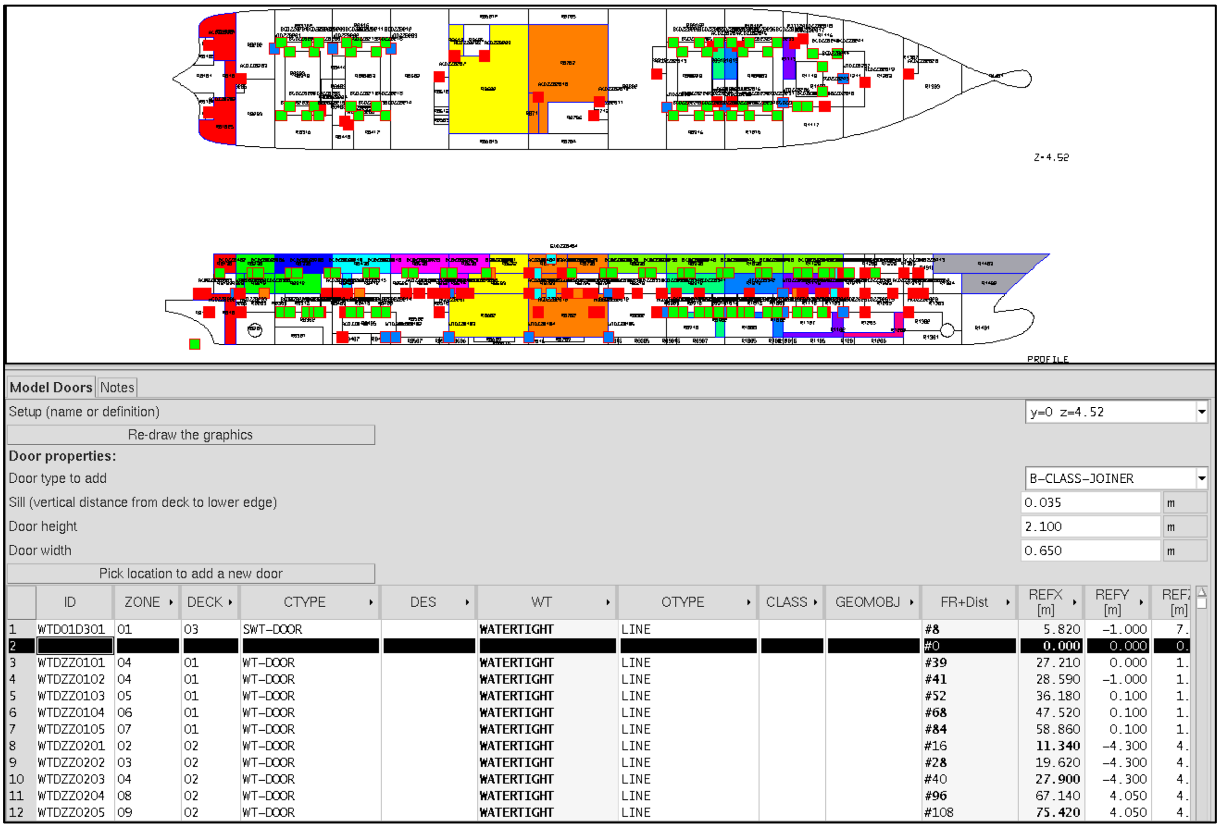
Opening table

The spaces were firstly connected through openings, doors and hatches in NAPA Flooding Simulation tool. Each opening was defined in terms of:

- (X-Y-Z) Location
- Deck on which the opening is located
- Name of the two spaces connected
- Area of the opening (height*width)
- Opening discharge coefficient

- Collapse height in metres
- Leak height in metres

The values of the last two parameters were given as input by the software, according to FLOODSTAND recommendation [D4.1] once the type of door was defined.



	ID	ZONE	DECK	CTYPE	DES	WT	OTYPE	CLASS	GEOMOBJ	FR+Dist	REFX [m]	REFY [m]	REFZ [m]
1	WTD01D301	01	03	SWT-DOOR		WATERTIGHT	LINE			#8	5.820	-1.000	7.
2										#0	0.000	0.000	0.
3	WTDZZ0101	04	01	WT-DOOR		WATERTIGHT	LINE			#39	27.210	0.000	1.
4	WTDZZ0102	04	01	WT-DOOR		WATERTIGHT	LINE			#41	28.590	-1.000	1.
5	WTDZZ0103	05	01	WT-DOOR		WATERTIGHT	LINE			#52	36.180	0.100	1.
6	WTDZZ0104	06	01	WT-DOOR		WATERTIGHT	LINE			#68	47.520	0.100	1.
7	WTDZZ0105	07	01	WT-DOOR		WATERTIGHT	LINE			#84	58.860	0.100	1.
8	WTDZZ0201	02	02	WT-DOOR		WATERTIGHT	LINE			#16	11.340	-4.300	4.
9	WTDZZ0202	03	02	WT-DOOR		WATERTIGHT	LINE			#28	19.620	-4.300	4.
10	WTDZZ0203	04	02	WT-DOOR		WATERTIGHT	LINE			#40	27.900	-4.300	4.
11	WTDZZ0204	08	02	WT-DOOR		WATERTIGHT	LINE			#96	67.140	4.050	4.
12	WTDZZ0205	09	02	WT-DOOR		WATERTIGHT	LINE			#108	75.420	4.050	4.

Figure 1 – Example of opening defined in NAPA Flooding simulation tool

NAPA opening table has been saved in CSV format (Comma Separated Values). Then a macro has been used to convert the openings generated by Napa software to a format readable by Proteus (.POM2).

With that new format the openings have been imported within Proteus (see example Figure 2 and Figure 3).

The openings so imported needs to be checked and adjusted within the Proteus Manger as the macro used and the new format (.POM2) are not working properly in each situation yet.

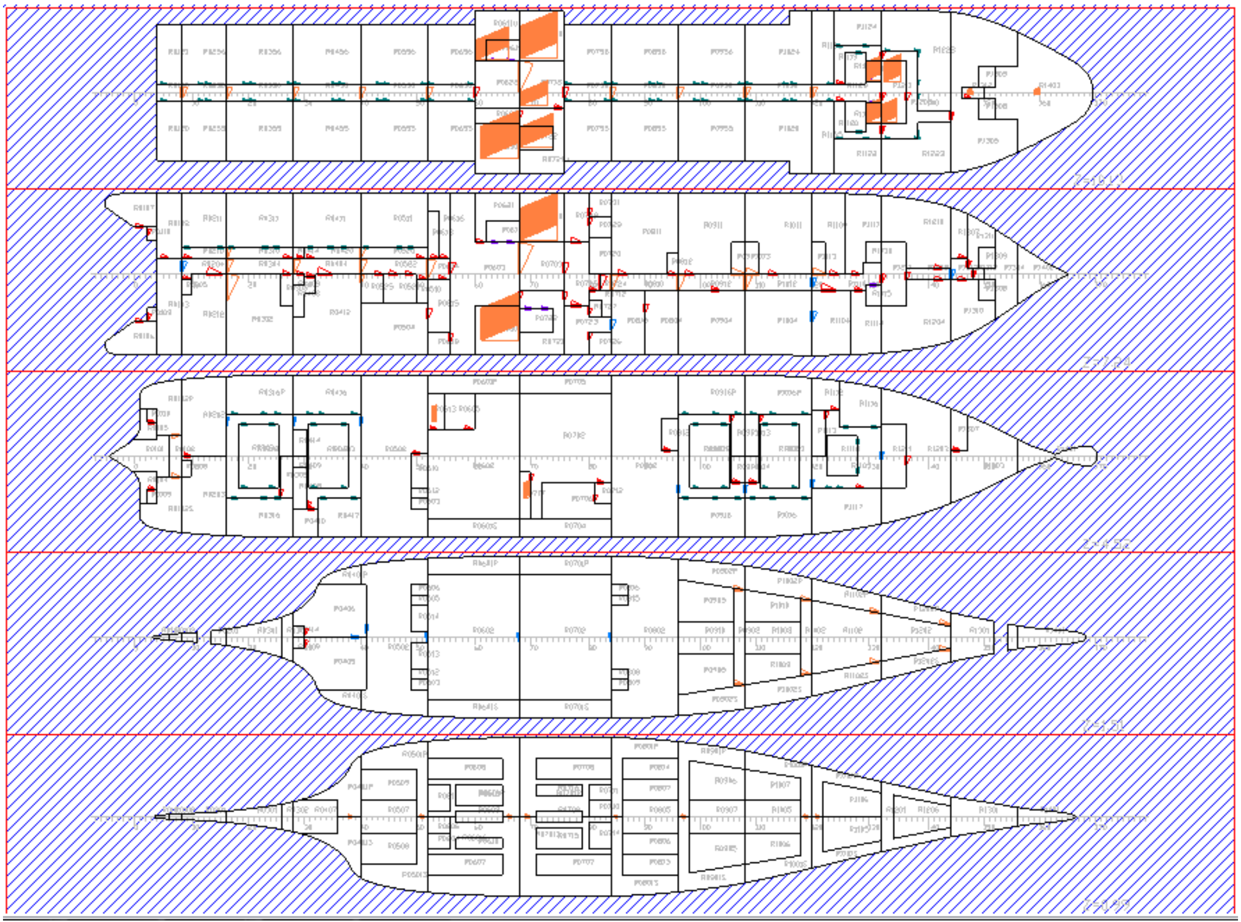


Figure 2 – Example of openings imported in Proteus Manager (horizontal sections)

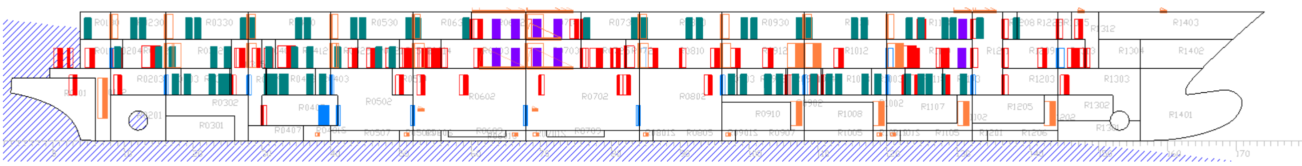


Figure 3 – Example of openings imported in Proteus Manager (longitudinal sections)

As there is no specific max roll angle described in the survival criteria, a number of openings on top of the buoyant hull have been defined to reflect progressive flooding in the event of very large heeling angles.

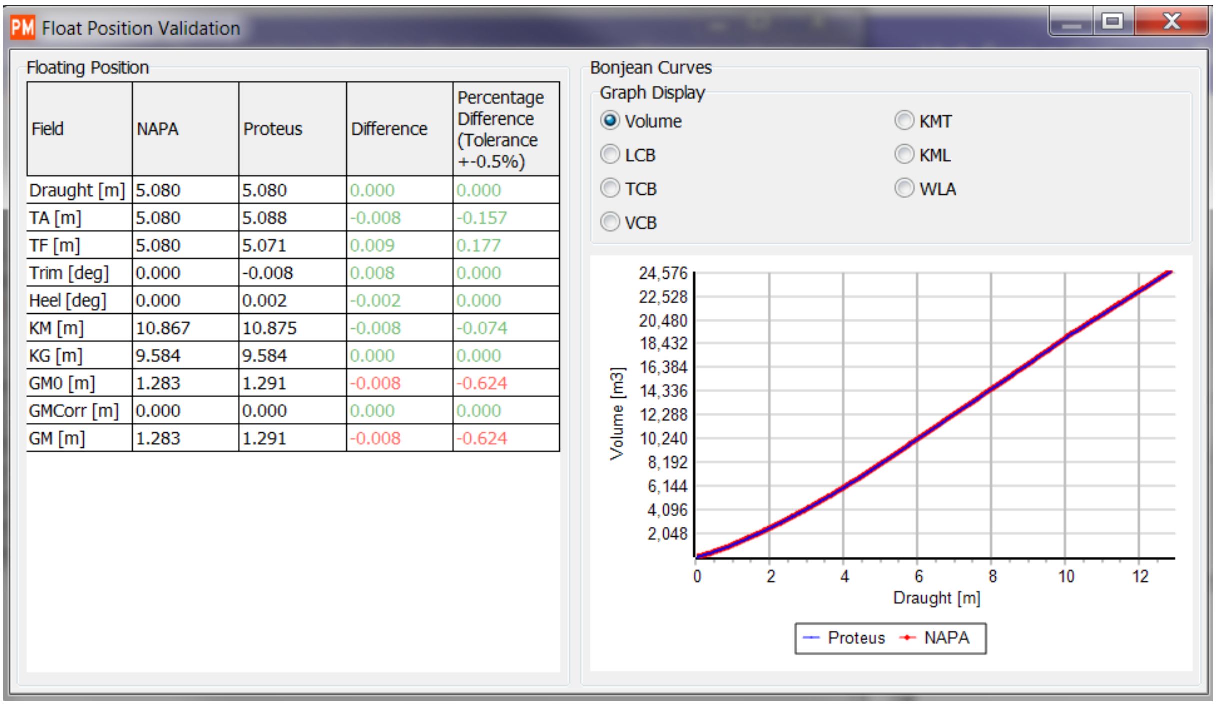
2.2 Simulation set generation

All the data imported into Proteus and the definition of the openings represent the geometric data of the ship.

The check of the imported data and the preparations of the file for the simulations have been made through the "simulation set" functions, where the following elements have been generated within Proteus:

- GZ simulation
- Floating Position simulation
- Forces simulation
- Loading Case Validation
- Time Domain simulation
- Damaged Simulation

The simulation for GZ and Floating Position and the Loading case validation permitted to compare the main geometric input and the hydrostatic data obtained from NAPA and Proteus and to check whether the differences were acceptable (Figure 4 and Figure 5).



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	5.080	5.080	0.000	0.000
TA [m]	5.080	5.088	-0.008	-0.157
TF [m]	5.080	5.071	0.009	0.177
Trim [deg]	0.000	-0.008	0.008	0.000
Heel [deg]	0.000	0.002	-0.002	0.000
KM [m]	10.867	10.875	-0.008	-0.074
KG [m]	9.584	9.584	0.000	0.000
GM0 [m]	1.283	1.291	-0.008	-0.624
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	1.283	1.291	-0.008	-0.624

Figure 4 – Check of Floating Position in Proteus Manager

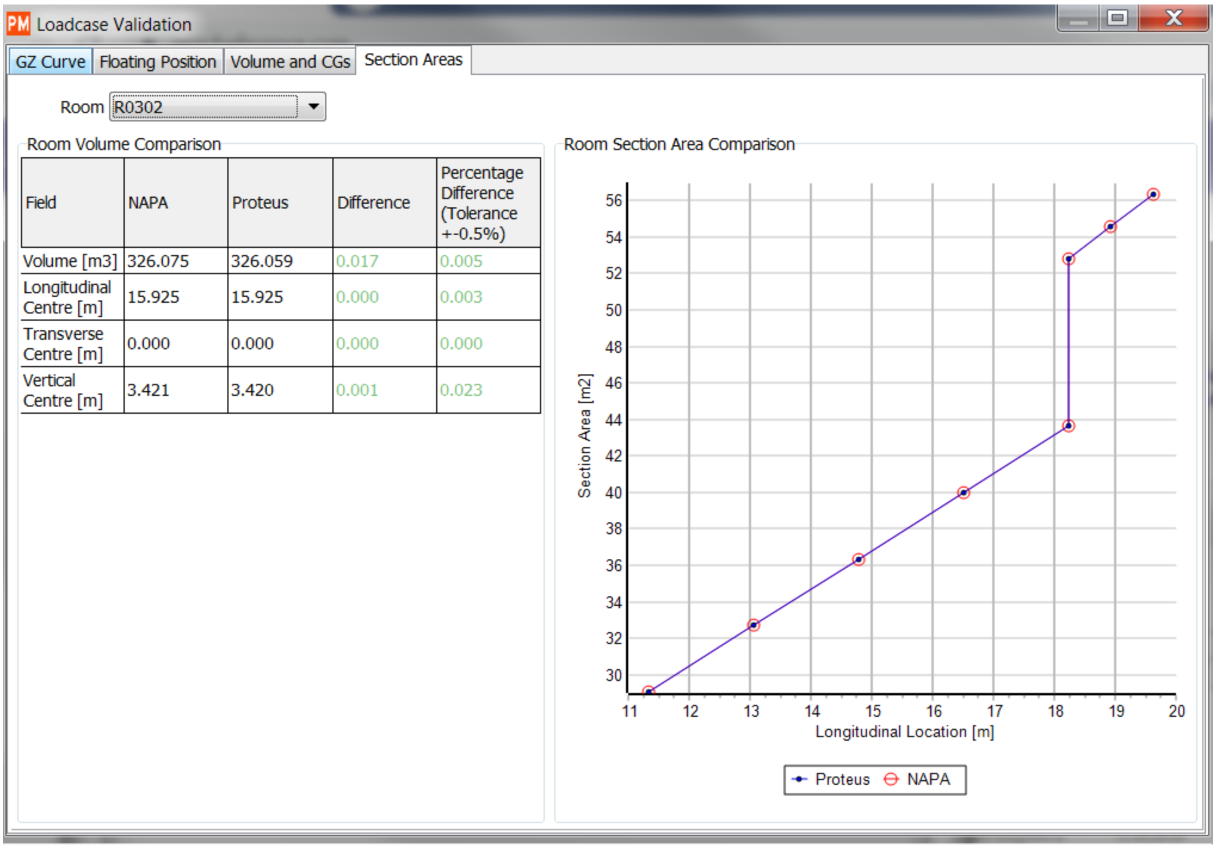


Figure 5 – Check of Rooms data in Proteus Manager

In the time domain simulation and damage simulation windows some important parameters have been set up:

- Waves Heading
- Ship Speed
- Wave type and height
- Max Run Time
- Time to open for the breach

The "Max Roll Limit" option has been deactivated as this criterion is not to be used according to the FLARE procedure.

All the values used for the above parameters in the software are shown in Figure 6 and Figure 7.

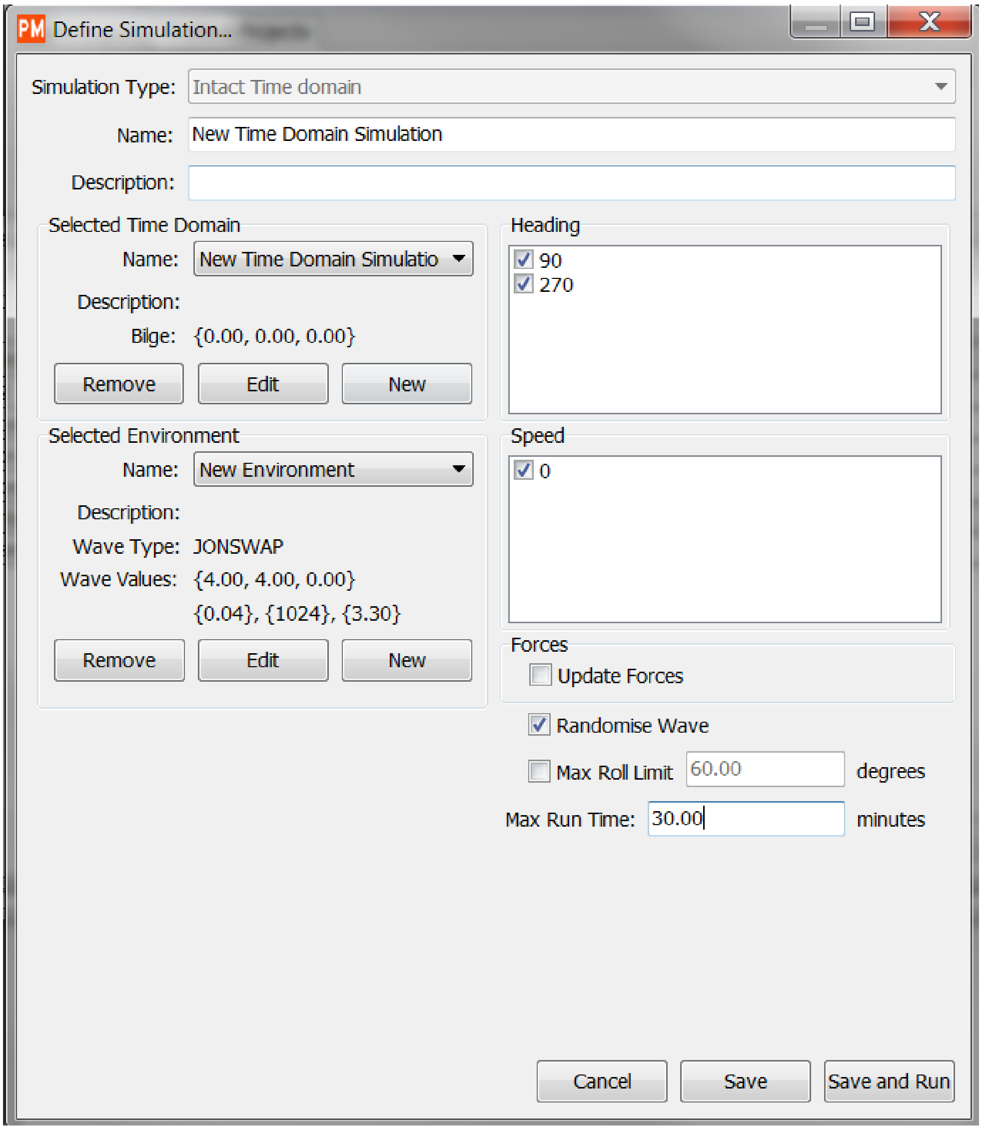


Figure 6 – Input data for Time Domain Simulation

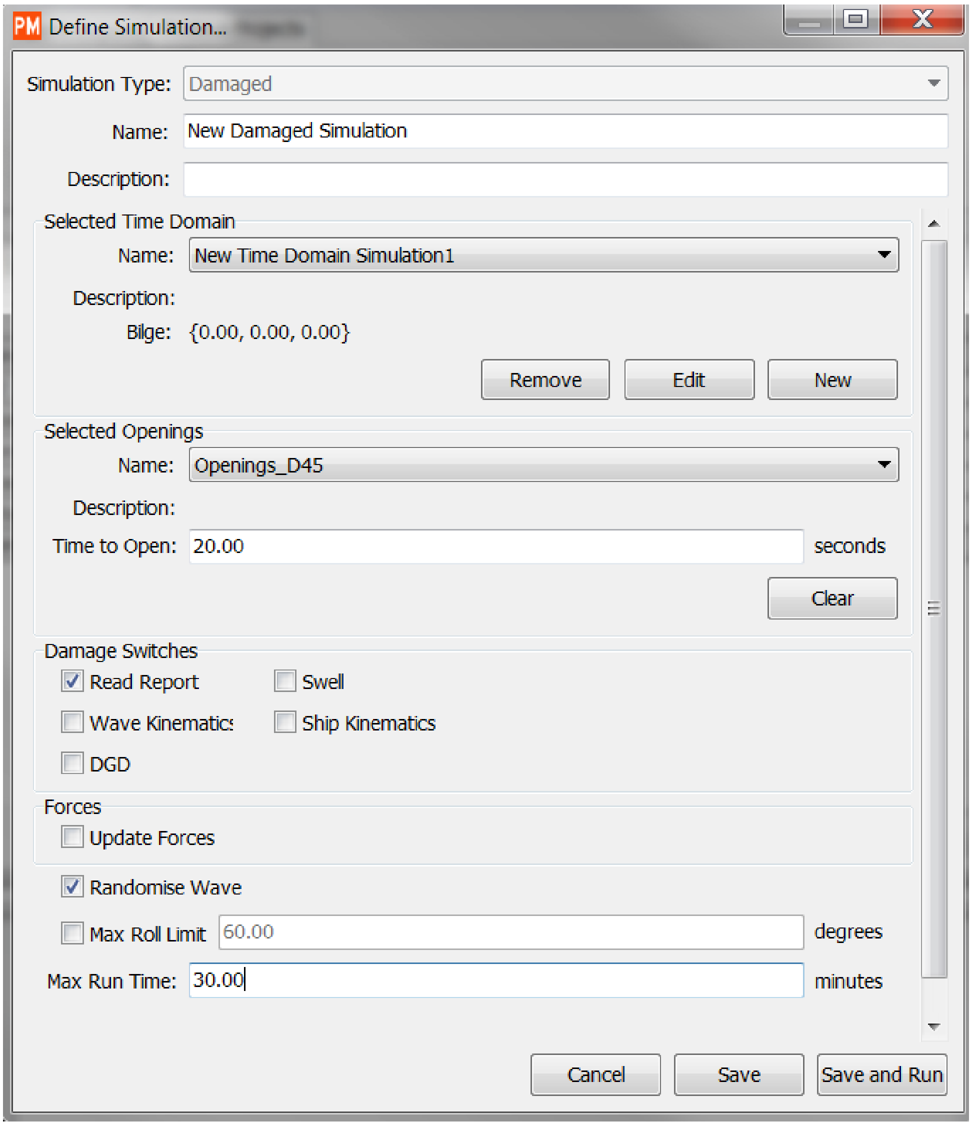


Figure 7 – Input data for Damaged Simulation

In the first round of calculations two simulations sets have been generated (one per draught). A simulation time of 30 min has been selected for the first round of simulations for all the sample ships, then a second simulation set has been defined with simulation time not less than 60 min for RoPax vessels and small cruise (ship#5) while 80 min has been used for the other ships.

2.3 Preparation of the breaches

According to the calculation procedure, the selected damage cases from the static analysis need to be associated to a table of breaches to be simulated. For that reason, some Microsoft® Excel files with macro have been used in order to associate the corresponding breach with higher opening area to each selected damage case. Six tables (one table per draught and hazard) have been obtained by the Microsoft® Excel macro and they have been prepared for the simulation with the Proteus Dispatcher.

The collision and side grounding breaches used for non-zonal analysis according to eSAFE project [2] have a non-box shape which depends on the waterline and location of the breach itself. Such shapes have not been implemented yet in the Proteus code which is currently using a box for any type of breach. Due to this, an external tool (NON-ZONAL BREACHES CONVERTER FOR PROTEUS hereinafter called *Proteus NZO tool*) has been created in the FLARE project with the aim to prepare and fix the damage cases to be simulated by Proteus so that the correct shape is used.

The Proteus NZO tool needs the following input:

- Hull used to generate the forces and exported by Proteus Manager in the simulation set directory (.sus file)
- Internal layout for intact ship exported by Proteus Manager in the simulation set directory (.dam file)
- Rooms limit exported by Proteus Manager in the simulation set directory (.compextents file)
- Shell thickness (in metres)
- Time to open the breach(in seconds)
- Aft and forward end of the hull to be used (it should be the subdivision length L_s for the collision and Load Line length *L* for grounding)
- Breaches table generated by NAPA (.csv file)

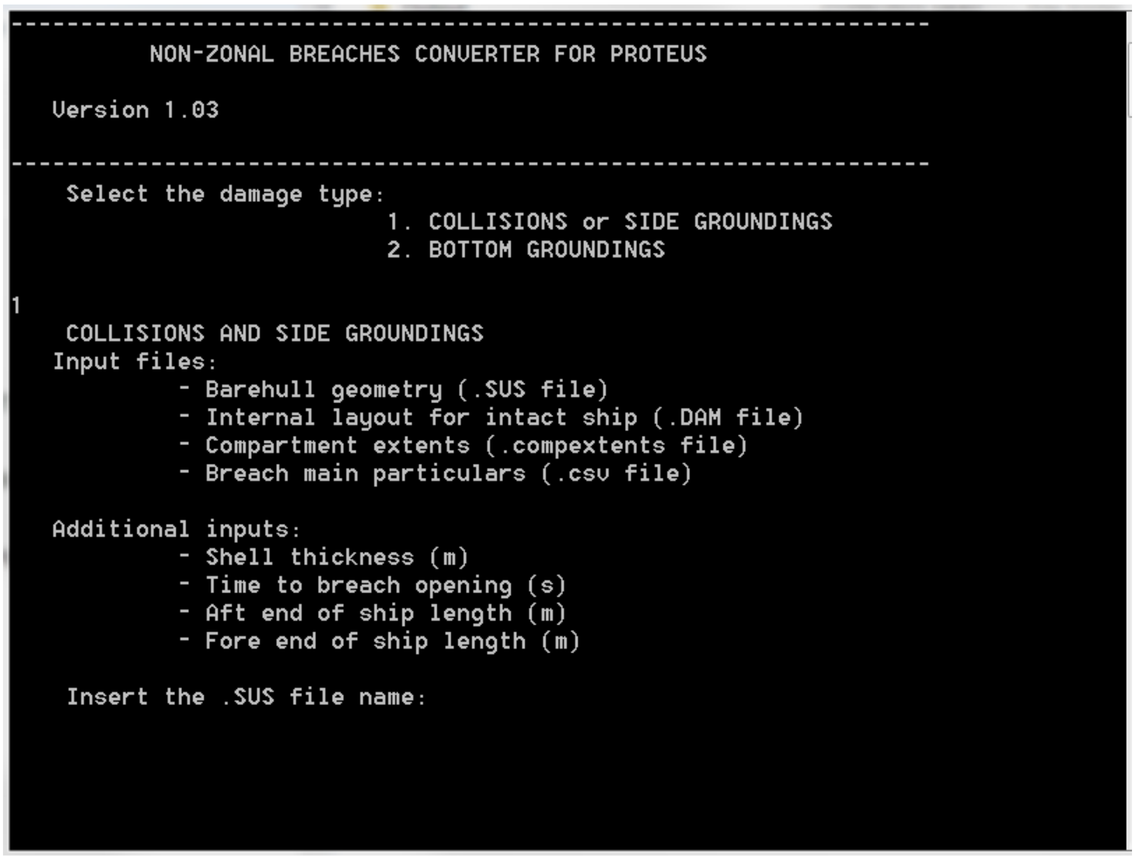


Figure 8 – Proteus NZO tool

Based on the above inputs, the tool generates a .dam file which may be used by Proteus Dispatcher to simulate the correct breach shape for collision and side grounding.

For the bottom grounding no correction is needed for the shape of the breaches as they are box shaped (eSAFE project [2]).

The Proteus NZO tool also helps to correct the limits of each breach given the different reference system of Proteus compared to NAPA, therefore it is used for the correction of the bottom grounding breaches too; in that case a single file (.s) is generated instead of many files (.dam) corresponding to the different breaches.

3 SIMULATIONS

3.1 Running simulations

For the FLARE project no differentiation for the significant wave height (Hs) has been considered as a specific operational area is not defined for the majority of the sample ships, therefore the 4 m height has been used and no Hs step has been set.

The survivability criteria defined in the risk calculation procedure are to be checked; for that purpose, the max steady heel during the simulation has been calculated and the steady heave has been used to check that no progressive flooding is occurring at the end of simulation.

The steady heel has been calculated by the moving average of the roll angle with an interval of 60 seconds.

Then the moving average of the heave (here called *steady heave*) with an interval of 180 seconds has been calculated too. If the difference between the steady heave calculated at the end of simulations and three minutes before the end is less than 1 cm, it can be deduced that no progressive flooding is occurring at the end of simulations; otherwise the second a new round of simulation with extended time is needed.

When all the above settings are defined (see Figure 9) the Proteus Dispatcher Agent may be activated to launch the simulations by the available number of cores.

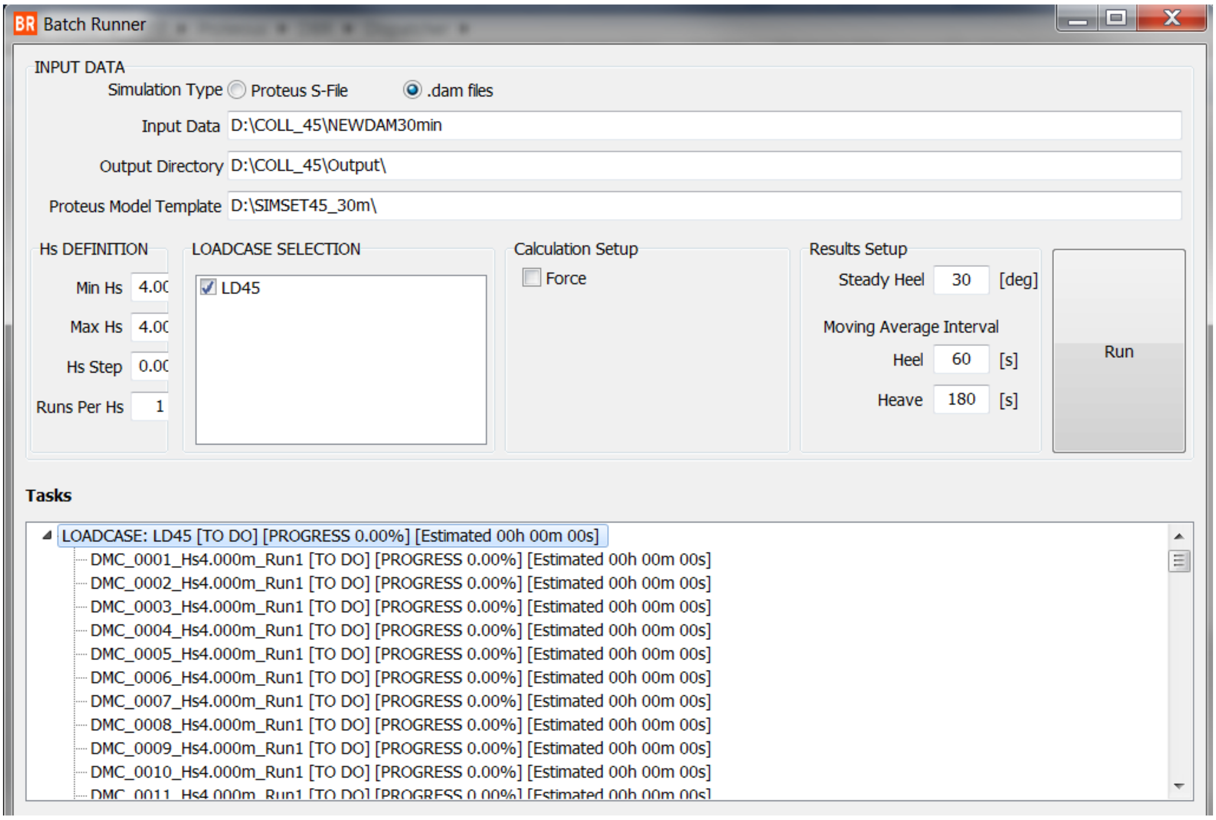


Figure 9 – Settings of the Proteus Dispatcher

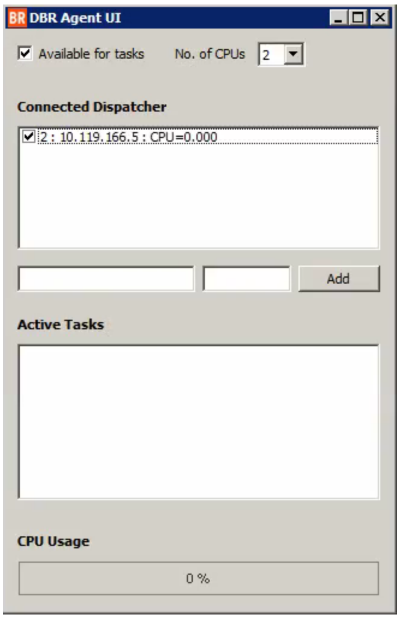


Figure 10 – Proteus Dispatcher Agent

3.2 Processing of results

When the simulations are completed, results are available breach by breach in the dedicated folders created by the Proteus Dispatcher in the selected output folder. It is to be observed that these files contain long and detailed results and it takes long time to investigate all of them if hundreds breaches are simulated. With the aim to get the essential information a summary file with a table is created by the Proteus Dispatcher (i.e. Results.csv).

In that file the following columns need to be checked at least for each case:

1) "Sim End Time" – if this value is lower than the simulation time it means that the ship capsized before the end;
2) "Time at Steady Heel at 30.00" – If this value is recorded it means that the ship reached a steady heel of 30 deg at reported time, therefore the ship has to be assumed not to survive and the value is to be selected as TTC (Time to capsize);
3) "Steady Heave at end" and "Steady Heave 3 mins before end" – if the difference between these two values is greater than 1 cm, the simulation needs to be extended up to 60 or 80 min.

The capsize probability is calculated according to Ch. 3.6 of the main report

In general, when the ship does not survive the TTC is the minimum value between "Sim End Time" and "Time at Steady Heel at 30.00".

The capsize probability and the Time to capsize are the results to be used for the calculation of the PLL level 2.1.

The files (other than Results.csv) with detailed results for each breach are needed in case the evacuation analysis is to be carried out.

4 REFERENCES

[1] Safety-At-Sea, 2021 *Proteus Manager* - beta version for research purpose released on 13th October 2021

[2] Henning Luhmann et al., eSAFE - A joint industry project on Damage Stability for Cruise Ships - *Executive Summary*, Oslo 2018

[3] Napa Ltd, *NAPA Release B30 2020.2 x64/WNT* - December 2020

ANNEX 3 – Calculation of the flooding Risk for Ship n.1

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a large cruise ship design. As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1). The refined model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

1 STATIC ASSESSMENT

1.1 Main data

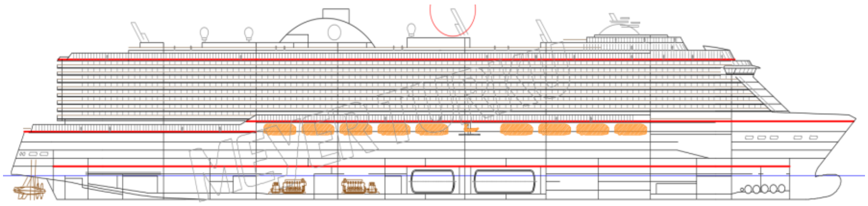


Figure 1 Profile view – Ship #1

The ship #1 is a large modern cruise vessel with liquefied natural gas as primary fuel. Capacities are optimized for a 7-day eastern Caribbean cruise with a large number of balcony cabins and suitable public rooms, like restaurants, shopping areas, conference centre, lounges and a spa area. The design is completed by large pool and sun deck areas, making the vessel suitable for worldwide operation.

The propulsion concept is based on triple screw podded propulsion and six dual fuel main engines driving generators. These generators provide the necessary electrical energy for propulsion and the hotel services. The anticipated service speed is with 21.0 knots nowadays relatively high; however, the actual service speed may vary with the specific service.

Table 1 Main characteristics – Ship #1

Length over all	Approx. 373 m
Length between perpendiculars	346.50 m
Subdivision length	366.00 m
Breadth	48.00 m
Design draught	8.80 m
Subdivision draught	9.10 m
Height of bulkhead deck	12.40 m
Number of passengers, max.	7,800
Number of crew	2,200
Max. persons on board	10,000
Gross tonnage	230,000
Deadweight	13,000 t

No of cabins	2,960

The business model and detailed description of the vessel are included in deliverable D.2.1.1.

Here following the Attained and Required Index according to SOLAS 2020 ch.II-1:

Number of persons	POB = 10 000
Required subdivision index	R = 0.9173
Updated Attained subdivision index	A = 0.9185 * (0.9240 in deliverable D.2.1.1)

*__Note__

Differences between General Arrangement and ship model used in static stability calculations in deliverable D.2.1 have been noticed. Therefore, it was necessary to update SOLAS2020 calculations, which will be explained more in the deliverable D2.7. In partial draft, GM has to be increased from 4.5 m into 4.55 m and in subdivision draft from 4.5 m into 4.65 m. Because the change in GM is so small and there is well reserve for the loading cases, the necessary update in SOLAS2020 calculations seems to be reasonable. Furthermore, this basic ship is later in line with the dynamic model.

1.2 Static calculations with new draughts and permeabilities

Here following the diagram showing the draughts and GM for this vessel based on what is described in paragraph. 2.1.

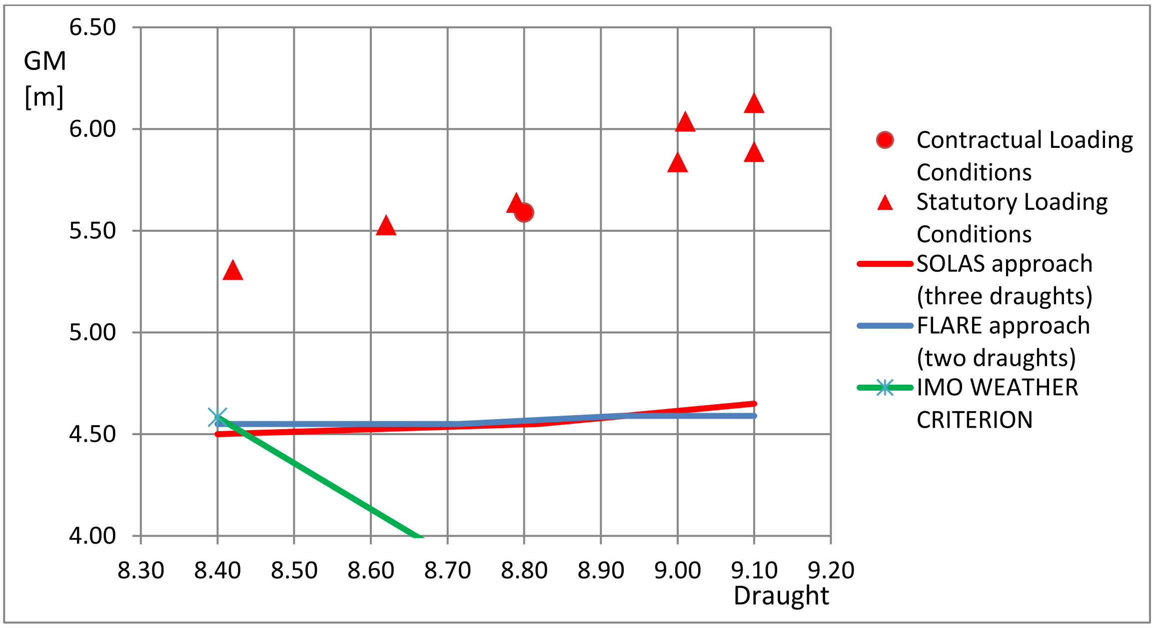


Figure 2 GM limiting curve with new FLARE draughts – Ship #1

1.2.1 Static calculations with new draughts and permeabilities same model as used in WP2

Calculation has been executed with the software NAPA rel.2020.2 generating damages up to 4 adjacent zones.

These observations led to an attained index A = 0.93039 (with reference to the SOLAS A index +1.3 %).

Table 2 Static results with new draughts and permeabilities – Ship #1

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	8.71	4.54	0.93529	0.5	0.46764	0.93039
T0.75	8.93	4.59	0.92550	0.5	0.46275	

1.2.2 Static calculations with new draughts and permeabilities & void spaces divided in CL

SOLAS2020 calculations are based on the separate verification of instantaneous crossflooding within 60 seconds through the crossduct on the other side of the void space.

According to FLARE modelling guidelines (Annex 1) double bottom void spaces shall be divided in centre line and U-shaped void spaces on the double bottom level into three different spaces.

These observations led to an attained index A = 0.92347 (with reference to the SOLAS A index + 0.55%). By dividing void spaces decrease in the attained index is -0.7 % (0.93039 => 0.92347).

However, it has been assumed, that despite the modelling guidelines for simulation the compliance according SOLAS have been based on instantaneous flooding of the voids.

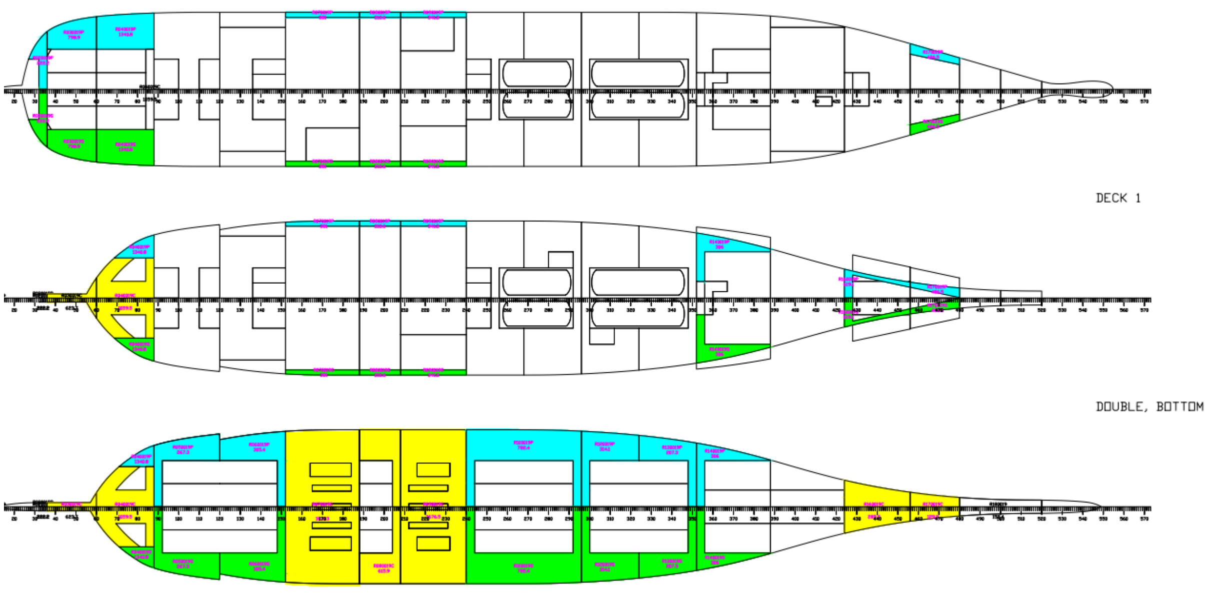


Figure 3 Divided U-void spaces – Ship #1

Table 3 Static results with new draughts, permeabilities and divided void spaces – Ship #1

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	8.71	4.54	0.92827	0.5	0.46414	0.92347
T0.75	8.93	4.59	091867	0.5	0.45934	

1.3 Non-zonal static analysis

With the refined model according to the FLARE modelling guidelines (Annex 1) an increase of number of rooms and connections has been obtained (see Table 4).

Table 4 Comparison between simplified model and refined model – Ship #1

Description	Before modelling	After modelling
Damhull volume	29 3407 m^3	34 8981 m^3
Rooms number	290	485
Connections number	68	219

The refined model reflects as close as possible the geometry of the physical ship or its design and the following items have been refined or added (see D.2.7):

- Staircases and lifts
- U-shaped compartments above double bottom
- U-shaped compartments below tank top

Once the geometrical model has been updated according with the modeling guidelines, static damage stability has been calculated again.

The subdivision table is also affected by minor changes in order to consider also the damage cases that involve new rooms.

However, all the differences in how to set up the geometrical model determine in this sample ship a different result in A-index +1.2 % (0.92347 => 0.93453).

Table 5 Static results with refined model – Ship #1

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	8.71	4.54	0.93944	0.5	0.46972	0.93453
T0.75	8.93	4.59	0.92964	0.5	0.46482	

1.3.1 Non-damage area

Internal watertight integrity is based on the fact that a "NON-DAMAGE AREA" was not assumed in the central part of the ship. Progressive flooding is prevented with remote control valves or by routing the pipes in the same watertight compartment above the most severe waterline and range of residual stability before routing longitudinally.

1.4 Calculation of PLL level 1

For this vessel, breaches for collision, side and bottom grounding have been generated according to Ch. 3.2 and the grouping of breaches, leading to the same sets of flooded rooms, permitted to reduce the damage cases to be calculated by abt. 64% for collision, abt. 71% for bottom grounding, and by abt. 78% for side grounding.

With the results of the static calculation, PLL level 1 was calculated according to procedure described in Ch.2. In particular, in Table 6, the non-zonal results are showed and in

Table 7, the PLL (Potential loss of life) calculation is reported.

Table 6 Non-zonal static analysis results – Ship #1

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**	
Init condition	D45	D75	D45	D75	D45	D75
Draught	8.715m	8.925m	8.715m	8.925m	8.715m	8.925m
Breaches	10000	10000	10000	10000	10000	10000
Number of Empty cases	36	65	124	108	211	236
Number of Unique damage cases	3608	3654	2231	2255	2860	2898
Partial Index	0.9618	0.9547	0.9062	0.9022	0.9316	0.9279
Total Attained Subdivision Index A_i	**0.9583**		**0.9042**		**0.9298**	

Table 7 PLL level 1 – Ship #1

Damage Type	**Collision**		**Side Grouding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		4.33E-03
Relative frequency	0.388		0.328		0.284		1.000
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	8.715	8.925	8.715	8.925	8.715	8.925	
Attained Index	0.9618	0.9547	0.9062	0.9022	0.9316	0.9279	0.9324
$\sum pfac$ (for cases with s=1)	0.8916	0.8549	0.8821	0.8687	0.9157	0.9061	0.8846

$\sum pfac \cdot (1 - sfac)$	0.0382	0.0453	0.0938	0.0978	0.0684	0.0721	0.0676
PLL level 1 (1/ship year)	2.57E-01	3.04E-01	5.33E-01	5.55E-01	3.36E-01	3.54E-01	**2.3400**
	0.5611		**1.0880**		**0.6909**		

Even though the PLL is eventually the parameter to be used as a risk metric in FLARE, the Combined Attained Index is also shown in Table 7 for information only. These values are calculated by using the relative frequency for collision, Side grounding and Bottom Grounding, which are based on the updated damage statistics of FLARE (WP2).

1.5 Filtering of static results and selecting cases for dynamic simulations

The screening of the static result according to filtering criteria identified within Ch. 3.4 permitted to select 500 cases for the dynamic simulations. In the following table, a summary of the filtered breaches is reported.

Table 8 Filtering results for dynamic simulation – Ship #1

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught (m)	8.715	8.925	8.715	8.925	8.715	8.925	
Number of filtered damage cases	50	62	131	155	47	55	500
$\sum pfac$ (for the filtered damage cases)	0.0118	0.0140	0.0376	0.0442	0.0104	0.0137	0.0218
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0106	0.0121	0.0371	0.0410	0.0104	0.0124	0.0204
Potential PLL (if the ships would not capsize for all selected cases)	1.85E-01	2.23E-01	3.22E-01	3.23E-01	2.85E-01	2.94E-01	1.6317
	0.4081		0.6448		0.5787		
Potential PLL reduction (if the ships would not capsize for all selected cases)	27.3%		40.7%		16.2%		30.3%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. In particular, for this ship the PLL would be reduced by about 30% if none of the cases to be simulated lead to capsizing.

In the following diagrams, some typical damage parameters of the selected breaches are presented in non-dimensional form.

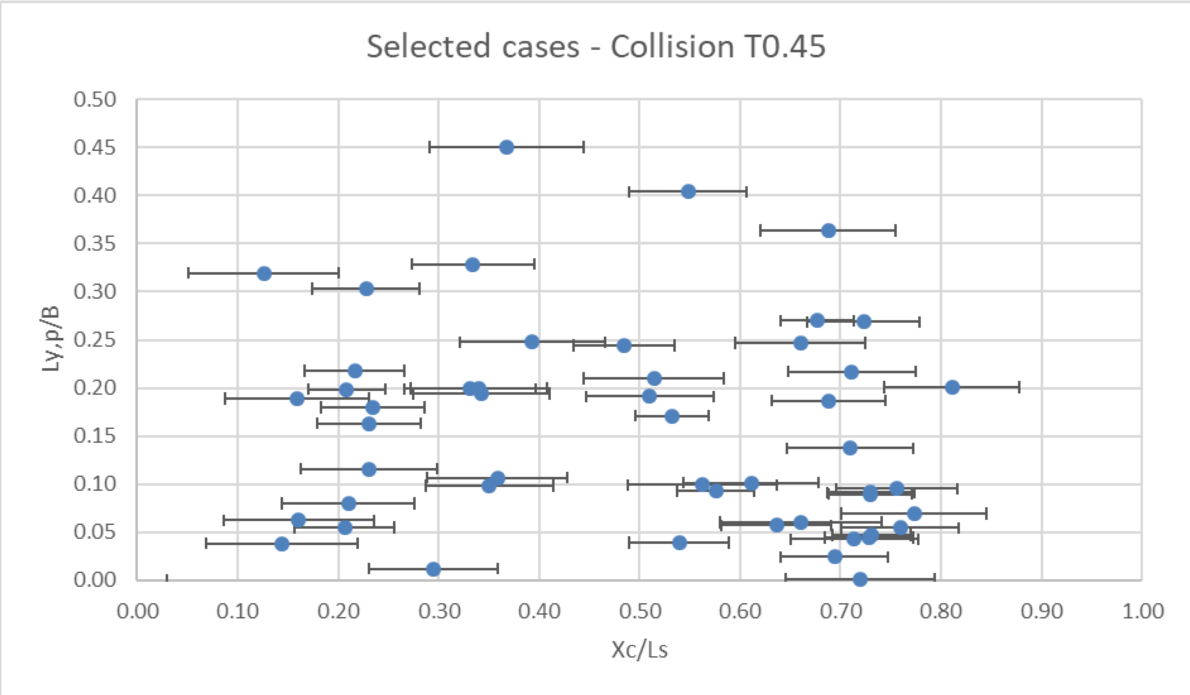


Figure 4 Selected collision breaches T0.45 – Ship #1

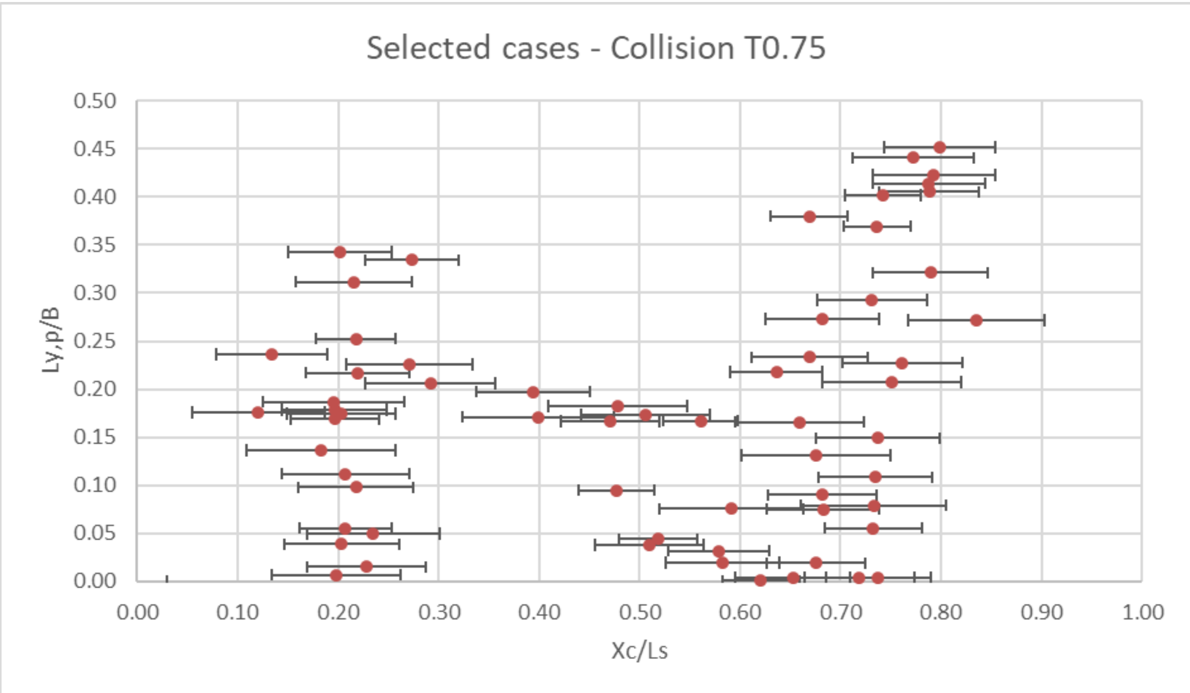


Figure 5 Selected collision breaches T0.75 – Ship #1

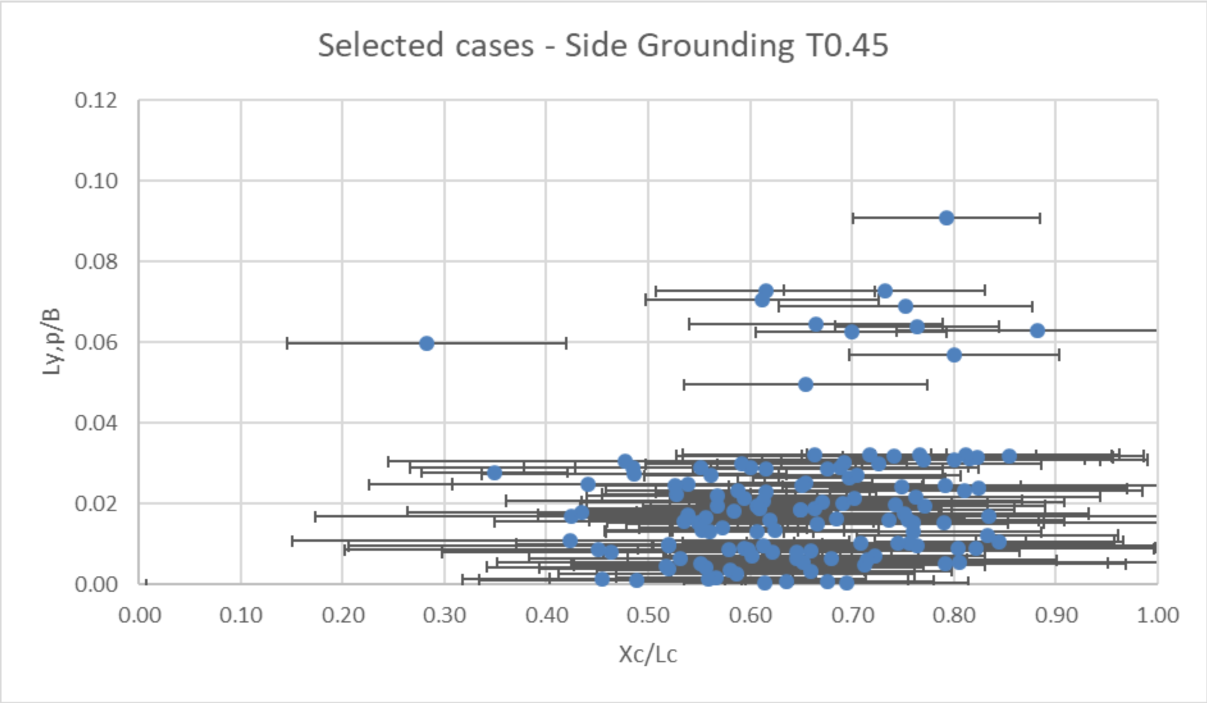


Figure 6 Selected side grounding breaches T0.45 – Ship #1

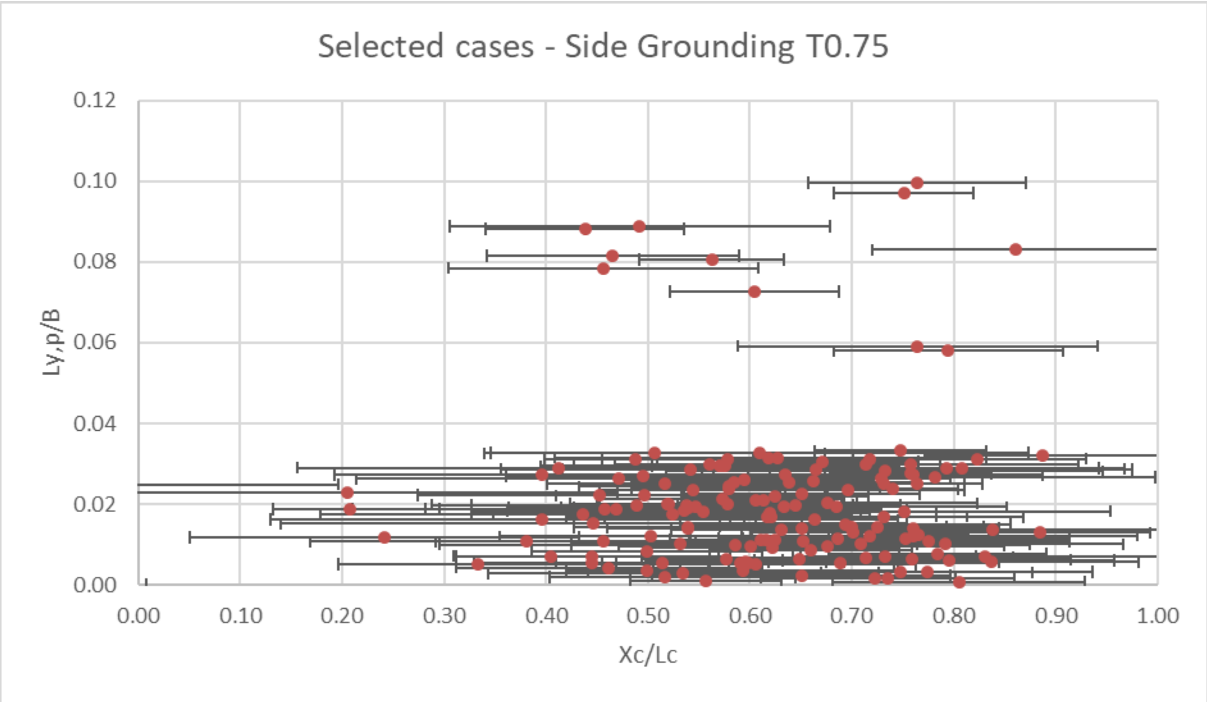


Figure 7 Selected side grounding breaches T0.75 – Ship #1

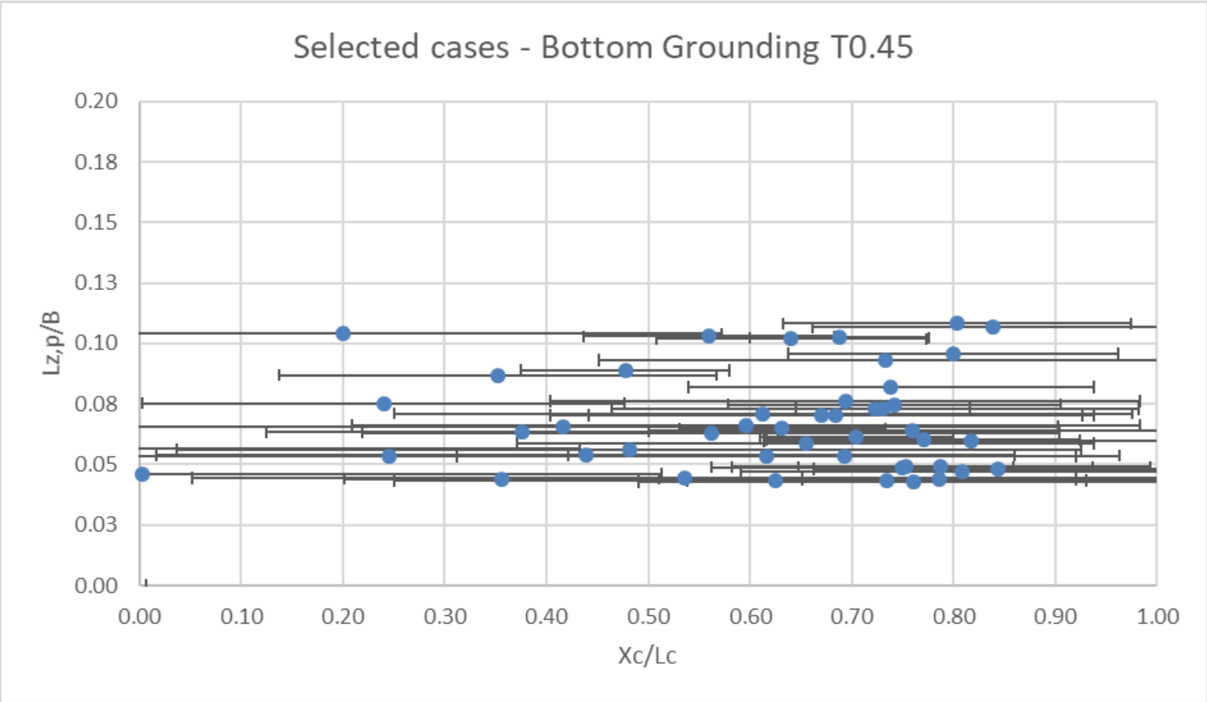


Figure 8 Selected bottom grounding breaches T0.45 – Ship #1

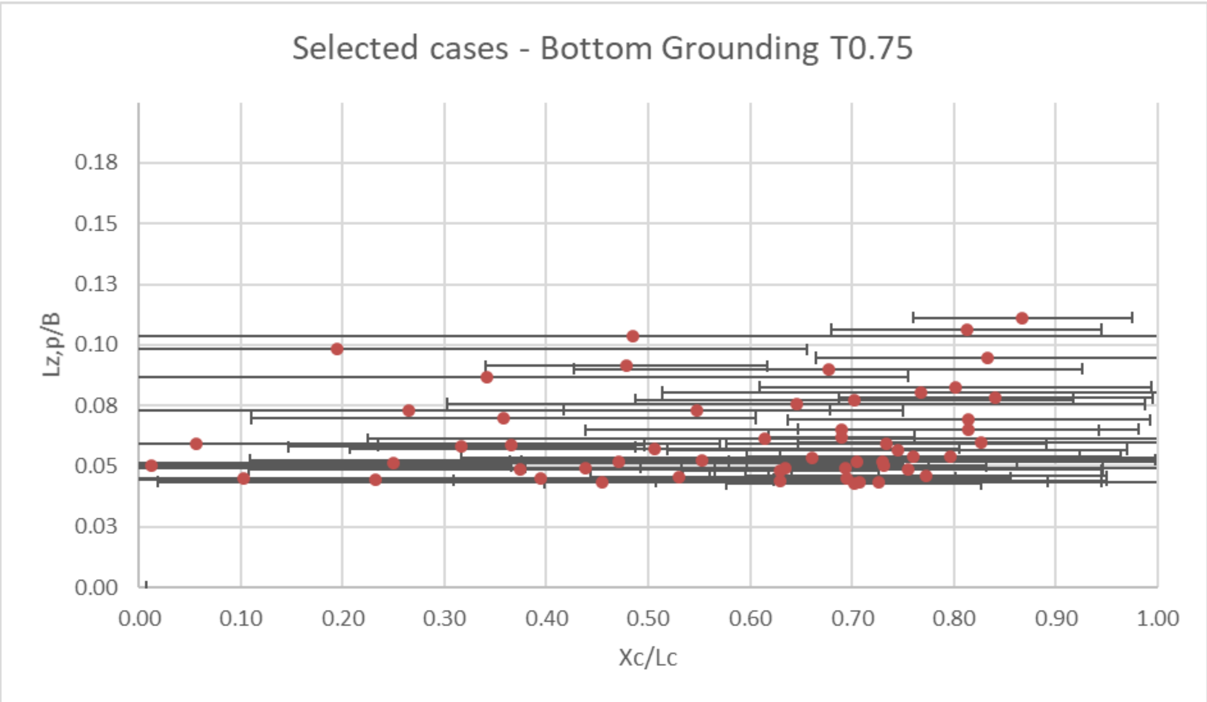


Figure 9 Selected bottom grounding breaches T0.75 – Ship #1

Particularly for the deeper draught collision damages, there are clearly two vulnerable areas: the aft machinery compartments and compartments in the fore shoulder region where the heeling tanks are located. A large majority of selected breaches for side and bottom groundings have a huge length and therefore, they affect a large number of compartments.

Regarding bottom groundings, the ship capsizes just when very long breaches affecting the double bottom are considered or when the vertical penetration of the damage is higher than the double bottom height.

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with s-factor equal to zero and failure modes for cases with s-factor between 0 and 1, are showed in the following tables.

Table 9 Breakdown of failure mode for Sfac=0 cases – Ship #1

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	5	5	27	14	0	0	**51**
Heeling Angle (>15 deg)	11	13	44	61	0	1	**130**
Smom=0	12	22	44	49	46	51	**224**
Opening immersion	4	10	4	6	1	0	**25**
Sfac=0 - Total cases	**32**	**50**	**119**	**130**	**47**	**52**	**430**

Table 10 Breakdown of failure mode for 0<Sfac<1 cases – Ship #1

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	1	0	1	13	0	0	**15**
Insufficient Range	3	4	0	2	0	2	**11**
Heeling Angle (>7 deg)	0	0	0	0	0	0	**0**
Insufficient Restoration (GZmax) + Range	12	8	11	8	0	1	**40**
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	**0**
Insufficient Range + Excessive Heel	0	0	0	0	0	0	**0**

Insufficient Restoration (GZmax) + Range + Excessive Heel	2	0	0	2	0	0	**4**
0<Sfac<1 - Total cases	**18**	**12**	**12**	**25**	**0**	**3**	**70**

A large percentage of captured cases resulted into Sfac=0 (430 cases over 500) and about 80% of the captured cases had a failure mode corresponding to either a heeling angle greater than 15 deg or Smom = 0. This occurred essentially for breaches leading to a big asymmetry in the flooding scenario.

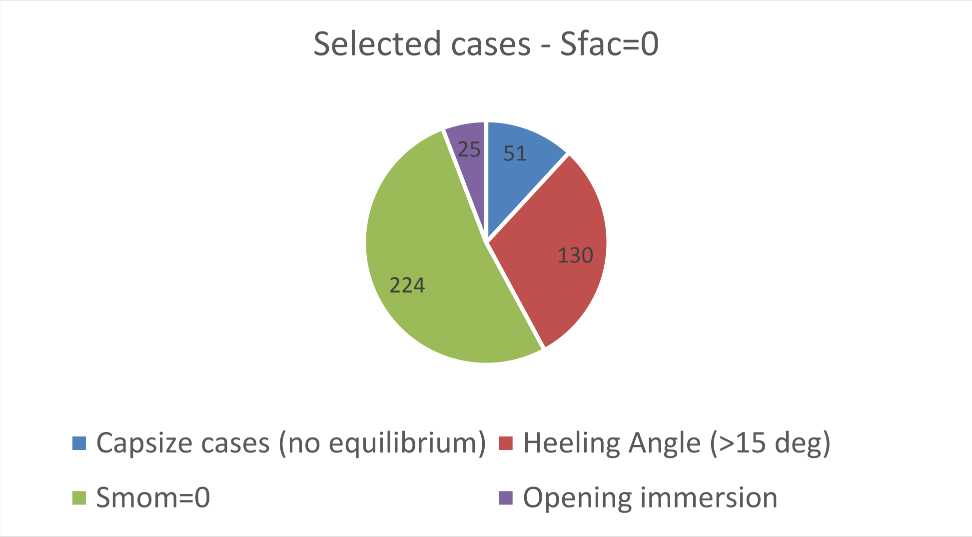


Figure 10 Diagram of failure mode for Sfac=0 cases – Ship #1

Equilibrium was not reached in the static calculation for 51 cases, whereas 25 cases have been identified due to the immersion of openings. These cases are very important to be selected too as it is expected that the outcome of the dynamic simulation will be completely different. In fact, the approach for connections and openings definition is completely different between static and dynamic calculation.

70 damage cases with 0 < Sfac < 1 has been selected and the majority (57%) of these cases resulted in an insufficient GZmax and excessive Range. The rest comprised of insufficient restoration (21%), insufficient range (16%) and insufficient restoration + rage + excessive heel (6%).

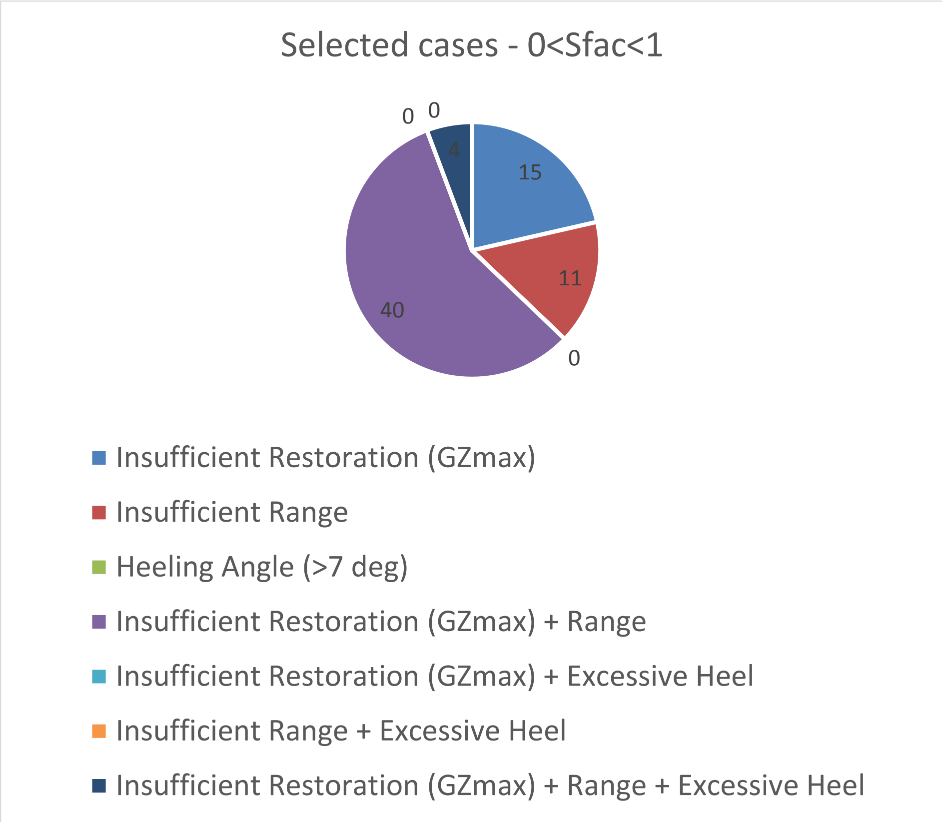


Figure 11 Diagram of failure mode for 0 < Sfac < 1 cases – Ship #1

2 DYNAMIC ASSESSMENT

2.1 Preparation of the PROTEUS model

The dynamic analysis has been carried out by using the *PROTEUS* software (last release distributed in November 2021). In particular, for the preparation of the model the tool Proteus Manager has been used.

To generate in the *Proteus Manager* the loading conditions defined in NAPA and corresponding to the two calculation draughts at 45% and 75%, the following lightships have been generated:

$T_1 = 8.715$ m → LIG_1 [Δ=102531.8 t ; CG (161.126 , 0 , 25.113) m]

$T_2 = 8.925$ m → LIG_2 [Δ=105630.6 t ; CG (160.977 , 0 , 24.702) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at five different deck slices:

DB = 0.1 m ; D1 = 2.1 m ; D2 = 6.9 m ; D3 = 9.7 m ; D4 = 12.5 m ; D5 = 15.5 m

For this large cruise ship, 1497 openings have been defined.

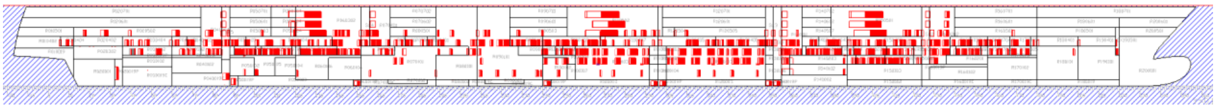


Figure 12 – Openings imported in Proteus Project (longitudinal section) – Ship #1

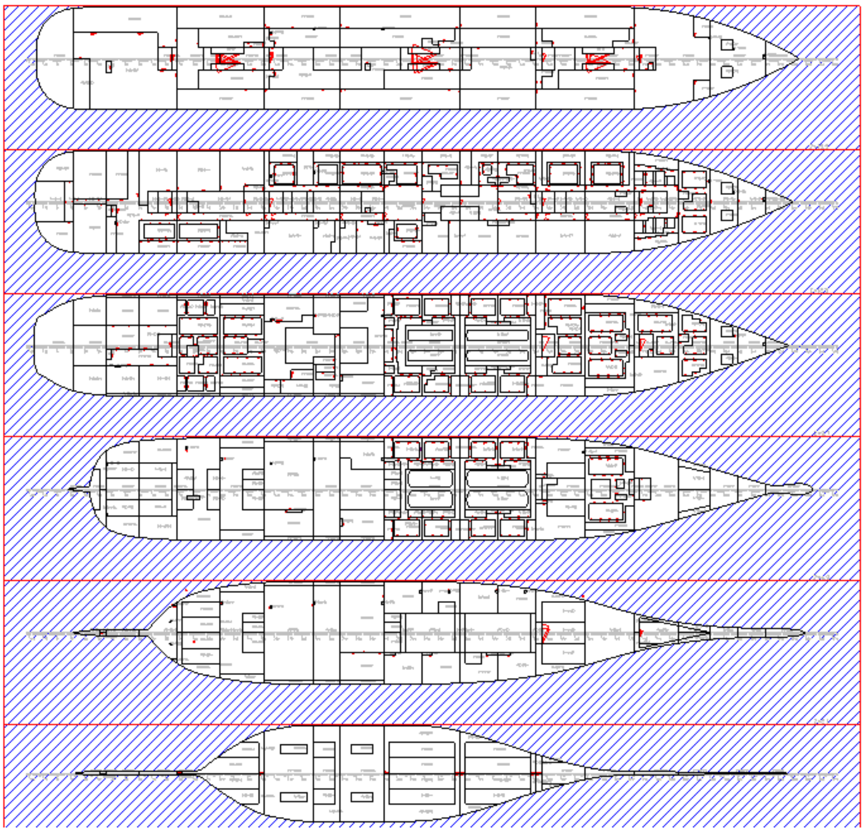


Figure 13 – Openings imported in Proteus Project (horizontal section) – Ship #1

Table 11 – Opening types in Proteus Manager – Ship #1

TYPE	1 to 2	2 to 1	1 to 2 [meters]	2 to 1 [meters]	[meters]	[meters]	HEff Switch	[seconds]	[seconds]
CONNECTION	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
B-CLASS-JOINER	0.03000	0.03000	1.50	1.50	0.000	0.000	False	0	999999
FDOOR-A-HINGED	0.03000	0.02000	2.50	2.50	0.000	0.000	False	0	999999
FDOOR-A-SLIDING	0.00000	0.00000	1.00	1.00	0.000	0.000	False	0	999999
FDOOR-A-DOUBLELEAF	0.00000	0.00000	2.00	2.00	0.000	0.000	False	0	999999
COLDROOM-DOOR	0.01000	0.01000	3.50	3.50	0.000	0.000	False	0	999999
LIFT-DOOR	0.03000	0.03000	1.50	1.50	0.000	0.000	False	0	999999
SWT-DOOR	0.01000	0.01000	10.00	10.00	8.000	0.000	False	0	999999
WT-DOOR	0.00000	0.00000	100.00	100.00	99.000	0.000	False	999999	0
WT-DOOR_LBHD	0.00000	0.00000	100.00	100.00	99.000	0.000	False	999999	0
SHELL-DOOR_LARGE	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
SHELL-DOOR_NORMAL	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999

Since in Proteus the discharge coefficient for the flow through openings is set to a constant value of 0.6 and it may be not changed, the area of the cross-flooding openings has been partly reduced in order to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation sets have been created and the comparison of the geometric and hydrostatic data between NAPA and Proteus showed that the differences are negligible in general (from Figure 14 to Figure 20 and Table 12).

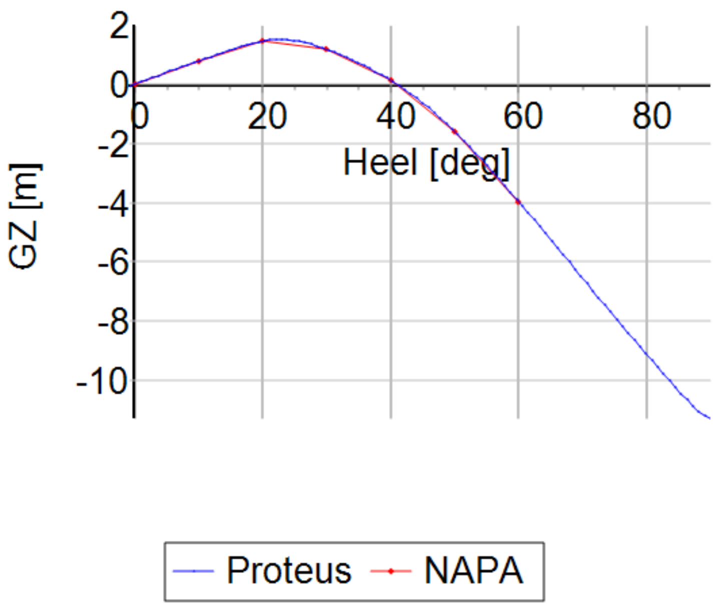


Figure 14 – GZ comparison between NAPA and Proteus – Ship #1

Table 12 – Floating Position comparison between NAPA and Proteus – Ship #1

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	8.715	8.714	0.001	0.011
TA [m]	8.715	8.719	-0.004	-0.046
TF [m]	8.715	8.709	0.006	0.069
Trim [deg]	0.000	0.010	-0.010	0.000
Heel [deg]	0.000	0.000	0.000	0.000
KM [m]	29.653	29.660	-0.007	-0.024
KG [m]	25.113	25.110	0.003	0.012
GM0 [m]	4.540	4.547	-0.007	-0.154
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	4.540	4.547	-0.007	-0.154

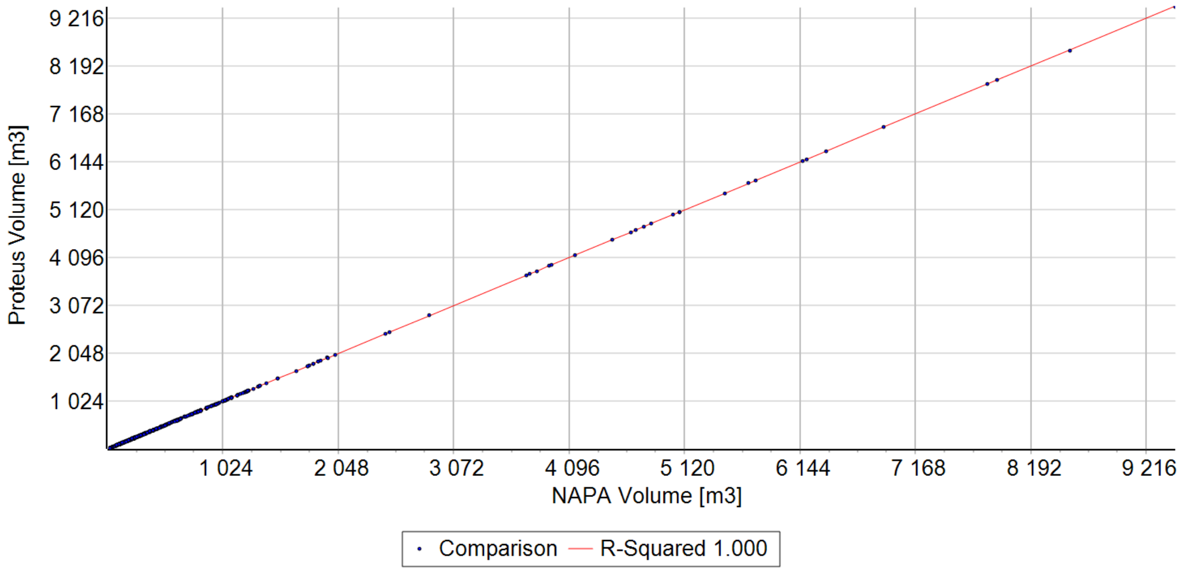


Figure 15 – Hull volume comparison between NAPA and Proteus – Ship #1

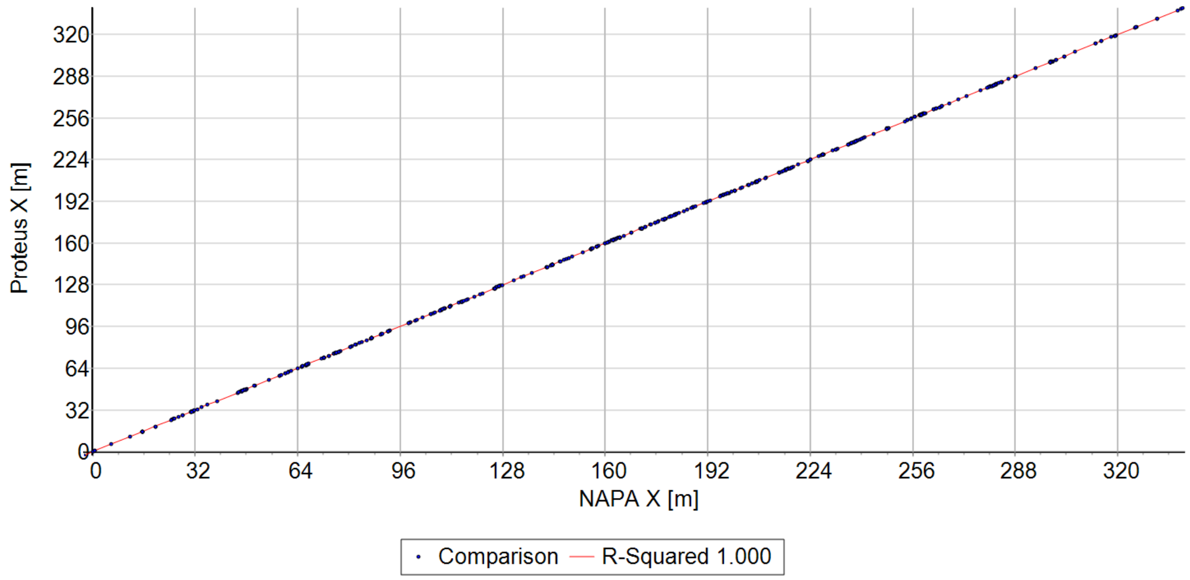


Figure 16 – Hull LCB comparison between NAPA and Proteus – Ship #1

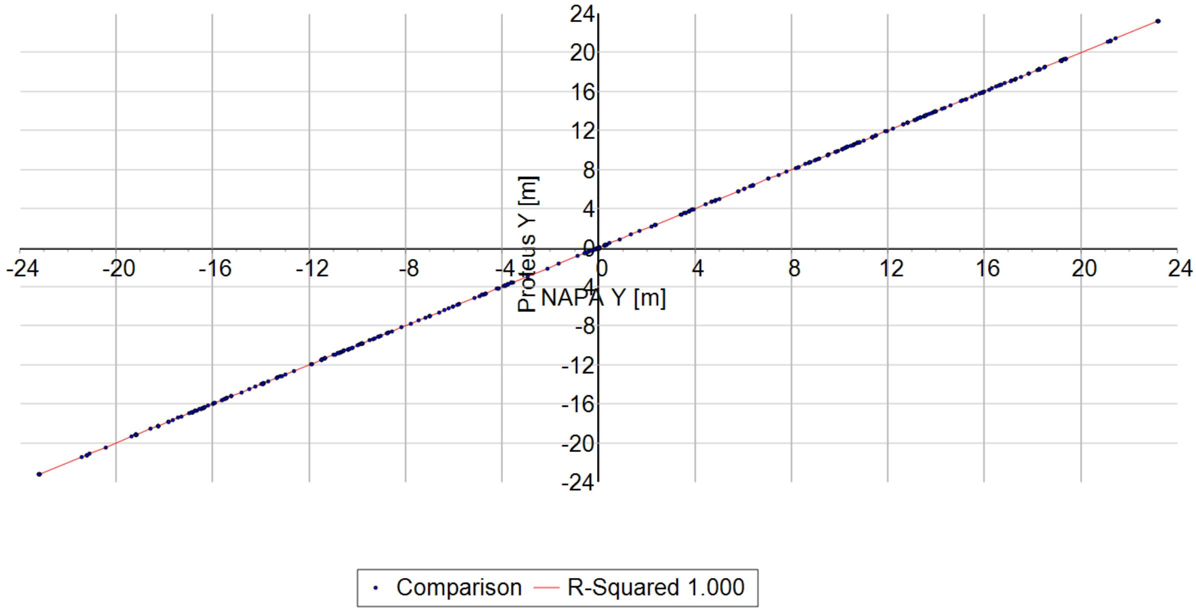


Figure 17 – Hull TCB comparison between NAPA and Proteus – Ship #1

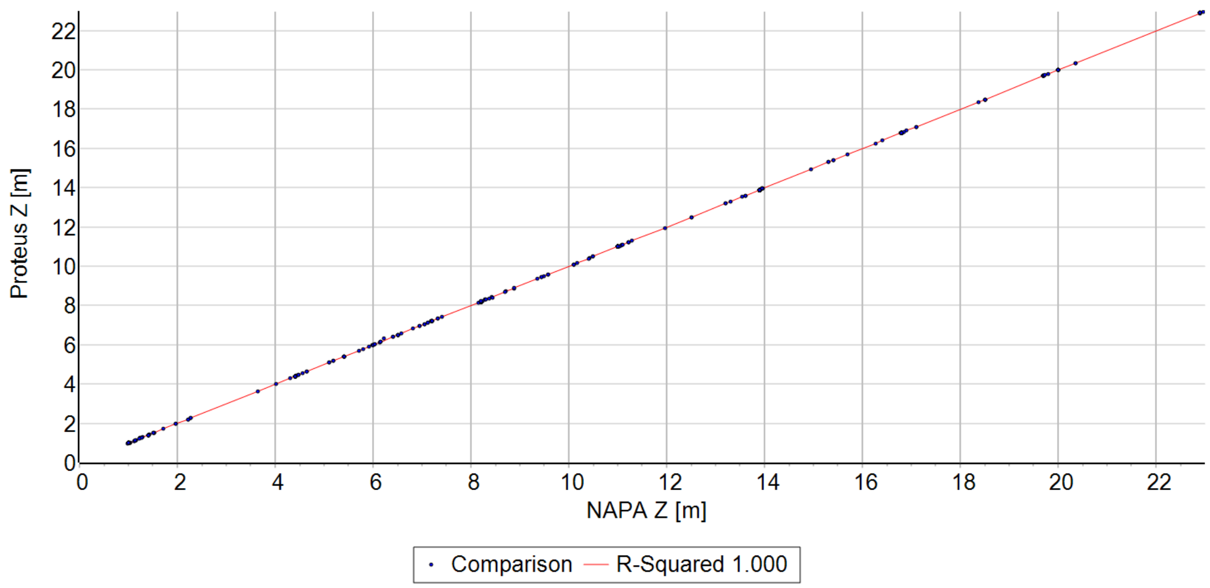


Figure 18 – Hull VCB comparison between NAPA and Proteus – Ship #1

Room R020019P

Room Volume Comparison

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	222.215	225.777	-3.563	-1.603
Longitudinal Centre [m]	19.447	19.363	0.084	0.432
Transverse Centre [m]	10.318	10.318	0.000	-0.004
Vertical Centre [m]	7.192	7.203	-0.011	-0.152

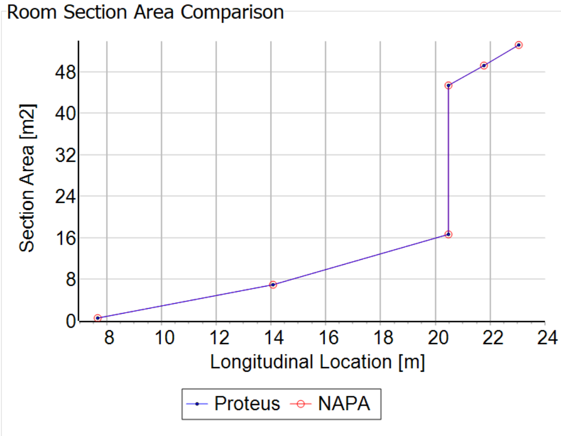


Figure 19 – Aftpeak comparison between NAPA and Proteus – Ship #1

Room R200001

Room Volume Comparison

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	1202.568	1208.644	-6.076	-0.505
Longitudinal Centre [m]	340.319	340.313	0.006	0.002
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	8.438	8.379	0.059	0.700

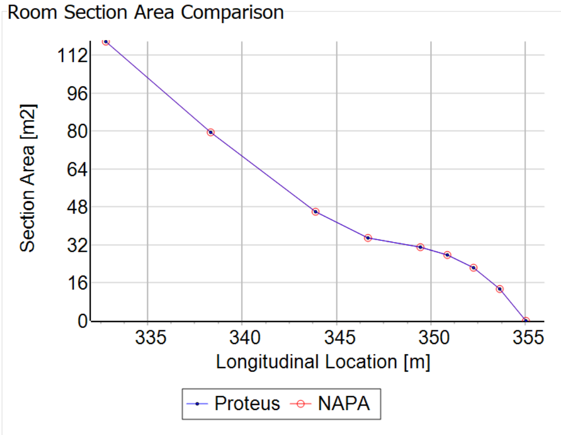


Figure 20 – Forepeak comparison between NAPA and Proteus – Ship #1

2.2 Results of dynamic simulations

In the first round of dynamic simulations by Proteus, all the 500 breaches have been simulated up to 30 minutes, then for 275 breaches a second simulation round has been executed up to 90 minutes, as these were found with progressive flooding still occurring at the end of the first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1 = capsize 0 = not capsize) and TTC for cases where a capsize occurred. In the following graphs, the results for each hazard and the global results of simulations are presented.

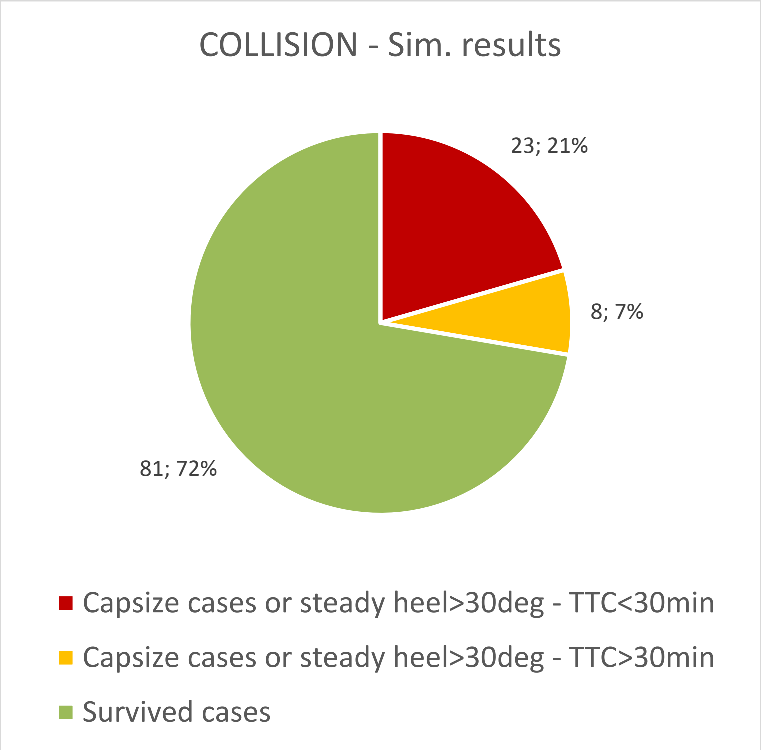


Figure 21 – Dynamic simulation results for collision – Ship #1

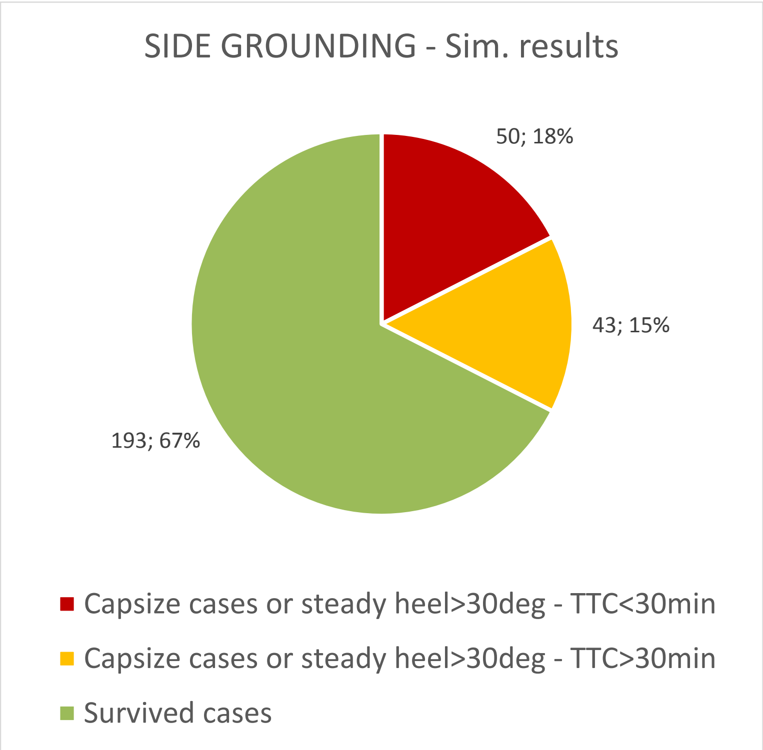


Figure 22 – Dynamic simulation results for side grounding – Ship #1

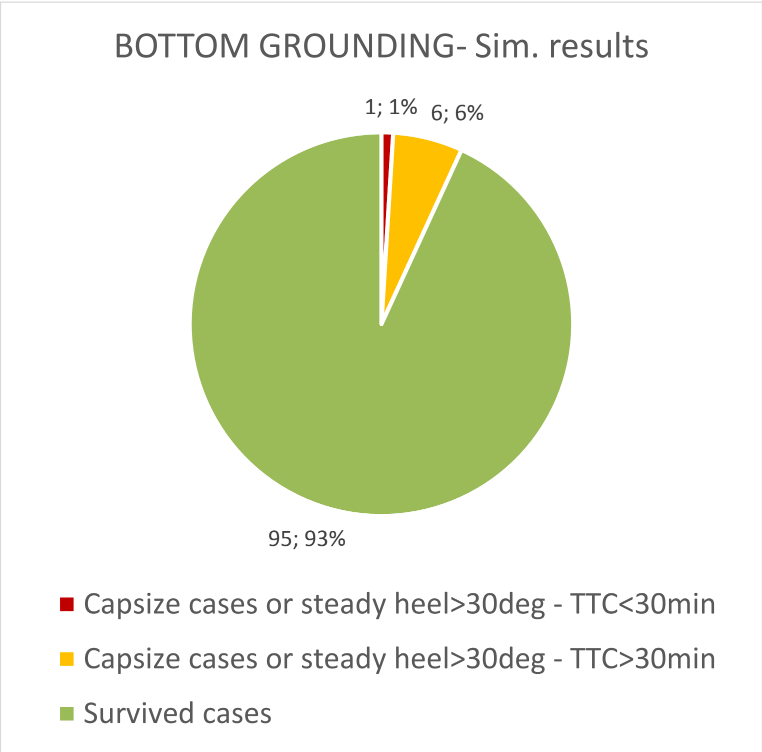


Figure 23 – Dynamic simulation results for bottom grounding – Ship #1

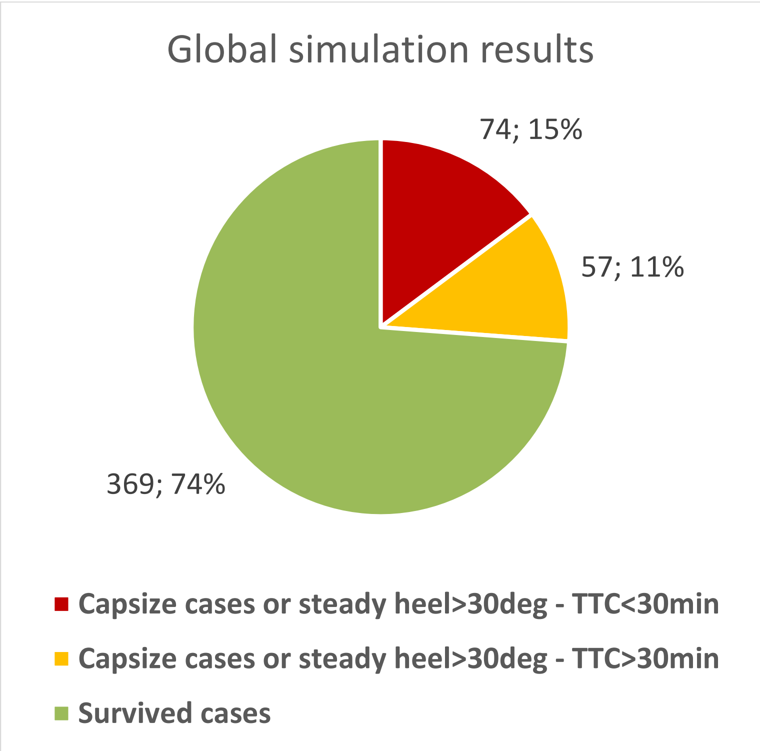


Figure 24 – Global dynamic simulation results for the 500 filtered breaches – Ship #1

The results obtained clearly show that for most of cases the ship did not capsize, which confirmed that the static results are conservative as almost all of these cases had an sfac = 0 in the static analysis.

Slightly over half of the capsize cases (56%) are considered fast capsizes as the TTC is less than 30 minutes. For these cases, there is no sufficient time to orderly evacuate persons.

2.3 Calculation of PLL level 2.1

The results of the flooding simulations permit to get the TTC too, therefore the fatality rate may be estimated for the cases with TTC > 30 min according to the procedure for calculation of Risk (Level 2.1).

In Table 13, the details of the results obtained by static and dynamic simulations are reported. It can be observed that the PLL from the static calculation has been reduced by approximately 24% from 2.34 (Level 1) to 1.773 (Level 2.1).

Table 13 PLL level 2.1 – Ship #1

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	8.715	8.925	8.715	8.925	8.715	8.925	
PLL L1 (1/ship year) (static assessment)	**2.57E-01**	**3.04E-01**	**5.33E-01**	**5.55E-01**	**3.36E-01**	**3.54E-01**	**2.3400**
	0.5611		**1.0880**		**0.6909**		
Number of filtered damage cases	50	62	131	155	47	55	500
Capsize cases or steady heel>30deg - TTC<30min	9	14	25	25	0	1	74
Capsize cases or steady heel>30deg - TTC>30min	5	3	19	24	3	3	57
Survived cases	36	45	87	106	44	51	369
PLL L2.1 (1/ship year) (dynamic assessment)	**2.06E-01**	**2.43E-01**	**3.68E-01**	**3.73E-01**	**2.87E-01**	**2.96E-01**	**1.7730**
	0.4482		**0.7417**		**0.5831**		
PLL L2.1 vs L1 (variation percentage)	**-20.1%**		**-31.8%**		**-15.6%**		**-24.2%**

In the following figures, the diagrams for the characteristics of the breaches, which lead to capsize after dynamic simulations, are reported.

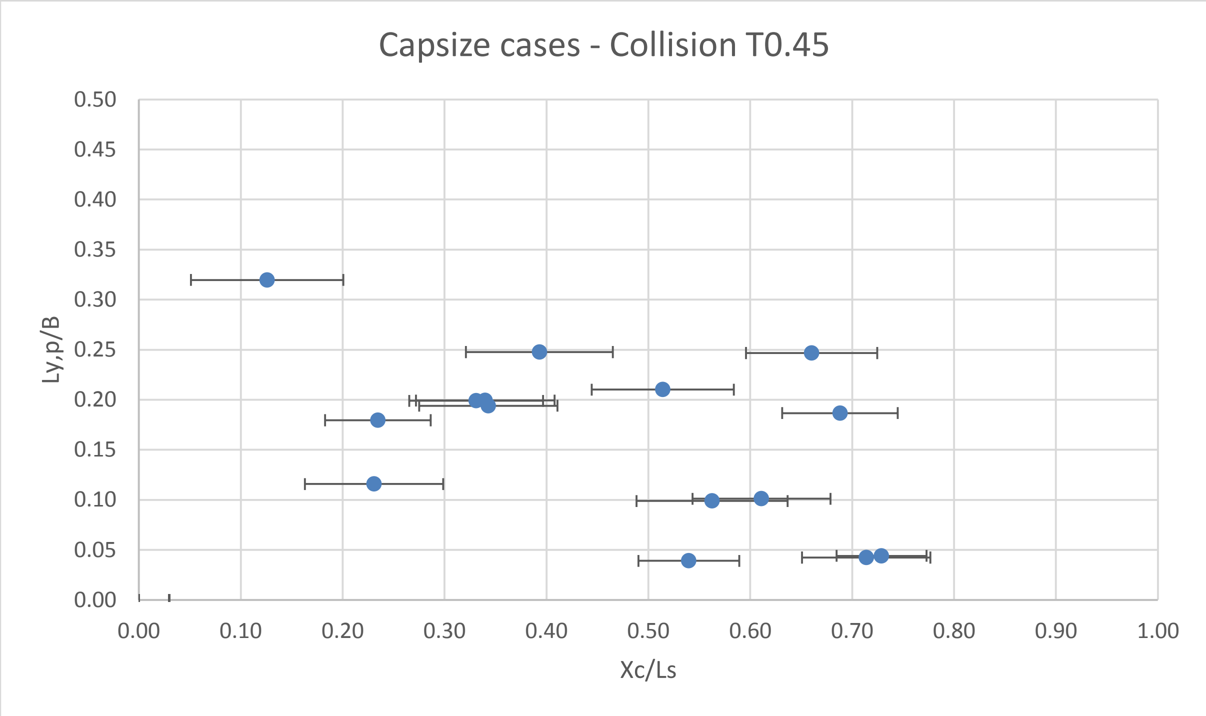


Figure 25 Collision characteristics leading to capsize T0.45 – Ship #1

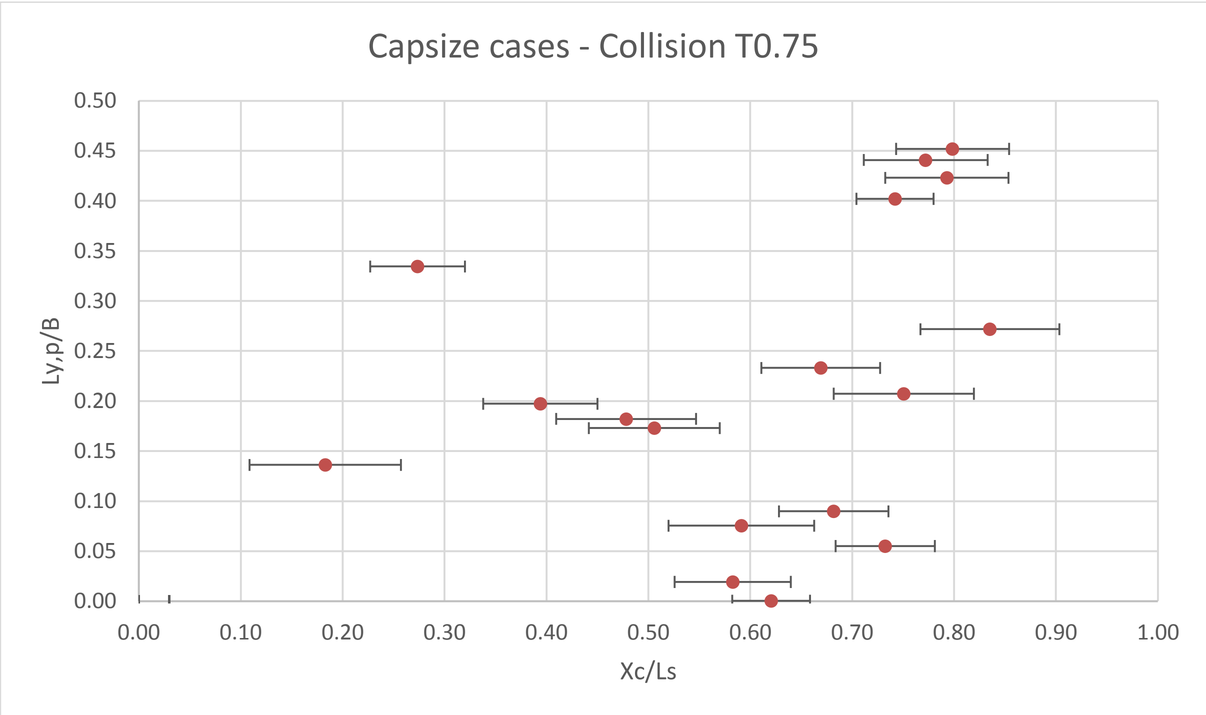


Figure 26 Collision characteristics leading to capsize T0.75 – Ship #1

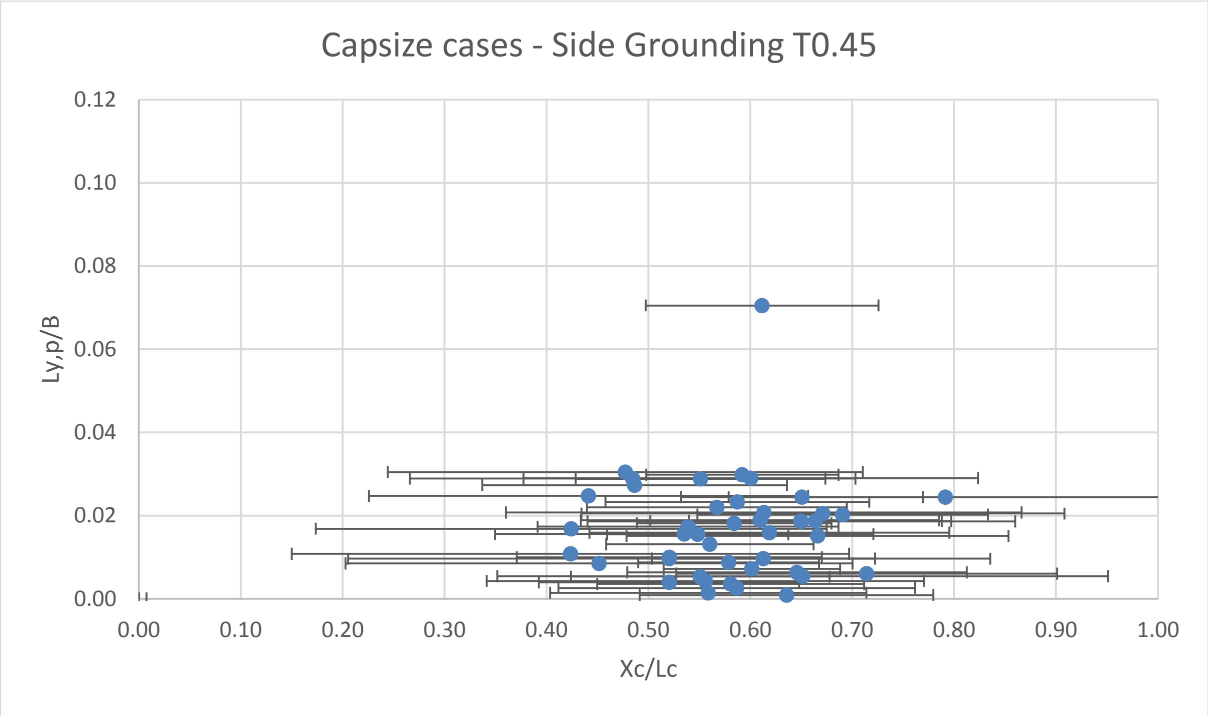


Figure 27 Side grounding breaches leading to capsize T0.45 – Ship #1

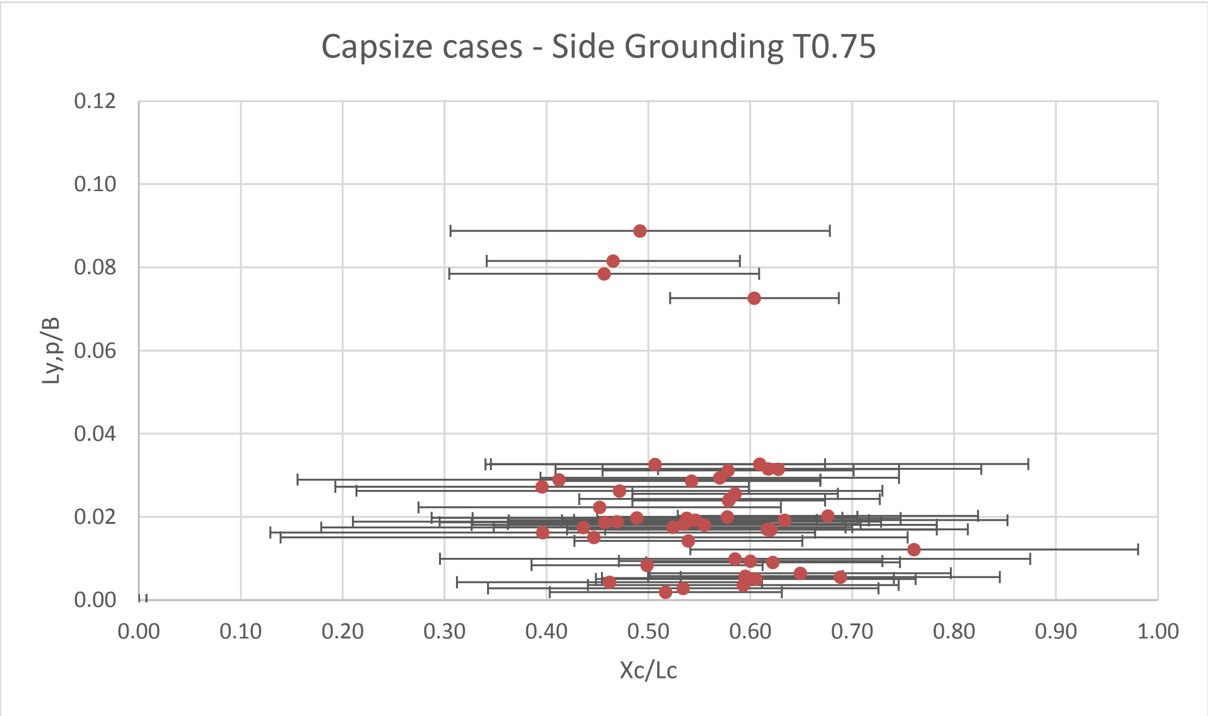


Figure 28 Side grounding breaches leading to capsize T0.75 – Ship #1

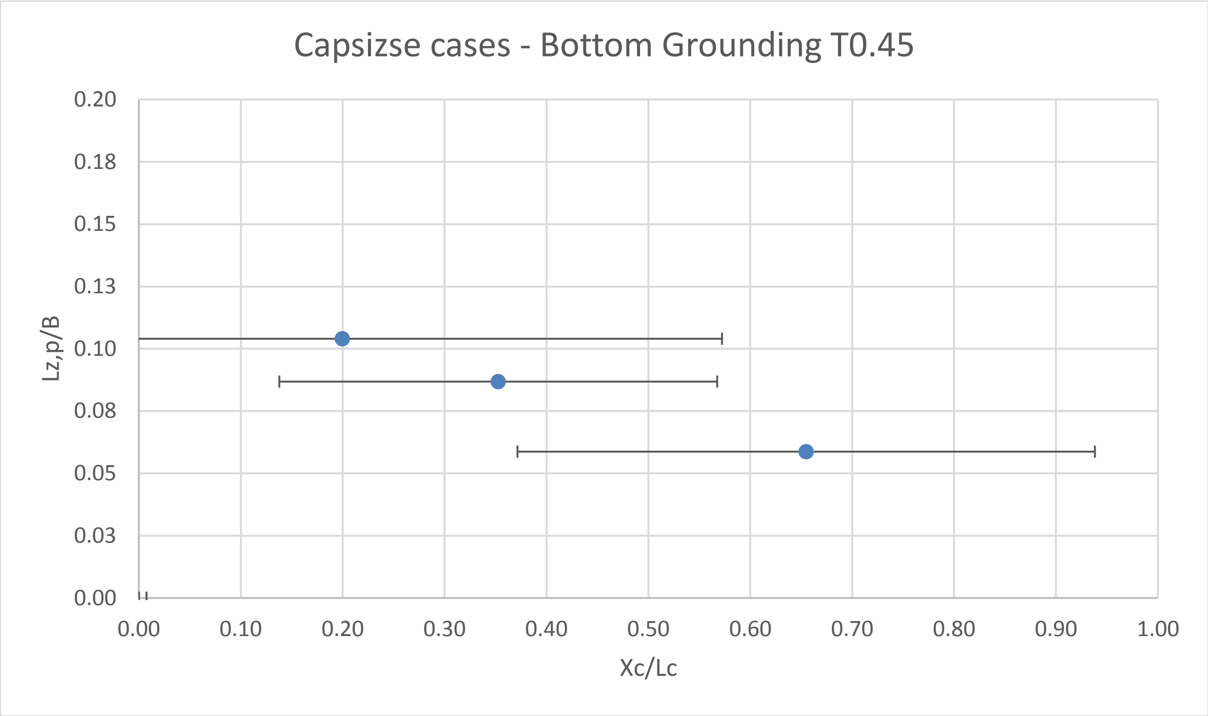


Figure 29 Bottom grounding breaches leading to capsize T0.45 – Ship #1

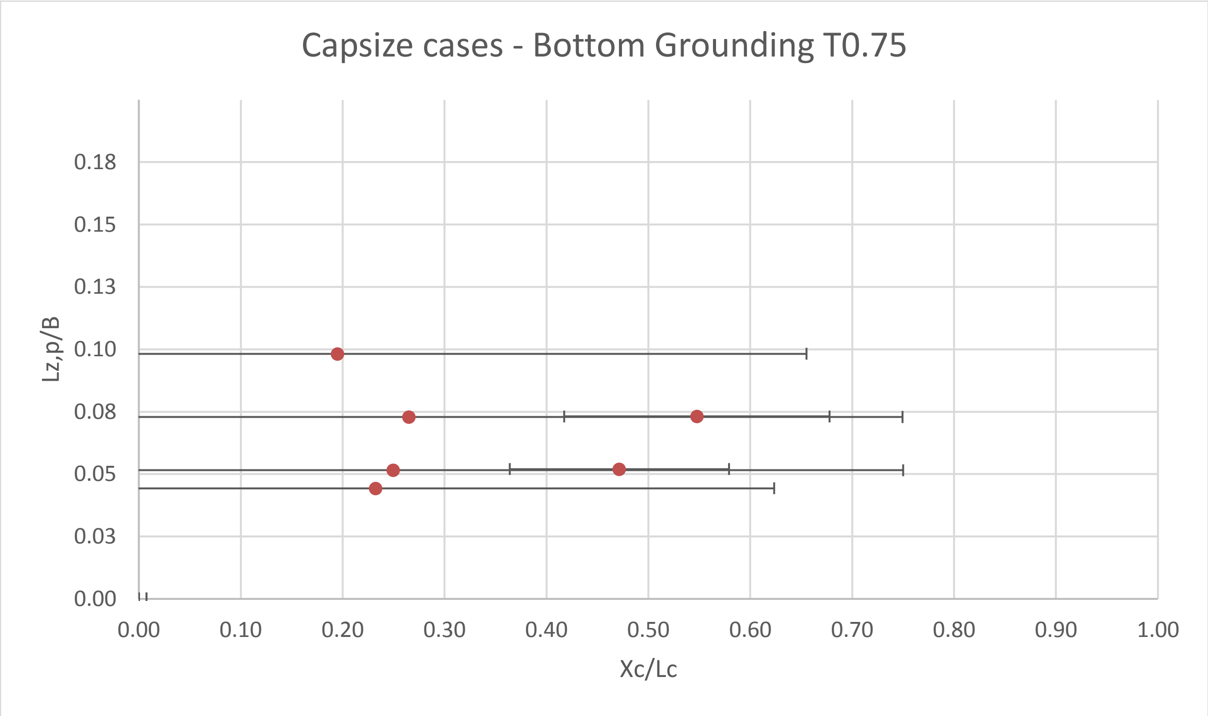


Figure 30 Bottom grounding breaches leading to capsize T0.75 – Ship #1

The identified capsizal cases showed from the Figure 25 to Figure 30 may be investigated in WP7.2 when Risk Control Options are to be implemented.

2.4 Sensitivity analysis of the fatality rate

From the dynamic simulation results, it has been observed that 57 cases resulted into a TTC greater than 30 minutes but lower than 90 minutes. For those cases, linear Interpolation between 0% and 80% has been used for the estimation of the fatality rates. Furthermore, there are further 105 cases where progressive flooding is still occurring after 90 min and for these cases, no fatalities have been assumed (Figure 31).

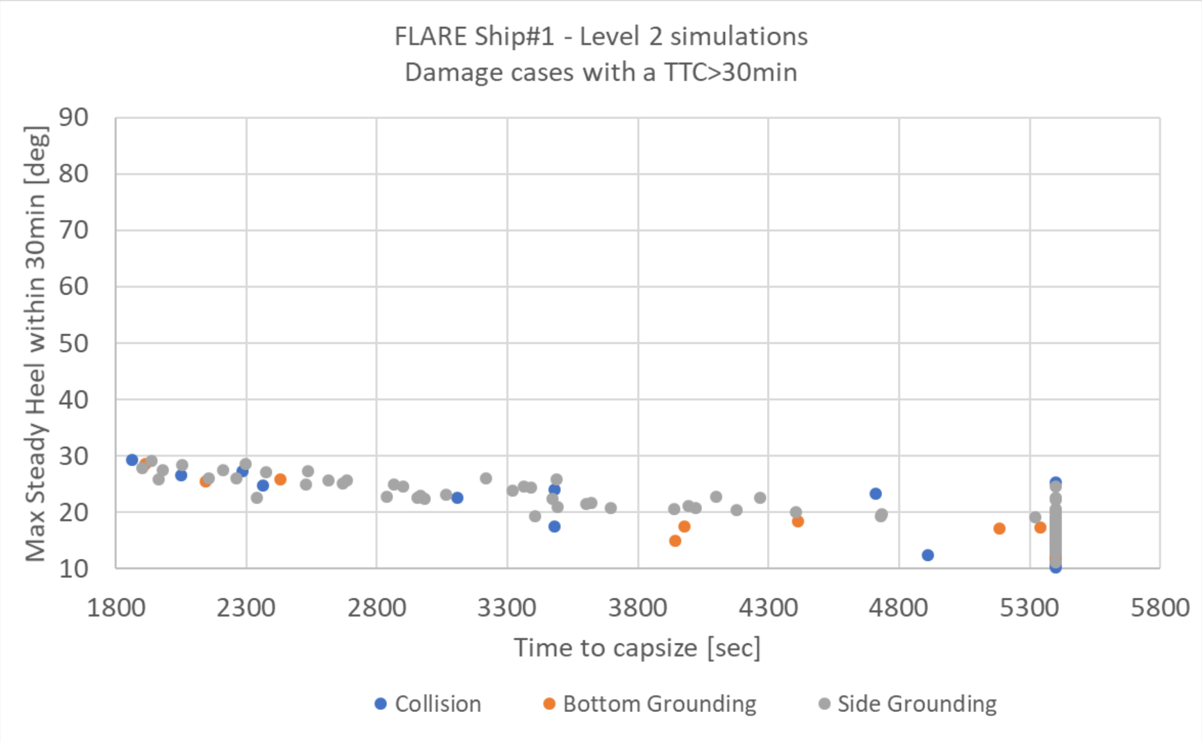


Figure 31 Cases with TTC>30min or progressive flooding still occurring after 90min – Ship #1

With the aim to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out on the total 162 cases (with TTC > 30 min or progressive flooding still occurring after 90 min). For such purpose, the impact on the PLL has been evaluated in case of variation of the fatality rate by ±30% of the POB.

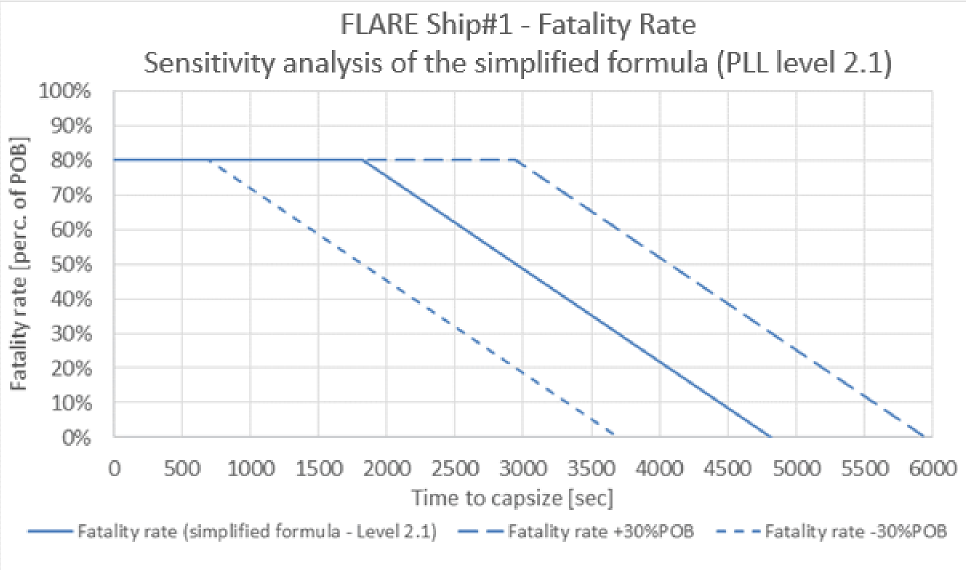


Figure 32 Sensitivity analysis of simplified formula for fatality rate calculation – Ship #1

The calculation with +30% in the fatality rate resulted into a PLL of 1.795 (+1.2% compared to the reference PLL) while the calculation with -30% for the fatality rate resulted into a PLL of 1.7482 (-1.4% compared to the reference PLL). These values demonstrated that for this ship the simplified formula to derive the fatality rate used in the calculation of risk (Level 2.1) has a low impact on the PLL because PLL is mainly based, for this ship, on the scenarios leading to fast capsize.

3 CONCLUSIONS

The complete procedure for calculation of Risk has been applied on Ship #1 and the results obtained demonstrated that the procedure is coherent with the multi-level approach. In fact, the PLL has been reduced from 2.340 (level 1) to 1.773 (level 2.1).

The PLL Level 1 is conservative, but it seems more robust than PLL calculated by EMSA3 Risk Model as the fast/slow sinking node has not been used in the FLARE procedure.

The Dynamic analysis in level 2 leaded to a reduction of the PLL by about 24% with the simulation of 500 breaches. Such reduction of the PLL is essentially based on the fact that about 74% of cases have been found to survive in the dynamic analysis while they had sfac = 0 in the static analysis.

Furthermore, a sensitivity analysis demonstrated that the impact on the PLL level 2.1 by even a large deviation of the fatality rate (calculated with the simplified formula) is negligible.

The flooding simulations showed that 56% of the capsizes were fast capsize cases (TTC < 30min) and 44% were discovered slow capsize cases (TTC > 30min). This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model for which only 18% capsizing rate was used.

ANNEX 4 – Calculation of the flooding Risk for Ship n.2

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a large cruise ship design. As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1). The refined model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

1 STATIC ASSESSMENT

1.1 Main data

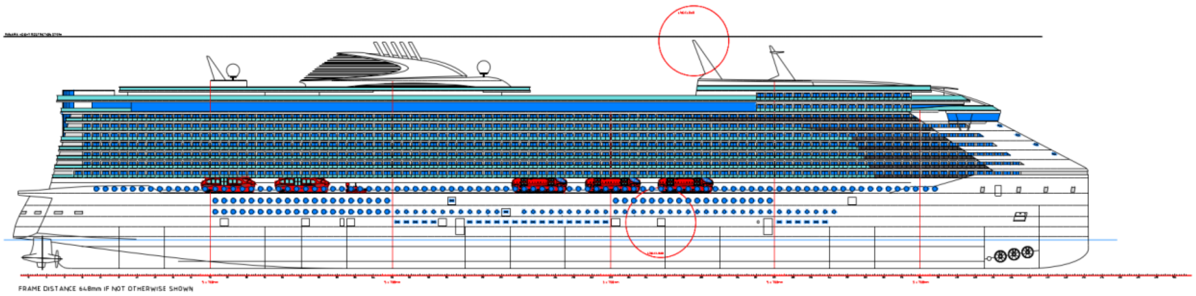


Figure 1 Profile view – Ship #2

Ship #2 is a large modern cruise vessel with liquefied natural gas as prime fuel for worldwide operation. Here following the main characteristics:

Table 1 Main characteristics – Ship #2

Length over all	~308 m
Length between perpendiculars	299.4 m
Subdivision length	307.7 m
Breadth	39.8 m
Subdivision draught	8.5 m
Height of bulkhead deck	11.8 m
Number of passengers (double occupancy) Number of passengers (max.)	3238 3640
Number of crew	1300
Gross tonnage	130000 GT
Deadweight	10200 t
No of pax cabins	1619
Service speed	22 knots
Installed propulsion power	39000 kW
Installed power of main engines	55050 kW

The business model and detailed description of the vessel are included in deliverable D.2.1.5.

Here following the Attained and Required Index according to SOLAS 2020 ch.II-1:

Number of persons	POB = 4940
Required subdivision index	R = 0.8935
Attained subdivision index	A = 0.90668

1.2 Static calculations with new draughts and permeabilities

The following diagram is showing the draughts and the calculated GM for this vessel based on Ch. 3.1 of the main report.

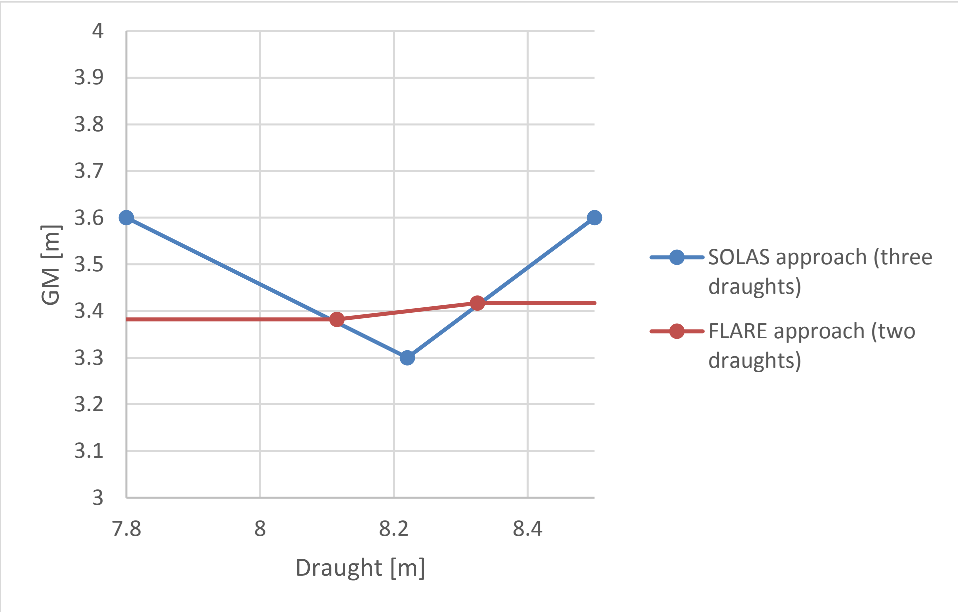


Figure 2 GM limiting curve with new FLARE draughts – Ship #2

The calculation has been executed with the software NAPA rel.2020.2-1, using the NEI approach for A-Class bulkheads and generating damages up to 5 adjacent zones.

These observations led to an attained index A = 0.913 (with reference to the SOLAS A index +0.6%).

Table 2 Static results with new draughts and permeabilities acc. to FLARE – Ship #2

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	8.115	3.382	0.9151	0.25	0.2288	0.913
T0.75	8.325	3.417	0.9109	0.25	0.2277	

1.3 Non-zonal static analysis

With the refined model according to the FLARE modelling guidelines (Annex 1) an increase of number of rooms and connections has been generated (Table 3).

Table 3 Comparison between simplified model and refined model – Ship #2

Description	Before modelling	After modelling
Damhull volume	170712 m^3	170713 m^3
Rooms number	247	405
Connections number	82	299

For this ship the U-shaped void spaces within the DB were already subdivided in the CL with cross-flooding opening defined, hence there was no change for these void spaces in the new model.

The updated model includes new direct connections between cabin areas and corridors (for B-class boundaries) and between the parts of U-shaped voids above the double bottom. Moreover, new smaller A-class spaces that would impact the flooding have been modelled and provided with A-class connections accordingly.

The subdivision table is also affected by minor changes in order to consider also the damage cases that involve new rooms.

However, considering the refined model and using NAPA, a slightly lower value for the Attained Index (-0.6%) resulted.

Table 4 Static results with refined model – Ship #2

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	8.115	3.382	0.9062	0.25	0.22655	0.90682
T0.75	8.325	3.416	0.9074	0.25	0.22685	

1.3.1 Non-damage area

In the reference subdivision table, used for the zonal calculation, a "NON-DAMAGE AREA" was defined in the central part of the ship. This is used to route pipes generating progressive flooding that may not be controlled by remote control valves

Since the non-zonal analysis does not take into account the subdivision table, it is very important to define a virtual room to simulate that "NON-DAMAGE AREA".

That room is assumed having a permeability equal to zero and an unprotected opening in connection with the DAMHULL room in its lowest point at frame #72 has been defined too. The purpose of this definition is to make sure that every time a breach from collision or side/bottom grounding involves the "NON-DAMAGE AREA", such opening should be considered relevant by the used NAPA software and therefore the Sfac is set to zero.

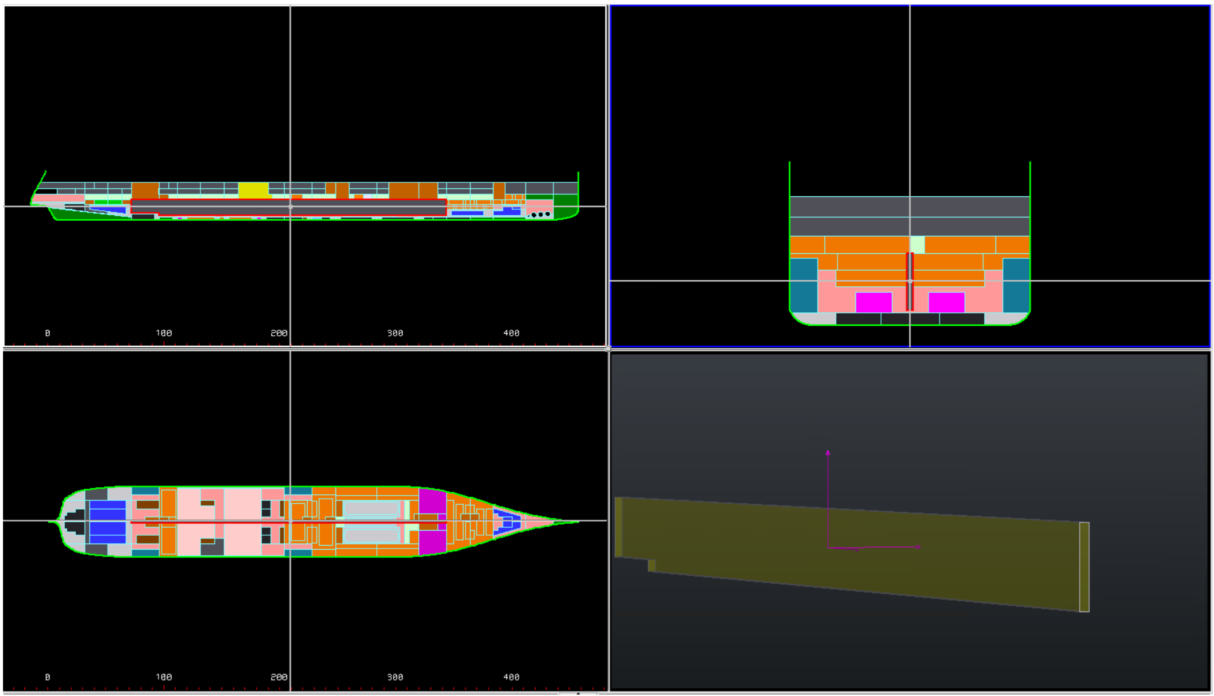


Figure 3 Defined room for *NON-DAMAGE AREA* in the non-zonal approach by NAPA – Ship #2

1.4 Calculation of PLL level 1

For this vessel breaches for collision, side and bottom grounding have been generated according to Ch. 3.2 of the main report and the grouping of breaches, leading to the same sets of flooded rooms, permitted to reduce the damage cases to be calculated by abt. 69% for collision and bottom grounding, and by abt. 80% for side grounding.

With the results of the static calculation for the attained index in hand, the PLL level 1 was calculated according to procedure described in Ch.2.4-2.5 of the main report. In particular in the Table 5 the non-zonal results are showed and in Table 6 the PLL (Potential loss of life) calculation is reported.

Table 5 Non-zonal static analysis results – Ship #2

Damage Type	Collision		Side Grounding		Bottom Grounding	
Initial condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75
Draught	8.115m	8.325m	8.115m	8.325m	8.115m	8.325m
Breaches	10000	10000	10000	10000	10000	10000
Number of Empty cases	5	3	15	15	154	143
Number of Unique damage cases	3142	3111	1992	2019	3142	3139
Partial Index	0.9518	0.9497	0.9300	0.9317	0.9397	0.9392
Total Attained Subdivision Index A_i	**0.95075**		**0.93085**		**0.93945**	

Table 6 PLL level 1 – Ship #2

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		4.33E-03
Relative frequency	0.388		0.328		0.284		1.000
Initial condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	8.115	8.325	8.115	8.325	8.115	8.325	
Attained Index	0.9518	0.9497	0.9300	0.9317	0.9397	0.9392	0.9410
$\sum pfac$ (for cases with s=1)	0.9061	0.8908	0.9060	0.9066	0.9286	0.9261	0.9092
$\sum pfac \cdot (1 - sfac)$	0.0482	0.0503	0.0700	0.0683	0.0603	0.0608	0.0590
PLL level 1 (1/ship year)	1.60E-01	1.67E-01	1.96E-01	1.92E-01	1.47E-01	1.48E-01	1.0091
	0.3269		0.3878		0.2944		

Although the PLL is the parameter to be used for the risk measurement, the Combined Attained Index is showed in Table 6 for information only, too. That value is calculated by using the relative frequency for collision, side grounding/contact and bottom grounding.

1.5 Filtering of static results and selecting cases for dynamic simulations

The screening of the static result according to filtering criteria identified within Ch. 3.4 of the main report permitted to select 500 cases for the dynamic simulations. In the following table a summary of the filtered breaches is reported.

Table 7 Filtering results – Ship #2

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Initial condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	8.115m	8.325m	8.115m	8.325m	8.115m	8.325m	
Number of filtered damage cases	54	231	103	101	8	3	500
$\sum pfac$ (for the filtered damage cases)	0.0162	0.0320	0.0282	0.0251	0.0018	0.0006	0.0184
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0121	0.0292	0.0264	0.0241	0.0018	0.0006	0.0166
Potential PLL (if the ships would not capsize for all selected cases)	1.20E-01	7.01E-02	1.22E-01	1.24E-01	1.42E-01	1.46E-01	0.7247
	0.1899		0.2464		0.2885		
Potential PLL reduction (if the ships would not capsize for all selected cases)	41.9%		36.5%		2.0%		28.2%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. In particular for this ship the PLL would be reduced by about 28% if all the cases to be simulated are not capsizing.

In the following diagrams some typical damage parameters of the selected breaches are presented in non-dimensional form.

It is very interesting to note that for collision there are two vulnerable area: the aft compartments and the compartments just forward the main engine rooms. A large majority of selected breaches for side grounding has a huge length therefore they affect a high number of compartments.

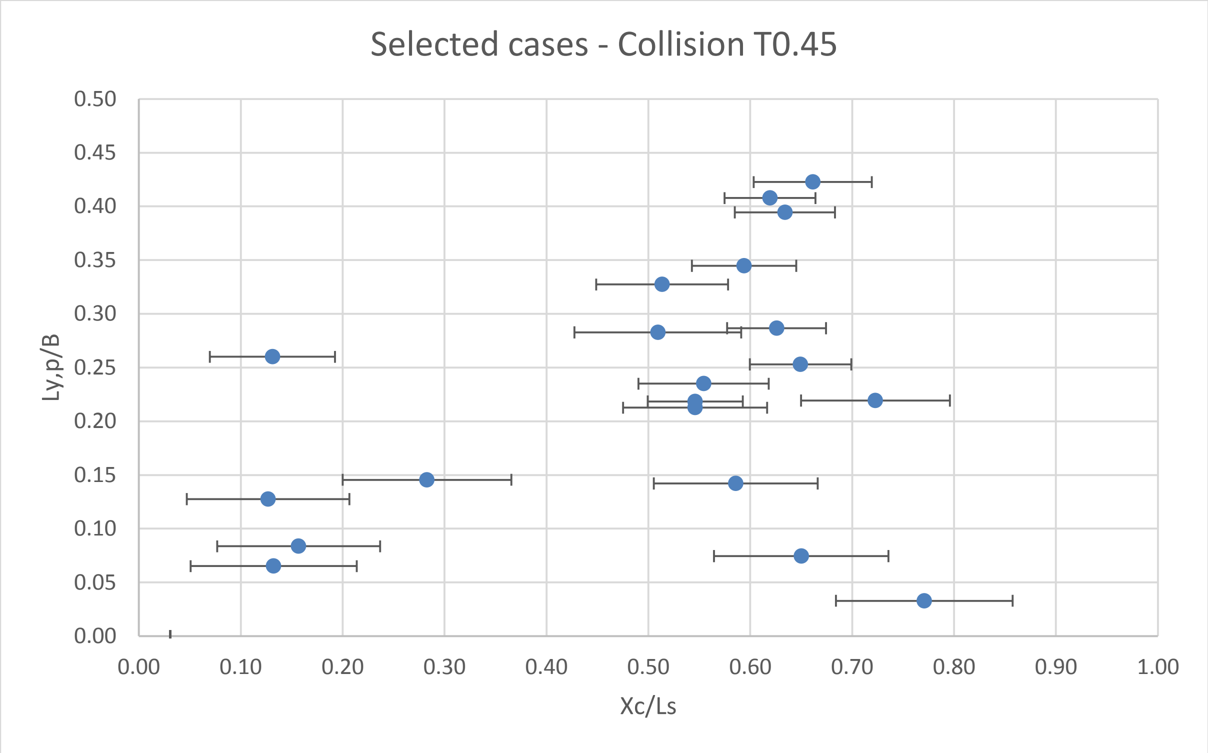


Figure 4 Selected collision breaches T0.45 – Ship #2

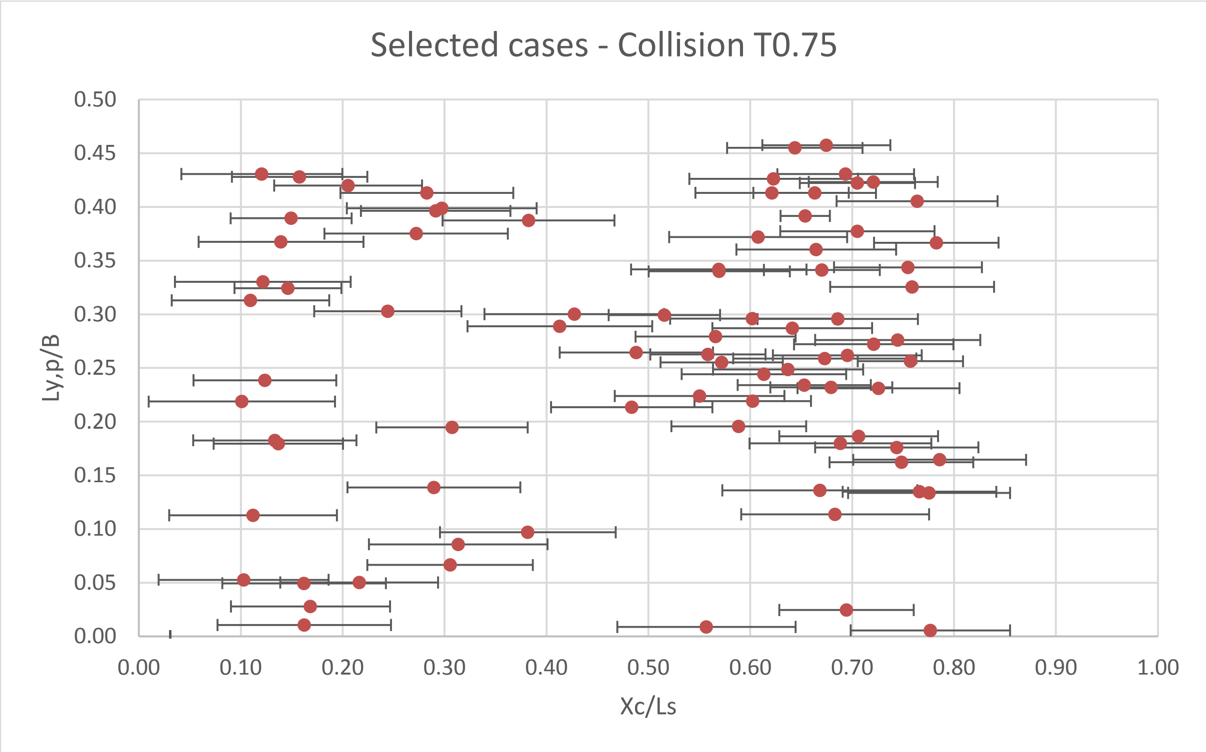


Figure 5 Selected collision breaches T0.75 – Ship #2

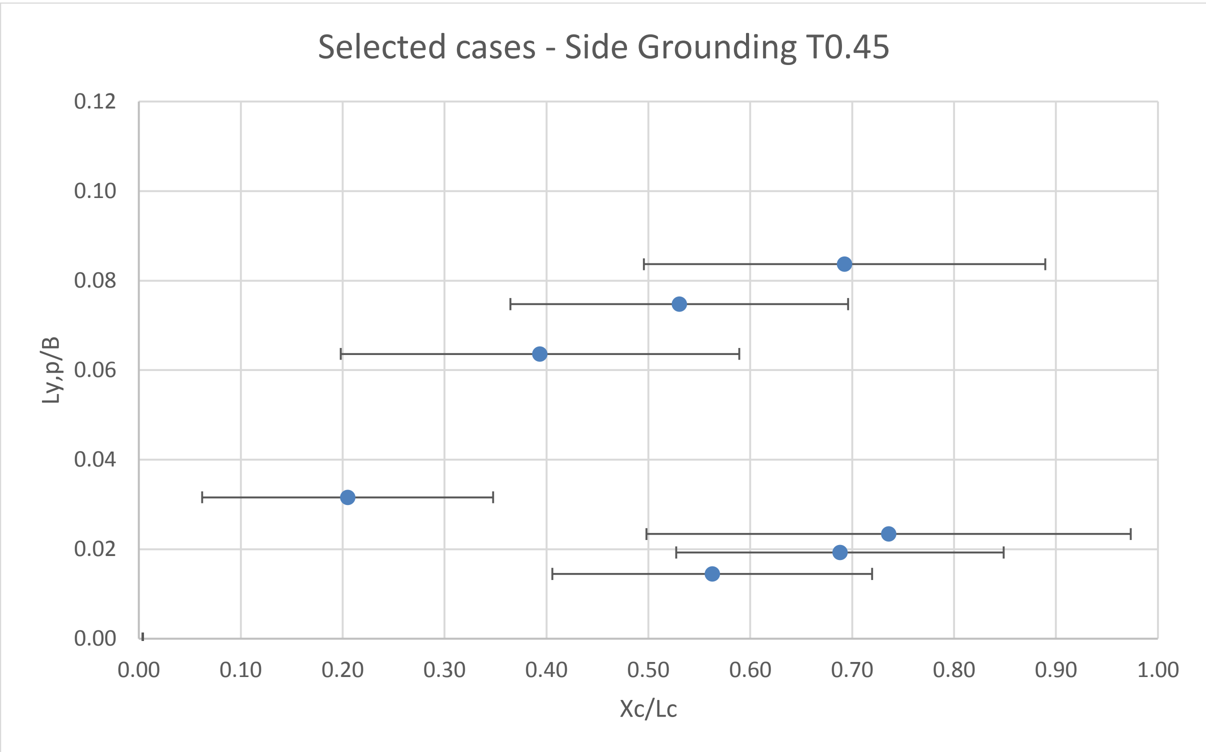


Figure 6 Selected side grounding breaches T0.45 – Ship #2

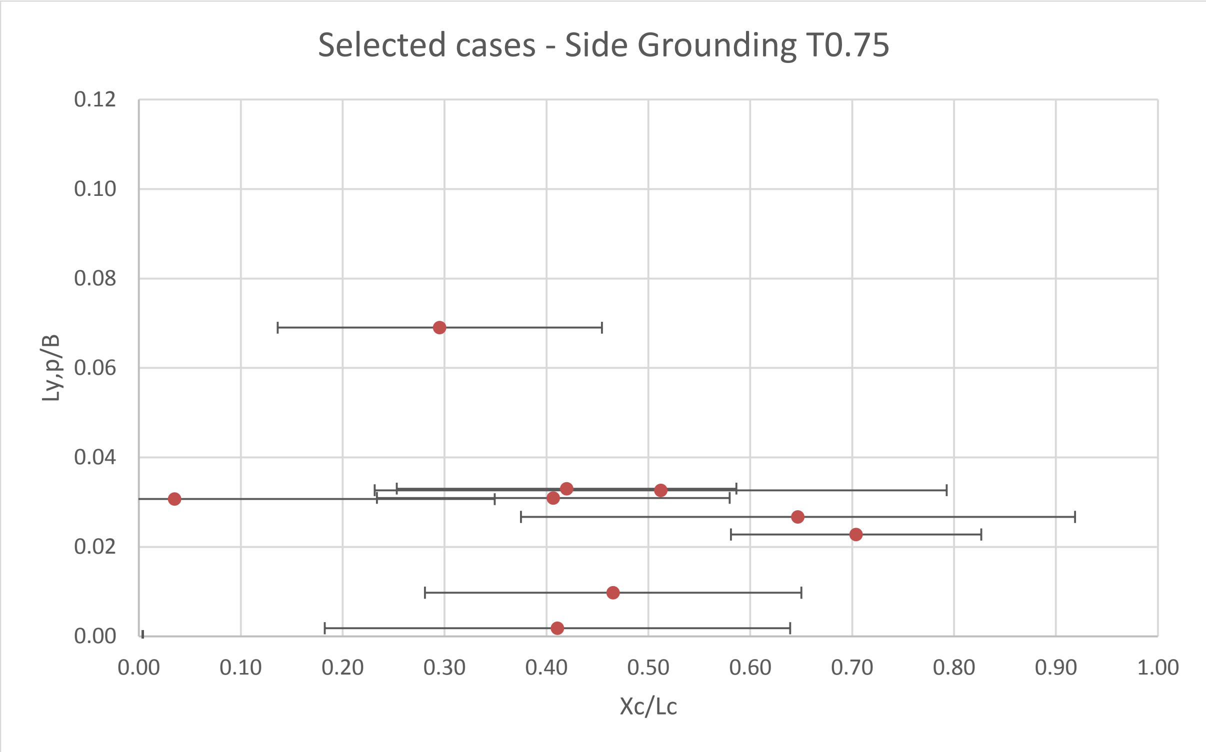


Figure 7 Selected side grounding breaches T0.75 – Ship #2

For the bottom grounding, instead, are just few filtered breaches, this is due to the fact the ship survives when only the double bottom is affected by flooding. Hence only those case with a vertical penetration higher than the double bottom height and with a high value *freq*pfac*(1-sfac)* are selected.

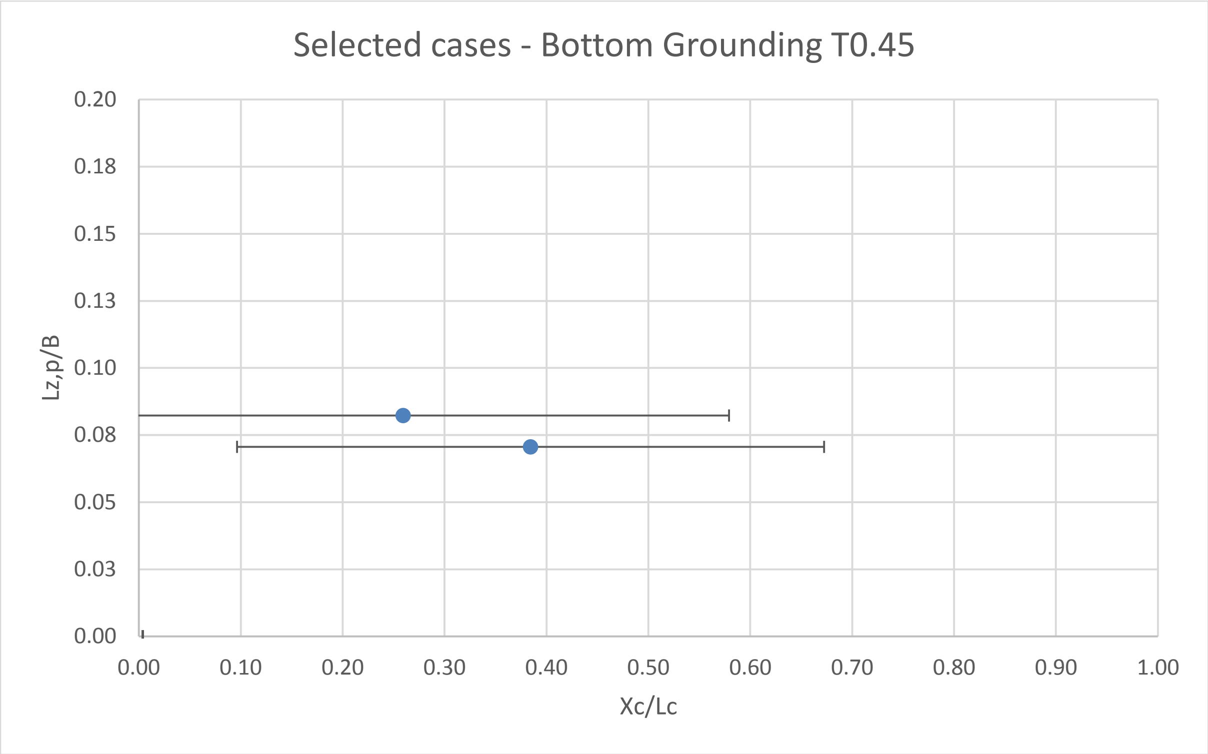


Figure 8 Selected bottom grounding breaches T0.45 – Ship #2

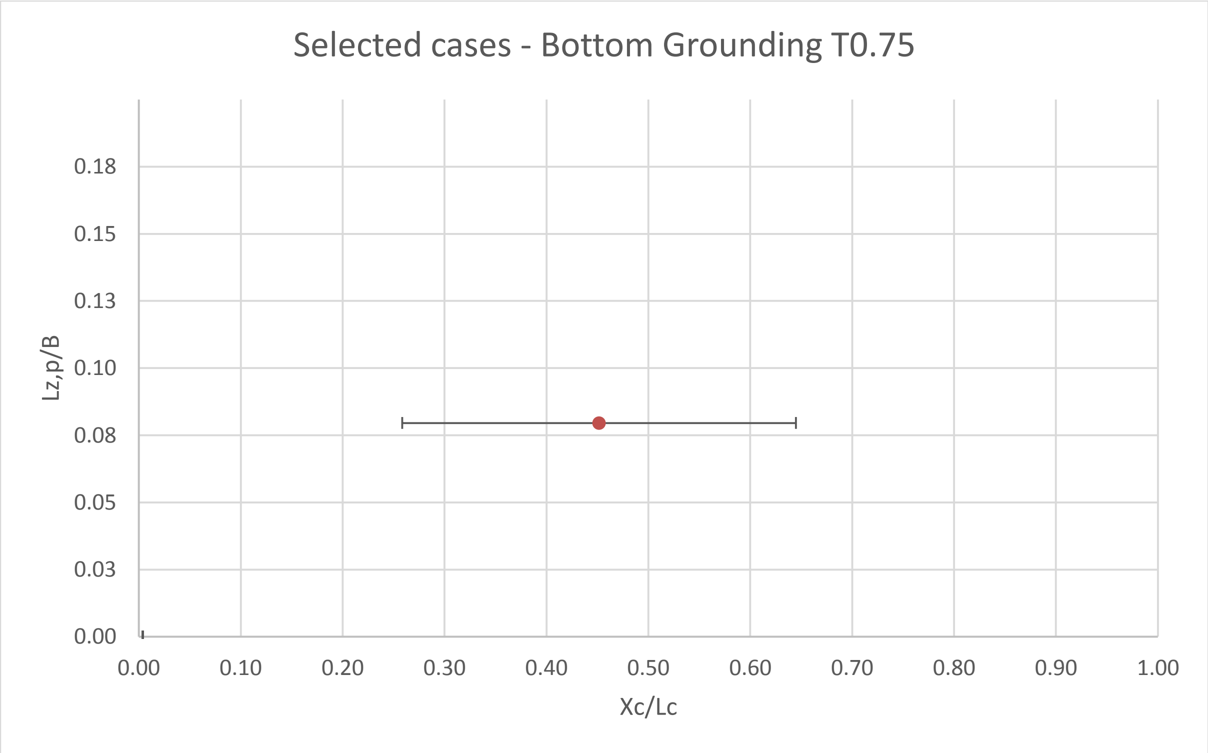


Figure 9 Selected bottom grounding breaches T0.75 – Ship #2

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with Sfac = 0 and failure modes for cases with 0 < Sfac < 1, are showed in the following tables.

Table 8 Breakdown of failure mode for Sfac=0 cases – Ship #2

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	9	53	12	17	0	0	91
Heeling Angle (>15 deg)	14	65	16	16	6	3	120
Smom=0	0	50	39	41	1	0	131
Opening immersion	10	52	15	18	1	0	96
Sfac=0 - Total cases	**33**	**220**	**82**	**92**	**8**	**3**	**438**

Table 9 Breakdown of failure mode for 0<Sfac<1 cases – Ship #2

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	6	0	2	1	0	0	**9**
Insufficient Range	0	0	0	0	0	0	**0**
Heeling Angle (>7 deg)	4	2	0	0	0	0	**6**
Insufficient Restoration (GZmax) + Range	1	0	7	6	0	0	**14**
Insufficient Restoration (GZmax) + Excessive Heel	0	0	10	0	0	0	**10**
Insufficient Range + Excessive Heel	9	8	0	1	0	0	**18**

Insufficient Restoration (GZmax) + Range + Excessive Heel	1	1	2	1	0	0	**5**
0<Sfac<1 - Total cases	**21**	**11**	**21**	**9**	**0**	**0**	**62**

A large percentage of captured cases resulted into Sfac = 0 (438 cases out of 500) and about 90% of the captured cases had a failure mode corresponding to a heeling angle greater than 15 deg. This occurred for collision and side grounding essentially as these breaches type lead to a big asymmetry in the flooding scenario.

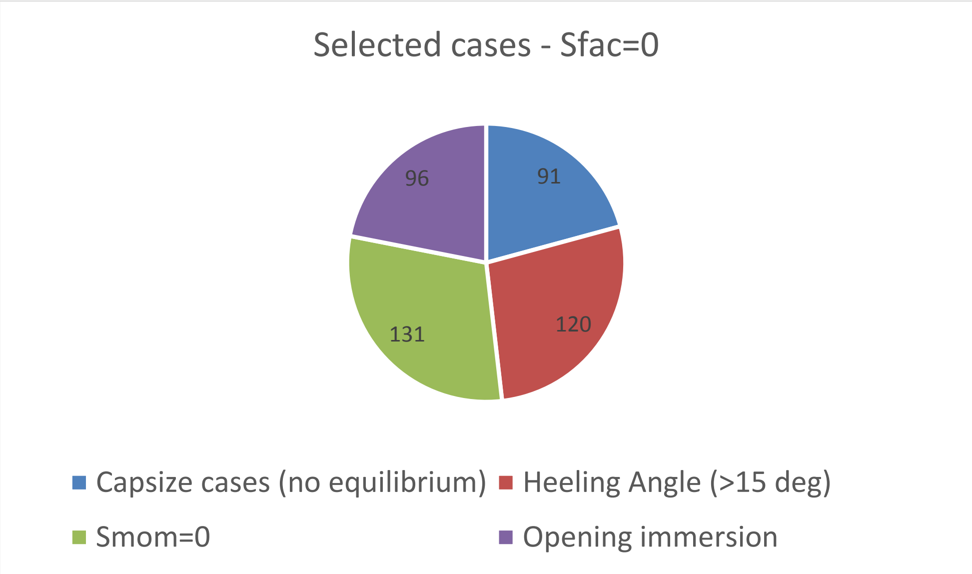


Figure 10 Diagram of failure mode for Sfac = 0 cases – Ship #2

A lot of damage cases (131) with Smom = 0 have been found, too, while the equilibrium was not reached in the static calculation for 91 cases.

In the majority of the cases where equilibrium was not achieved the failure was found at the first stage of flooding when the cross-flooding is not started yet. That stage is not used to calculate the survivability factor s but it is requested by the explanatory notes of SOLAS Ch.II-1 that a positive GZ is achieved at that stage in order to calculate the cross-flooding time. It will be very important to assess those cases by dynamic simulations so that the real physics of the phenomenon will be investigated.

Finally, 96 cases have been identified due to the immersion of openings. These cases are very important to be selected too as it is expected that the outcome of the dynamic simulation should be quite different. In fact, the approach for connections and openings definition is completely different between static and dynamic calculation.

A limited number of damage cases with 0 < Sfac < 1 have been selected and the majority of these cases resulted in an insufficient GZmax and excessive Range, then eighteen cases resulted in an insufficient Range and excessive heeling angle too. And six cases resulted in a heeling angle (>7 deg).

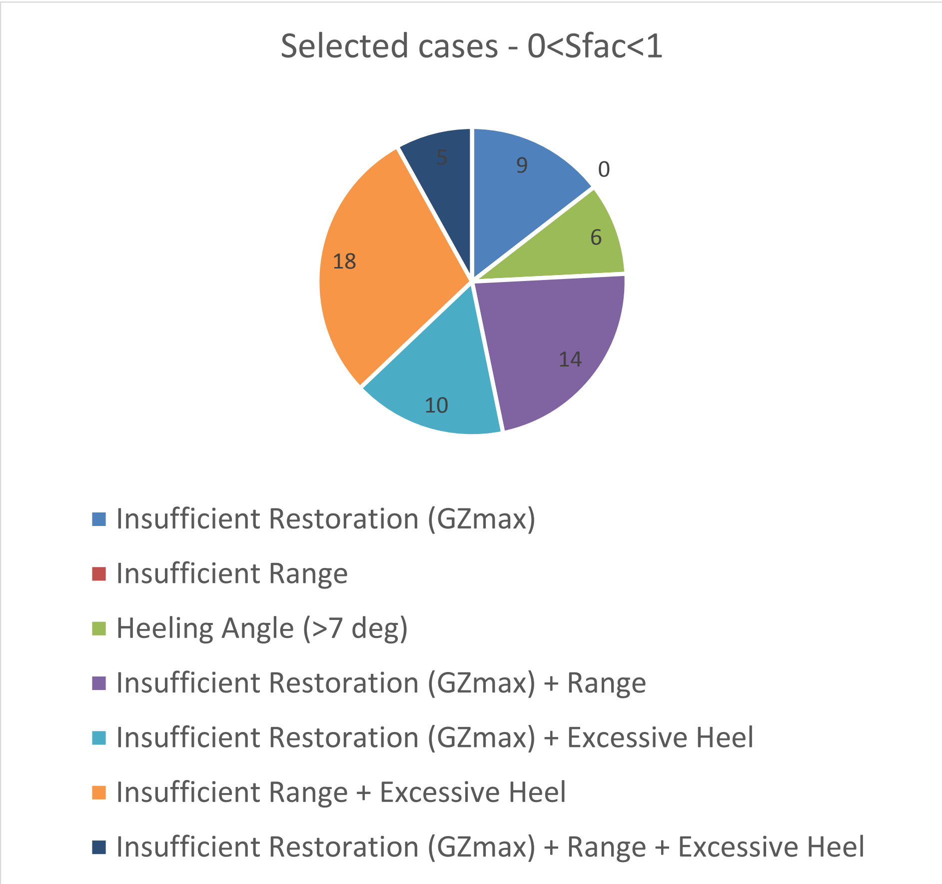


Figure 11 Diagram of failure mode for 0 < Sfa c< 1 cases – Ship #2

2 DYNAMIC ASSESSMENT

2.1 Preparation of the PROTEUS model

The dynamic analysis has been carried out by use of the software *PROTEUS* (last release distributed in November 2021). In particular for the preparation of the model the tool Proteus Manager has been used.

To generate in the Proteus Manager the loading conditions defined in NAPA and corresponding to the two calculation draughts at 45% and 75%, the following ship weights have been generated:

$T_1 = 8.115$ m $\rightarrow$ LIG_1 [Δ=62,960 t ; CG (136.00 , 0 , 20.55) m]

$T_2 = 8.325$ m $\rightarrow$ LIG_2 [Δ=65,126 t ; CG (135.78 , 0 , 20.28) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at seven different deck slices:

DB=1.99 m ; D1=2.01 m ; D2=6.31 m ; D3=9.11 m ; D4=11.91 m ; D5=14.81 m ; D6=18.01 m

For this big cruise ship a total of 591 openings have been defined. Horizontal openings have been defined on the higher deck of the model to capture the down-flooding through engine casings, stair trunks, vertical escape and lifts.

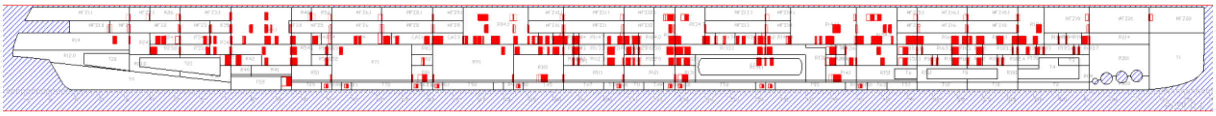


Figure 12 – Openings imported in Proteus Project (longitudinal section)– Ship #2

Table 10 Opening Types in Proteus Manager

TYPE	Leak Area Rat 1 to 2	Leak Area Rat 2 to 1	Collapse Pressu 1 to 2 [meters]	Collapse Pressu 2 to 1 [meters]	Leak Heigh [meters]	Gap Heigh [meters]	Effective Heigl HEff Switch	Open At Tir [seconds]	Close At Tim [seconds]
CONNECTION	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
B-CLASS-JOINER	0.00000	0.00000	1.50	1.50	0.000	0.000	False	0	999999
FDOOR-A-HINGED	0.00000	0.00000	2.50	2.50	0.000	0.000	False	0	999999
FDOOR-A-SLIDING	0.00000	0.00000	1.00	1.00	0.000	0.000	False	0	999999
FDOOR-A-DOUBLELEAF	0.00000	0.00000	2.00	2.00	0.000	0.000	False	0	999999
COLDROOM-DOOR	0.00000	0.00000	3.50	3.50	0.000	0.000	False	0	999999
LIFT-DOOR	0.00000	0.00000	1.50	1.50	0.000	0.000	False	0	999999
SWT-DOOR	0.00000	0.00000	10.00	10.00	8.000	0.000	False	0	999999
WT-DOOR	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
WT-DOOR_LBHD	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
SHELL-DOOR_LARGE	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
SHELL-DOOR_NORMAL	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
New...									

Since in Proteus the discharge coefficient for the holes is set to 0.6 and it may be not changed, the area of the cross-flooding openings has been reduced in order to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation sets have been created and the comparison of the geometric and hydrostatic data between NAPA and Proteus showed that the differences are negligible in general (from Figure 13 to Figure 19 and Table 11).

To be noted that the ship was originally defined with left-handed coordinate system in NAPA but then it has been changed into right-handed when the model has been imported in Proteus. This generated some false warning when checking the tolerance in the differences for trim and TCG between NAPA and Proteus.

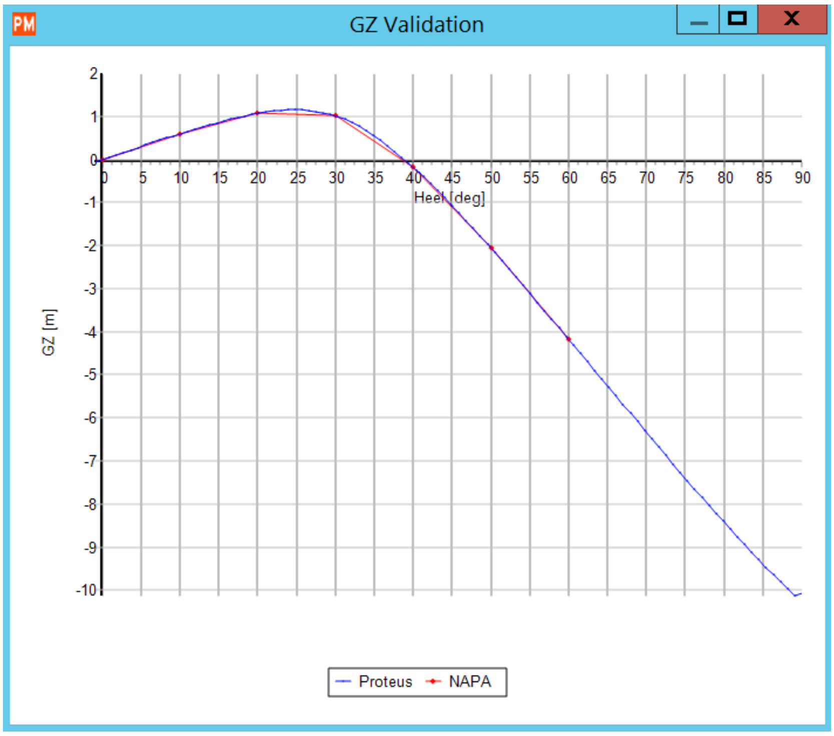


Figure 13 – GZ comparison between NAPAand Proteus – Ship #2

Table 11 – Floating Position comparison between NAPA and Proteus – Ship #2

Loadcase Validation

GZ Curve | Floating Position | Volume and CGs | Section Areas

Floating Position

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	8.115	8.119	-0.004	-0.049
TA [m]	8.116	8.123	-0.007	-0.086
TF [m]	8.114	8.115	-0.001	-0.012
Trim [deg]	0.002	0.008	-0.006	0.000
Heel [deg]	0.000	0.000	0.000	0.000
KM [m]	23.933	23.992	-0.059	-0.247
KG [m]	20.554	20.550	0.004	0.019
GM0 [m]	3.379	3.438	-0.059	-1.746
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	3.379	3.438	-0.059	-1.746

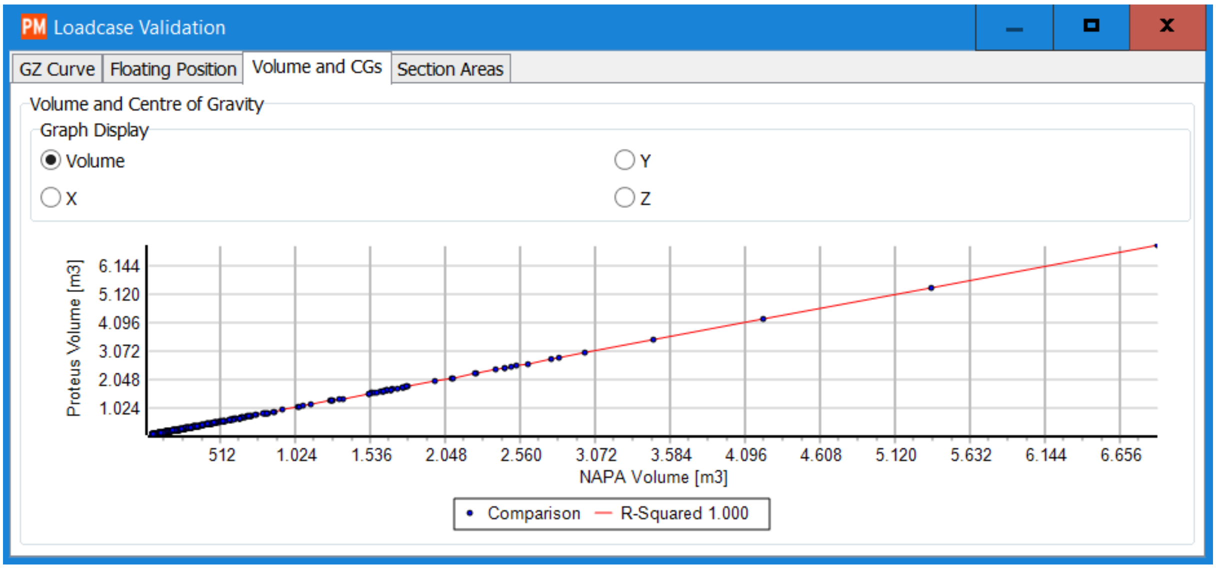


Figure 14 – Hull volume comparison between NAPA and Proteus – Ship #2

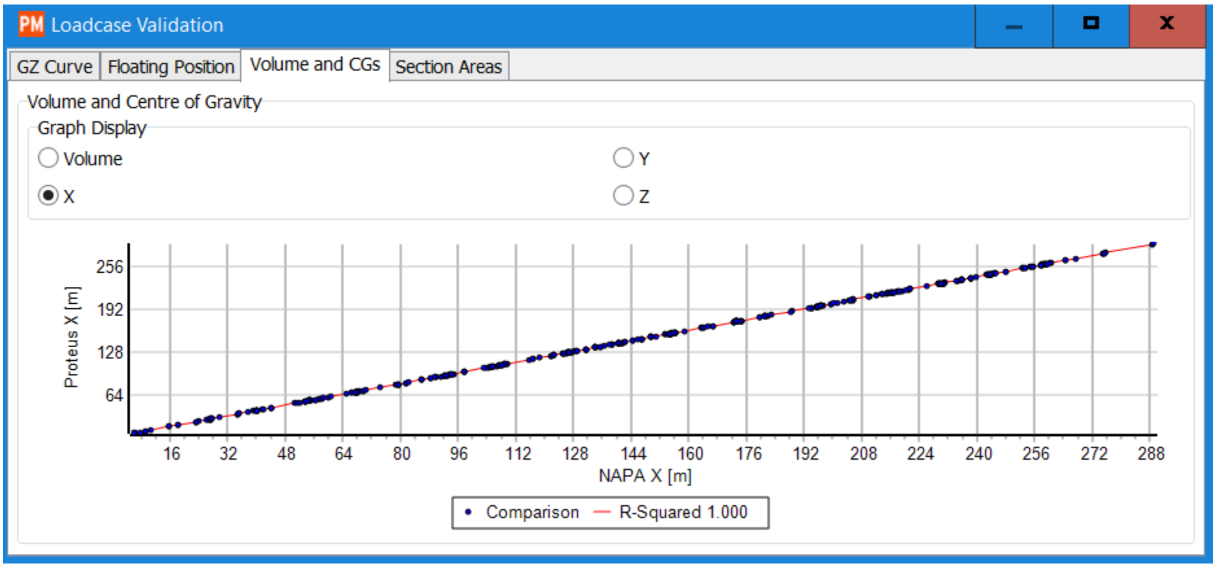


Figure 15 – Hull LCB comparison between NAPA and Proteus – Ship #2

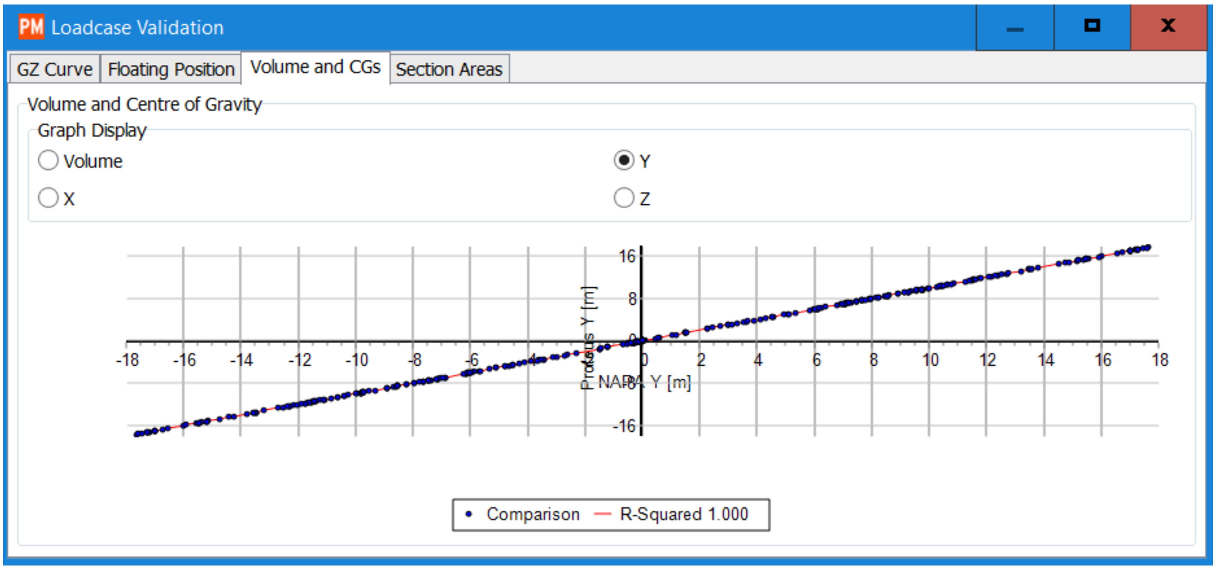


Figure 16 – Hull TCB comparison between NAPA and Proteus – Ship #2

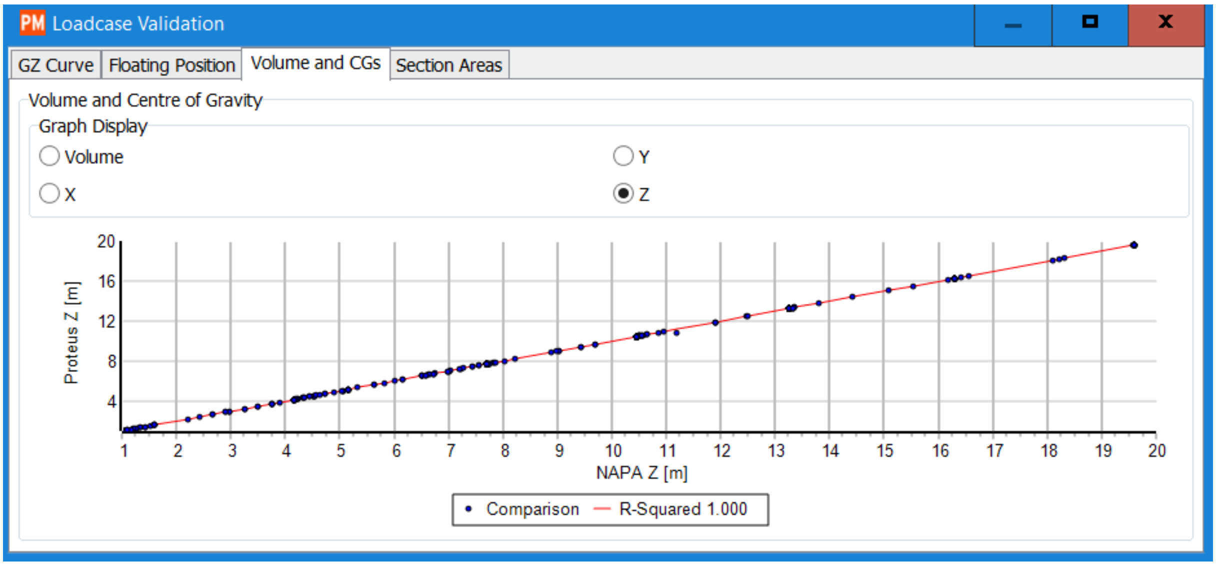


Figure 17 – Hull VCB comparison between NAPA and Proteus – Ship #2

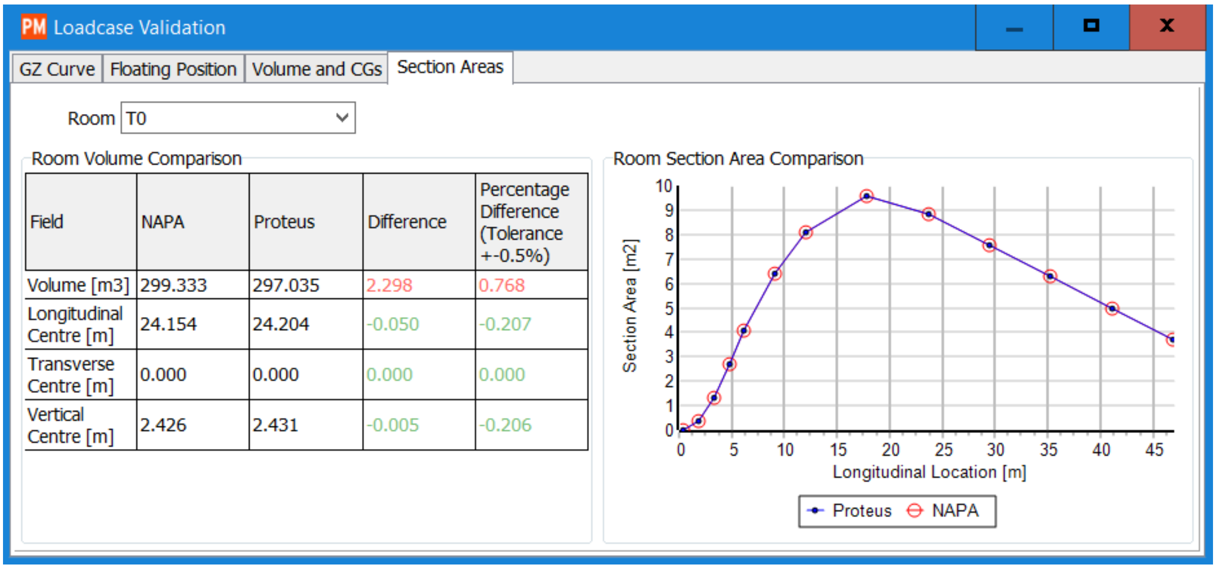
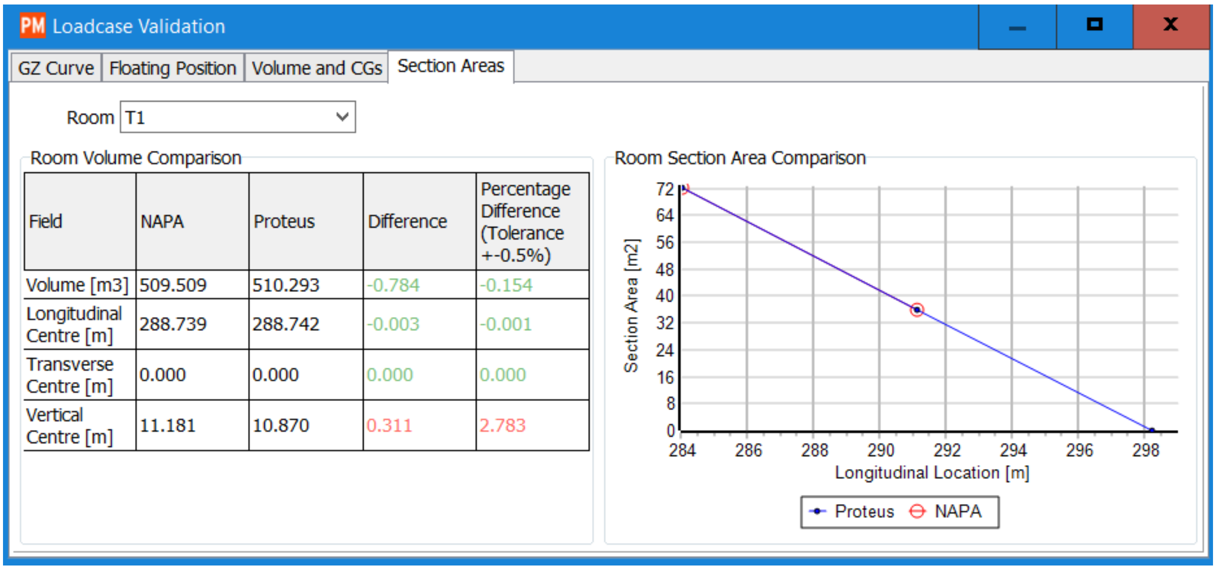


Figure 18 – Aftpeak comparison between NAPA and Proteus – Ship #2



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	509.509	510.293	-0.784	-0.154
Longitudinal Centre [m]	288.739	288.742	-0.003	-0.001
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	11.181	10.870	0.311	2.783

Figure 19 – Forepeak comparison between NAPA and Proteus – Ship #2

2.2 Results of dynamic simulations

In the first round of simulations all the 500 breaches have been simulated up to 30 minutes, then for 43 breaches a second simulation round has been executed up to 90 minutes, as these were found with progressive flooding still occurring at the end of first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1 = capsize 0 = not capsize) and TTC for cases where a capsize was found. In the following graphs the results for each hazard and the global results of simulations are presented.

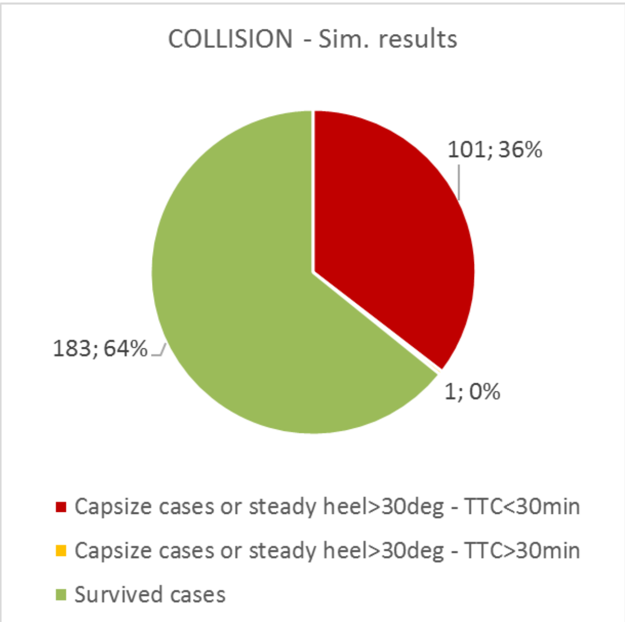


Figure 20 – Simulation results for collision – Ship #2

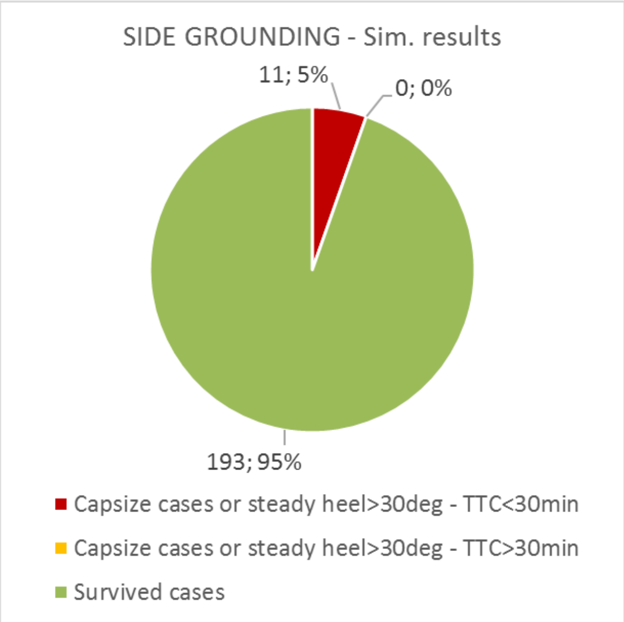


Figure 21 – Simulation results for side grounding – Ship #2

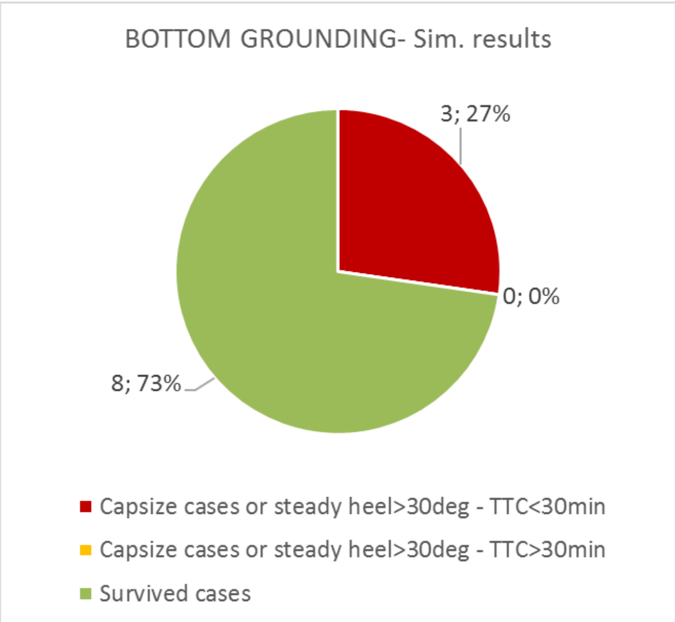


Figure 22 – Simulation results for bottom grounding – Ship #2

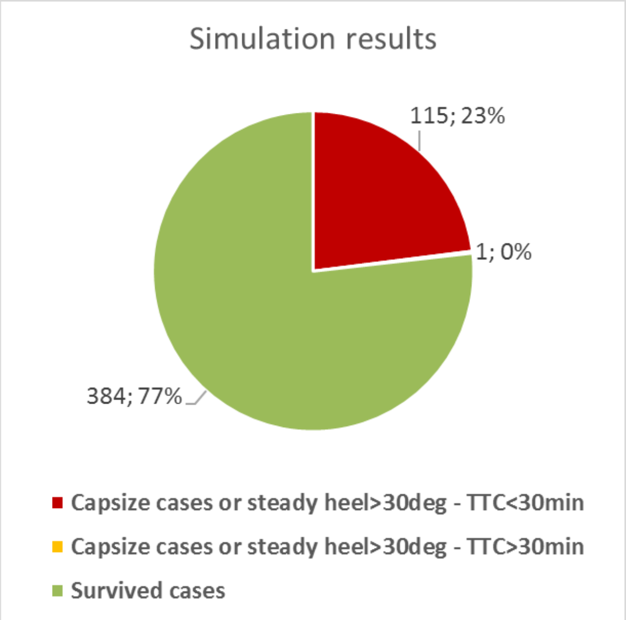


Figure 23 – Global simulation results for the 500 filtered breaches – Ship #2

The results obtained clearly show that there is a majority of cases which did not results in the capsize of the ship, this confirms that the static results are conservative as almost all of those case had a Sfac= 0 in the static analysis.

Furthermore it is equally clear that a nearly all of the capsize cases are to be considered fast capsize as the TTC is less than 30 minutes therefore there is no sufficient time to evacuate persons in such cases.

2.3 Calculation of PLL level 2.1

The results of the flooding simulations permit to get the TTC too, therefore the fatality rate may be estimated for the cases with TTC > 30min according to the procedure for calculation of Risk (Level 2.1).

Table 12 PLL level 2.1 – Ship #2

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	8.115	8.325	8.115	8.325	8.115	8.325	
PLL L1 (1/ship year) (static assessment)	**1.60E-01**	**1.67E-01**	**1.96E-01**	**1.92E-01**	**1.47E-01**	**1.48E-01**	**1.0091**
	0.3269		**0.3878**		**0.2944**		
Number of filtered damage cases	54	231	103	101	8	3	500
Capsize cases or steady heel>30deg - TTC<30min	20	81	3	8	2	1	115
Capsize cases or steady heel>30deg - TTC>30min	0	1	0	0	0	0	1
Survived cases	34	149	100	93	6	2	384
PLL L2.1 (1/ship year) (dynamic assessment)	**1.39E-01**	**1.03E-01**	**1.24E-01**	**1.29E-01**	**1.43E-01**	**1.47E-01**	**0.7840**
	0.2415		**0.2525**		**0.2900**		
PLL L2.1 vs L1 (variation percentage)	**-26.1%**		**-34.9%**		**-1.5%**		**-22.3%**

In the Table 12 the details of the results obtained are reported and it can be noted that the PLL has been reduced from 1.0091 (Level 1) to 0.784 (Level 2.1).

In the following figures the diagrams of the breaches which lead to capsize after dynamic simulations are reported.

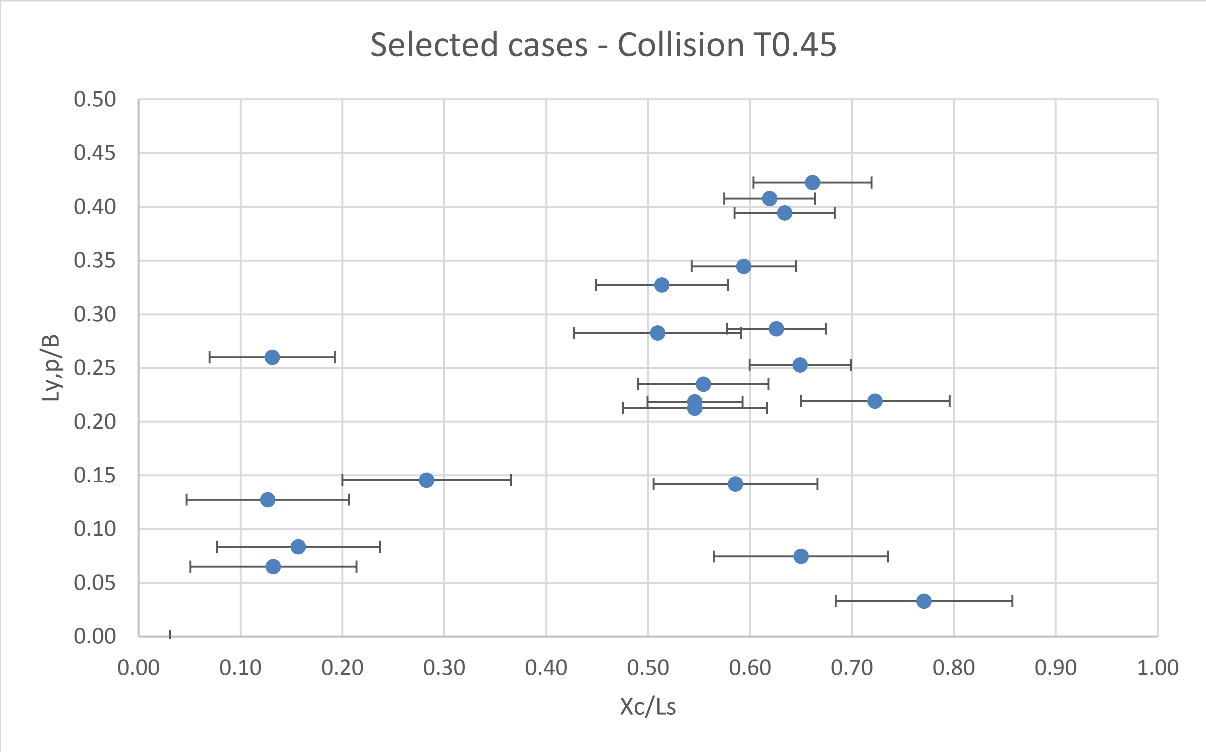


Figure 24 Collision leading to capsize T0.45 – Ship #2

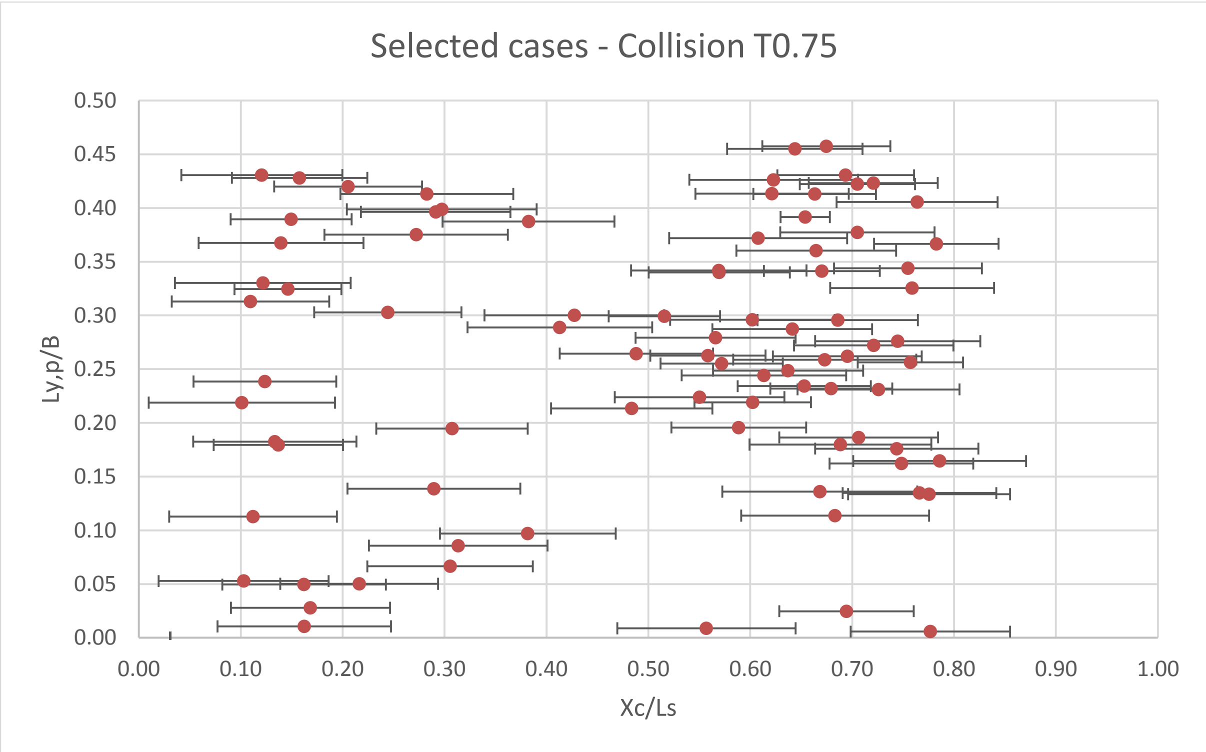


Figure 25 Collision leading to capsize T0.75 – Ship #2

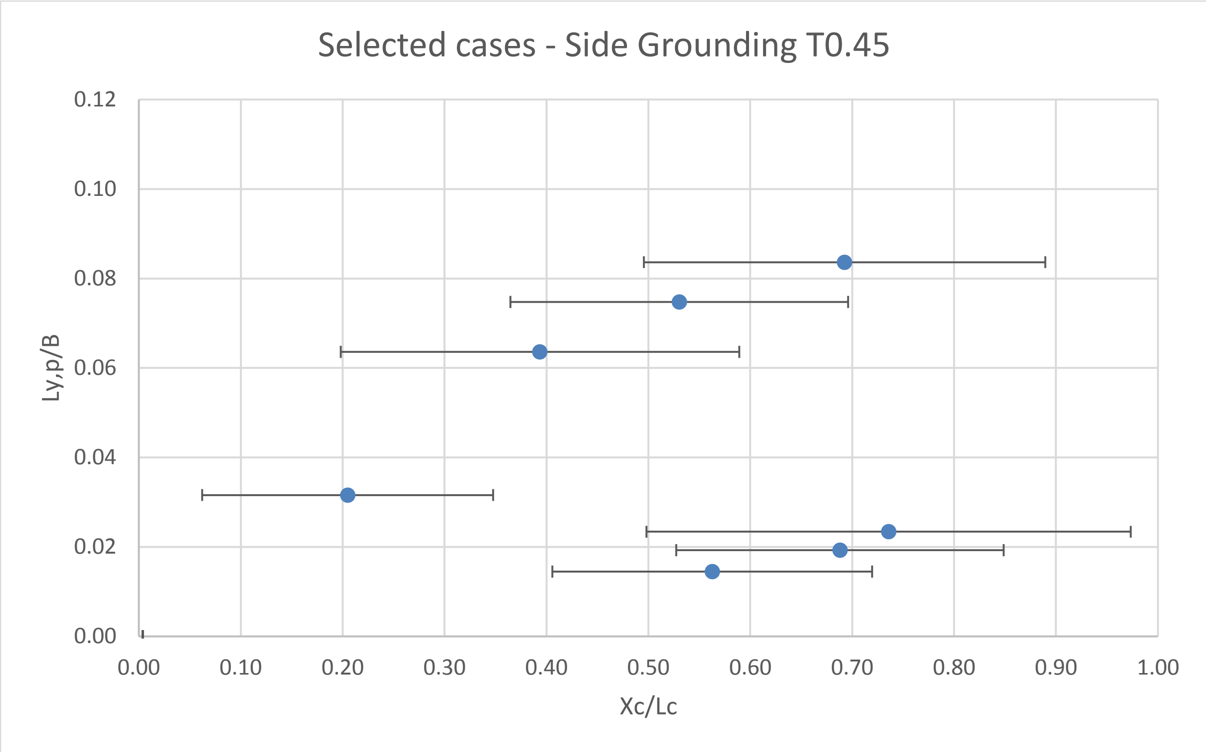


Figure 26 Side grounding breaches leading to capsize T0.45 – Ship #2

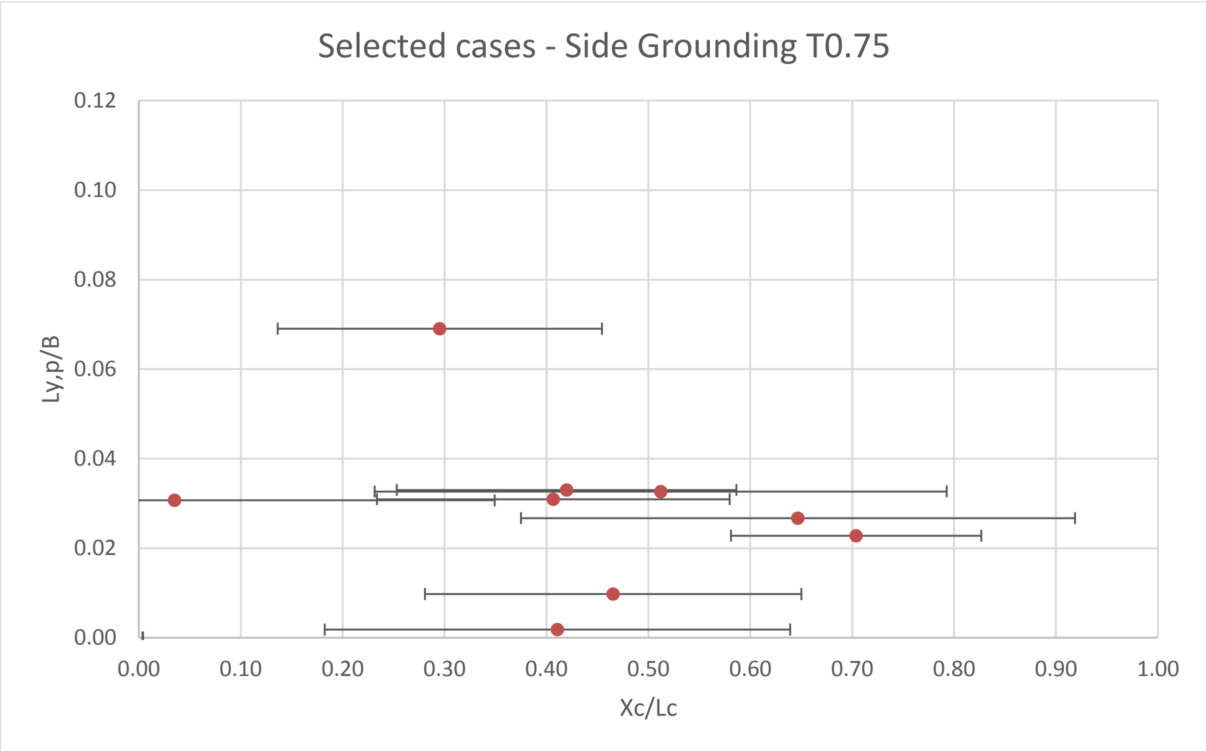


Figure 27 Side grounding breaches leading to capsize T0.75 – Ship #2

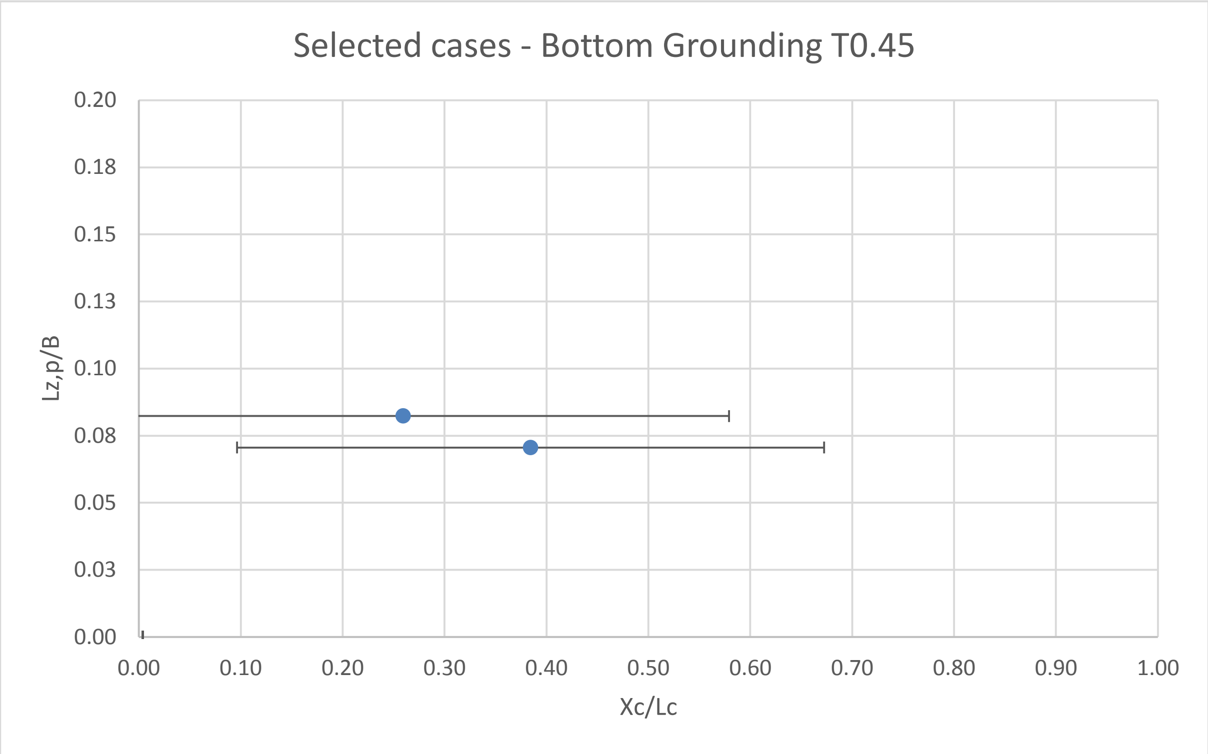


Figure 28 Bottom grounding breaches leading to capsize T0.45 – Ship #2

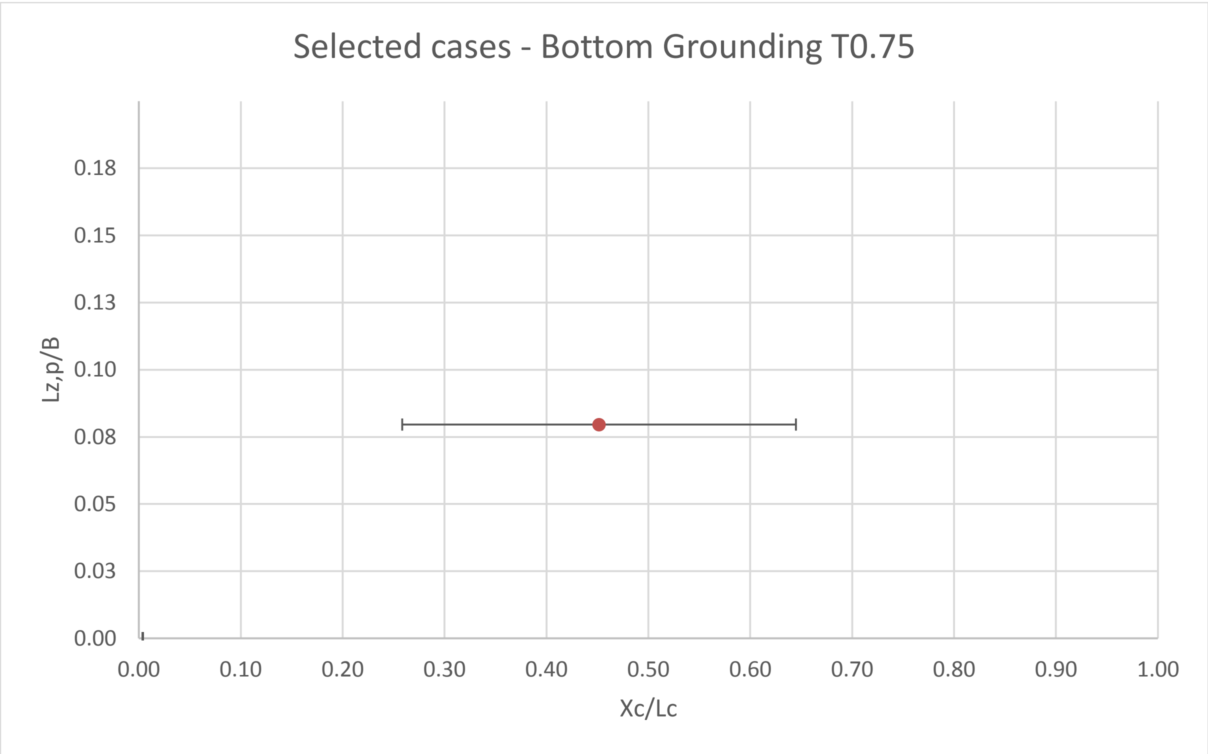


Figure 29 Bottom grounding breaches leading to capsize T0.75 – Ship #2

The cases showed from the Figure 24 to Figure 29 may be investigated in WP7.2 when Risk Control Options are to be implemented.

2.4 Sensitivity analysis of the fatality rate

With the aim to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out on the one case, with TTC > 30 min or progressive flooding still occurring after 60 min. For such purpose, the impact on the PLL has been evaluated in case of variation of the fatality rate by ± 30% of the POB.

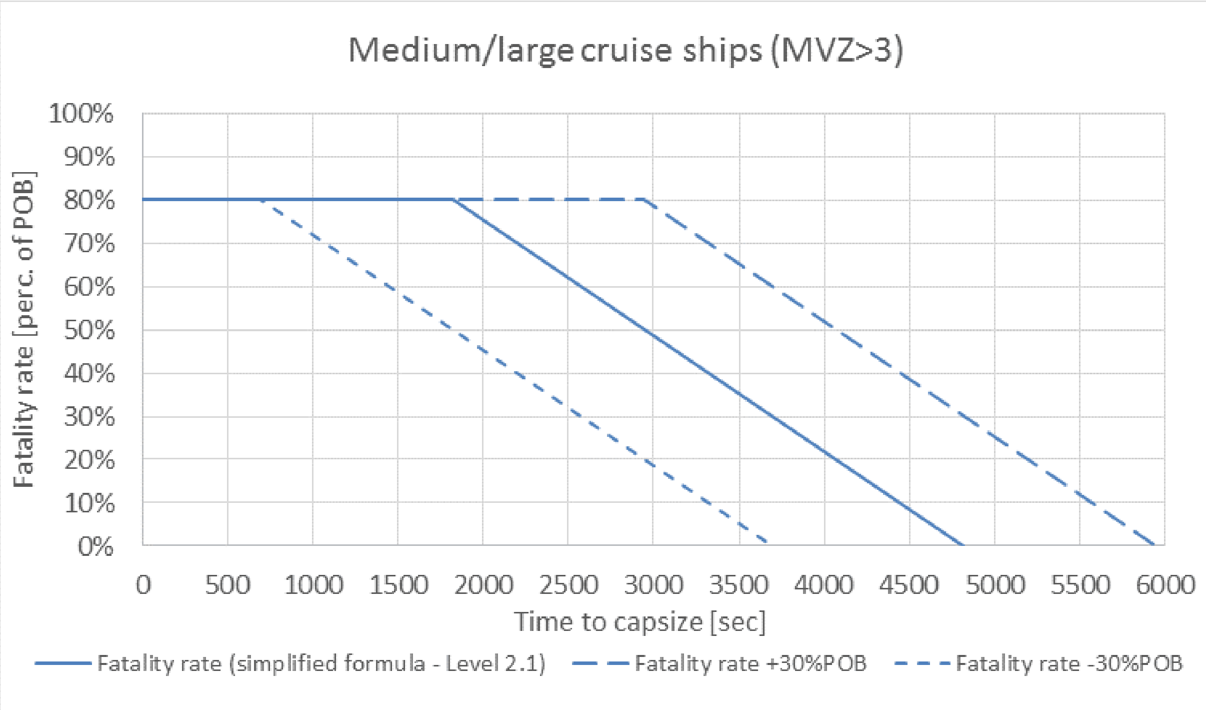


Figure 30 Sensitivity analysis of simplified formula for fatality rate calculation – Ship #2

The calculation with +30% in the fatality rate resulted into a PLL of 0.7841 (+0.01% compared to the reference PLL) while the calculation with -30% for the fatality rate resulted into a PLL of 0.7839 (-0.01% compared to the reference PLL). These values demonstrated that for this ship the simplified formula to derive the fatality rate used in the calculation of risk (Level 2.1) has a low impact on the PLL, because PLL is mainly based, for this ship, by the scenarios leading to fast capsize.

3 CONCLUSIONS

The complete procedure for calculation of Risk has been applied on Ship #2 and the results obtained demonstrated that the procedure is coherent with the multi-level approach. In fact the PLL has been reduced from 1.0091 (level 1) to 0.784 (level 2.1)

The PLL Level 1 is conservative, but it seems more robust than PLL calculated by EMSA3 Risk Model as the fast/slow sinking node has not been used in the FLARE procedure.

The dynamic analysis in level 2 leaded to a reduction of the PLL by about 22% with the simulation of 500 breaches. Such reduction of the PLL is essentially based on the fact that about 77% of cases with Sfac = 0 in the static analysis, have been found to survive in the dynamic analysis.

Furthermore a sensitivity analysis demonstrated that the impact on the PLL level 2.1 by even a large deviation of the fatality rate (calculated with the simplified formula) is negligible.

The flooding simulations showed a percentage of 99% of fast capsize cases (TTC < 30min) and 1% only for slow capsize cases (TTC > 30min). This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model for which only 18% capsizing rate was used.

ANNEX 5 – Calculation of the flooding Risk for Ship n.3

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

Duration: 36 months - Project Start: 01/06/2019 - Project End: 31/05/2022

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a medium cruise ship design. As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1). The refined model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

1. STATIC ASSESSMENT

1.1 Main data

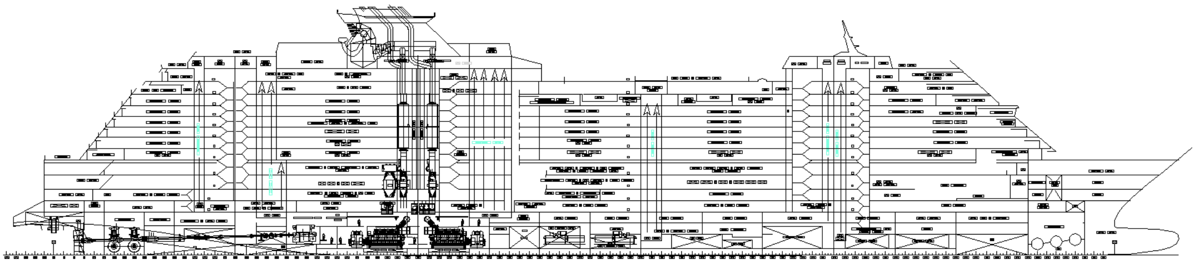


Figure 1 Profile view – Ship #3

Ship#3 is a medium size cruise vessel, designed to accommodate on long international voyage 3,750 persons, 2,750 passengers and 1,000 crew members.

The main characteristics are described below as a reminder.

Table 1 Main characteristics – Ship #3

Length over all	About 300 m
Length between perpendiculars	270.00 m
Subdivision length	296.74 m
Breadth	35.00 m
Subdivision draught	8.20 m
Height of bulkhead deck	11.00 m
Number of passengers	2750
Number of crew	1000
Gross tonnage	95 900
Deadweight	8500 t
No of pax cabins	1270

The business model and detailed description of the vessel are included in deliverable D.2.1.

Here following the Attained and Required Index according to SOLAS 2020 ch.II-1:

Number of persons POB = 3750
Required subdivision index R = 0.8835
Updated Attained subdivision index A = 0.8938

1.2 Static calculations with new draughts and permeabilities

The first step of FLARE damage stability analysis starts with a static damage calculation in accordance with SOLAS/II-1 but using new draughts as per deliverable D2.2 and new permeability as per deliverable D2.3.

Since this vessel is at a design stage, the optimal non-dimensional calculation drafts 0.45-0.75 and a weighting factor of 0.5 for both draughts have been used.

GM values for the new draughts have been obtained by interpolation from the original GM limiting curve used for SOLAS calculation.

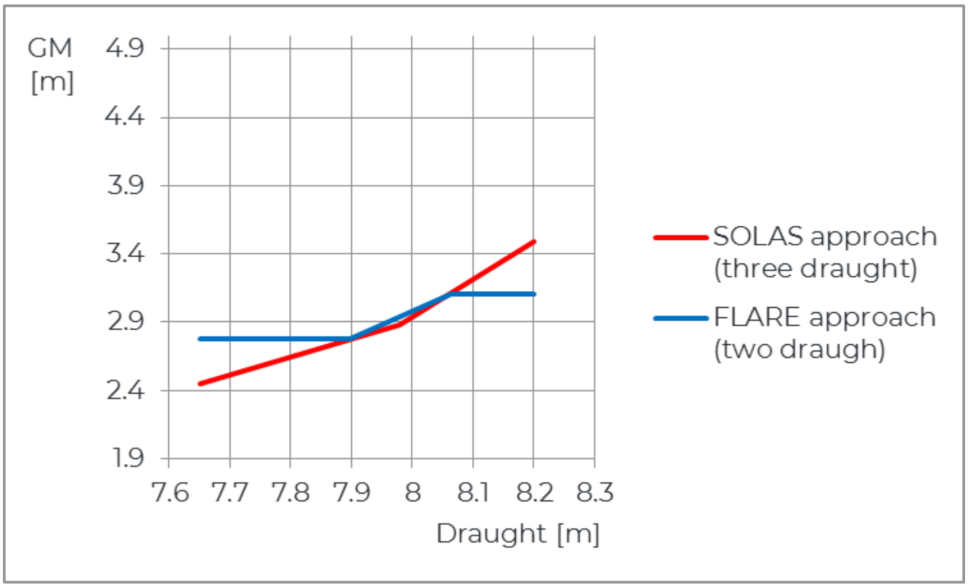


Figure 2 GM limiting curve with new FLARE draughts – Ship #3

Considering the outcome of D.2.3, the permeability values shown in the last two columns of following table have been used:

Table 2 Permeability – Ship #3

Rooms	SOLAS perm.	FLARE perm. T0.45	FLARE perm. T0.75
Engine rooms	0.85	0.90	0.90
Auxiliary machinery spaces	0.95	0.90	0.90
Stores	0.60	0.90	0.90
Accommodation (cabin areas, galleys, offices, workshops etc)	0.95	0.90	0.90
Public spaces, crew mess, corridors, staircases	0.95	0.95	0.95
Marine Gas Oil, Lube Oil, Potable Water, Waste Water, Technical water, Water ballast, Misc.	0.95	0.540	0.507
RoRo spaces, Car Deck	0.95/0.90	0.91	0.90
Heeling tanks	0.95	0.51	0.51
Void Spaces	0.95	0.95	0.95

Calculation has been executed with the software NAPA rel.2020.2 generating damages up to 5 adjacent zones.

These observations led to an attained index A = 0.91129 (with reference to the SOLAS A index in the previous calculation in D2.1 +1.25 %).

Table 3 Static results with new draughts and permeabilities - Ship #3

INIT	T (m)	GM (m)	A	WCOEF	A*WCOEF	Attained Index
PS						
T0.75	8.063	3.109	0.92000	0.5	0.46000	0.91567
T0.45	7.898	2.773	0.91134	0.5	0.45567	
SB						
T0.75	8.063	3.109	0.90957	0.5	0.45478	0.90690
T0.45	7.898	2.773	0.90423	0.5	0.45212	

1.3 Static calculations with refined model

Subsequently the geometry model used for calculations has been updated according to the FLARE modelling guidelines [8].

The refined model reflects as close as possible the geometry of the physical ship or its design and the following items have been refined or added:

- Staircases and lifts
- U-shaped compartments above double bottom
- Void space below tank top

Adding the above modifications generates a significant increase of the number of rooms and connections :

Table 4 Comparison between simplified model and refined model – Ship #3

Description	Before modelling	After modelling
Damhull volume	127393 m^3	160982 m^3
Rooms number	190	526
Connections number	64	635

The subdivision table is also adjusted in order to consider the damage cases that involve new rooms.

The static damage stability calculation performed on this refined model results in a decrease on the attained index A. The A-index loss is about 2.3% (from 0.9113 to 0.8905).

Table 5 Static results with refined model – Ship #3

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	(m)	(m)				
PS						
T0.75	8.063	3.109	0.90152	0.5	0.45076	0.89770
T0.45	7.898	2.773	0.89388	0.5	0.44694	
SB						
T0.75	8.063	3.109	0.88352	0.5	0.44176	0.88336
T0.45	7.898	2.773	0.88320	0.5	0.44160	

1.3.1 Progressive flooding considered in this refined model

Progressive flooding via airducts crossing several watertight bulkhead have been added between the casing and technical compartments.

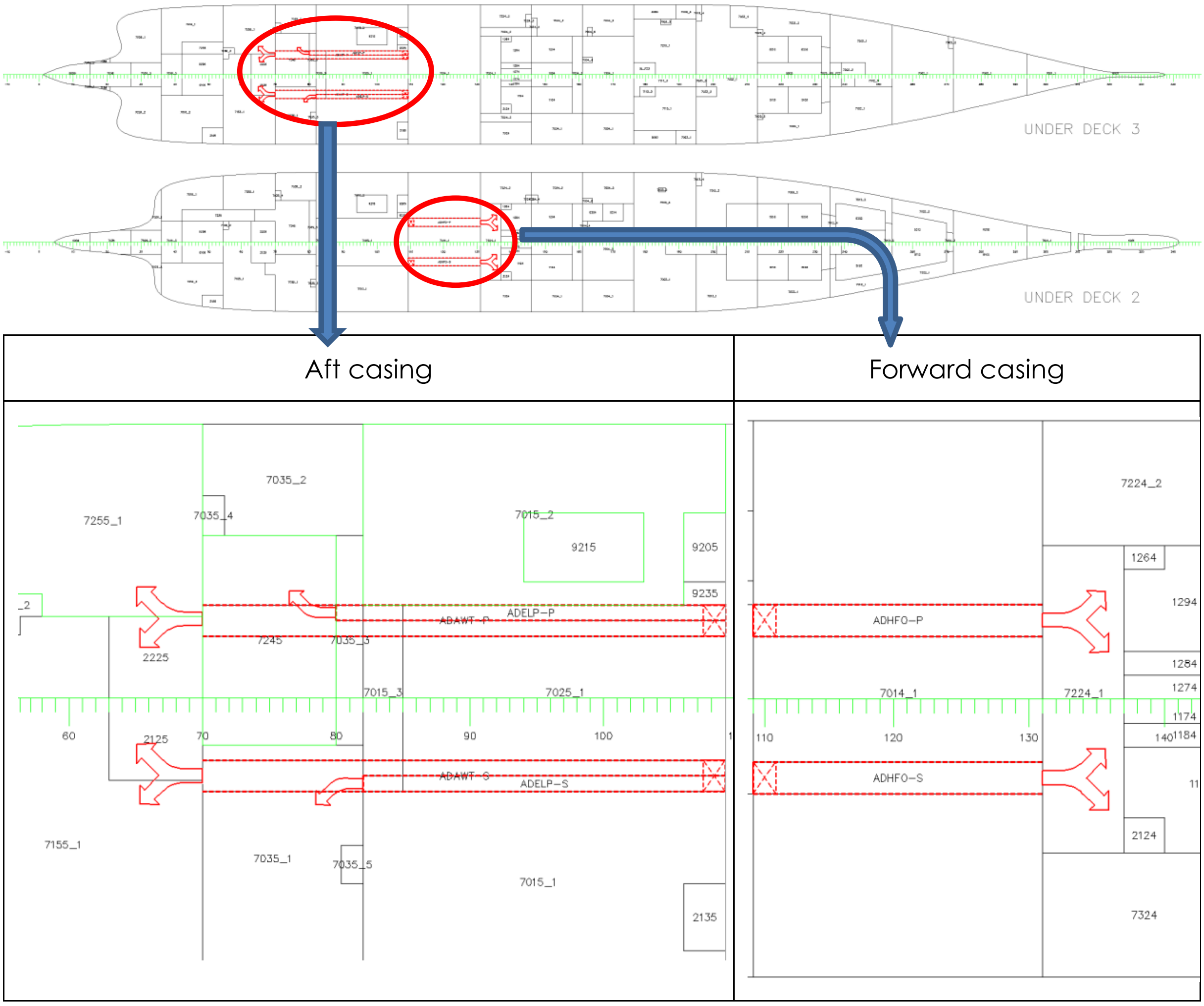


Figure 3 Progressive flooding via airducts – Ship #3

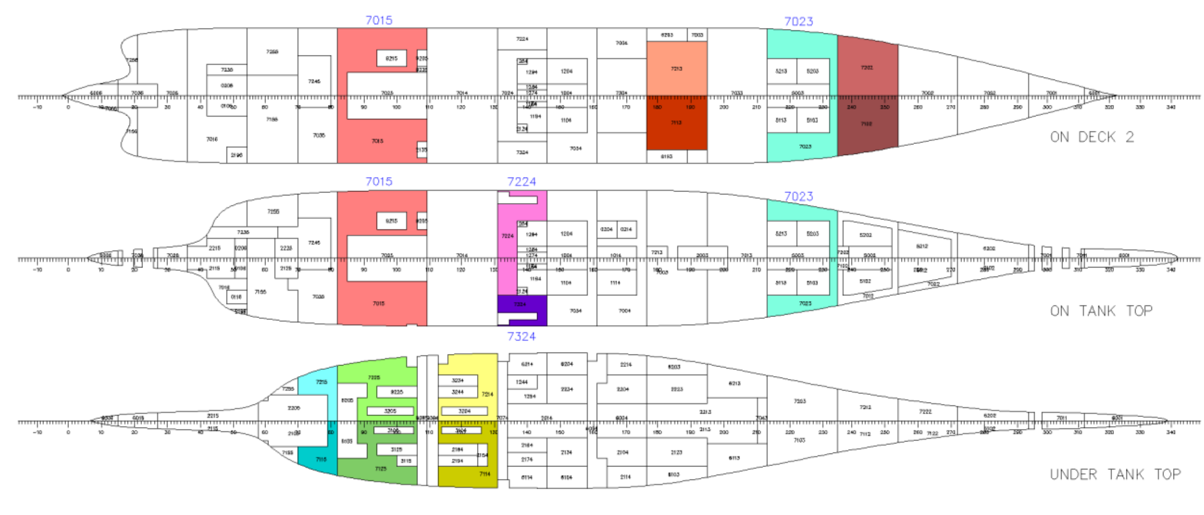
1.3.2 Cross flooding retained and modified

As shown before, the model refinement led to an index loss due to a logical increase of the damage asymmetry in the first flooding stages.

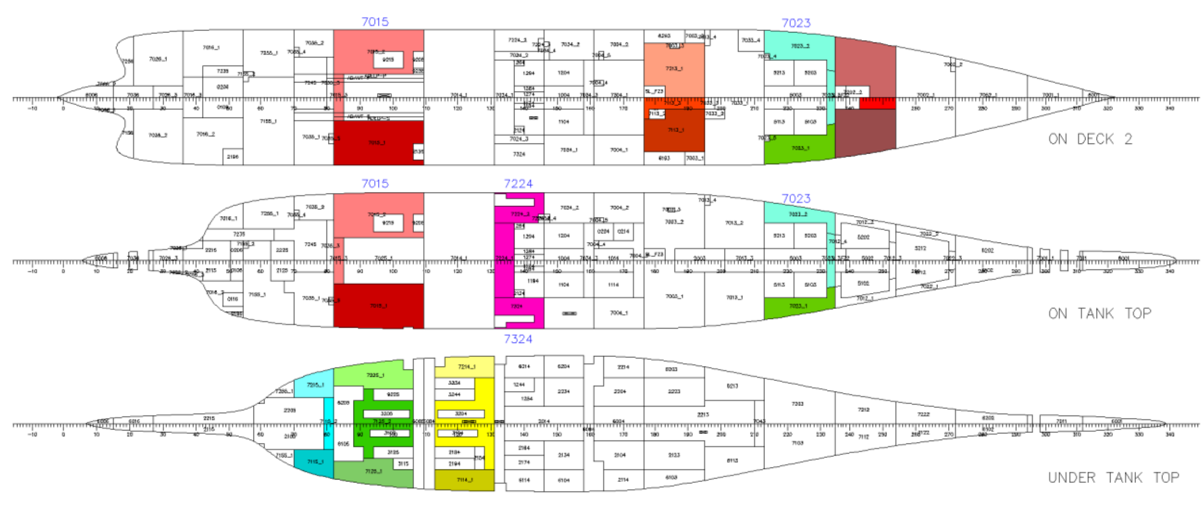
A simplified static calculation, based on the formulae's of the MSC362(92) allows to assume some cross-flooding as instantaneous (in less than 60 s) where the cross-flooding section is big enough. In these particular cases some compartment combinations have been done to fit these assumptions. However, this is not a modification to the model, which is refined as described in the guidelines. Therefore, we are still able to check these assumptions at a later stage, using PROTEUS.

The Figure 4 show the applied combinations on the refined model built according to the guidelines.

BEFORE refinement (initial model for static calculations



AFTER refinement and retained combination for PS connection



AFTER refinement and retained combination for SB connection

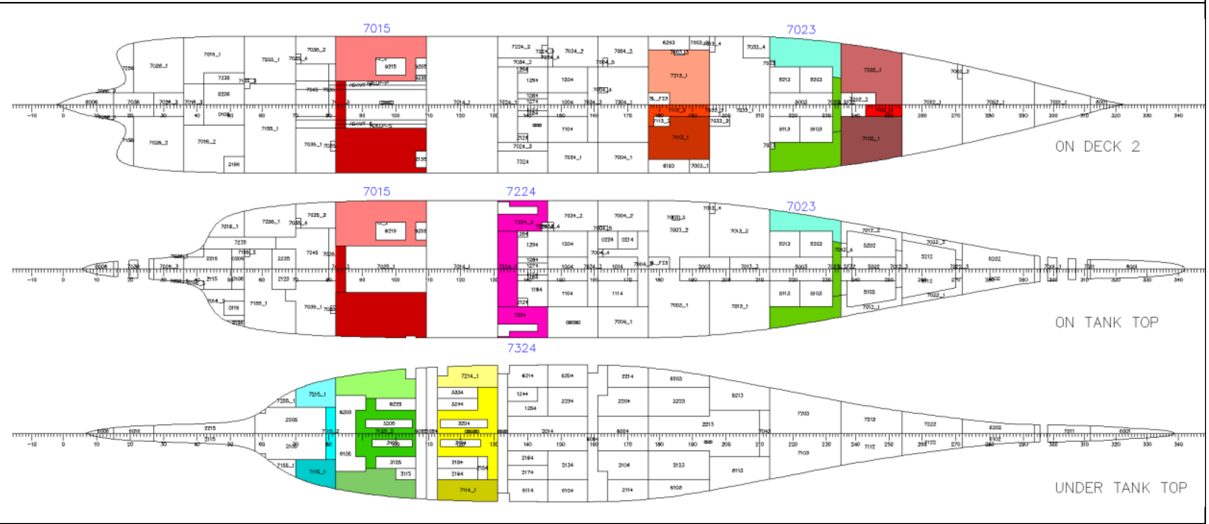


Figure 4 Refined model according to the modelling guidelines – Ship #3

1.4 Non-zonal static analysis

In addition to the zonal stability results for collision, the attained index following the non-zonal approach has been calculated for collision, bottom grounding and side grounding/contact.

For that purpose, the outcome of eSAFE project has been used [1].

1.4.1 Non-damage area

A "NON-DAMAGE AREA" has not been considered for this ship.

As explained in chapter 1.3.1, the progressive flooding via airducts crossing watertight bulkheads has been taken into account.

For the other systems, the progressive flooding is prevented with remote control valves or by routing the pipes in the same watertight compartment above the most severe waterline and range of residual stability before routing longitudinally.

1.4.2 Breach generations and results

In total, 10000 breaches have been generated with NAPA tool using the Monte Carlo method. Then frequencies and damage cases to be calculated are obtained by grouping breaches leading to the same sets of flooded rooms.

The following results have been obtained:

Table 6 Non zonal static analysis results – Ship #3

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**	
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75
Draught	7.898 m	8.063 m	7.898 m	8.063 m	7.898 m	8.063 m
Breaches	10000	10000	10000	10000	10000	10000
Number of Empty cases	28	48	28	27	96	100
Number of Unique damage cases	5740	5652	2616	2570	3301	3266
Partial Index	0.9211	0.9381	0.8719	0.8769	0.9484	0.9437
Total Index	**0.9296**		**0.8744**		**0.9461**	

1.5 Calculation of PLL level 1

With the results of the static calculation the PLL level 1 may be calculated according to procedure described in Ch.2. In Table 7 the PLL (Potential loss of life) calculation is reported.

Table 7 PLL level 1 – Ship #3

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		4.33E-03
Relative frequency	0.388		0.328		0.284		1.000
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	7.898	8.063	7.898	8.063	7.898	8.063	
Attained Index	0.9211	0.9381	0.8719	0.8769	0.9484	0.9437	0.9162
$\sum pfac$ (for cases with s=1)	0.8786	0.9142	0.8496	0.8636	0.9449	0.9397	0.8964
$\sum pfac \cdot (1 - sfac)$	0.0789	0.0619	0.1281	0.1231	0.0516	0.0563	0.0838
PLL level 1 (1/ship year)	1.99E-01	1.56E-01	2.73E-01	2.62E-01	9.52E-02	1.04E-01	**1.0888**
	0.3549		**0.5349**		**0.1990**		

Even if the PLL is the parameter to be used for the risk measurement in Table 7 the Combined Attained Index is showed too for information only. That value is calculated by using the relative frequency for collision, Side grounding and Bottom Grounding.

1.6 Filtering of static results and selecting cases for dynamic simulations

The screening of the static result according to filtering criteria identified within Ch. 3.4 of the main report permitted to select 500 cases for the dynamic simulations. In the following table a summary of the filtered breaches is reported.

Table 8 Filtering results for dynamic simulation – Ship #3

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	7.898	8.063	7.898	8.063	7.898	8.063	
Number of filtered damage cases	48	49	188	168	22	25	500
$\sum pfac$ (for the filtered damage cases)	0.0123	0.0082	0.0527	0.0496	0.0047	0.0057	0.0223
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0092	0.0081	0.0484	0.0487	0.0047	0.0056	0.0207
Potential PLL (if the ships would not capsize for all selected cases)	1.76E-01	1.36E-01	1.70E-01	1.58E-01	8.65E-02	9.35E-02	0.8193
	0.3111		0.3282		0.1799		
Potential PLL reduction (if the ships would not capsize for all selected cases)	-12.3%		-38.6%		-9.6%		-24.8%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. In particular for this ship the PLL would be reduced by about 25% if all the cases to be simulated are not capsizing.

In the following diagrams some parameters of the selected breaches are presented in non-dimensional form.

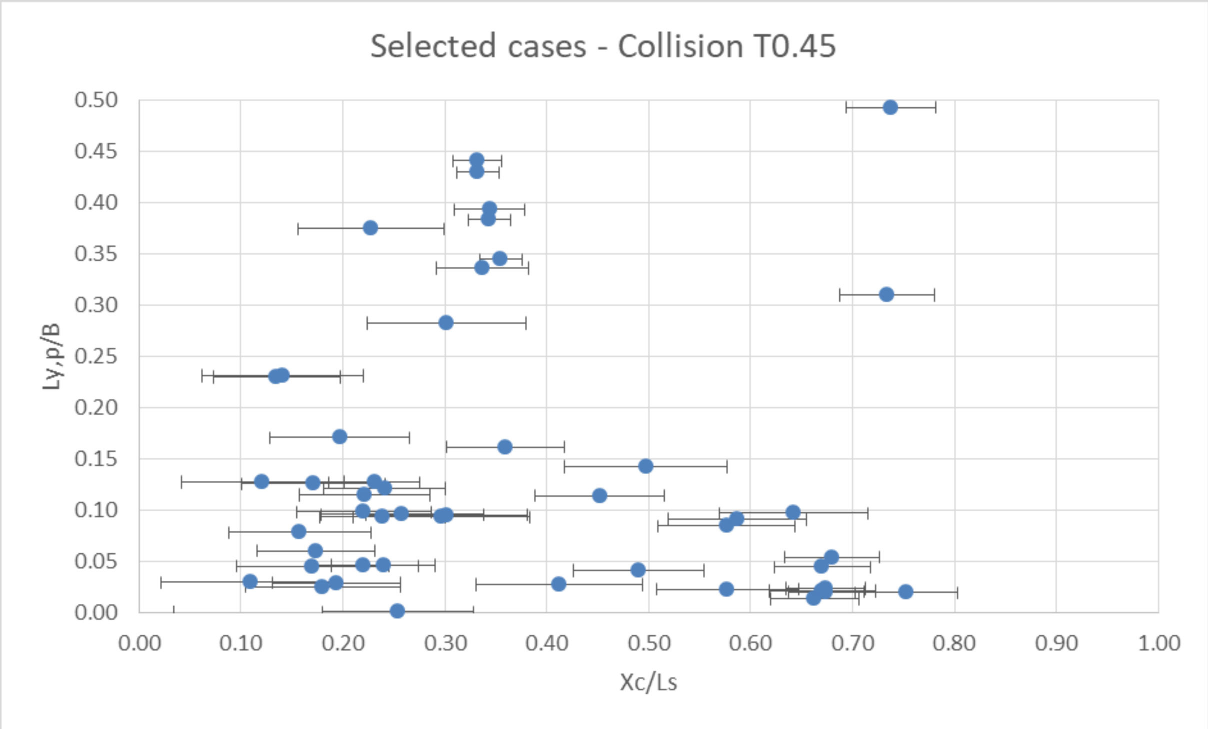


Figure 5 Characteristics of selected collision breaches T0.45 – Ship #3

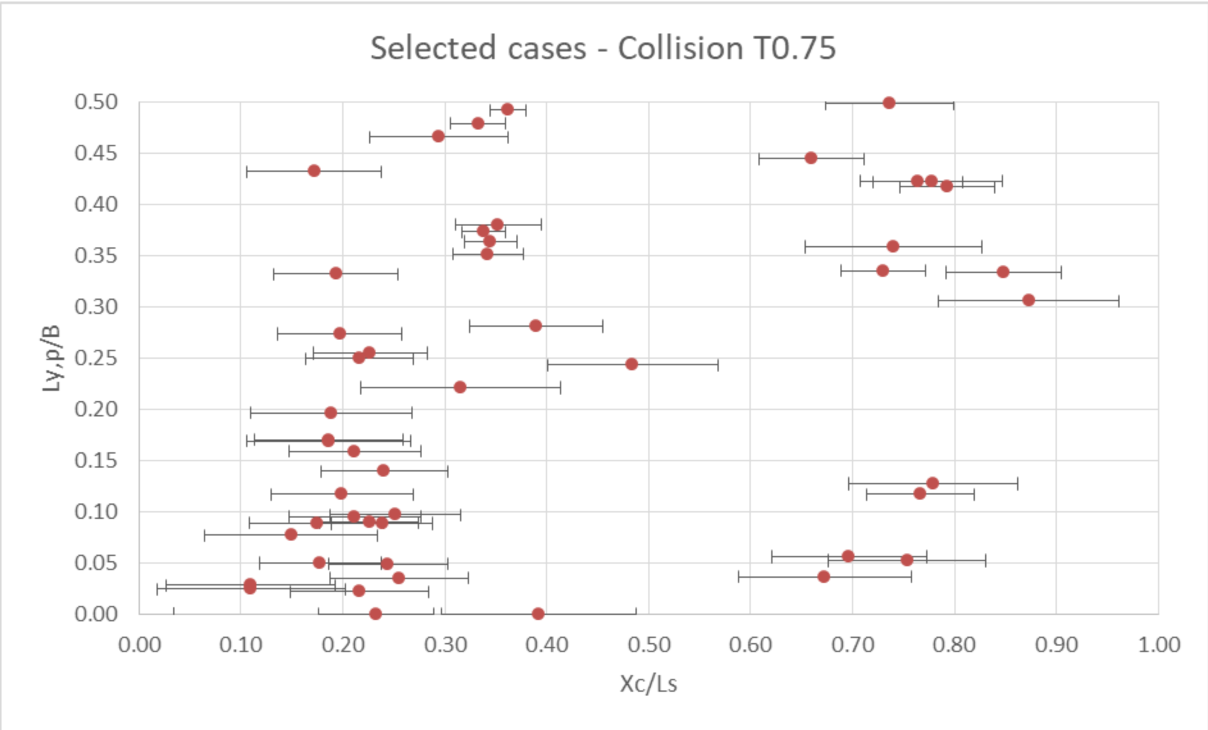


Figure 6 Characteristics of selected collision breaches T0.75 – Ship #3

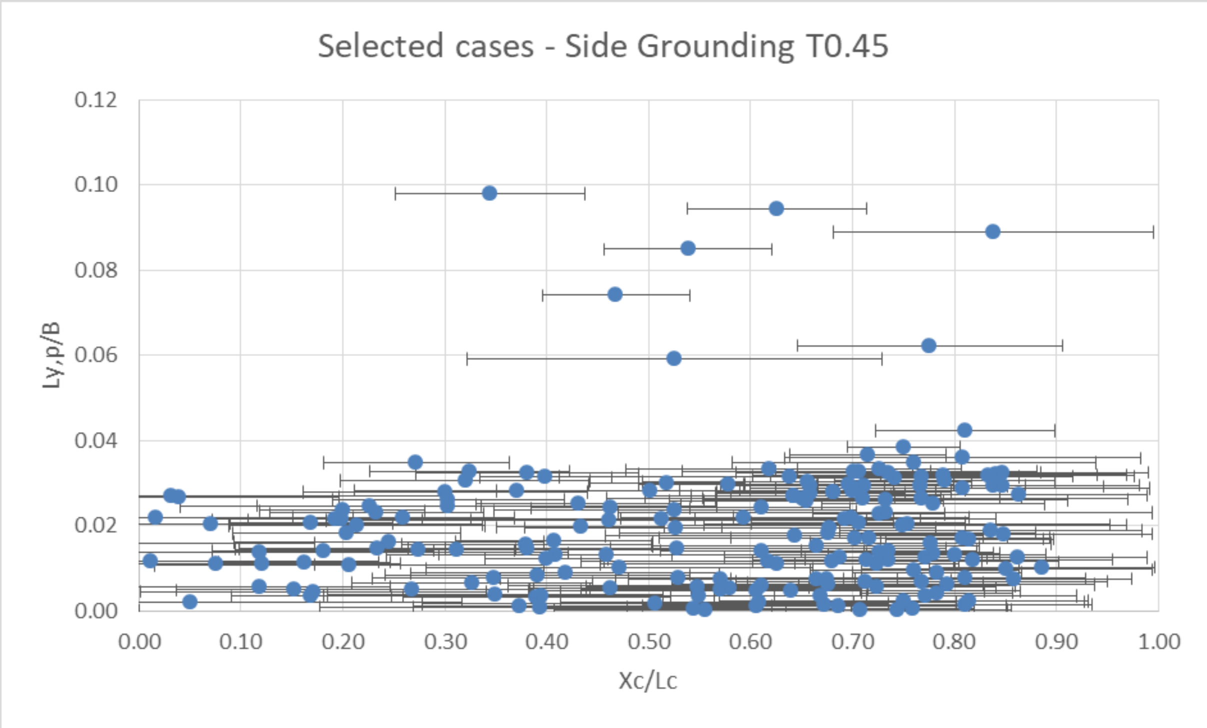


Figure 7 Characteristics of selected side grounding breaches T0.45 – Ship #3

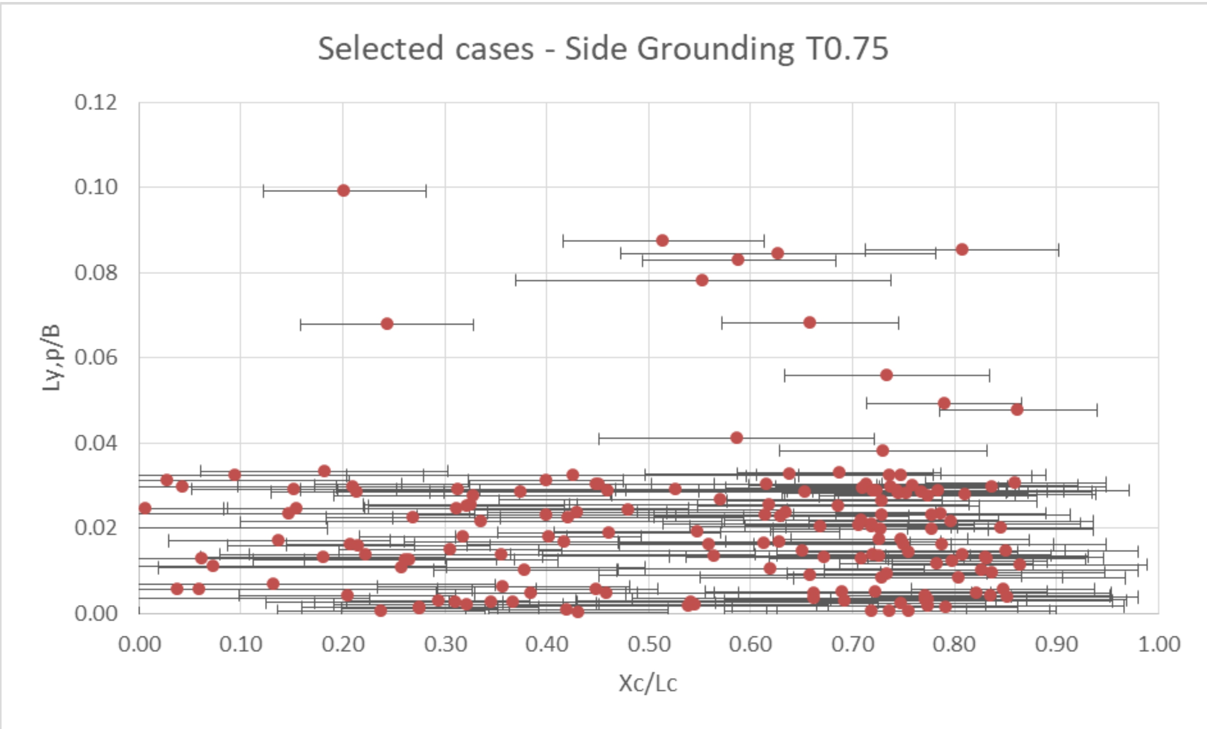


Figure 8 Characteristics of selected side grounding breaches T0.75 – Ship #3

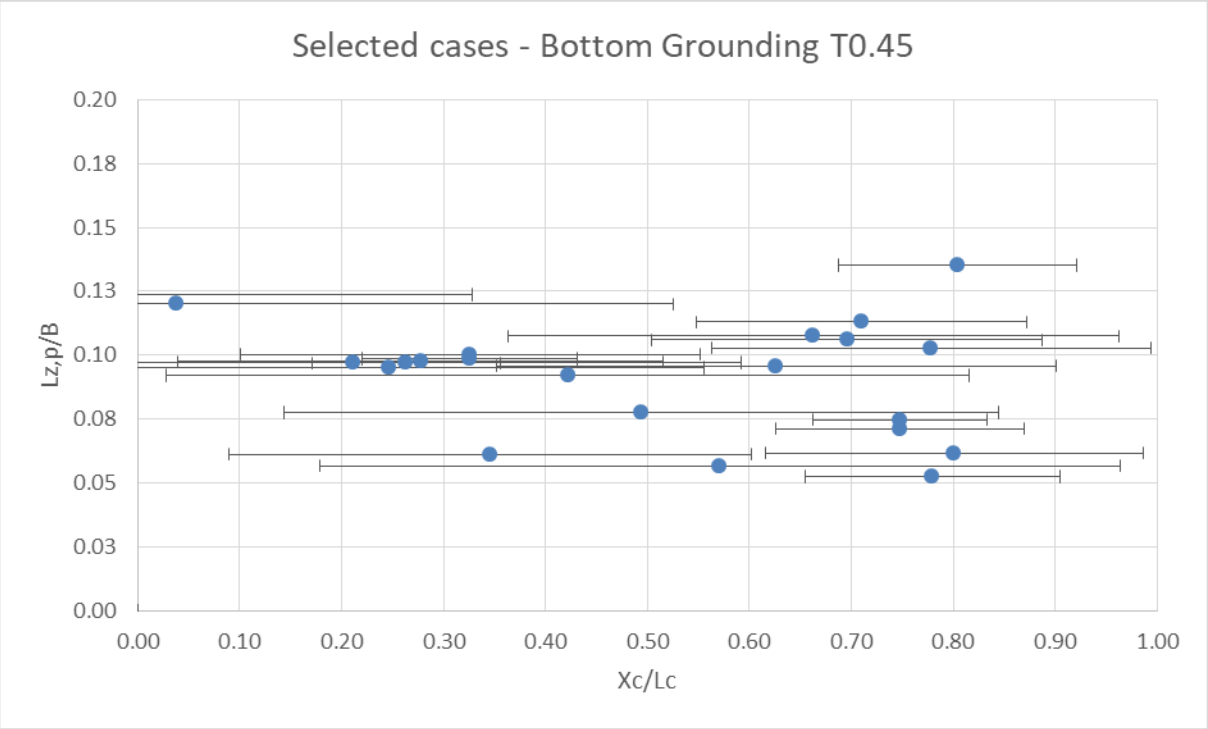


Figure 9 Characteristics of selected bottom grounding breaches T0.45 – Ship #3

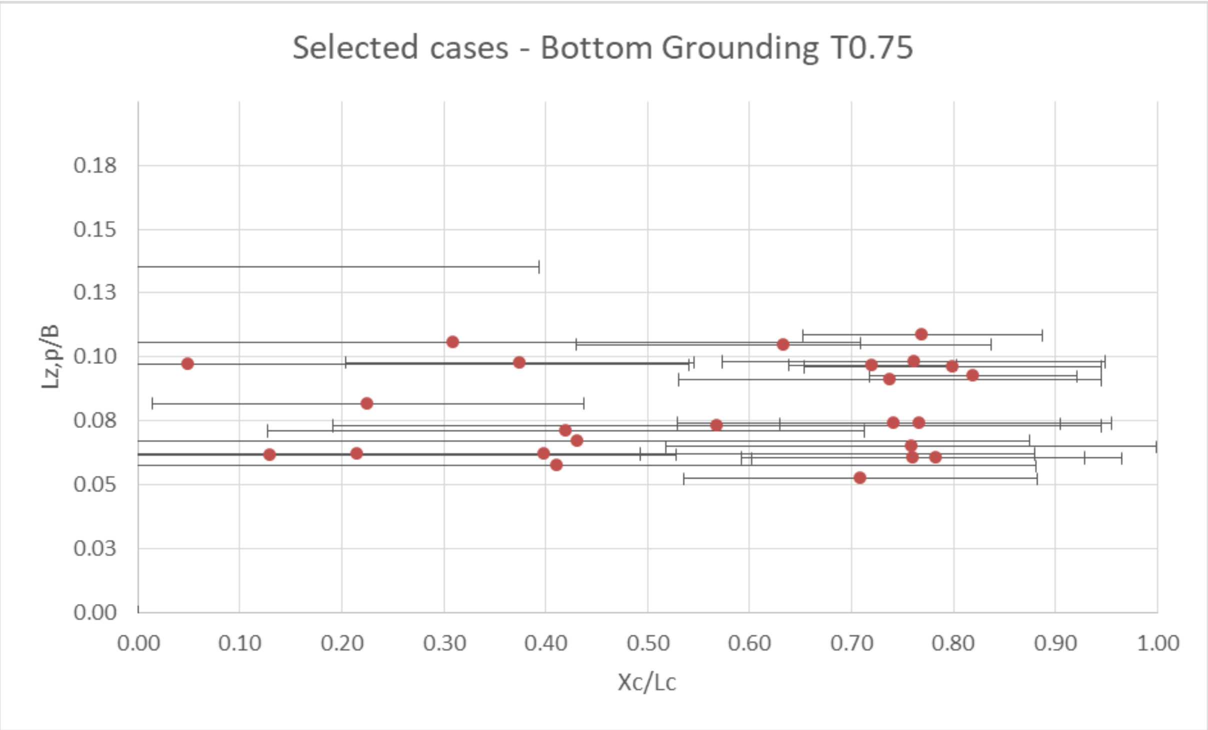


Figure 10 Characteristics of selected bottom grounding breaches T0.75 – Ship #3

From these graphs we can note:

- For collision breaches there are two vulnerable areas: in the aft compartments where the shaft lines PS and SB were separated by watertight compartments and in forward compartments where are the potable water tanks.
- For side grounding breaches there is the same vulnerable area around the potable tanks
- For the bottom grounding breaches there are less filtered breaches, this is due to the fact the ship does not capsize when just the double bottom is affected by flooding. However, we find the same vulnerable area as for the other types of breaches, around potable water tanks.

1.7 Breakdown of failure modes

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with s-factor equal to zero and failure modes for cases with s-factor between 0 and 1, are showed in the following tables.

Table 9 Breakdown of failure mode for Sfac = 0 cases – Ship #3

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	8	9	21	11	3	0	**52**
Heeling Angle (>15 deg)	15	11	37	35	0	3	**101**
Smom=0	5	22	101	92	19	21	**260**
Opening immersion	3	5	8	17	0	0	**33**
Sfac=0 - Total cases	**31**	**47**	**167**	**155**	**22**	**24**	**446**

Table 10 Breakdown of failure mode for 0<Sfac<1 cases – Ship #3

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	11	0	8	2	0	1	**22**
Insufficient Range	0	0	0	0	0	0	**0**
Heeling Angle (>7 deg)	0	0	0	0	0	0	**0**
Insufficient Restoration (GZmax) + Range	0	2	5	8	0	0	**15**
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	**0**
Insufficient Range + Excessive Heel	0	0	0	0	0	0	**0**
Insufficient Restoration (GZmax) + Range + Excessive Heel	2	0	3	3	0	0	**8**
0<Sfac<1 - Total cases	**17**	**2**	**21**	**13**	**0**	**1**	**54**

A large percentage of captured cases resulted into Sfac = 0 (446 cases over 500) and about 52% of the captured cases had a failure mode corresponding to the heel due to the moment of the wind.

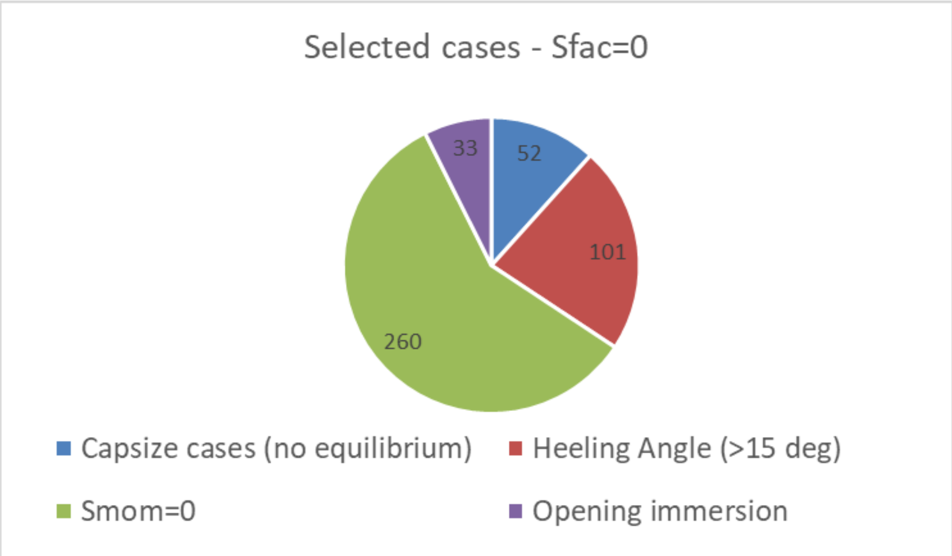


Figure 11 Diagram of failure mode for Sfac = 0 cases – Ship #3

A lot of damage cases (n.101) with heeling angle > 15 deg have been found too, while the equilibrium was not reached in the static calculation for 52 cases.

In the majority of the cases where equilibrium was not achieved the cause was found at the progressive stage of flooding after the cross-flooding. It is interesting to assess those cases by dynamic simulations so that the real physics of the phenomenon is investigated as the progressive flooding may begin during the cross-flooding stage.

Finally, 33 failing cases have been identified due to the immersion of openings. These cases are very important to be selected too as it is expected that the outcome of the dynamic simulation will be completely different. In fact, the approach for connections and openings definition is completely different between static and dynamic calculation.

A limited number of damage cases with 0 < Sfac < 1 has been selected. From these cases, 22 resulted in an insufficient restoration of GZmax, and 15 cases resulted in an insufficient restoration of GZmax and range, while 8 cases resulted in an insufficient Range and excessive heeling angle too.

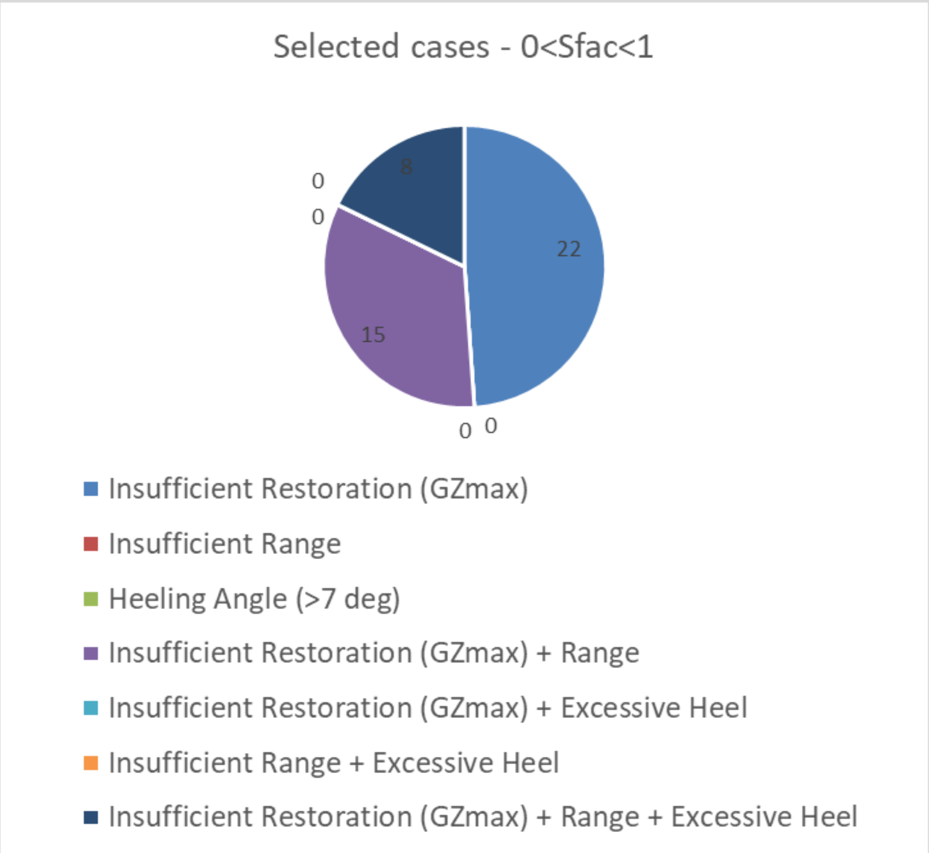


Figure 12 Diagram of failure mode for 0 < Sfac < 1 cases – Ship #3

2. DYNAMIC ASSESSMENT

1.8 Preparation of the PROTEUS model

The dynamic assessment has been carried out by the software *PROTEUS* (last release distributed in November 2021). In particular for the preparation of the model the tool Proteus Manager has been used.

To reproduce in the Proteus Manager the loading conditions defined in NAPA and corresponding to the two calculation draughts at 45% and 75%, the following lightships have been generated:

T_1 = 7.898 m → LIG_1 [Δ=50130 t ; CG (128.166 , 0.003 , 17.260) m]

T_2 = 8.063 m → LIG_2 [Δ=51548 t ; CG (127.889 , 0.003 , 16.985) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at 9 different deck slices:

D1- = 1.79 m; D1+ = 4.01 m; D2- = 4.51 m; D2+ = 5.31 m; D3- = 5.81 m; D3+ = 8.21 m;

D4+ = 11.01 m; D5+ = 13.96 m; D6+ = 16.81 m.

For this cruise ship a total of 751 openings have been defined. Horizontal openings have been defined on the higher deck of the model to capture the down-flooding through engine casings, stair trunks, vertical escape and lifts.

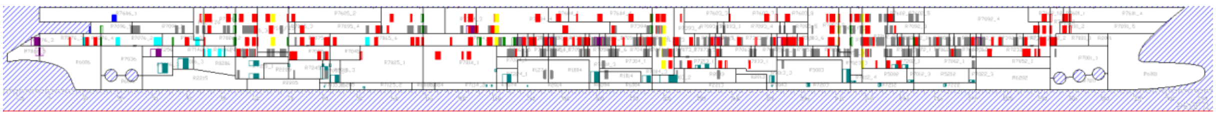


Figure 13 – Openings imported in Proteus Project (longitudinal section)– Ship #3

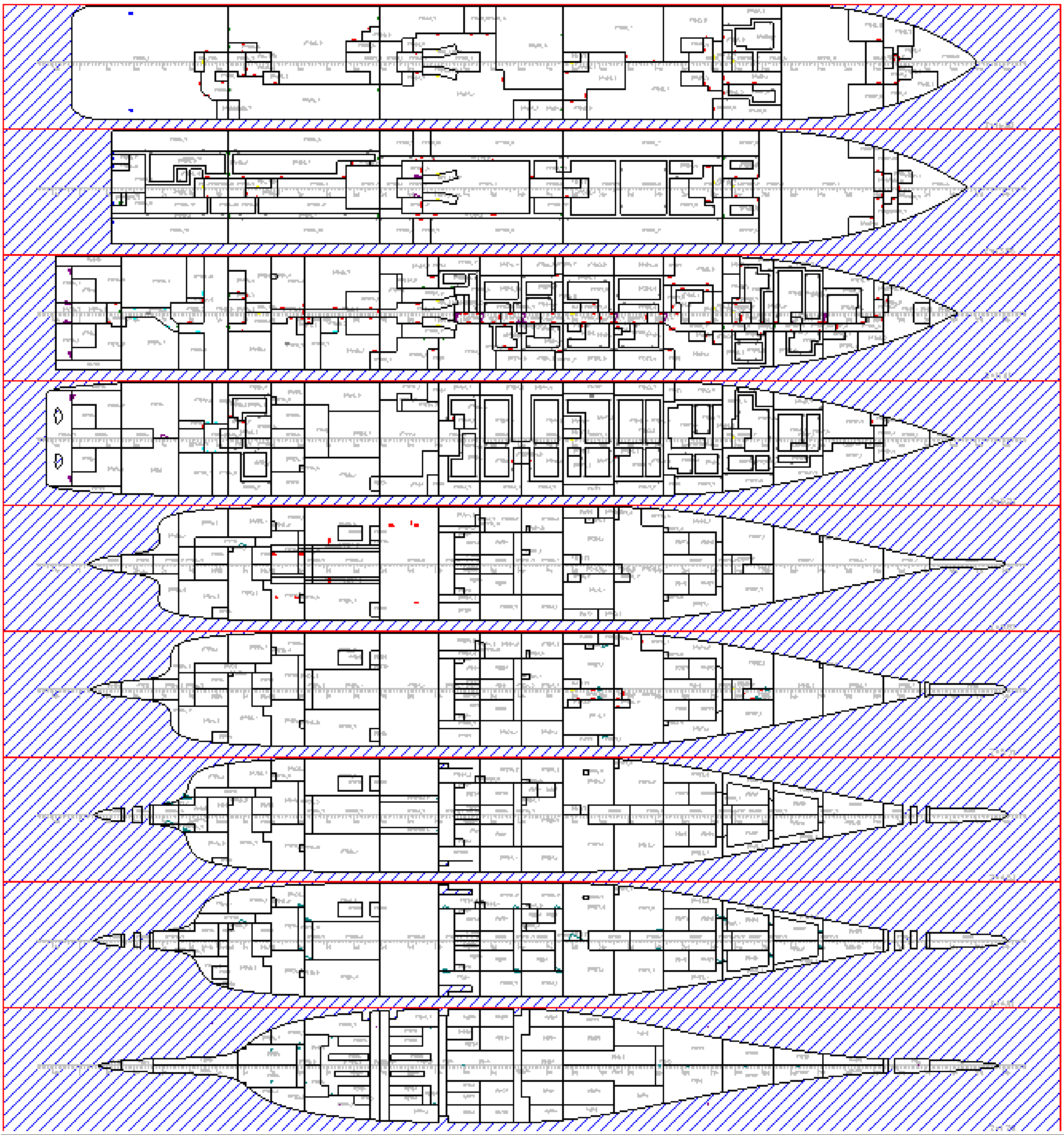


Figure 14 – Openings imported in Proteus Project (horizontal section)– Ship #3

Table 11 Opening Types in Proteus Manager

TYPE	Leak Area I 1 to 2	Leak Area I 2 to 1	Collapse Pre 1 to 2 [mete	Collapse Pre 2 to 1 [mete	Leak Hei [meters]	Gap Hei [meters	Effective H HEff Switch	Open At T [seconds]	Close At Ti [seconds]
CONNECTION	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
WT-DOOR-LWD	0.02500	0.02500	2.60	2.60	0.000	0.000	False	0	999999
WT-DOOR-SWD	0.02500	0.02500	2.60	2.60	0.000	0.000	False	0	999999
ESCAPE_HATCH	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
ESCAPE_DOOR	0.03000	0.02000	2.50	2.50	0.000	0.000	False	0	999999
FDOOR-HINGED	0.03000	0.02000	2.50	2.50	0.000	0.000	False	0	999999
FDOOR-HINGED-DOUBLE	0.02500	0.02500	2.00	2.00	0.000	0.000	False	0	999999
FDOOR-SLIDING	0.02500	0.02500	1.00	1.00	0.000	0.000	False	0	999999
COLDROOM-DOOR-SLID	0.03000	0.03000	3.50	3.50	0.000	0.000	False	0	999999
COLDROOM-DOOR-HING	0.03000	0.02000	3.50	3.50	0.000	0.000	False	0	999999
CABINS-DOOR	0.03000	0.03000	1.50	1.50	0.000	0.000	False	0	999999
LIFT-SLIDING_DOOR	0.03000	0.03000	1.50	1.50	0.000	0.000	False	0	999999
EXTERNAL-DOOR	0.00100	0.00100	100.00	100.00	99.000	0.000	False	0	999999
FREE-OPENING	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
CROSS_FLOODING-PIPE	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
CROSS_FLOODING-HATC	0.00000	0.00000	0.50	0.50	0.000	0.000	False	0	999999

Since in Proteus the discharge coefficient for the flow through openings is set to a constant value of 0.6 and it may be not changed, the area of the cross-flooding openings has been partly reduced in order to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation set have been created and the comparison of the geometric and hydrostatic data between NAPA and Proteus showed that the differences are negligible in general (from Figure 15 to Figure 22).

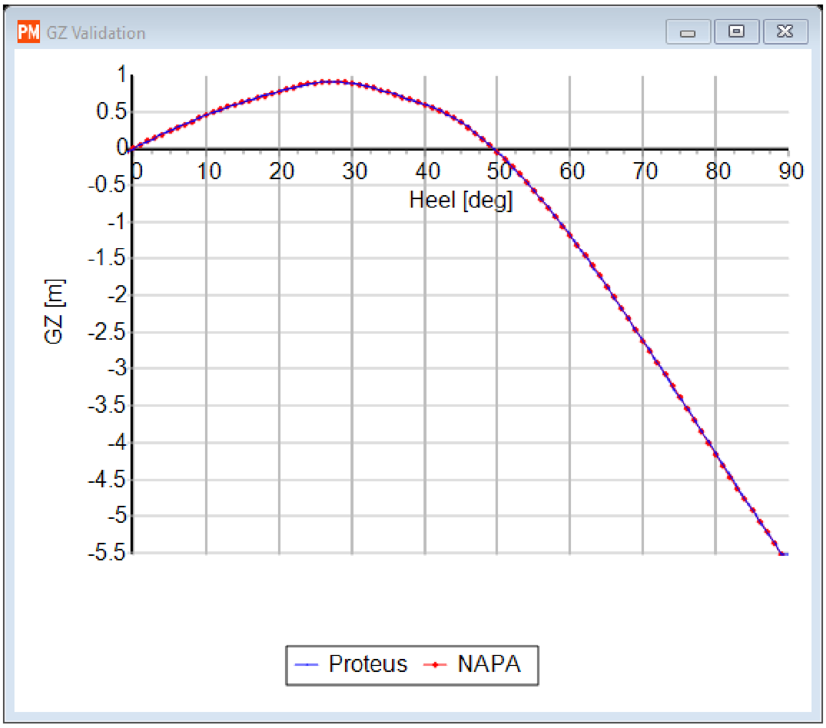
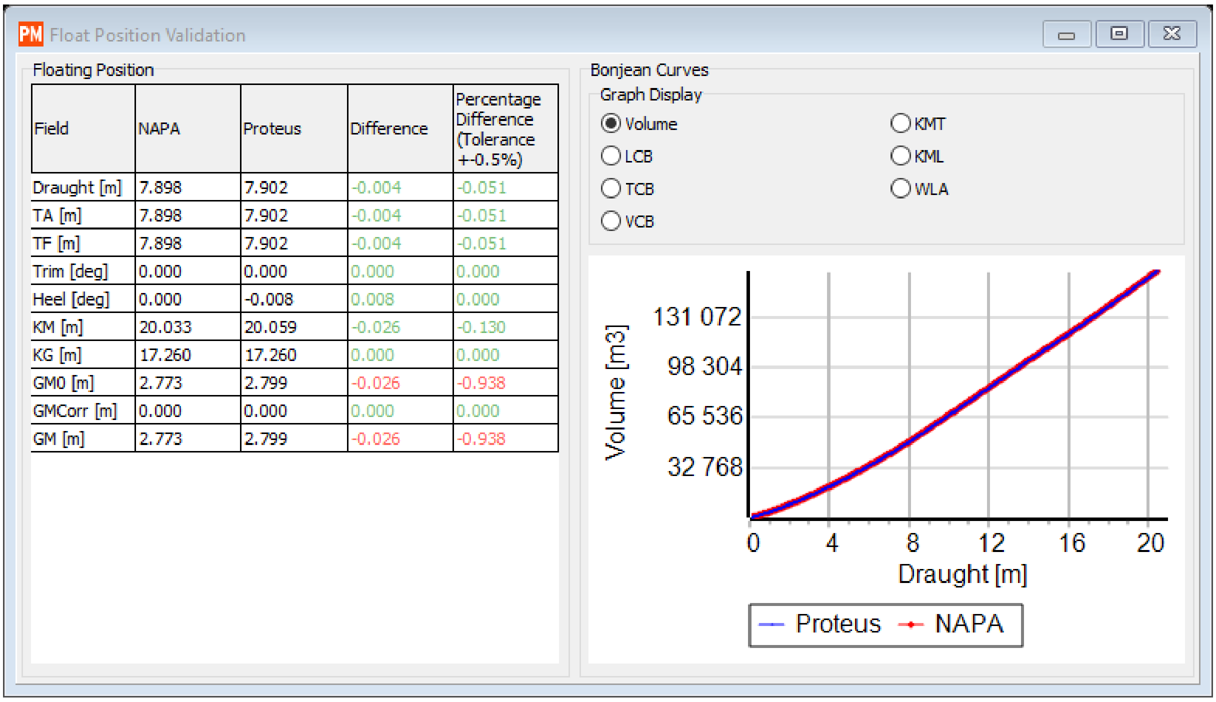


Figure 15 – GZ comparison between NAPA and Proteus – Ship #3



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	7.898	7.902	-0.004	-0.051
TA [m]	7.898	7.902	-0.004	-0.051
TF [m]	7.898	7.902	-0.004	-0.051
Trim [deg]	0.000	0.000	0.000	0.000
Heel [deg]	0.000	-0.008	0.008	0.000
KM [m]	20.033	20.059	-0.026	-0.130
KG [m]	17.260	17.260	0.000	0.000
GM0 [m]	2.773	2.799	-0.026	-0.938
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	2.773	2.799	-0.026	-0.938

Figure 16 – Floating Position comparison between NAPA and Proteus – Ship #3

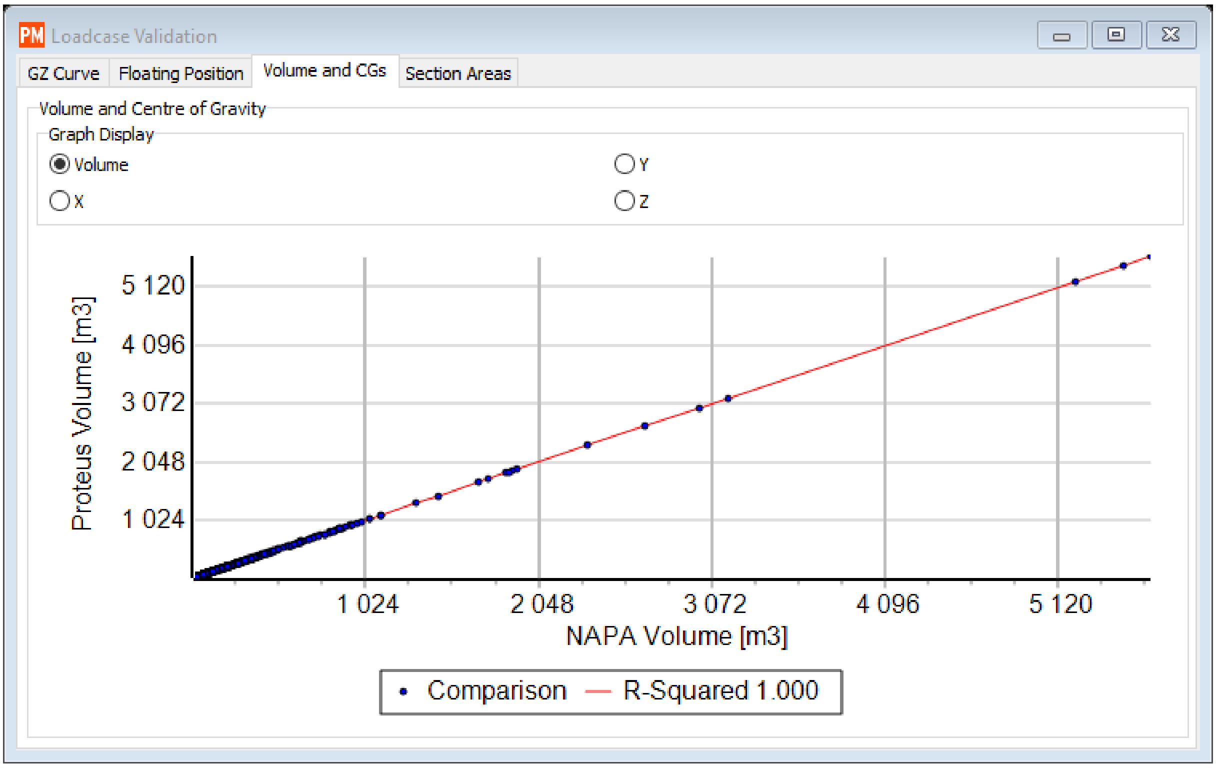


Figure 17 – Hull volume comparison between NAPA and Proteus – Ship #3

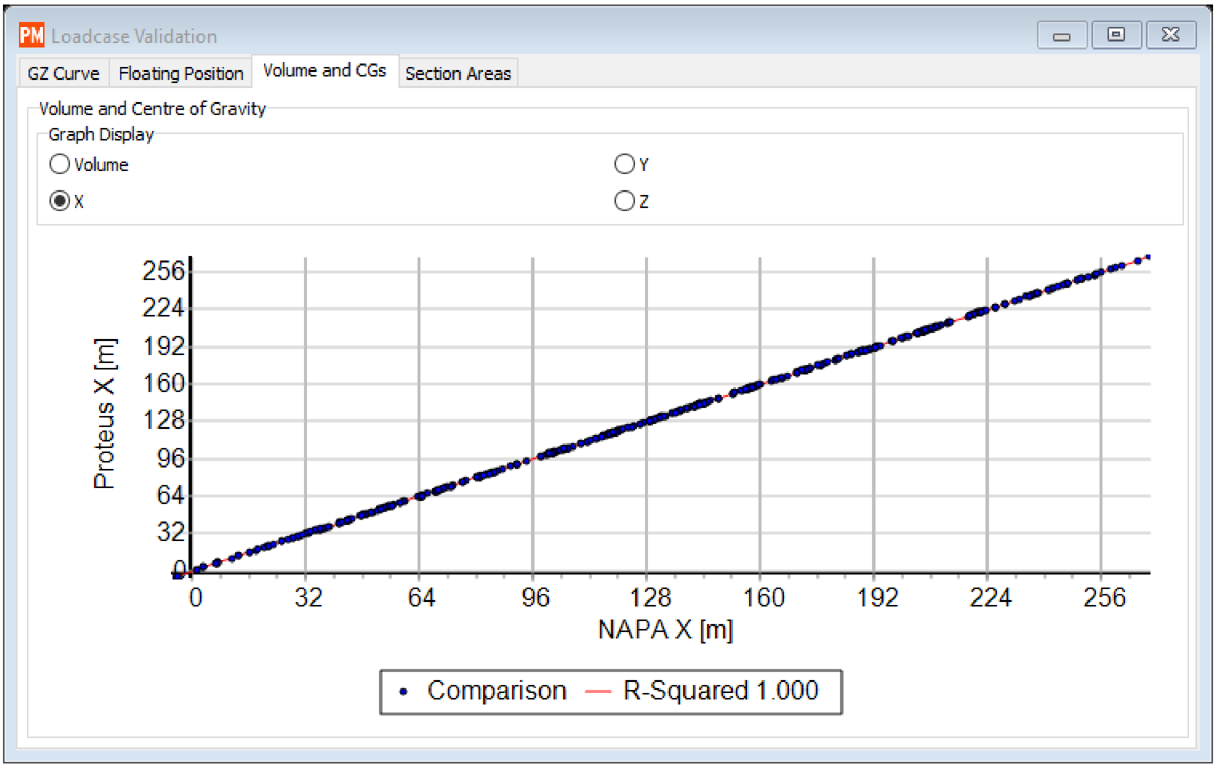


Figure 18 – Hull LCB comparison between NAPA and Proteus – Ship #3

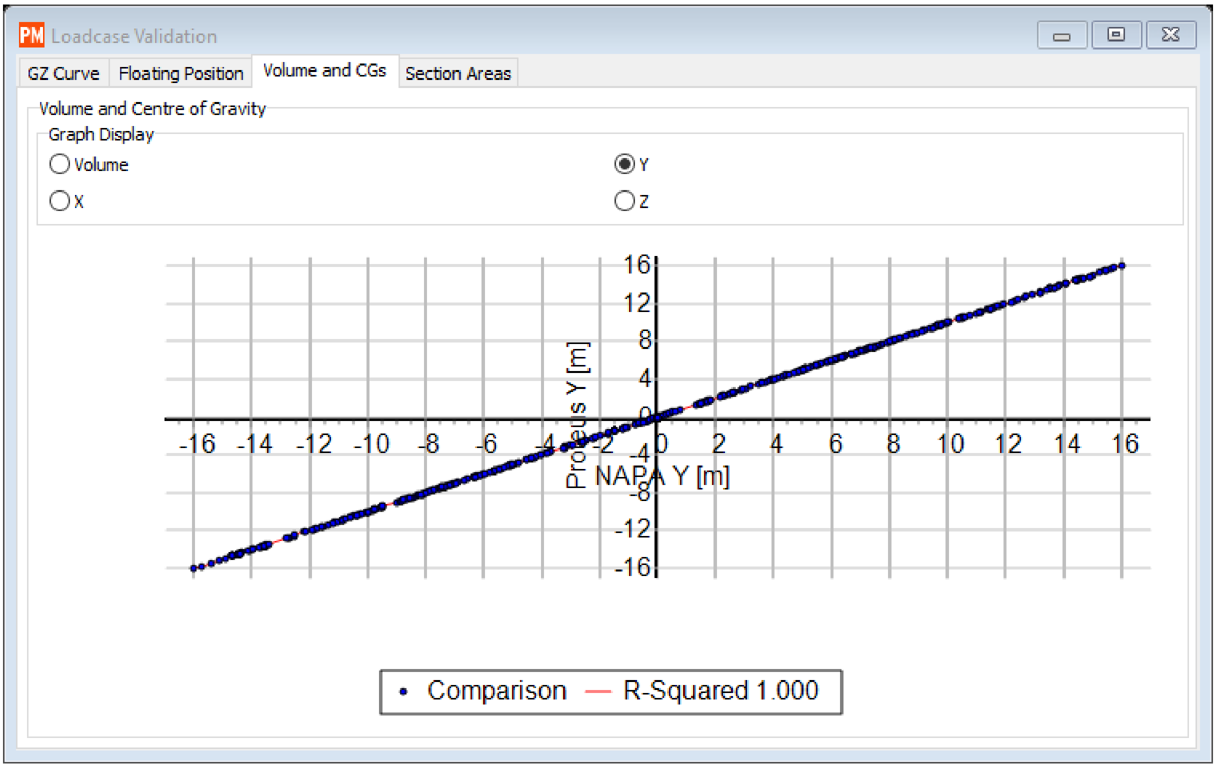


Figure 19 – Hull TCB comparison between NAPA and Proteus – Ship #3

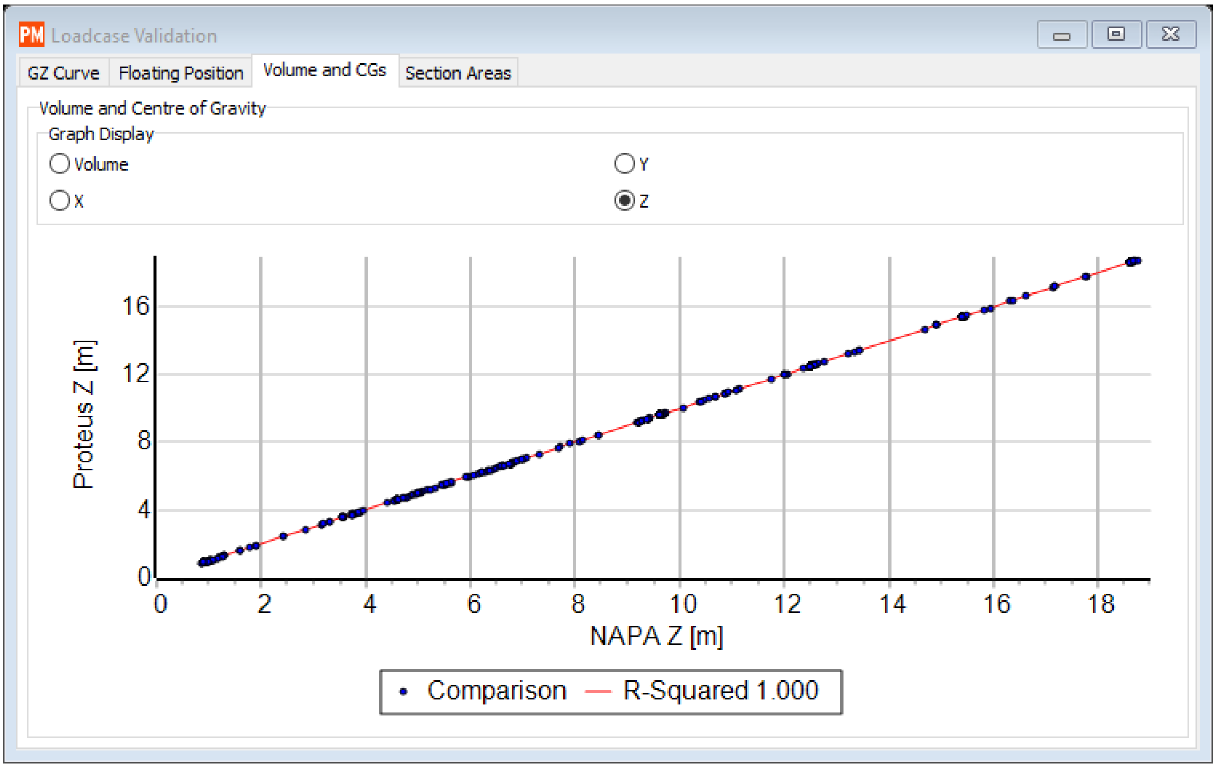
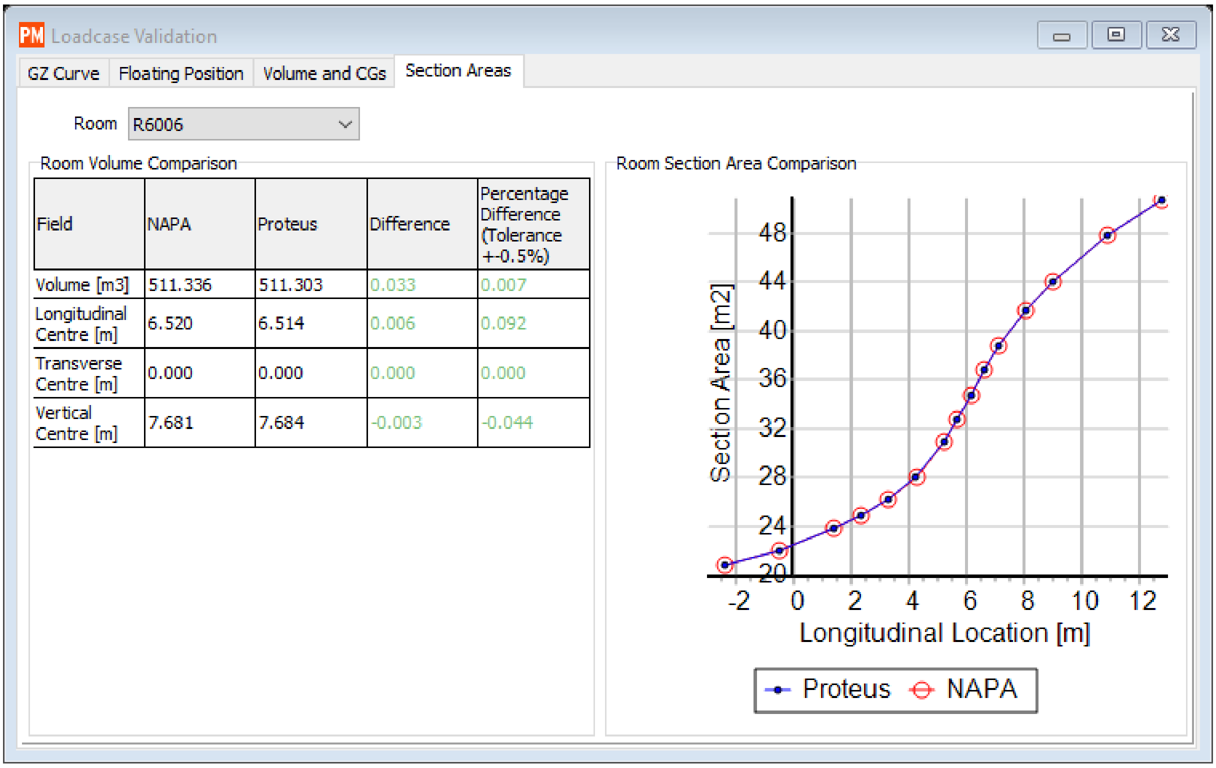
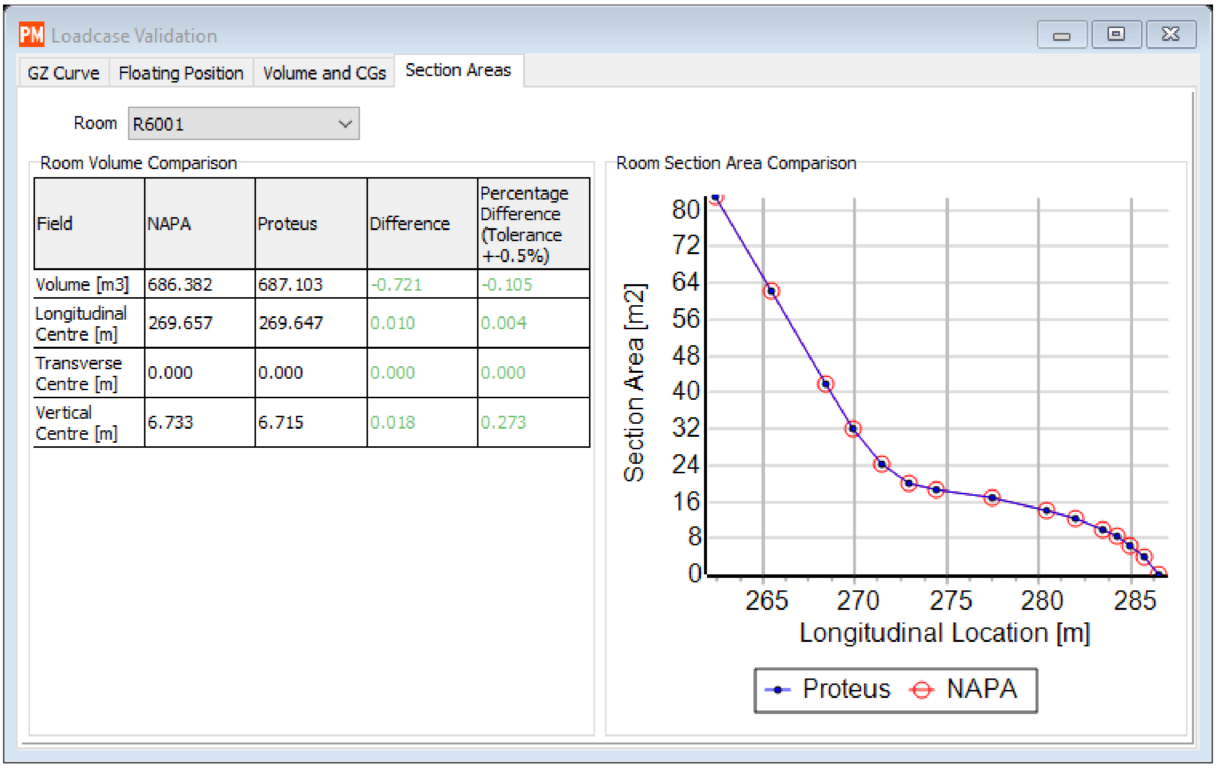


Figure 20 – Hull VCB comparison between NAPA and Proteus – Ship #3



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	511.336	511.303	0.033	0.007
Longitudinal Centre [m]	6.520	6.514	0.006	0.092
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	7.681	7.684	-0.003	-0.044

Figure 21 – Aftpeak comparison between NAPA and Proteus – Ship #3



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	686.382	687.103	-0.721	-0.105
Longitudinal Centre [m]	269.657	269.647	0.010	0.004
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	6.733	6.715	0.018	0.273

Figure 22 – Forepeak comparison between NAPA and Proteus – Ship #3

1.9 Results of dynamic simulations

In the first round of dynamic simulations by Proteus all the 500 breaches have been simulated up to 30 minutes, then for 120 breaches a second simulation round has been executed up to 80 minutes (cruise ship with 6 MVZ main vertical zone), as these were found with progressive flooding still occurring at the end of the first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1 = capsize 0 = not capsize) and TTC for cases where a capsize was found. In the following graphs the results for each hazard and the global results of simulations are presented.

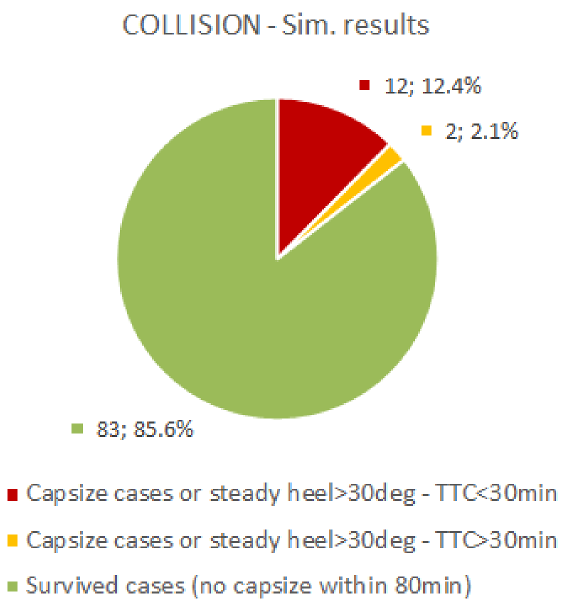


Figure 23 – Simulation results for collision – Ship #3

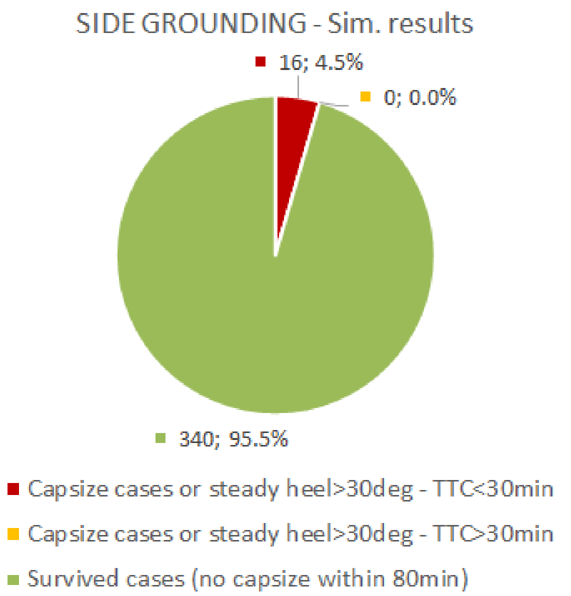


Figure 24 – Simulation results for side grounding – Ship #3

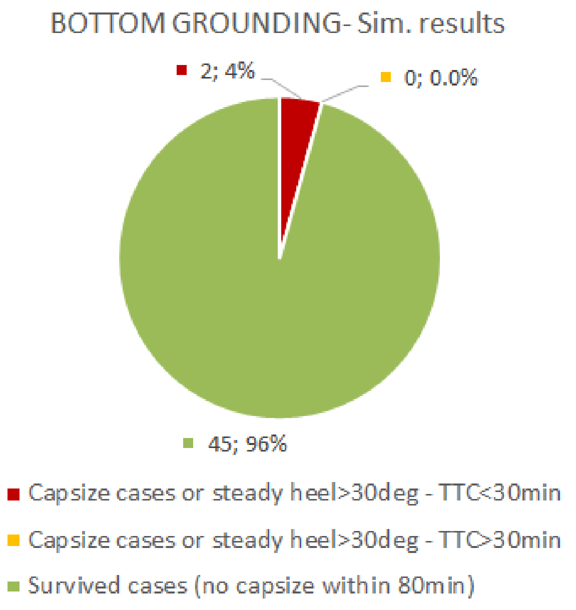


Figure 25 – Simulation results for bottom grounding – Ship #3

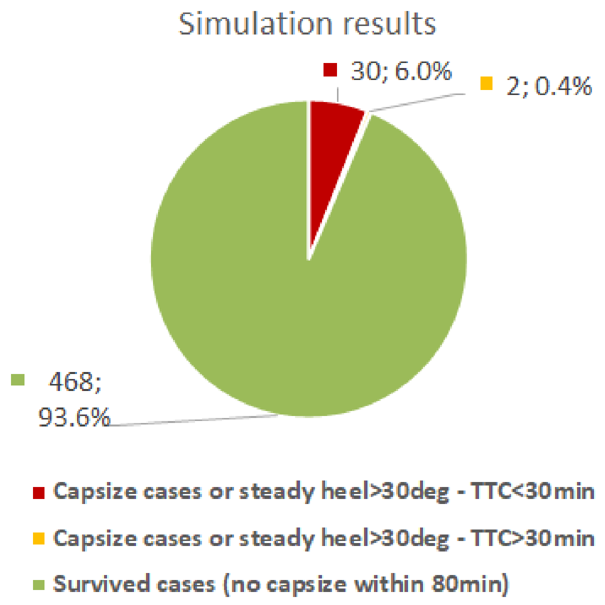


Figure 26 – Global simulation results for the 500 filtered breaches – Ship #3

The results obtained clearly show that for most of cases the ship did not capsize, which confirmed , that the static results are conservative as almost all of these cases have a Sfac = 0 in the static analysis (90% of cases).

This last graph shows that 93.7% of the capsize cases are fast capsize cases. For those cases, there is no sufficient time to evacuate as the TTC is less than 30 minutes.

The capsize cases represent about 12% of 500 simulated cases. It is interesting to note that although 90% of the cases had Sfac = 0, only 10% of those cases had no equilibrium in the static calculation. For this vessel, it seems that the proportion of capsize cases found with dynamic simulation is close to the cases with no equilibrium from the static analysis.

1.10 Calculation of PLL level 2.1

The results of the flooding simulations permit to get the TTC, therefore the fatality rate may be estimated for the cases with TTC > 30 min according to the procedure for calculation of Risk (Level 2.1).

In the Table 12 the details of the results obtained are reported and it can be noted that the PLL has been reduced from 1.0888 (Level 1) to 0.8334 (Level 2.1).

Table 12 PLL level 2.1 – Ship #3

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	7.898	8.063	7.898	8.063	7.898	8.063	
PLL L1 (1/ship year) (static assessment)	**1.99E-01**	**1.56E-01**	**2.73E-01**	**2.62E-01**	**9.52E-02**	**1.04E-01**	**1.0888**
	0.3549		**0.5349**		**0.1990**		
Number of filtered damage cases	48	49	188	168	22	25	500
Capsize cases or steady heel>30deg - TTC<30min	6	6	11	5	2	0	30
Capsize cases or steady heel>30deg - TTC>30min	0	2	0	0	0	0	2
Survived cases	42	41	177	163	20	25	468
PLL L2.1 (1/ship year) (dynamic assessment)	1.79E-01	1.38E-01	1.75E-01	1.61E-01	8.74E-02	9.35E-02	**0.8334**
	0.3173		**0.3353**		**0.1809**		
PLL L2.1 vs L1 (variation percentage)	**-10.6%**		**-37.3%**		**-9.1%**		**-23.5%**

In the following figures the diagrams of the breaches which lead to capsize after dynamic simulations are reported.

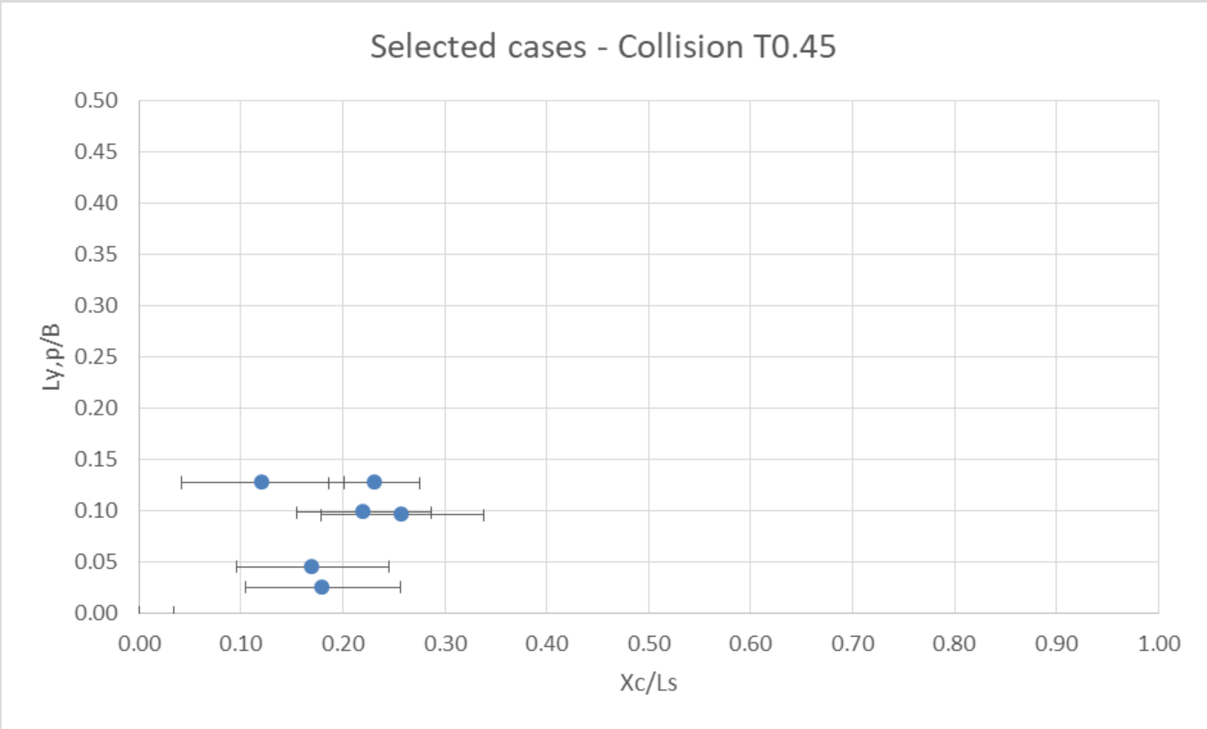


Figure 27 Characteristics of collision breaches leading to capsize T0.45 – Ship #3

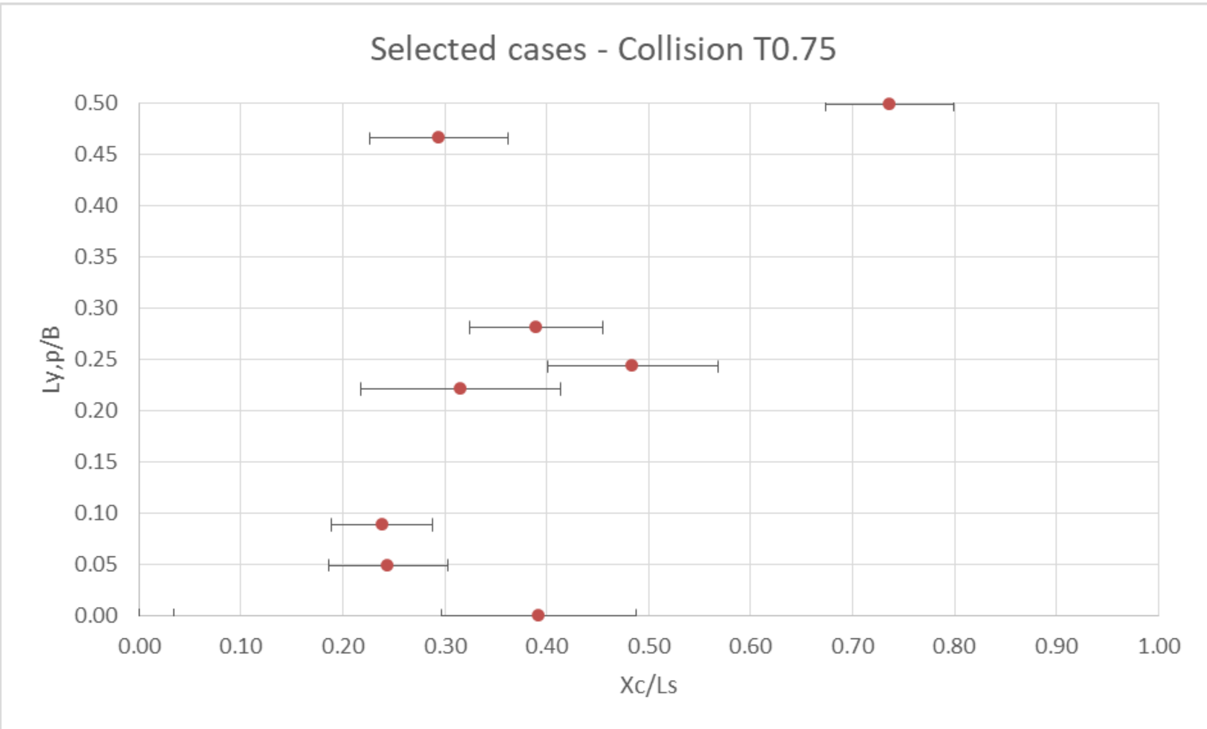


Figure 28 Characteristics of collision breaches leading to capsize T0.75 – Ship #3

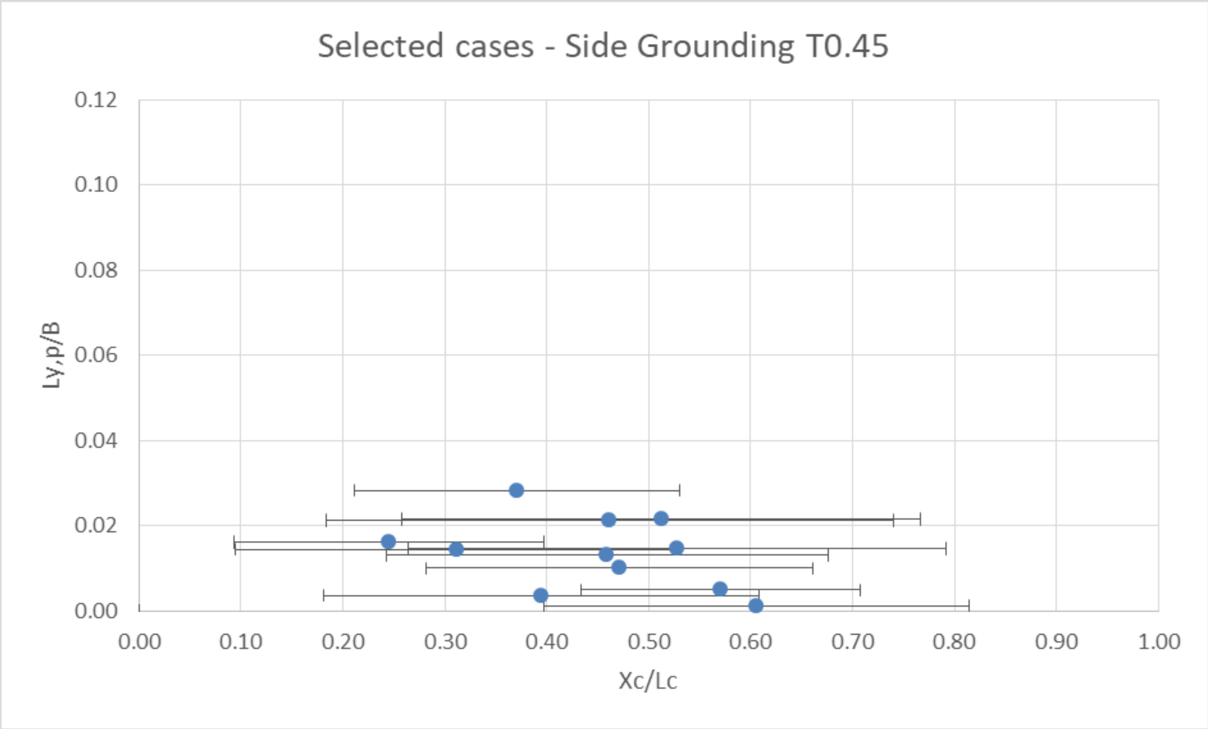


Figure 29 Characteristics of side grounding breaches leading to capsize T0.45 – Ship #3

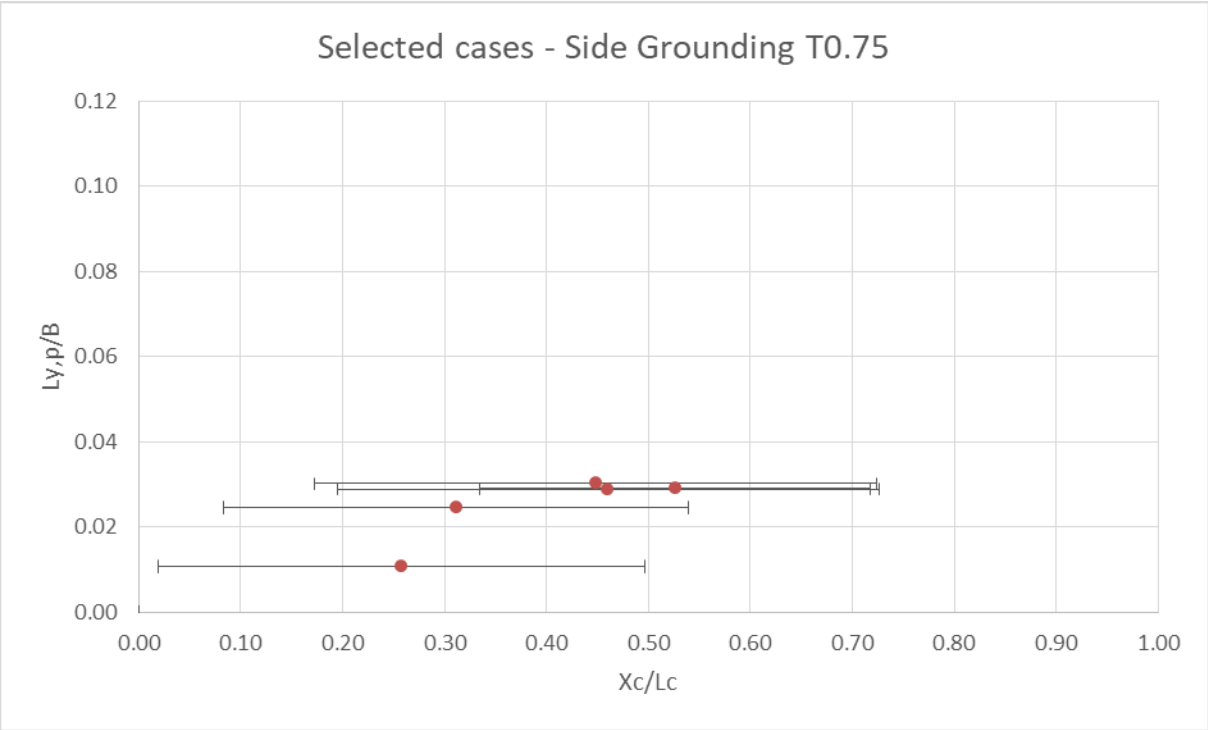


Figure 30 Characteristics of side grounding breaches leading to capsize T0.75 – Ship #3

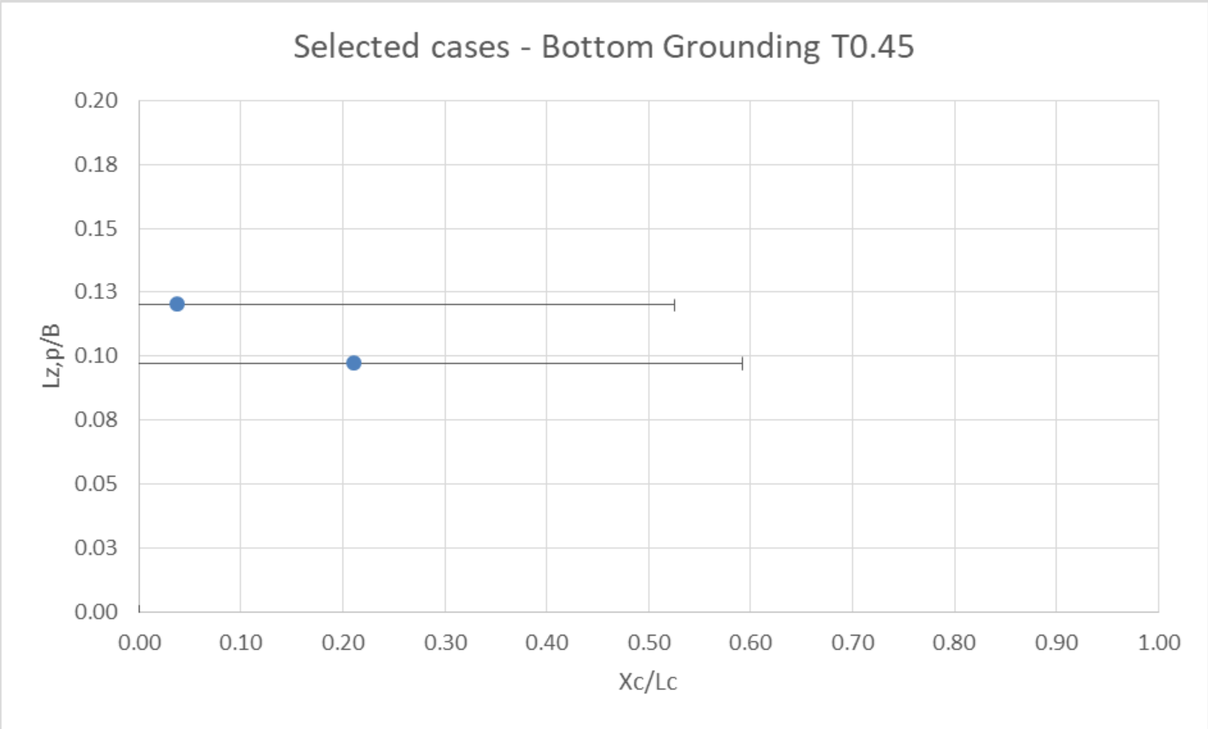


Figure 31 Characteristics of bottom grounding breaches leading to capsize T0.45 – Ship #3

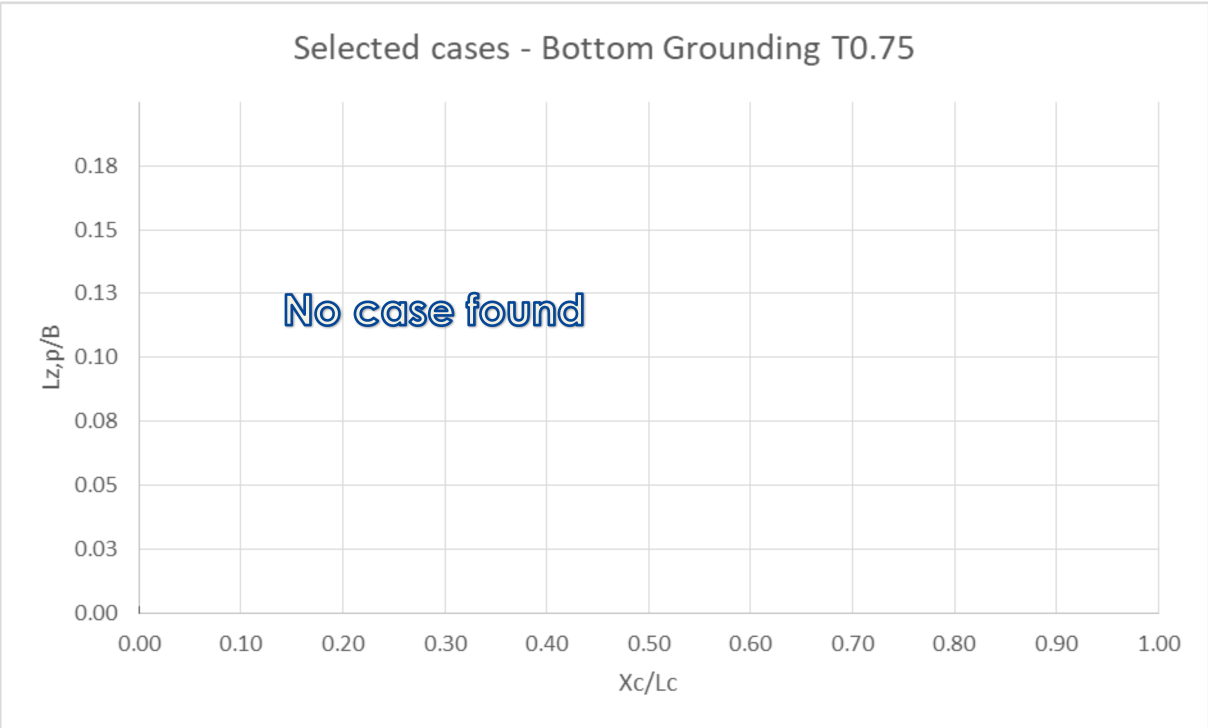


Figure 32 Characteristics of bottom grounding breaches leading to capsize T0.75 – Ship #3

The identified capsizal cases showed in the Figure 27 to Figure 32 may be investigated in WP7.2 when Risk Control Options are to be implemented.

One collision breach seems very narrow (see Figure 33) but 10% of the length of the ship corresponds to about 30m. In this particular case, the breach is affecting 3 compartments.

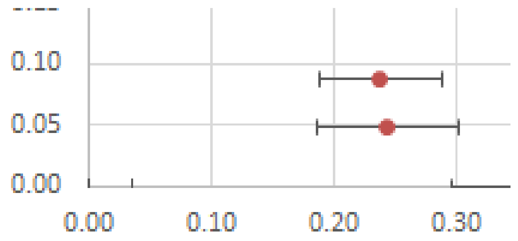


Figure 33 Characteristics of collision breaches leading to capsize in the aft part of the ship T0.75 – Ship #3

Generally for side grounding and bottom grounding, the capsize cases are extremely long breaches, which is in line with our expectations.

1.11 Sensitivity analysis of the fatality rate

From the dynamic simulation results it has been observed that about 2 cases resulted into a TTC greater than 30 min but lower than 80 min. For those cases linear Interpolation between 0% and 80% has been used for the estimation of the fatality rates (equation 5 of the main report. Furthermore, there are further 28 cases where progressive flooding is still occurring after 80 min and for these cases, no fatality has been assumed (Figure 34).

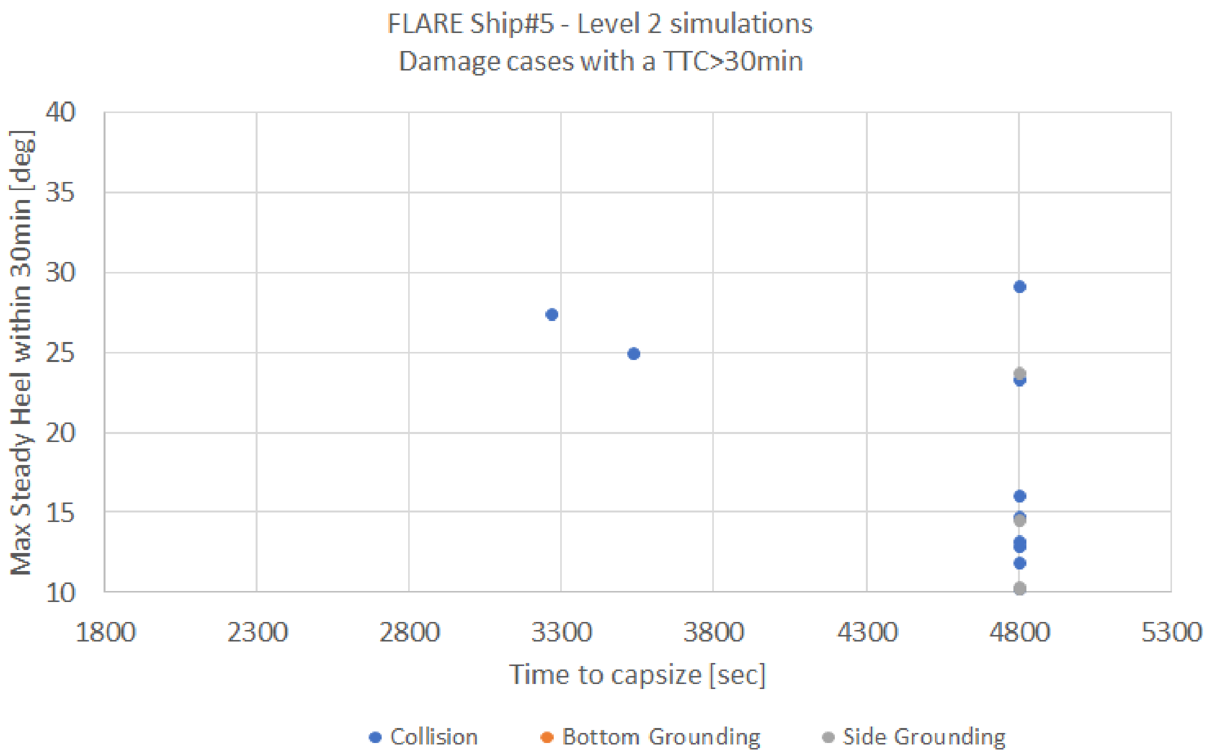


Figure 34 Cases with TTC > 30 min or progressive flooding still occurring after 80 min – Ship #3

In order to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out for the total 30 cases (with TTC > 30 min or progressive flooding still occurring after 80 min). For this purpose, the impact on the PLL has been evaluated by use of the simplify formula (main report equation 5) but assuming a variation of the fatality rate by ±30% of the POB.

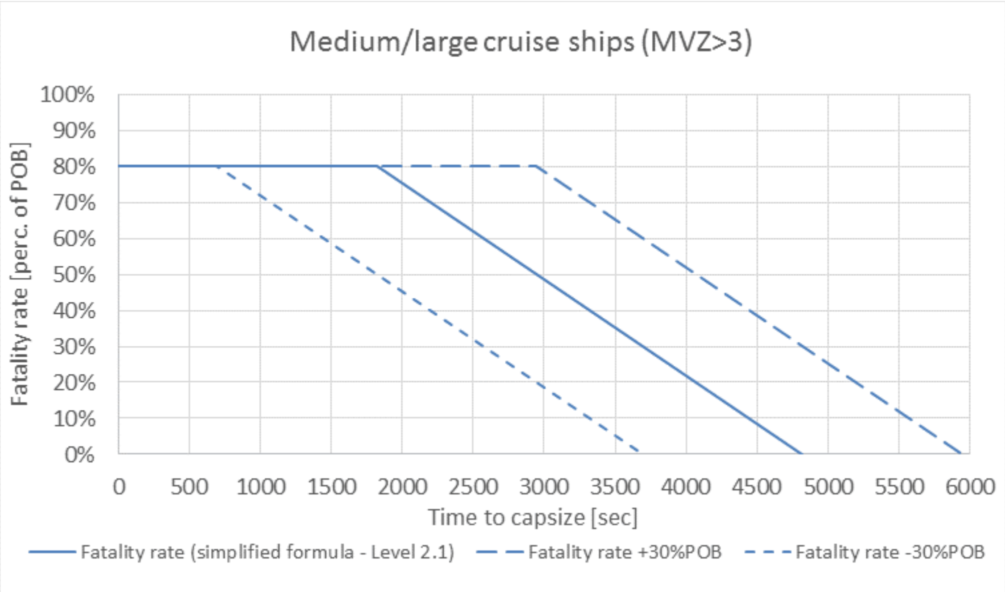


Figure 35 Sensitivity analysis of simplified formula for fatality rate calculation – Ship #3

Table 13 PLL level 2.1 variation of fatality rate – Ship #3

Damage Type	**Colision**		**Side Grouding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	7.898	8.063	7.898	8.063	7.898	8.063	
PLL L1 (1/ship year) (static assessment)	1.99E-01	1.56E-01	2.73E-01	2.62E-01	9.52E-02	1.04E-01	**1.0888**
	0.3549		0.5349		0.1990		
PLL L2.1 (1/ship year) (dynamic assessment)	1.79E-01	1.38E-01	1.75E-01	1.61E-01	8.74E-02	9.35E-02	**0.8334**
	0.3173		0.3353		0.1809		
PLL L2.1 vs L1 (variation percentage)	-10.6%		-37.3%		-9.1%		**-23.5%**
PLL L2.1 (1/ship year) with fatality rate increased by 30%	1.79E-01	1.39E-01	1.77E-01	1.63E-01	8.74E-02	9.36E-02	**0.8390**
	0.3178		0.3402		0.1810		
	+0.15%		+1.48%		+0.08%		**+0.70%**
PLL L2.1 (1/ship year) with fatality rate reduced by 30%	1.79E-01	1.38E-01	1.75E-01	1.61E-01	8.74E-02	9.35E-02	**0.8332**
	0.3170		0.3353		0.1809		
	-0.09%		-0.00%		-0.00%		**-0.03%**

The calculation with +30% in the fatality rate resulted into a PLL of 0.8390 (+0.70% compared to the reference PLL) while the calculation with -30% for the fatality rate resulted into a PLL of 0.8332 (-0.03% compared to the reference PLL). These values demonstrated that for this ship the simplified formula to derive the fatality rate used in the calculation of risk (Level 2.1) gives a reasonable accuracy. An evacuation simulation assessing the Time to Evacuate and therefore refining the fatality rate would not bring any added value.

3. CONCLUSIONS

The complete procedure for calculation of Risk has been applied on Ship 3 and the results obtained demonstrated that the procedure is consistent with the multi-level approach. In fact, the PLL has been reduced from 1.0888 (level 1) to 0.8334 (level 2.1)

The PLL Level 1 procedure appears conservative, while it seems to be more robust than PLL calculated by EMSA3 Risk Model as the fast/slow sinking node has not been used in the FLARE procedure.

The dynamic analysis in level 2 led to a reduction of the PLL by about 24% with the simulation of 500 breaches. Such reduction of the PLL is essentially based on the fact that about 94% of cases with Sfac = 0 in the static analysis, have been found to survive in the dynamic analysis. Moreover, although we have calculated the most efficient 500 breaches in term of PLL reduction, it is expected that the dynamic simulation applied on a higher sample of breaches would allow reducing more the PLL for our ship #3. The goal of this task was to demonstrate the process and it could be applied and extended in order to optimize further the results.

The flooding simulations showed a percentage of 94% of fast capsize cases (TTC < 30 min) and 6% only for slow capsize cases (TTC > 30 min). This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model (18% fast capsize).

Furthermore, a sensitivity analysis demonstrated that the impact on the PLL level 2.1 by even a large deviation of the fatality rate (calculated with the simplified formula) is negligible. This in turn shows that an evacuation analysis allowing to assess the time to evacuate would not bring any added value for the ship.

ANNEX 6 – Calculation of the flooding Risk for Ship n.5

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a small cruise ship design. As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1). The refined model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

The assumptions made for the fatality rate in the calculation for level 2.1 have been validated by an evacuation analysis carried out for the selected scenarios (level 2.2).

1 STATIC ASSESSMENT

1.1 Main data

Figure 1 Profile view – Ship #5

Ship #5 is a small cruise designed for unrestricted navigation but oriented for cruises in arctic and Antarctic regions. Here following the main characteristics:

Table 1 Main characteristics – Ship #5

Length over all	~128 m
Length between perpendiculars	113.7 m
Subdivision length	125.8 m
Breadth	20.0 m
Subdivision draught	5.3 m
Height of bulkhead deck	7.23 m
Number of passengers	323
Number of crew	155
Gross tonnage	11800 GT
Deadweight	1250 t
No of pax cabins	158
GT/Stateroom	74.7
GT/Lower Bed	37.3
Service speed	16 knots
Trial speed	17 knots
Installed propulsion power	7000 kW
Installed power of main engines	10300 kW

The business model and detailed description of the vessel are included in deliverable D.2.1.5.

Here following the Attained and Required Index according to SOLAS 2020 ch.II-1:

Number of persons	POB = 478
Required subdivision index	R = 0.7323
Attained subdivision index	A = 0.7436

1.2 Static calculations with new draughts and permeabilities

The following diagram is showing the draughts and the calculated GM for this vessel based on Ch. 3.1 of the main report.

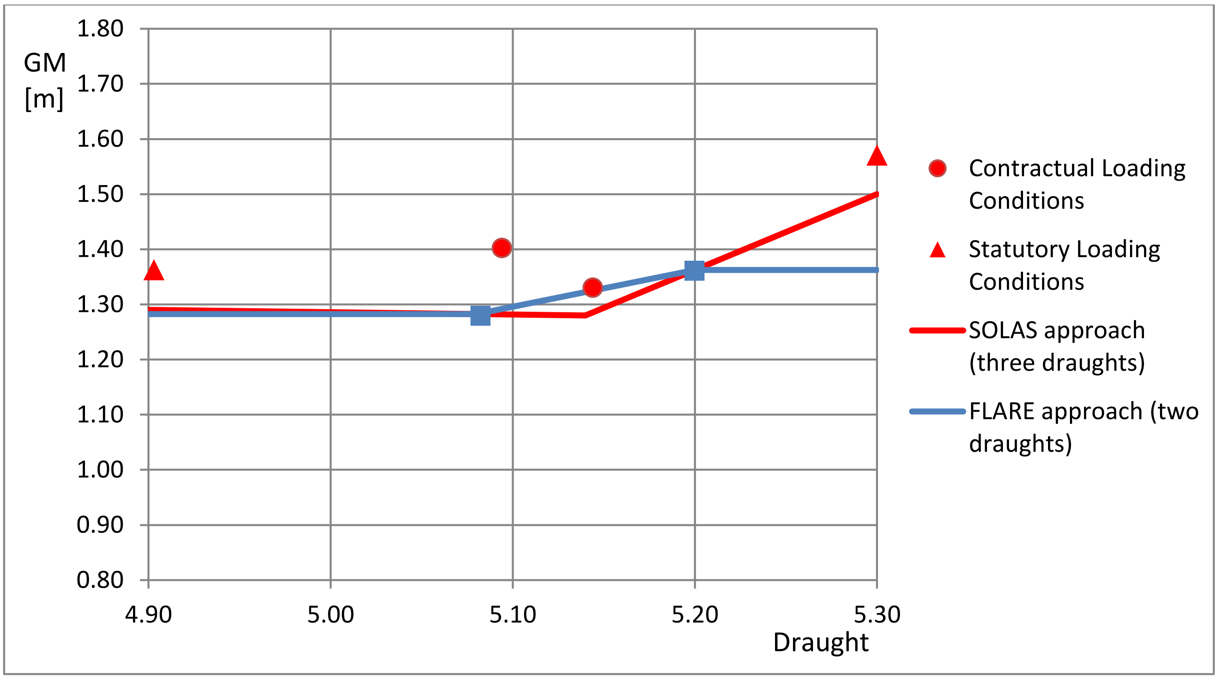


Figure 2 GM limiting curve with new FLARE draughts – Ship #5

The calculation has been executed with the software NAPA rel.2020.2, using the NEI approach for A-Class bulkheads and generating damages up to 5 adjacent zones.

These observations led to an attained index A = 0.7716 (with reference to the SOLAS A index +3.8%).

Table 2 Static results with new draughts and permeabilities acc. to FLARE – Ship #5

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	5.08	1.283	0.7691	0.5	0.3845	0.7716
T0.75	5.20	1.363	0.7742	0.5	0.3871	

1.3 Non-zonal static analysis

With the refined model according to the FLARE modelling guidelines (Annex 1) an increase of number of rooms and connections has been generated (see Table 3).

Table 3 Comparison between simplified model and refined model – Ship #5

Description	Before modelling	After modelling
Damhull volume	20,331 m^3	24,523 m^3
Rooms number	161	271
Connections number	113	227

For this ships the U-shaped void spaces within the DB were already subdivided in the CL with cross-flooding opening defined, hence there was no change for these void spaces in the new model.

The updated model includes new direct connections between cabin areas and corridors (for B-class boundaries) and between the parts of U-shaped voids above the double bottom. Moreover, new smaller A-class spaces that would impact the flooding have been modelled and provided with A-class connections accordingly.

The subdivision table is also affected by minor changes in order to consider also the damage cases that involve new rooms.

However, considering the refined model and using NAPA, a slightly lower value for the Attained Index (-0.3%) resulted.

Table 4 Static results with refined model – Ship #5

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	5.08	1.283	0.7670	0.5	0.3835	0.7692
T0.75	5.20	1.363	0.7713	0.5	0.3857	

1.3.1 Non-damage area

In the reference subdivision table, used for the zonal calculation, a "NON-DAMAGE AREA" was defined in the central part of the ship. This is used to route pipes generating progressive flooding that may not be controlled by remote control valves

Since the non-zonal analysis does not take into account the subdivision table, it is very important to define a virtual room to simulate that "NON-DAMAGE AREA".

That room is assumed having a permeability equal to zero and an unprotected opening in connection with the DAMHULL room in its lowest point at frame #70 has been defined too. The purpose of this definition is to make sure that every time a breach from collision or side/bottom grounding involves the "NON-DAMAGE AREA", such opening should be considered relevant by the used NAPA software and therefore the Sfac is set to zero.

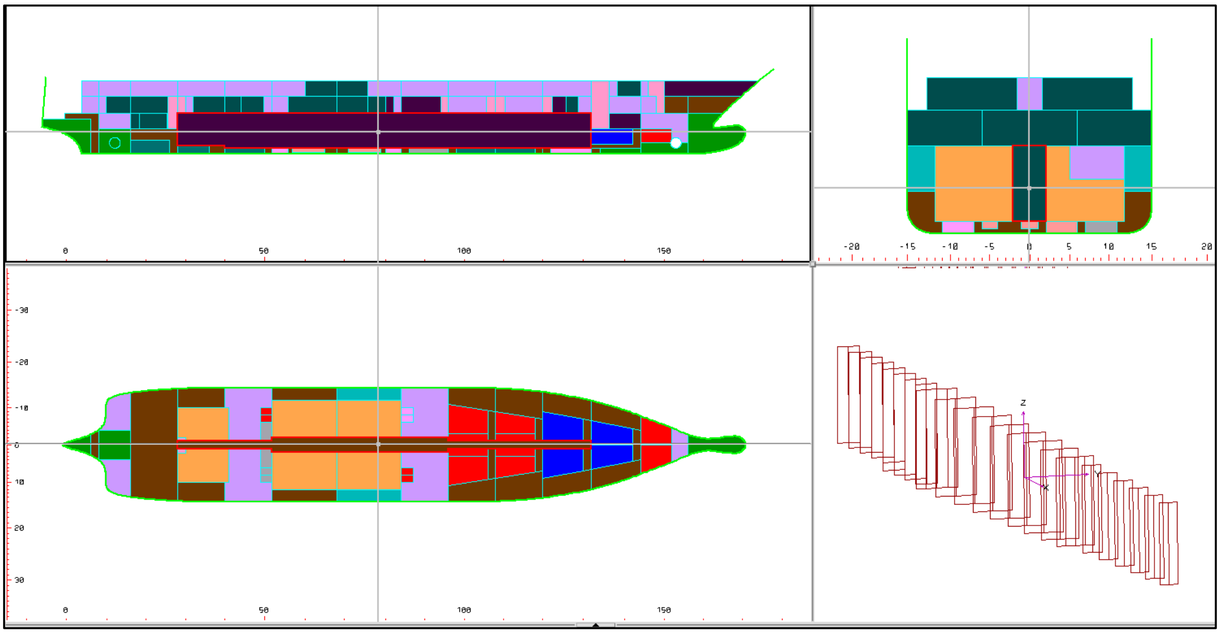


Figure 3 Defined room for ***NON-DAMAGE AREA*** in the non-zonal approach by NAPA – Ship #5

1.4 Calculation of PLL level 1

For this vessel breaches for collision, side and bottom grounding have been generated according to Ch. 3.2 of the main report and the grouping of breaches, leading to the same sets of flooded rooms, permitted to reduce the damage cases to be calculated by abt. 65% for collision and bottom grounding, and by abt. 85% for side grounding.

With the results of the static calculation for the attained index in hand, the PLL level 1 was calculated according to procedure described in Ch.2.4-2.5 of the main report. In particular in the Table 5 the non-zonal results are showed and in

Table 6 the PLL (Potential loss of life) calculation is reported.

Table 5 Non-zonal static analysis results – Ship #5

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**	
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75
Draught	5.08m	5.2m	5.08m	5.2m	5.08m	5.2m
Breaches	10000	10000	10000	10000	10000	10000
Number of Empty cases	80	74	0	0	96	93
Number of Unique damage cases	3391	3393	1682	1668	3407	3510
Partial Index	0.8003	0.8083	0.8610	0.8751	0.9003	0.8954
Total Attained Subdivision Index Ai	**0.8043**		**0.8681**		**0.8979**	

Table 6 PLL level 1 – Ship #5

Damage Type	**Collision**		**Side Grouding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		4.33E-03
Relative frequency	0.388		0.328		0.284		1.000
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	5.08	5.2	5.08	5.2	5.08	5.2	
Attained Index	0.8003	0.8083	0.8610	0.8751	0.9003	0.8954	0.8518
$\sum pfac$ (for cases with s=1)	0.7488	0.7436	0.8296	0.8441	0.8915	0.8841	0.8162
$\sum pfac \cdot (1 - sfac)$	0.1997	0.1917	0.1390	0.1249	0.0997	0.1046	0.1482

PLL level 1 (1/ship year)	6.41E-02	6.16E-02	3.77E-02	3.39E-02	2.35E-02	2.46E-02	**0.2454**
	0.1257		**0.0716**		**0.0481**		

Even though the PLL is eventually the parameter to be used as a risk metric by FLARE, the Combined Attained Index is also shown in

Table 6 for information only. These values are calculated by using the relative frequency (equation 7 of the main report) for collision, Side grounding and Bottom Grounding, which are based on the updated damage statistics of FLARE (WP2).

1.5 Filtering of static results and selecting cases for dynamic simulations

The screening of the static result according to filtering criteria identified within Ch. 3.4 of the main report permitted to select 500 cases for the dynamic simulations. In the following table a summary of the filtered breaches is reported.

Table 7 Filtering results for dynamic simulation – Ship #5

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	5.08m	5.2m	5.08m	5.2m	5.08m	5.2m	
Number of filtered damage cases	141	100	136	117	4	2	500
$\sum pfac$ (for the filtered damage cases)	0.0675	0.0554	0.0676	0.0590	0.0012	0.0006	0.0449
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0650	0.0538	0.0669	0.0571	0.0012	0.0006	0.0437
Potential PLL (if the ships would not capsize for all selected cases)	4.33E-02	4.43E-02	1.96E-02	1.84E-02	2.32E-02	2.45E-02	0.1732
	0.0876		0.0380		0.0476		
Potential PLL reduction (if the ships would not capsize for all selected cases)	30.4%		47.0%		0.9%		29.4%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. In particular for this ship the PLL would be reduced by about 29% if all the cases to be simulated are not capsizals.

In the following diagrams some typical damage parameters of the selected breaches are presented in non-dimensional form.

It is very interesting to note that for collision there are two vulnerable area: the aft compartments and the compartments just forward the main engine rooms. This is because a large majority of selected breaches for side grounding has a huge length therefore they affect a high number of compartments.

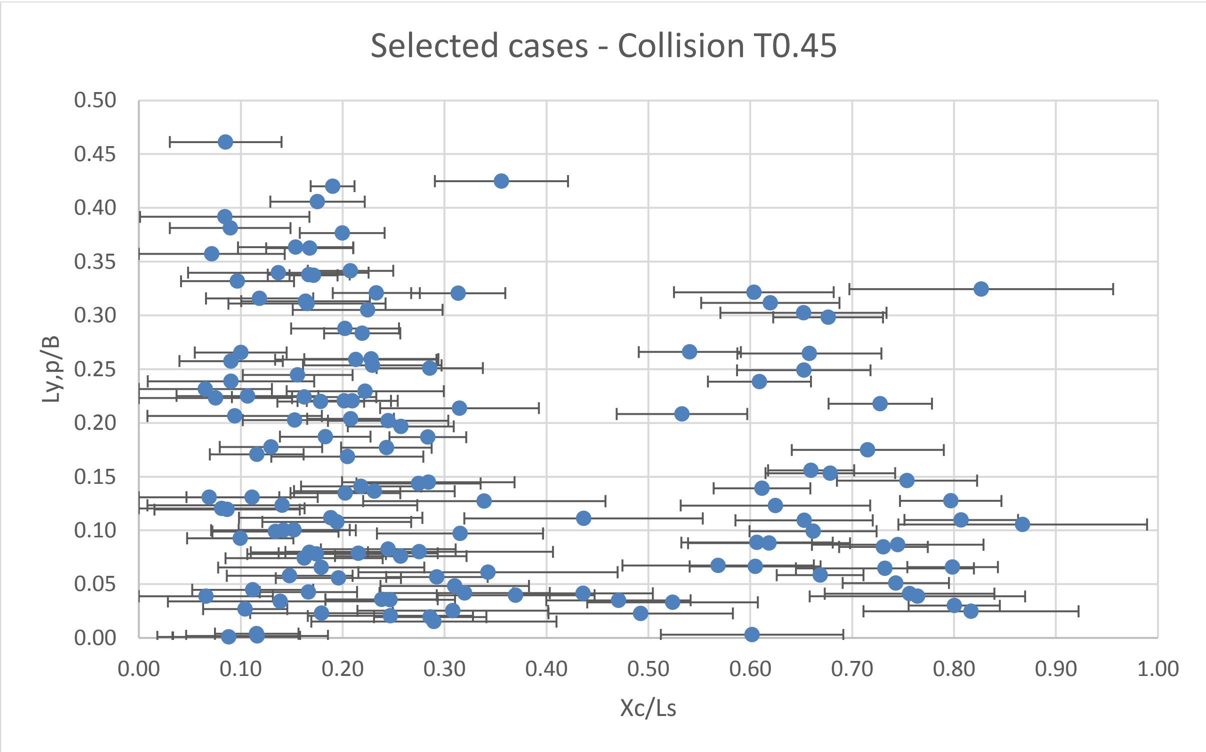


Figure 4 Selected collision breaches T0.45 – Ship #5

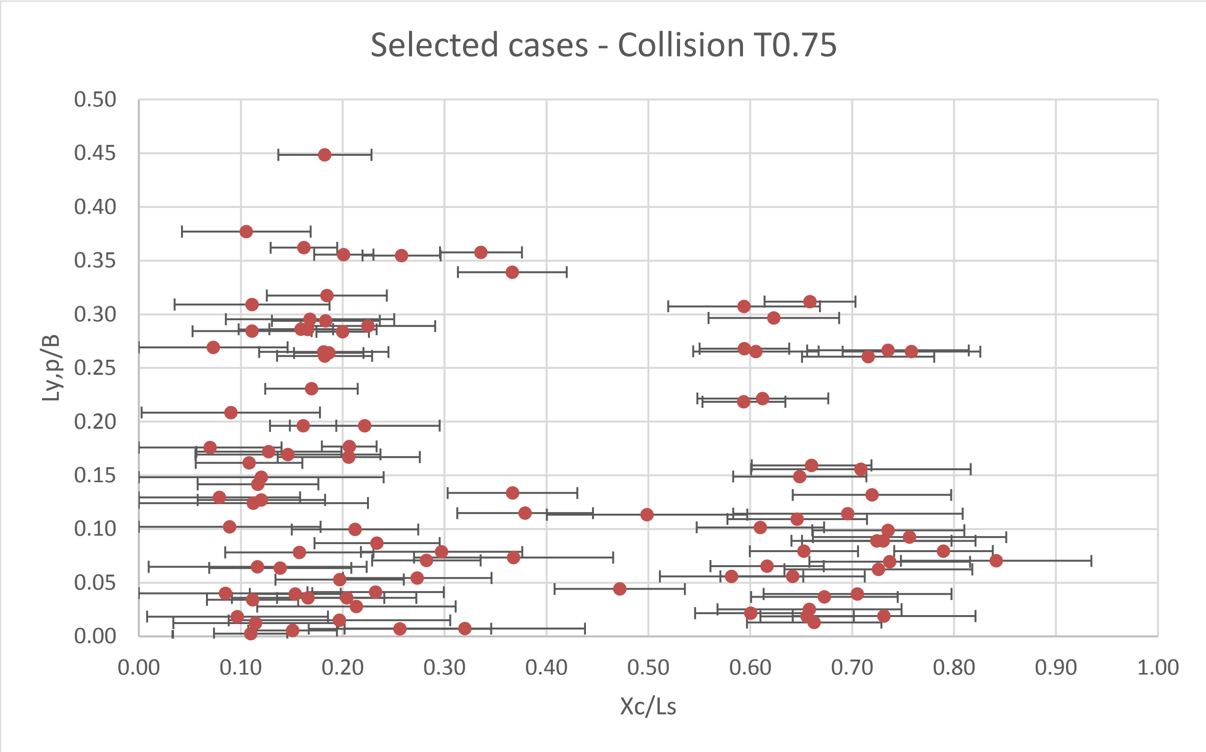


Figure 5 Selected collision breaches T0.75 – Ship #5

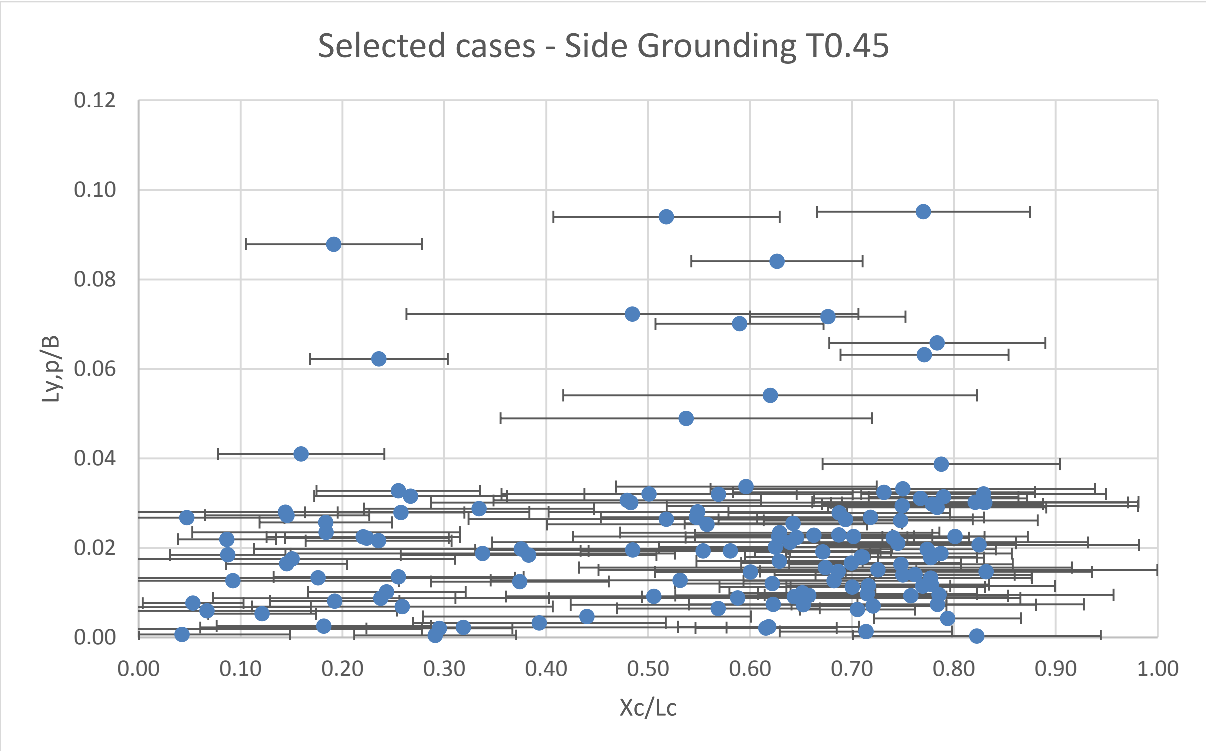


Figure 6 Selected side grounding breaches T0.45 – Ship #5

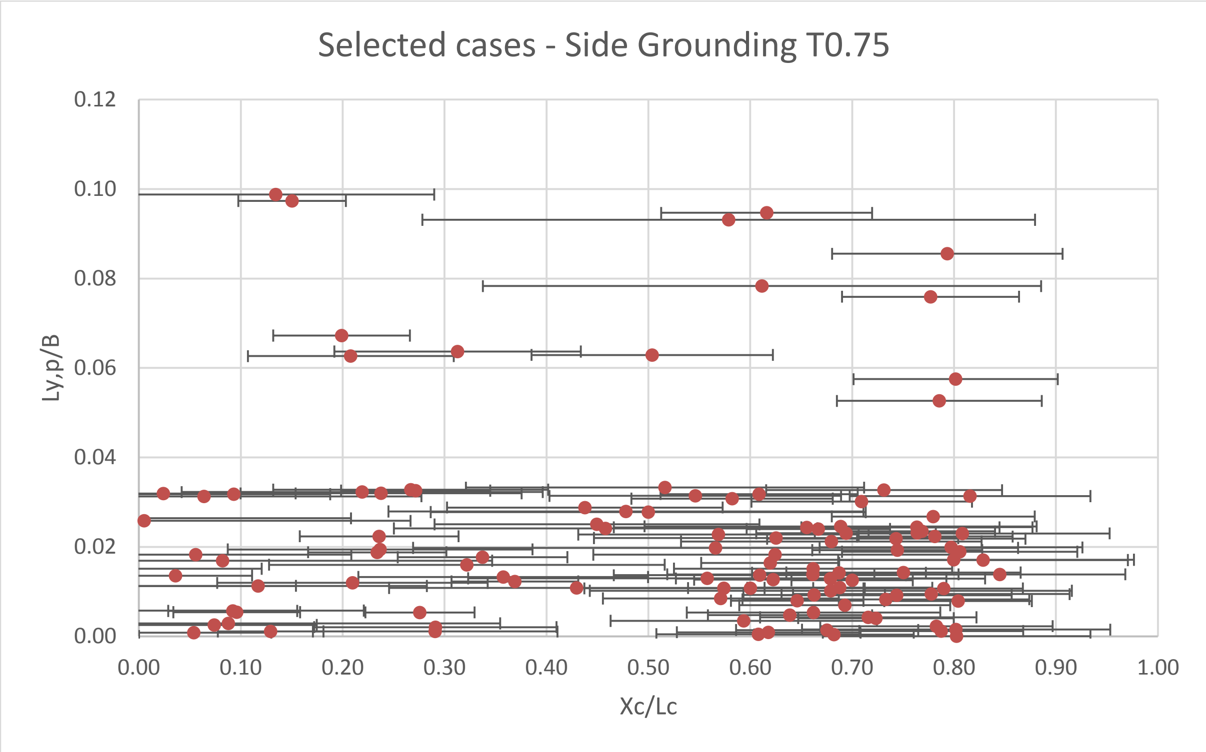


Figure 7 Selected side grounding breaches T0.75 – Ship #5

For the bottom grounding, instead, are just few filtered breaches, this is due to the fact the ship survives when only the double bottom is affected by flooding. Hence only those case with a vertical penetration higher than the double bottom height and with a high value *freq*pfac*(1-sfac)* are selected.

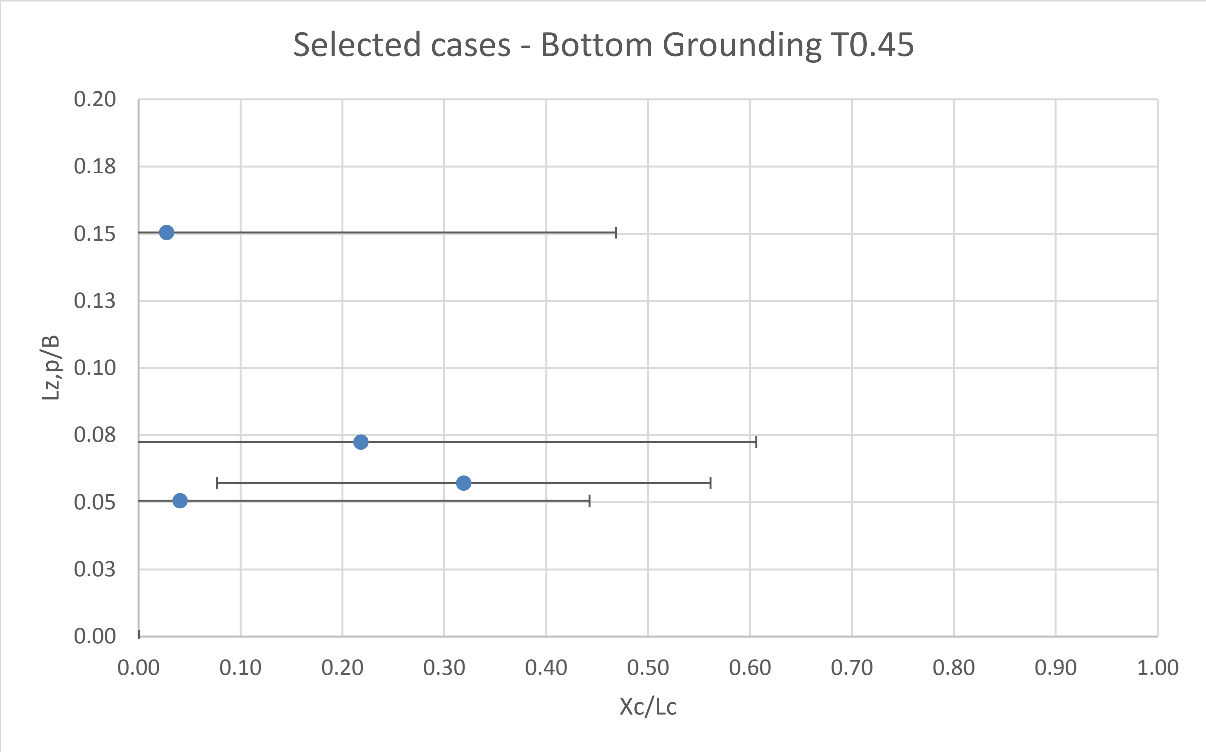


Figure 8 Selected bottom grounding breaches T0.45 – Ship #5

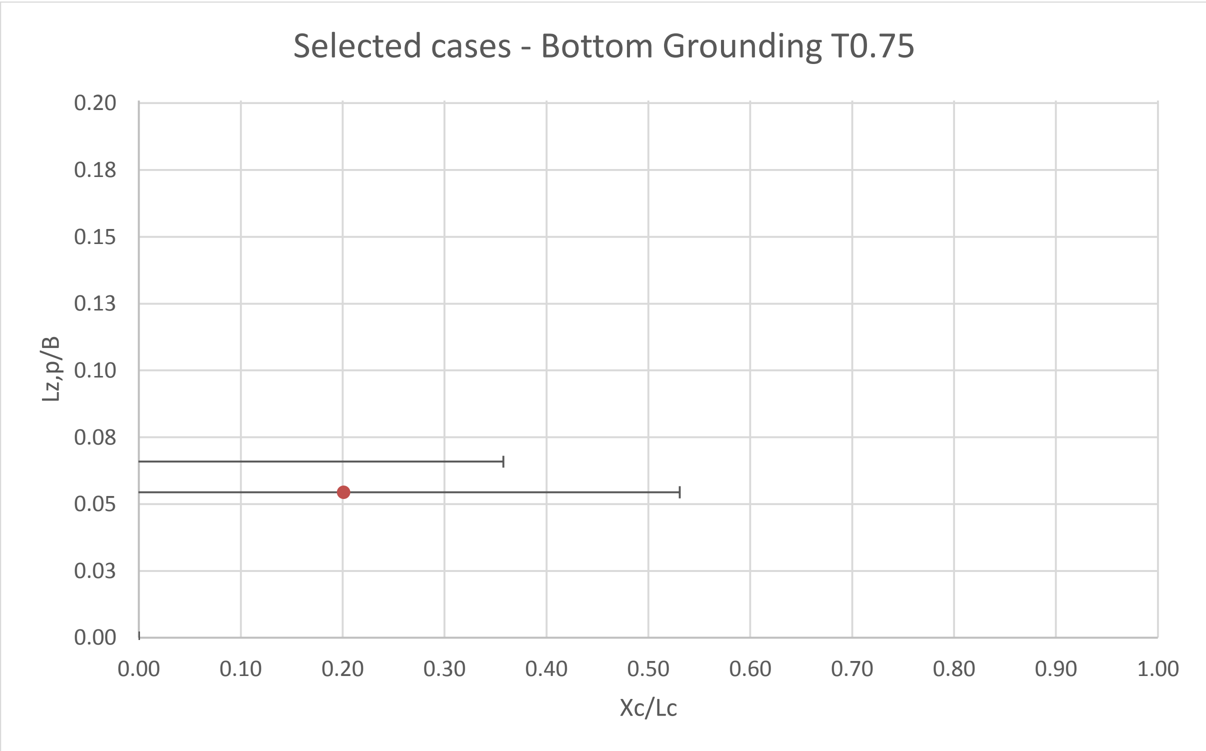


Figure 9 Selected bottom grounding breaches T0.75 – Ship #5

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with Sfac=0 and failure modes for cases with 0<Sfac<1, are showed in the following tables.

Table 8 Breakdown of failure mode for Sfac = 0 cases – Ship #5

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	23	9	12	13	0	0	**57**
Heeling Angle (> 15 deg)	70	25	92	49	1	0	**237**
Smom = 0	26	43	21	31	3	1	**125**
Opening immersion	18	12	8	16	0	1	**55**
Sfac = 0 - Total cases	**137**	**89**	**133**	**109**	**4**	**2**	**474**

Table 9 Breakdown of failure mode for 0 < Sfac < 1 cases – Ship #5

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	0	0	0	0	0	0	**0**
Insufficient Range	0	0	0	0	0	0	**0**
Heeling Angle (> 7 deg)	0	0	0	0	0	0	**0**
Insufficient Restoration (GZmax) + Range	1	9	0	4	0	0	**14**
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	**0**
Insufficient Range + Excessive Heel	1	1	3	3	0	0	**8**

Insufficient Restoration (GZmax) + Range + Excessive Heel	2	1	0	1	0	0	**4**
0 < Sfac < 1 - Total cases	**4**	**11**	**3**	**8**	**0**	**0**	**26**

A large percentage of captured cases resulted into Sfac = 0 (474 cases over 500) and about 50% of the captured cases had a failure mode corresponding to a heeling angle greater than 15 deg. This occurred for collision and side grounding essentially as these breaches type led to a big asymmetry in the flooding scenario.

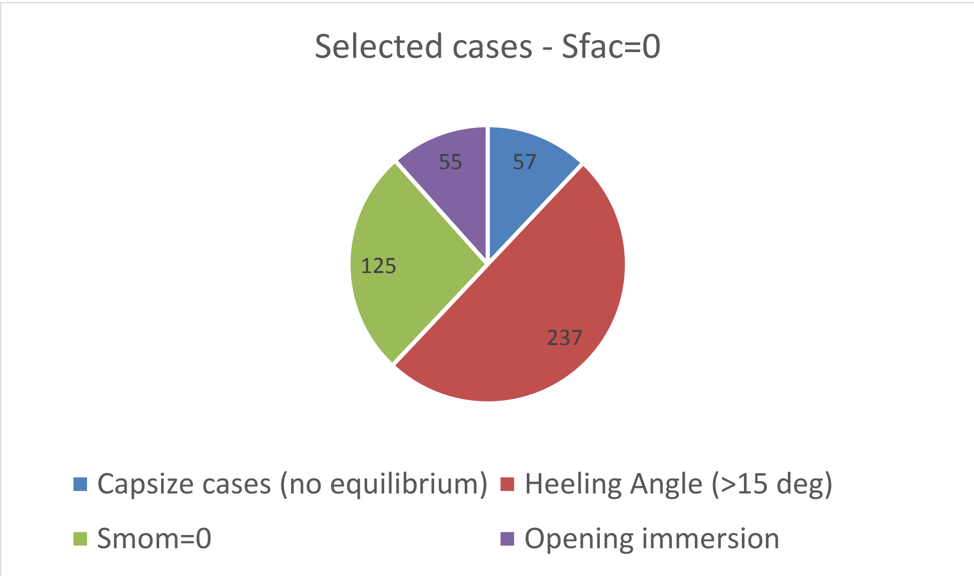


Figure 10 Diagram of failure mode for Sfac = 0 cases – Ship #5

A lot of damage cases (n.125) with Smom = 0 have been found too while the equilibrium was not reached in the static calculation for 57 cases.

In the majority of the cases where equilibrium was not achieved the failure (i.e. no equilibrium) was found at the first stage of flooding when the cross-flooding is not started yet. That stage is not used to calculate the survivability factor s but it is requested by the explanatory notes of SOLAS Ch.II-1 [11] that a positive GZ is achieved at that stage in order to calculate the cross-flooding time. It will be very important to assess those cases by dynamic simulations so that the real physics of the phenomenon will be investigated.

Finally, 55 cases have been identified due to the immersion of openings. These cases are very important to be selected too as it is expected that the outcome of the dynamic simulation should be quite different. In fact, the approach for connections and openings definition is completely different between static and dynamic calculation.

A limited number of damage cases with 0 < Sfac < 1 has been selected and the majority of these cases resulted in an insufficient GZmax and excessive Range, then eight cases resulted in an insufficient Range and excessive heeling angle too.

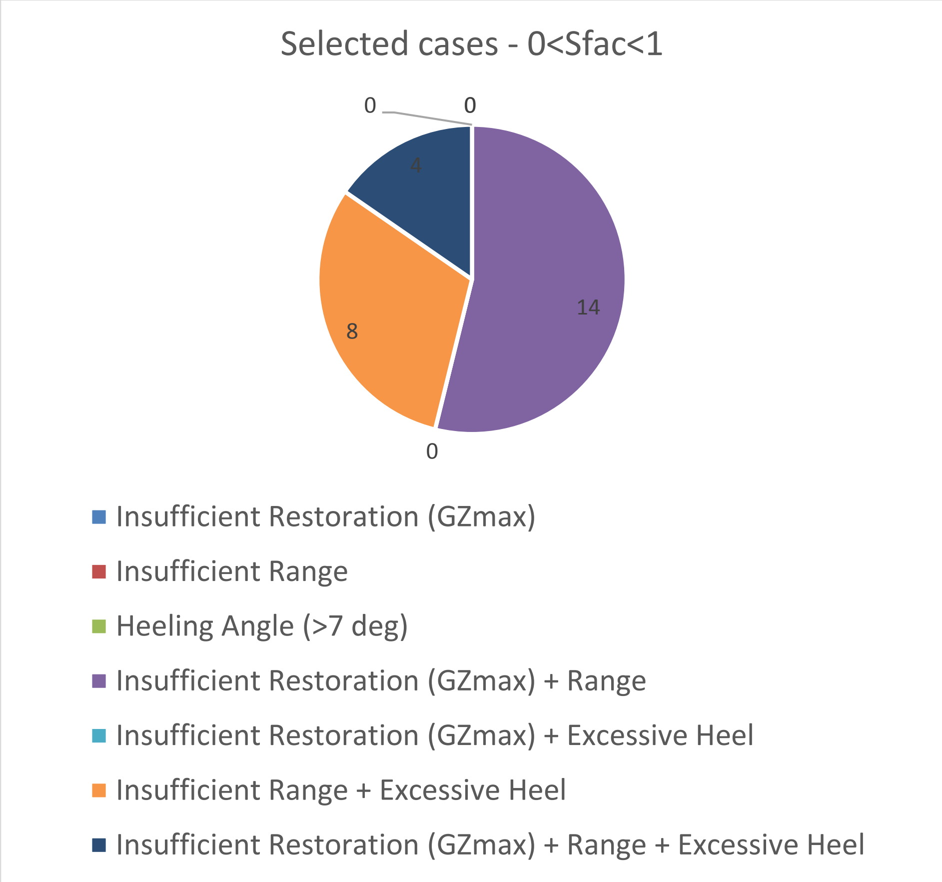


Figure 11 Diagram of failure mode for 0 < Sfac < 1 cases – Ship #5

2 DYNAMIC ASSESSMENT

2.1 Preparation of the PROTEUS model

The dynamic analysis has been carried out by use of the software *PROTEUS* [12]. In particular for the preparation of the model the tool Proteus Manager has been used.

To generate in the Proteus Manager the loading conditions defined in NAPA and corresponding to the two calculation draughts at 45% and 75%, the following lightships values have been generated:

$T_1 = 5.08$ m → LIG_1 [Δ=8405 t ; CG (55.30 , 0 , 9.37) m]

$T_2 = 5.20$ m → LIG_2 [Δ=8666 t ; CG (55.15 , 0 , 9.37) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at five different deck slices:

DB = 0.99 m; D1 = 1.51 m; D2 = 4.52 m; D3 = 7.24 m; D4 = 10.13 m

For this small cruise ship a total of 302 openings have been defined. Horizontal openings have been defined on the higher deck of the model to capture the down-flooding through engine casings, stair trunks, vertical escape and lifts.

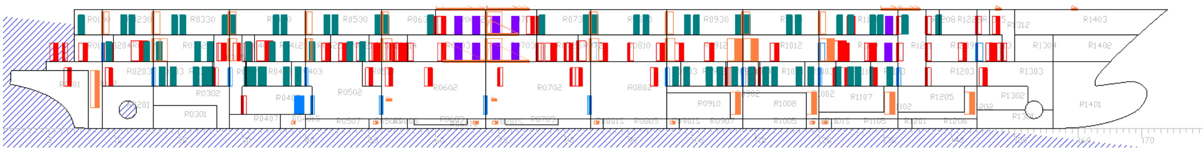


Figure 12 – Openings imported in Proteus Project (longitudinal section)– Ship #5

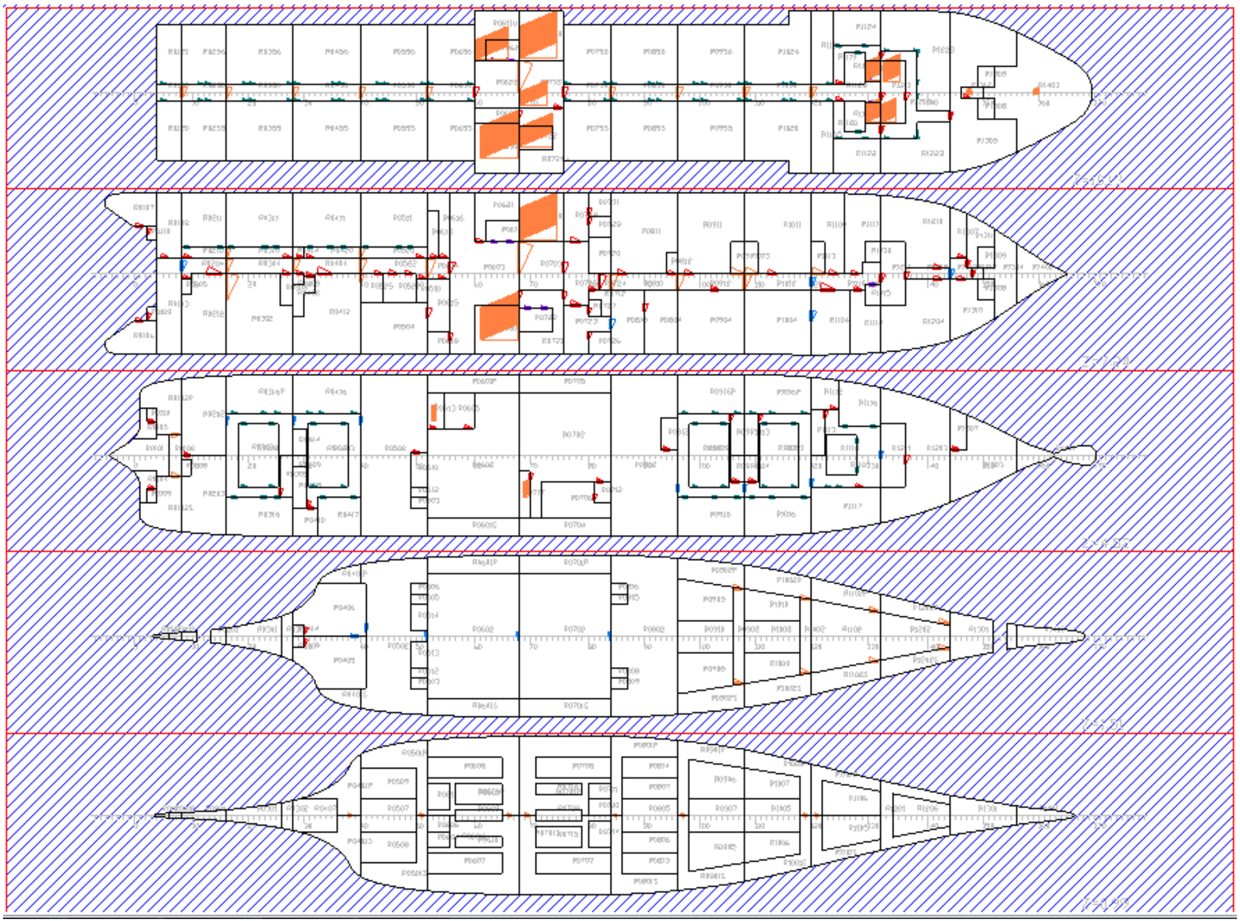


Figure 13 – Openings imported in Proteus Project (horizontal section)– Ship #5

Table 10 Opening Types in Proteus Manager

	Leak Area Rat	Leak Area Rat	Collapse Pressu	Collapse Pressu	Leak Heigh	Gap Heigh	Effective Heigl	Open At Tin	Close At Tim
TYPE	1 to 2	2 to 1	1 to 2 [meters]	2 to 1 [meters]	[meters]	[meters]	HEff Switch	[seconds]	[seconds]
Hinged Double Fire Door*	0.02500	0.02500	2.00	2.00	0.000	0.000	True	0	999999
Hinged Fire Door*	0.03000	0.02000	2.50	2.50	0.000	0.000	True	0	999999
Sliding Lift Door*	0.03000	0.03000	1.50	1.50	0.000	0.000	True	999999	0
B-CLASS-JOINER	0.03000	0.03000	1.50	1.50	0.000	0.000	True	999999	0
Hole*	1.00000	1.00000	0.00	0.00	0.000	0.000	True	0	999999
Sliding Semi-Watertight Door	0.01000	0.01000	10.00	10.00	8.000	0.000	True	0	999999
Sliding Watertight Door*	0.00100	0.00100	100.00	100.00	99.000	0.000	True	999999	0

Since in Proteus the discharge coefficient for the flow through openings is set to a constant value of 0.6 and it may be not changed, the area of the cross-flooding openings has been partly reduced in order to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation set have been created and the comparison of the geometric and hydrostatic data between NAPA and Proteus showed that the differences are negligible in general (from Figure 14 to Figure 20 and Table 11).

To be noted that the ship was originally defined with lefthanded coordinate system in NAPA but values were transformed to a righthanded system when the model has been imported in Proteus (Proteus does not accept lefthanded coordinate system). This generated some false warning when checking the tolerance in the differences for trim and TCG between NAPA and Proteus.

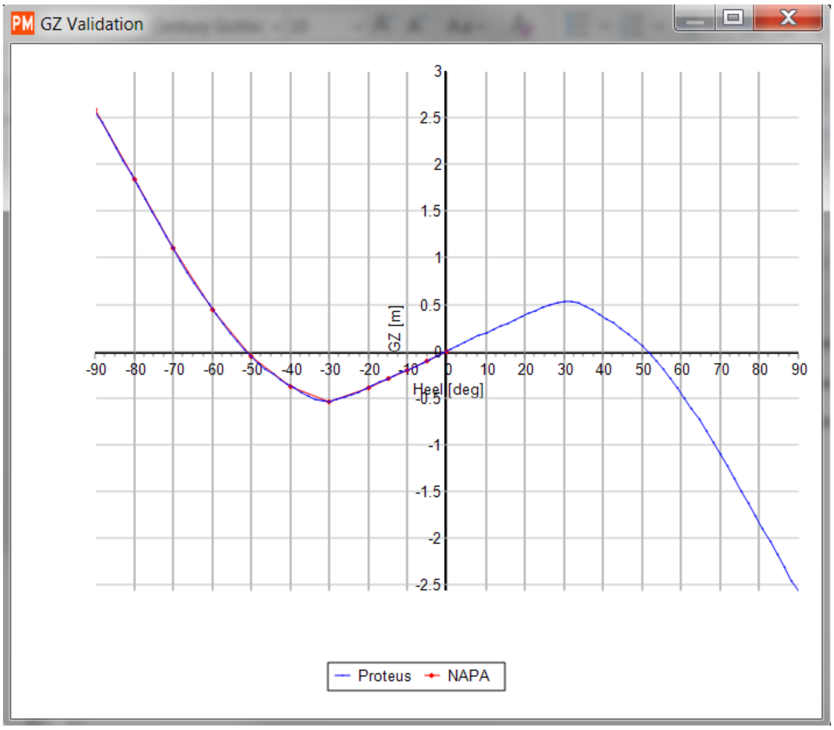


Figure 14 – GZ comparison between NAPA and Proteus – Ship #5

Table 11 Floating Position comparison between NAPA and Proteus – Ship #5

Loadcase Validation

GZ Curve | Floating Position | Volume and CGs | Section Areas

Floating Position

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	5.080	5.080	0.000	0.000
TA [m]	5.080	5.088	-0.008	-0.157
TF [m]	5.080	5.071	0.009	0.177
Trim [deg]	0.000	0.016	-0.016	-100.000
Heel [deg]	0.000	0.002	-0.002	0.000
KM [m]	10.867	10.888	-0.021	-0.193
KG [m]	9.584	9.580	0.004	0.042
GM0 [m]	1.283	1.304	-0.021	-1.637
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	1.283	1.304	-0.021	-1.637

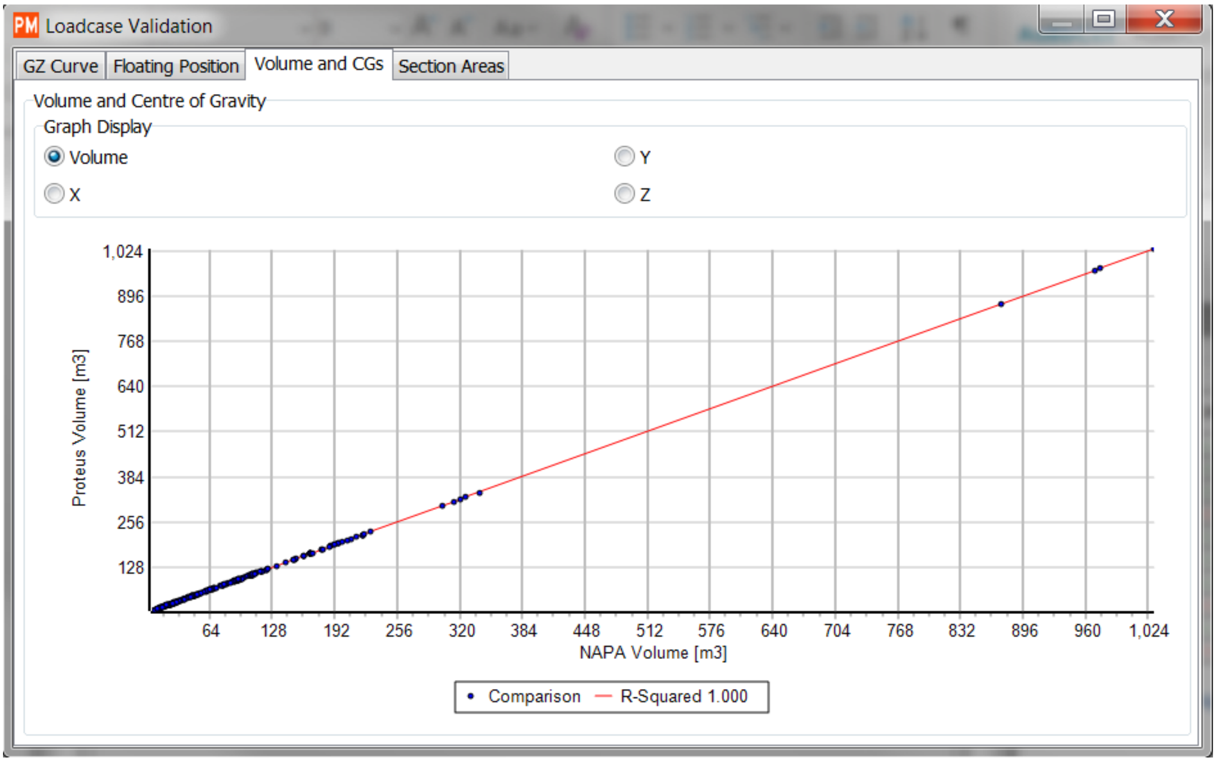


Figure 15 – Hull volume comparison between NAPA and Proteus – Ship #5

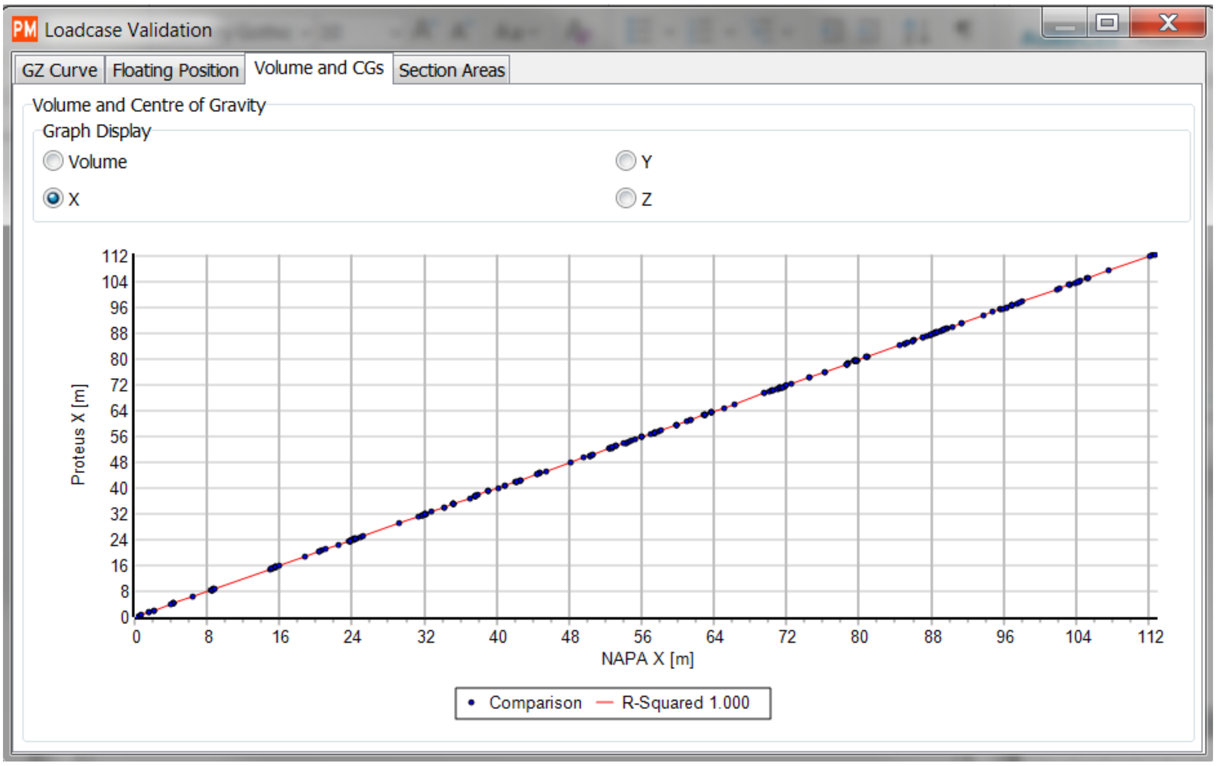


Figure 16 – Hull LCB comparison between NAPA and Proteus – Ship #5

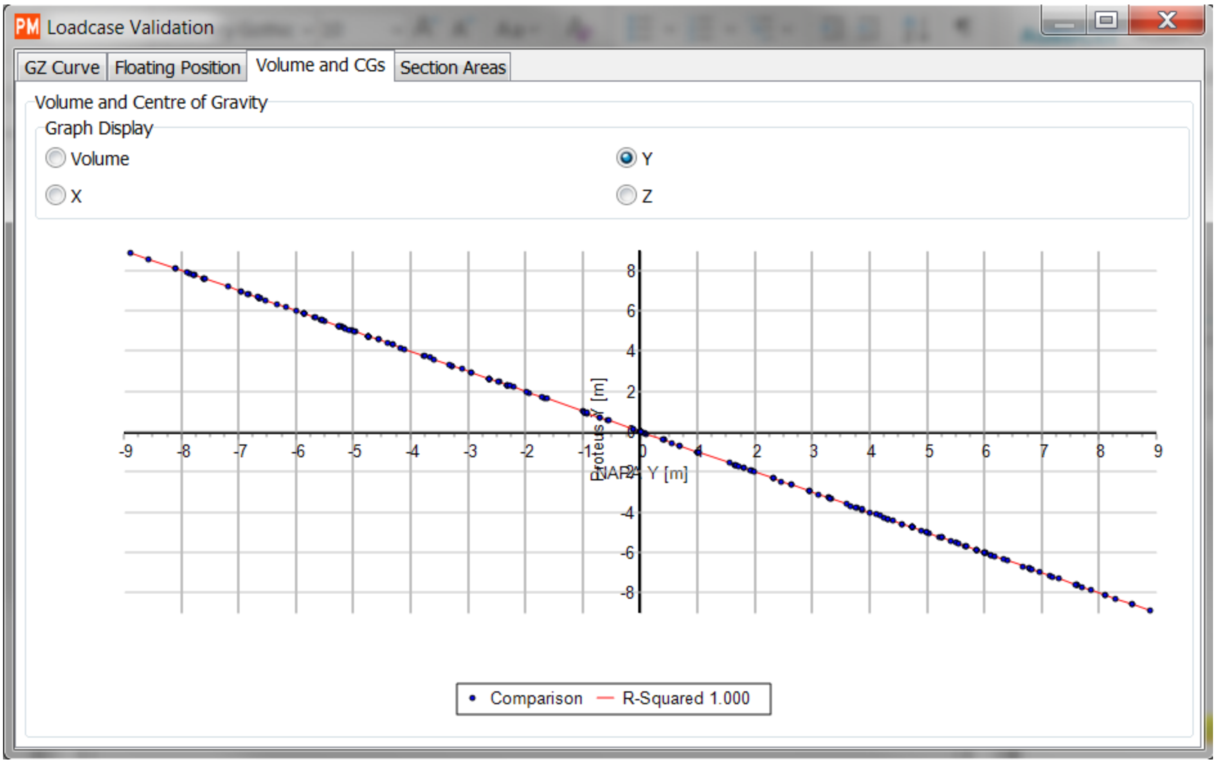


Figure 17 – Hull TCB comparison between NAPA and Proteus – Ship #5

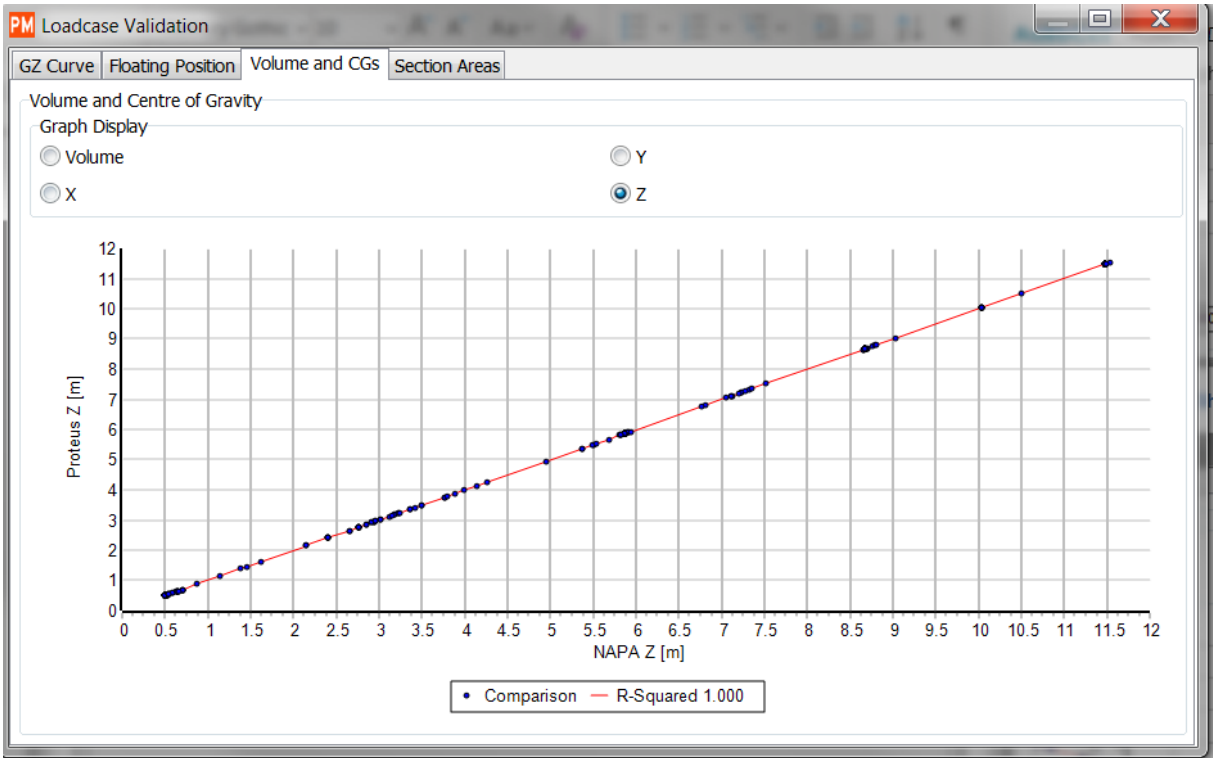
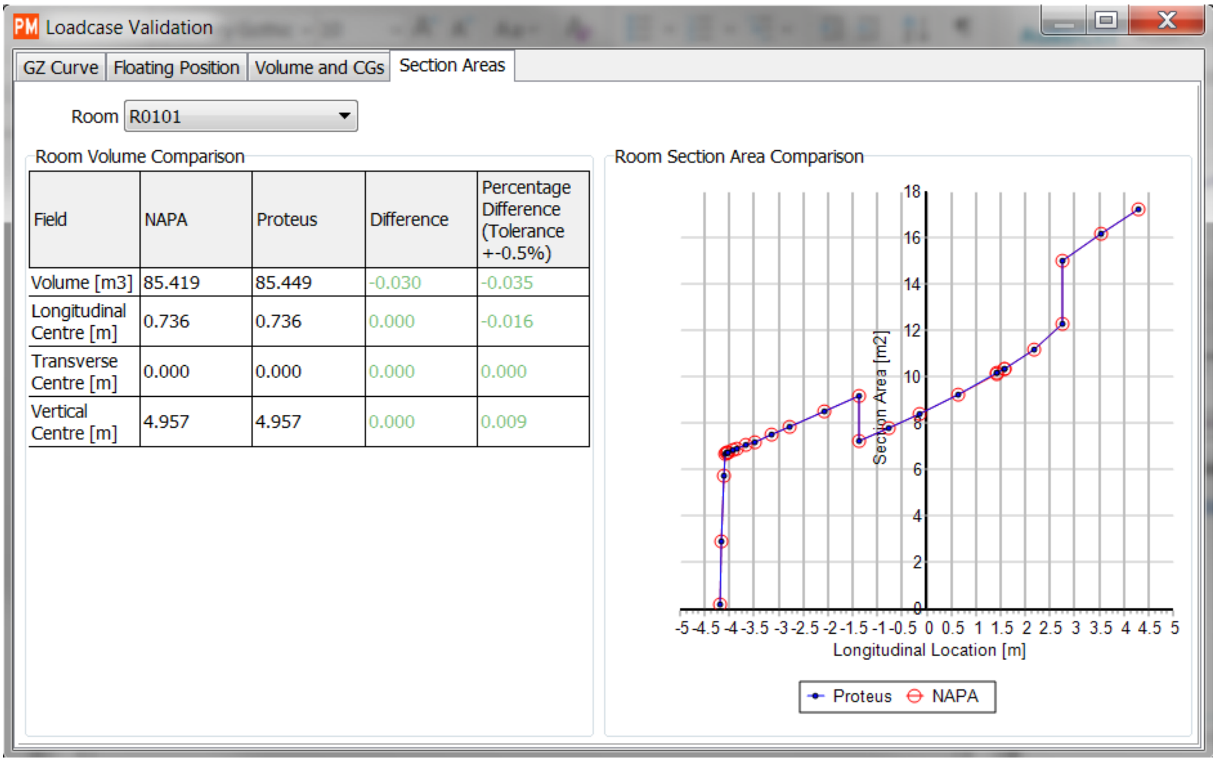
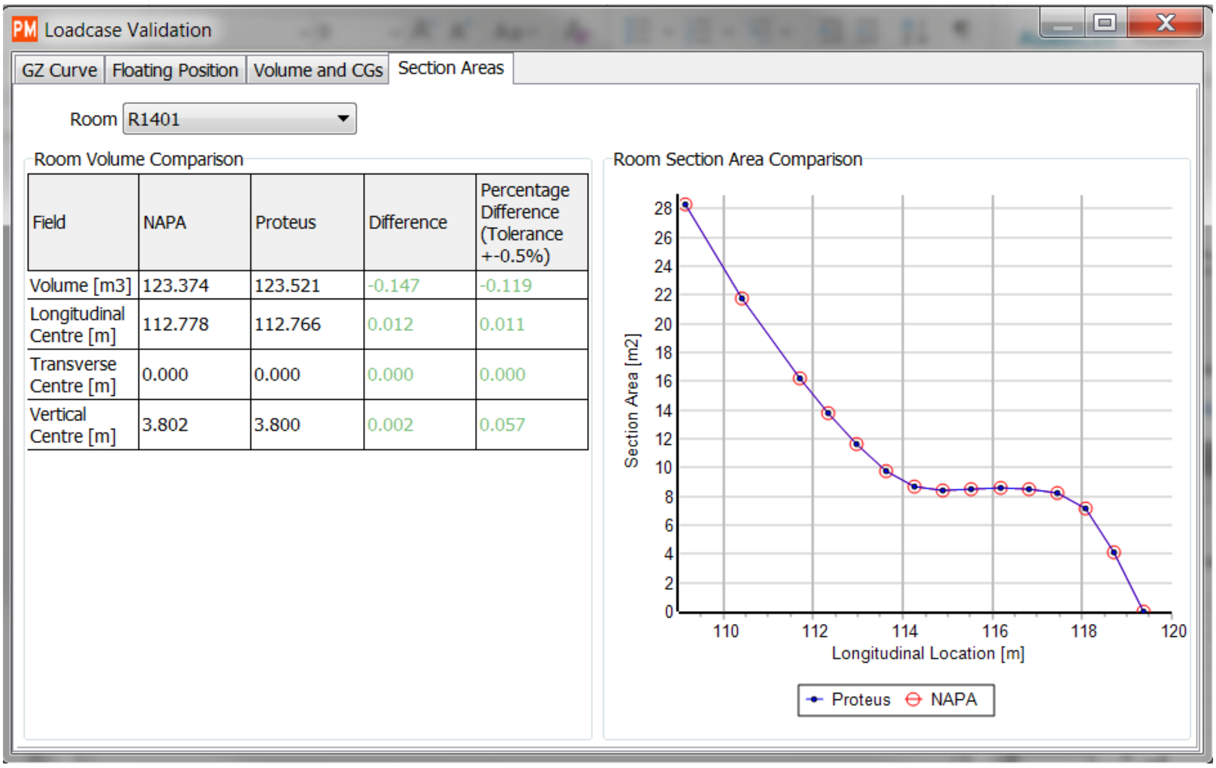


Figure 18 – Hull VCB comparison between NAPA and Proteus – Ship #5



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	85.419	85.449	-0.030	-0.035
Longitudinal Centre [m]	0.736	0.736	0.000	-0.016
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	4.957	4.957	0.000	0.009

Figure 19 – Aftpeak comparison between NAPA and Proteus – Ship #5



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	123.374	123.521	-0.147	-0.119
Longitudinal Centre [m]	112.778	112.766	0.012	0.011
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	3.802	3.800	0.002	0.057

Figure 20 – Forepeak comparison between NAPA and Proteus – Ship #5

2.2 Results of dynamic simulations

In the first round of dynamic simulations by Proteus all the 500 breaches have been simulated up to 30 minutes, then for 82 breaches a second simulation round has been executed up to 60 minutes, as these were found with progressive flooding still occurring at the end of the first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1 = capsize 0 = not capsize) and TTC for cases where a capsize was found. In the following graphs the results for each hazard and the global results of simulations are presented.

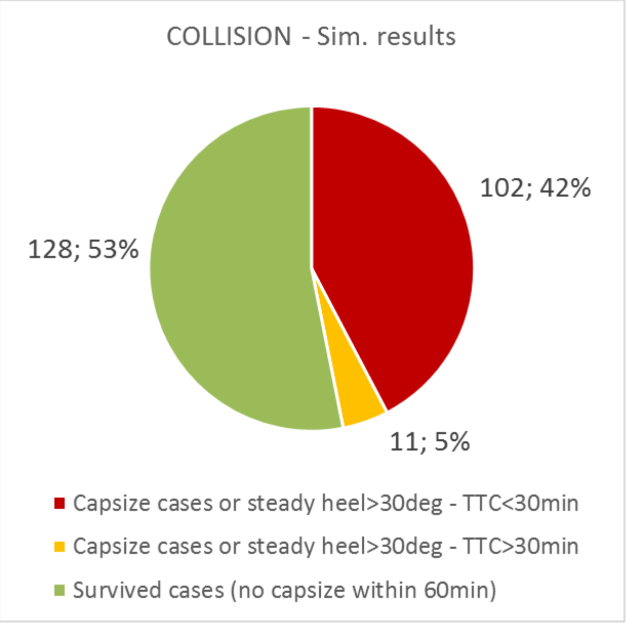


Figure 21 – Simulation results for collision – Ship #5

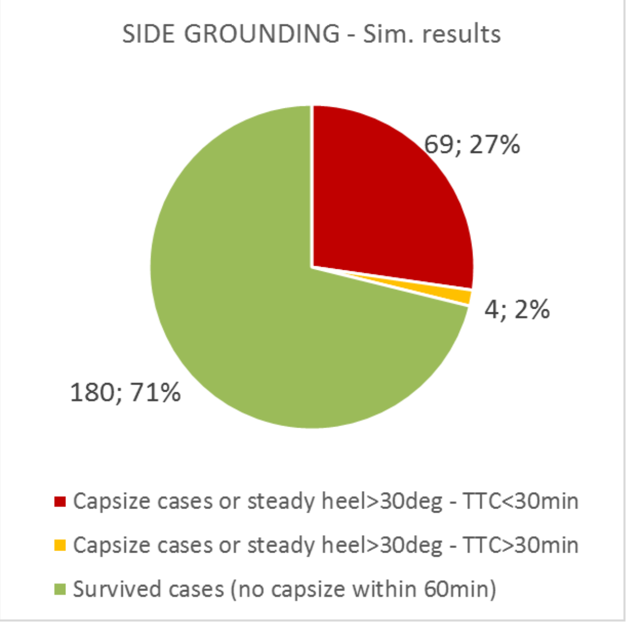


Figure 22 – Simulation results for side grounding – Ship #5

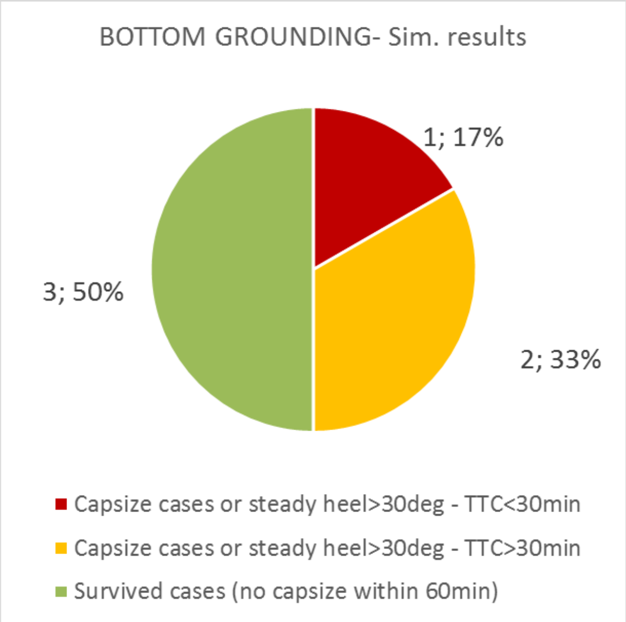


Figure 23 – Simulation results for bottom grounding – Ship #5

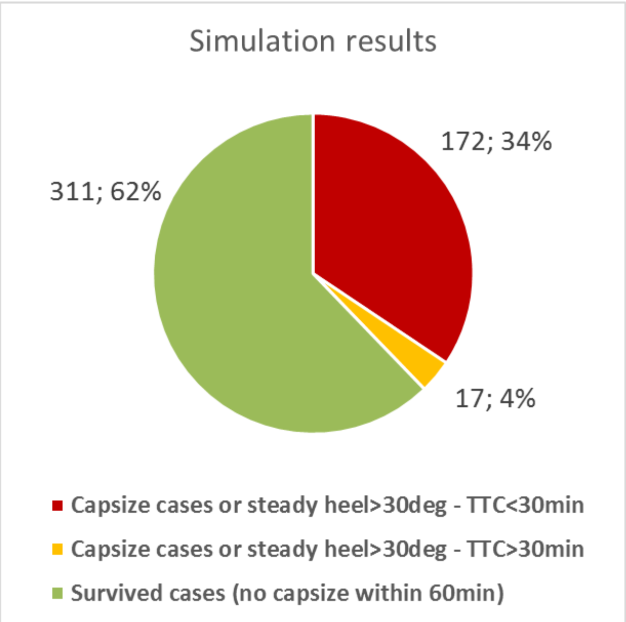


Figure 24 – Global simulation results for the 500 filtered breaches – Ship #5

The results obtained clearly show that for most of cases the ship did not capsize, which confirmed that the static results are conservative as almost all of these case have had an Sfac = 0 in the static analysis.

Furthermore, it is equally clear that a great majority of the capsize cases (91%) are to be considered fast capsize as the TTC is less than 30 minutes therefore there is no sufficient time to orderly evacuate persons in such cases.

2.3 Calculation of PLL level 2.1

The results of the flooding simulations permit to get the TTC too, therefore the fatality rate may be estimated for the cases with TTC > 30 min according to the procedure for calculation of Risk (Level 2.1).

In the Table 12 the details of the results obtained by static and dynamic simulations are reported. It can be observed that the PLL from the static calculation has been reduced by nearly 20% from 0.2454 (Level 1) to 0.1955 (Level 2.1) when using dynamic simulation.

Table 12 PLL level 2.1 – Ship #5

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	5.08	5.2	5.08	5.2	5.08	5.2	
PLL L1 (1/ship year) (static assessment)	**6.41E-02**	**6.16E-02**	**3.77E-02**	**3.39E-02**	**2.35E-02**	**2.46E-02**	**0.2454**
	0.1257		**0.0716**		**0.0481**		
Number of filtered damage cases	141	100	136	117	4	2	500
Capsize cases or steady heel>30deg - TTC<30min	59	43	42	27	1	0	172
Capsize cases or steady heel>30deg - TTC>30min	6	5	0	4	1	1	17
Survived cases	76	52	94	86	2	1	311
PLL L2.1 (1/ship year) (dynamic assessment)	**5.15E-02**	**5.08E-02**	**2.38E-02**	**2.15E-02**	**2.33E-02**	**2.45E-02**	**0.1955**
	0.1023		**0.0454**		**0.0478**		
PLL L2.1 vs L1 (variation percentage)	**-18.7%**		**-36.6%**		**-0.5%**		**-20.3%**

In the following figures the diagrams of the breaches which lead to capsize after dynamic simulations are reported.

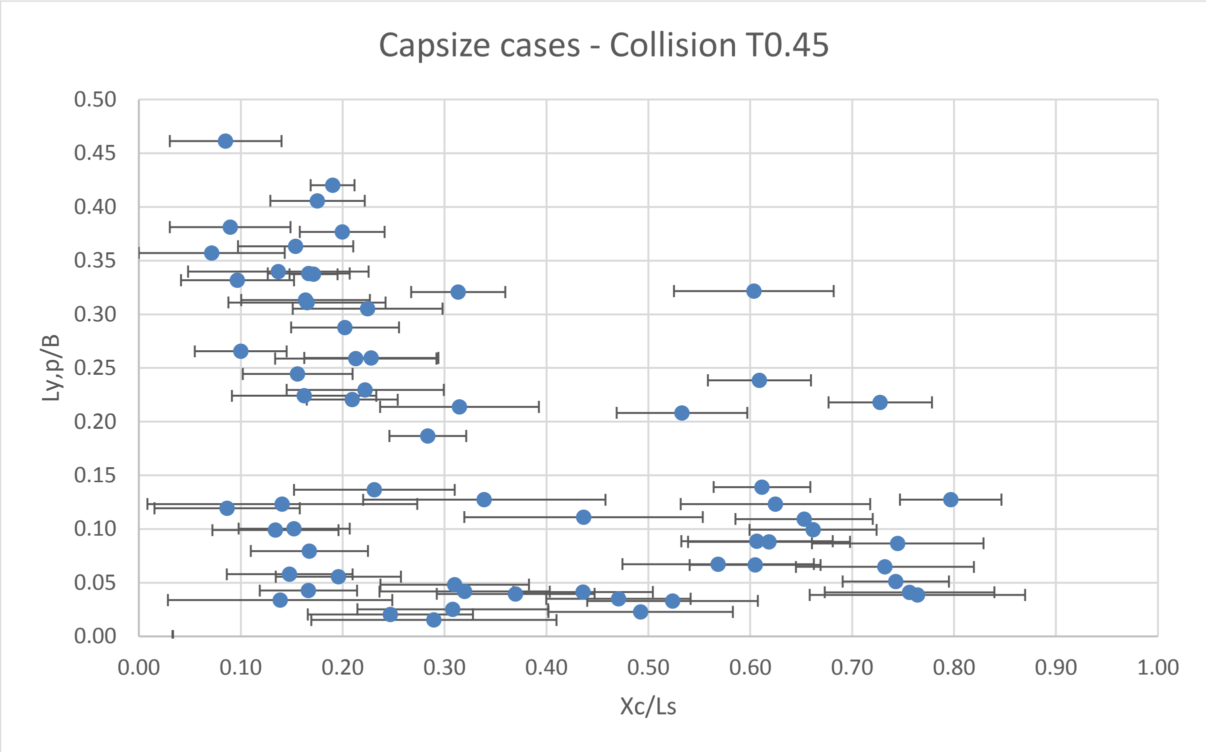


Figure 25 Characteristics of collision breaches leading to capsize T0.45 – Ship #5

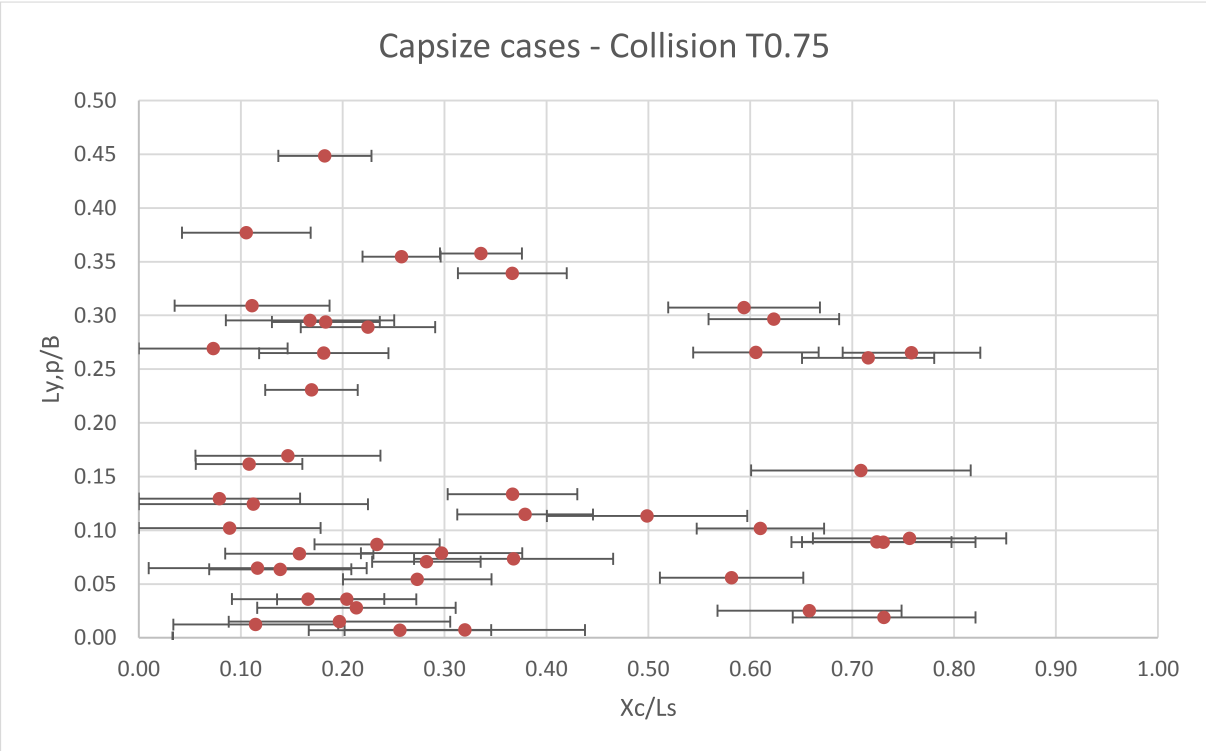


Figure 26 Characteristics of collision breachess leading to capsize T0.75 – Ship #5

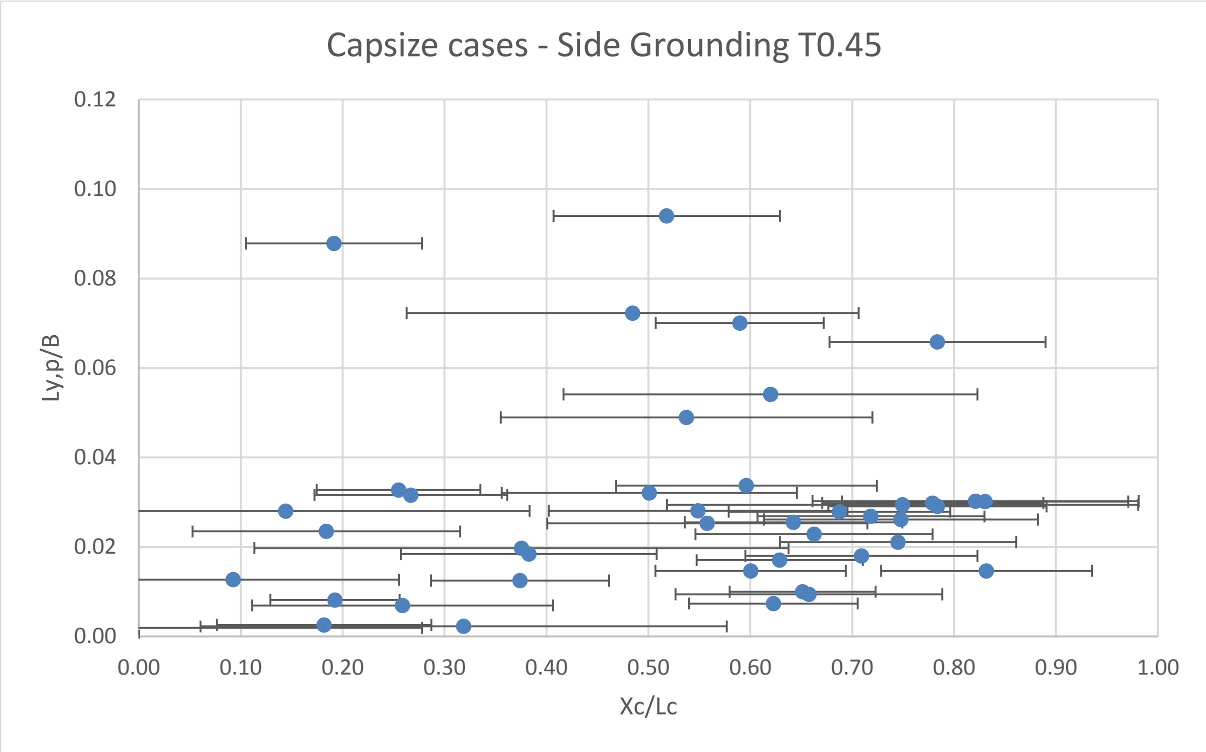


Figure 27 Characteristics of side grounding breaches leading to capsize T0.45 – Ship #5

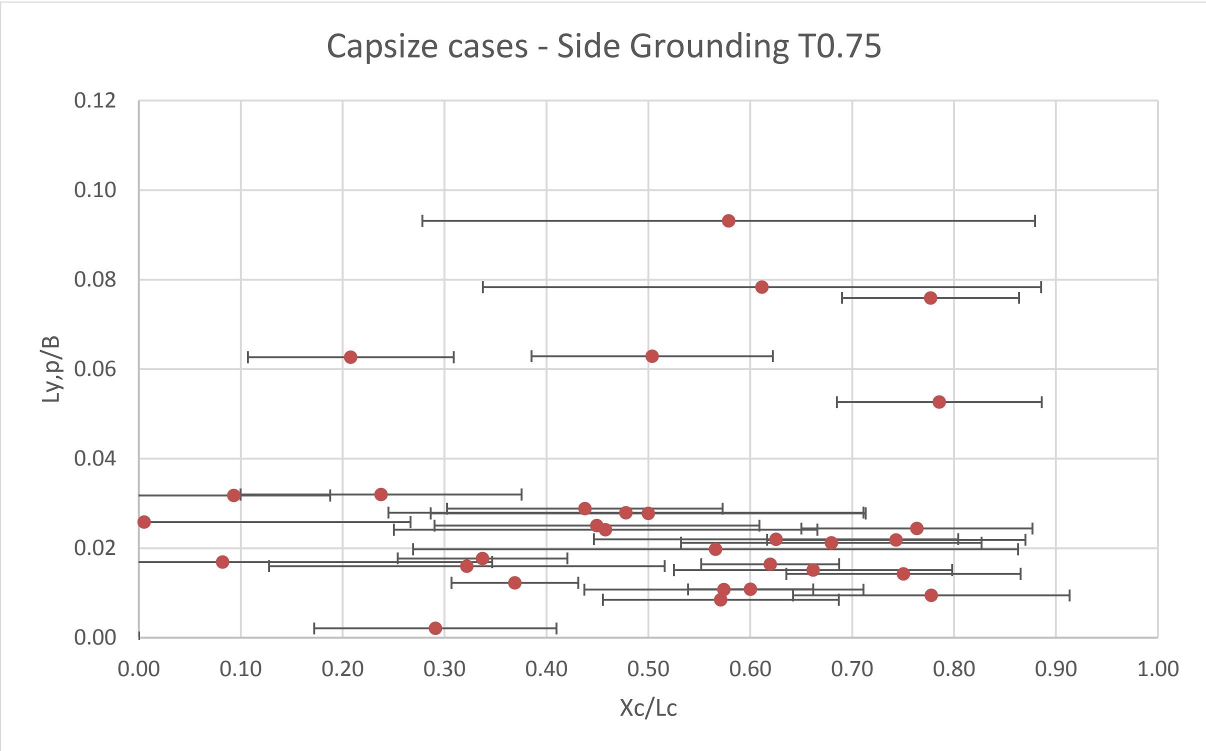


Figure 28 Characteristics of side grounding breaches leading to capsize T0.75 – Ship #5

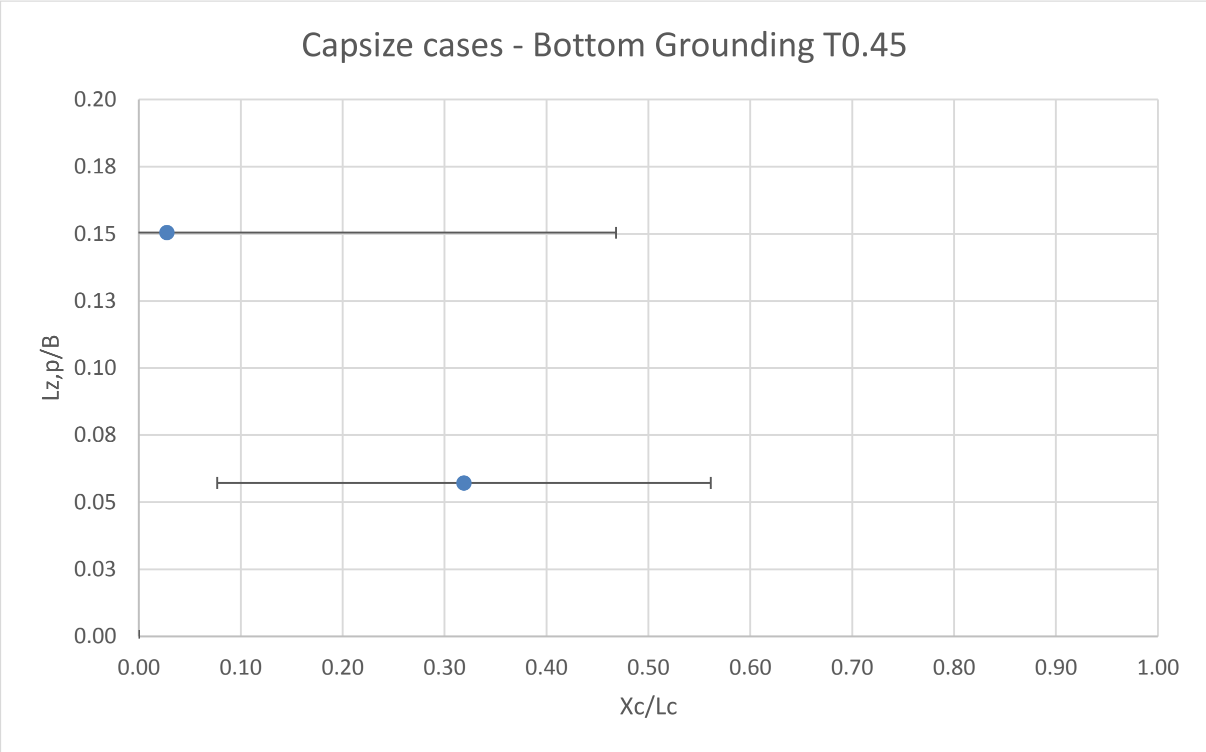


Figure 29 Characteristics of bottom grounding breaches leading to capsize T0.45 – Ship #5

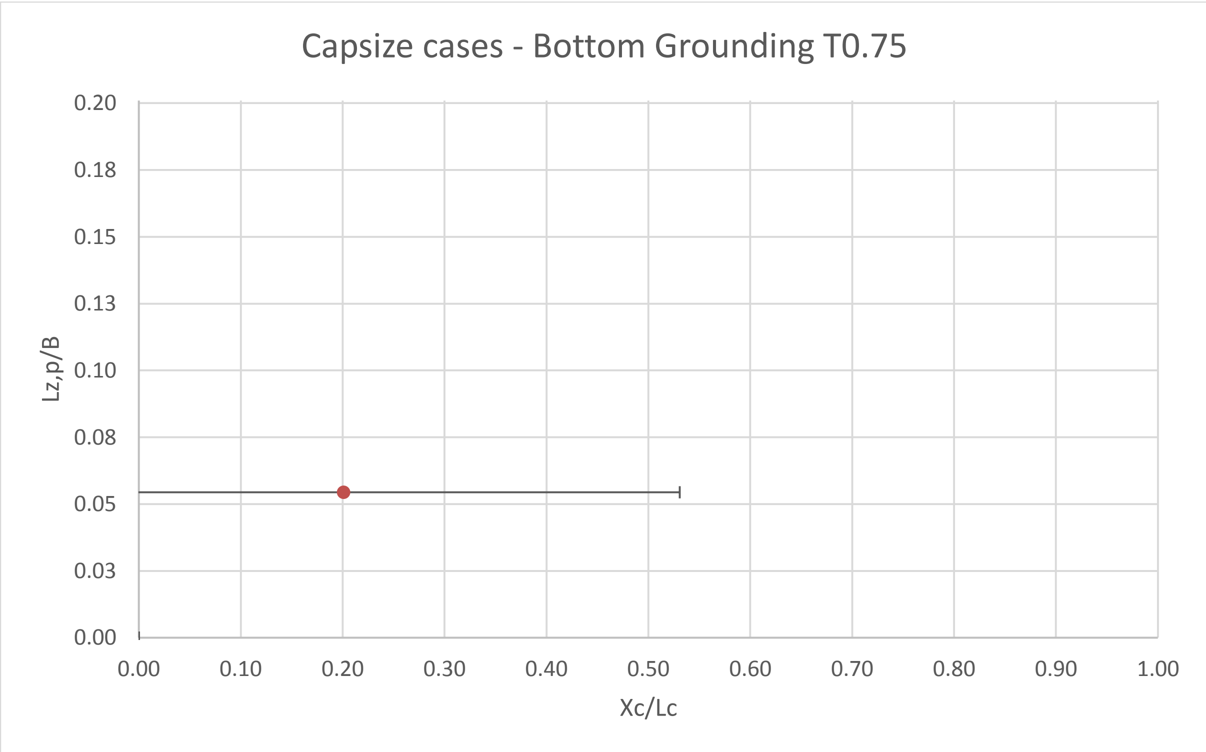


Figure 30 Characteristics of bottom grounding breaches leading to capsize T0.75 – Ship #5

The identified capsizal cases showed in Figure 25 to Figure 30 may be investigated in WP7.2 when Risk Control Options are to be implemented.

2.4 Sensitivity analysis of the fatality rate

From the dynamic simulation results it has been observed that about 17 cases resulted into a TTC greater than 30 min but lower than 60 min simulation; for those cases linear Interpolation between 0% and 80% has been used for the estimation of the fatality rates (equation 5 of the main report). Furthermore, there are further 27 cases where progressive flooding is still occurring after 60 min and for these cases no fatalities has been assumed (Figure 31).

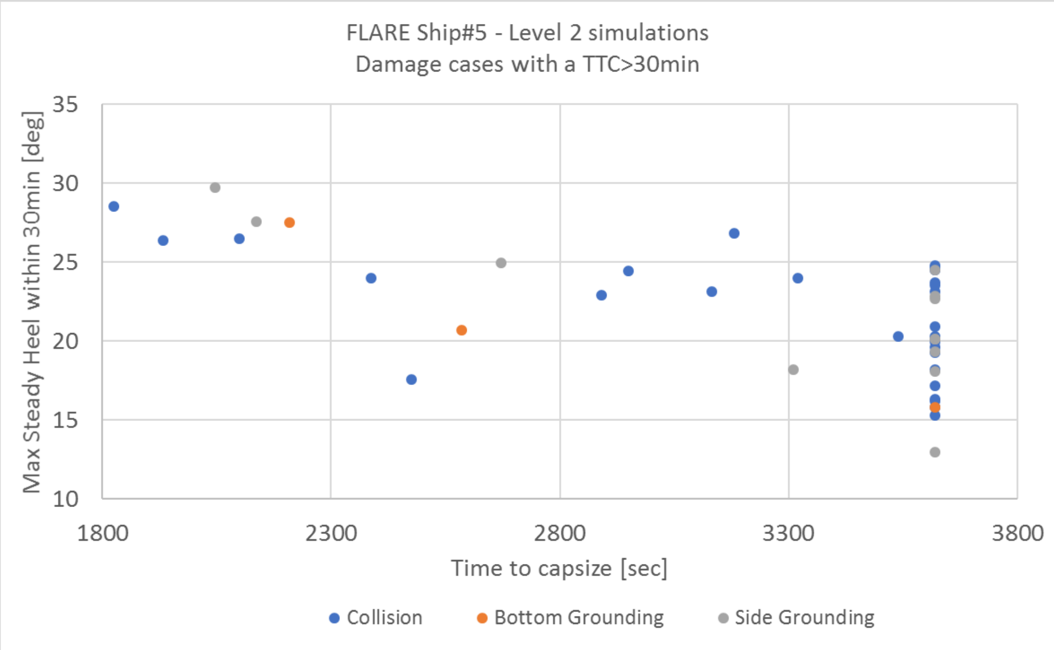


Figure 31 Cases with TTC > 30 min or progressive flooding still occurring after 60min – Ship #5

In order to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out for the total 44 cases (with TTC > 30 min or progressive flooding still occurring after 60 min). For this, the impact on the PLL has been evaluated by use of the simplified formula (main report equation 5) but assuming a variation of the fatality rate by ± 30% of the POB.

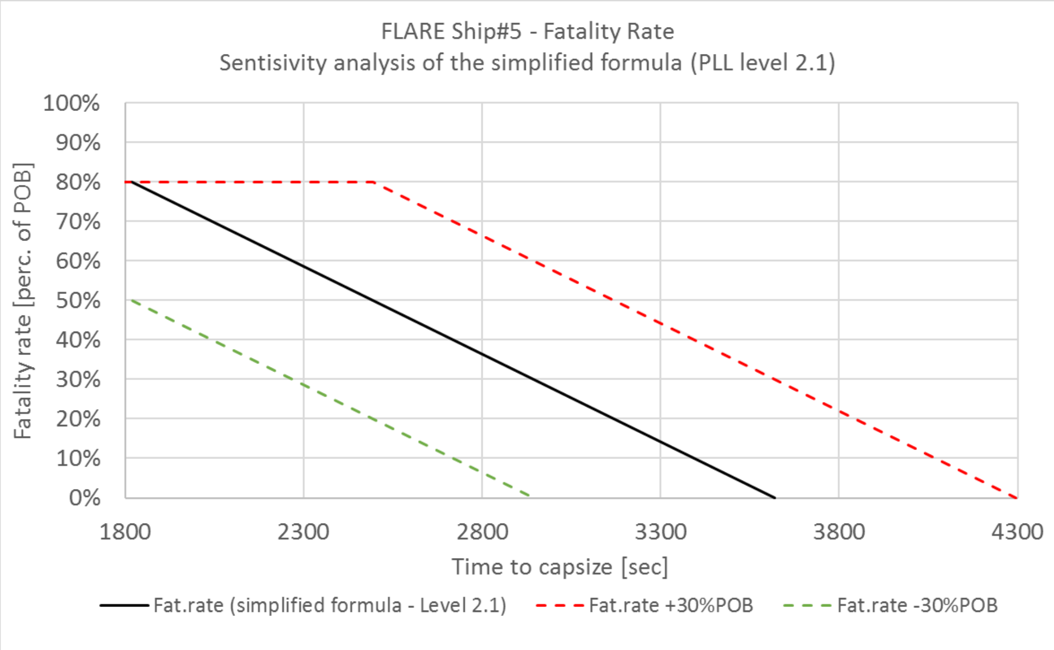


Figure 32 Sensitivity analysis of simplified formula for fatality rate calculation – Ship #5

The calculation with +30% in the fatality rate resulted into a PLL of 0.1976 (+1.1% compared to the reference PLL) while the calculation with -30% for the fatality rate resulted into a PLL of 0.1945 (-0.5% compared to the reference PLL). These values demonstrated that for this ship the simplified formula to derive the fatality rate used in the calculation of risk (Level 2.1) is insensitive with respect to PLL because PLL is mainly based, for this ship, by the scenarios leading to fast capsize.

3 EVACUATION ANALYSIS

3.1 Selection of cases for the evacuation analysis

The sensitivity analysis carried out in Ch. 2.4 for this ship demonstrated that the calculation of level 2.1 for PLL is robust enough and the evacuation analysis (level 2.2) would be not needed as it has a low impact on the PLL. Anyway, for this ship some cases have been selected in order to demonstrate the procedure for the evacuation analysis and to check if the simplified formula used to estimate the fatality rate for the PLL (level 2.1) is conservative.

Since one objective of this analysis is to demonstrate the conservativeness of the simplified formula for the fatality rate (PLL level 2.1), the choice of the cases to be simulated has been driven by the spread of the TTC and by the need to select cases with high steady heel (within 30 min). This approach is based on the fact that in the evacuation simulations the speed of the agents is reduced when large heeling angles occur.

Ten cases have been selected for the evacuation analysis on this ship and they are highlighted in the Figure 33.

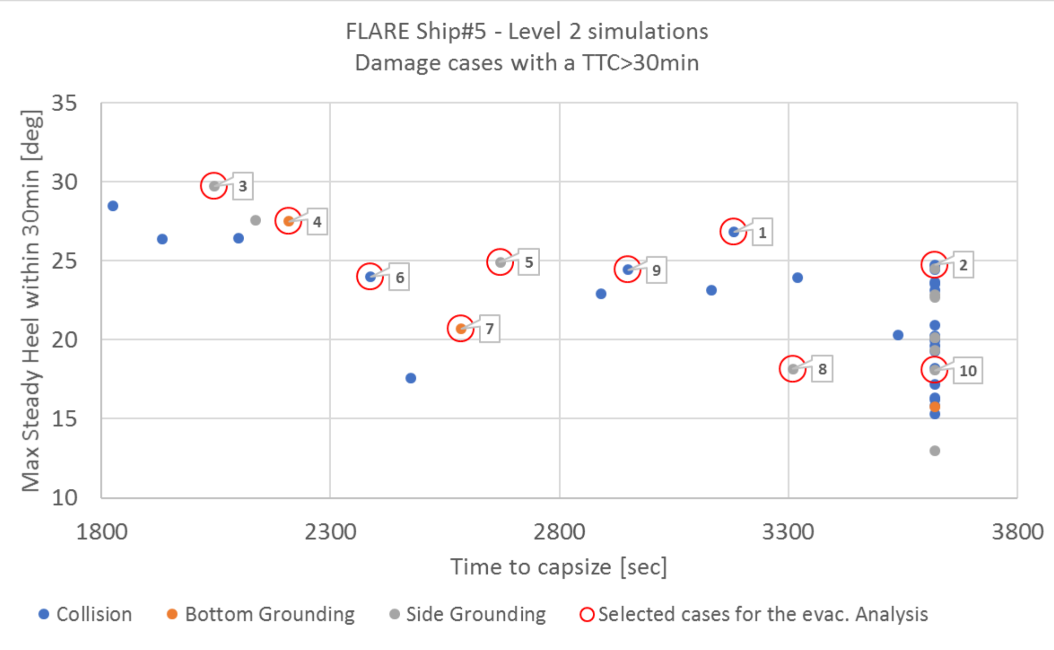


Figure 33 Cases selected for the evacuation analysis – Ship #5

3.2 Preparation of the EVI model

The last available research version of software EVI/EVE has been used for the evacuation analysis and a model has been created according to the General arrangement of the ship.

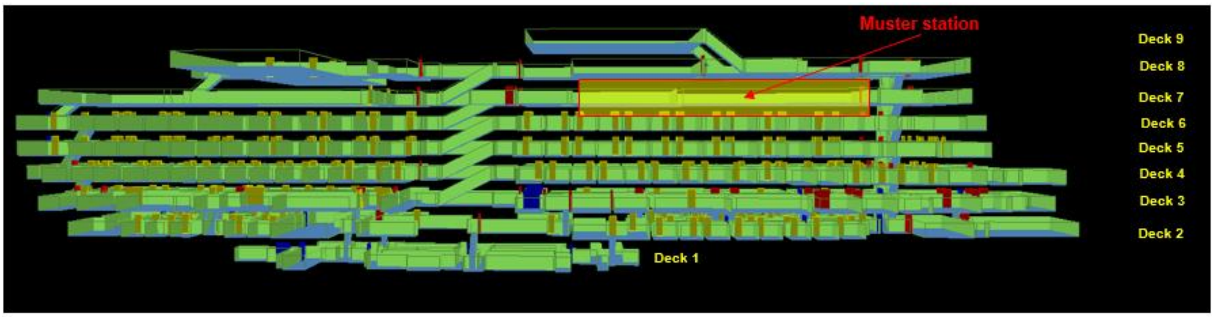


Figure 34 Side view of the EVI “exploded” model – Ship #5

The evacuation software (EVI) has been interfaced with the software for flooding simulation (PROTEUS) in order to simulate the evacuation with each specific flooding scenario as per the selected cases.

In general, the settings are based on MSC.1/Circ.1533 but there are some differences especially for the scenario. Here following the main settings/assumptions for this ship:

- Evacuation Night Scenario (as per Escape Calculation Distribution);
- Passengers and crew demographic: According to MSC.1/Circ. 1533 Annex 3, Appendix 1, Item 3.2, pages 3 ÷ 6;

- Response duration: Night Scenario - according to MSC.1/Circ. 1533 Annex 3, Appendix 1, Item 3.2.2 (About 300 s ± 90 s for the crew in service and 600 s ± 180 s for the resting people and);
- Agents located in the rooms affected by flooding have not been evacuated (they are considered lost);
- 10 runs for each breach scenario;
- Speed reduction function based on the heeling angle of the ship (Figure 35);

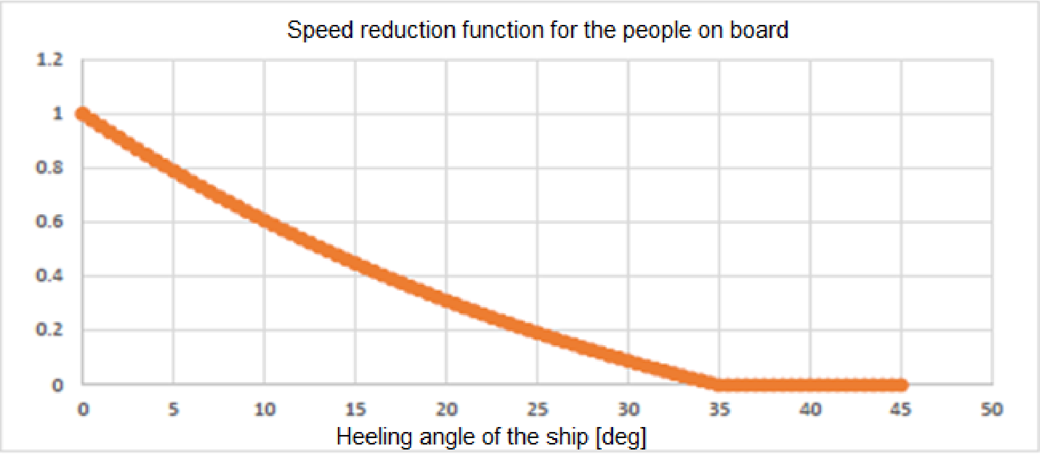


Figure 35 Speed reduction function vs heeling angle of the ship

The night scenario has been selected as it is conservative in terms of TTE (time to evacuate) as the response duration for the passenger is higher in the night.

For this analysis, only ten runs (instead of fifty requested by MSC.1/Circ.1533) have been performed to evaluate the 95%ile based some tests carried out on this ship which demonstrated that the difference in terms of TTE when just ten runs are executed is negligible.

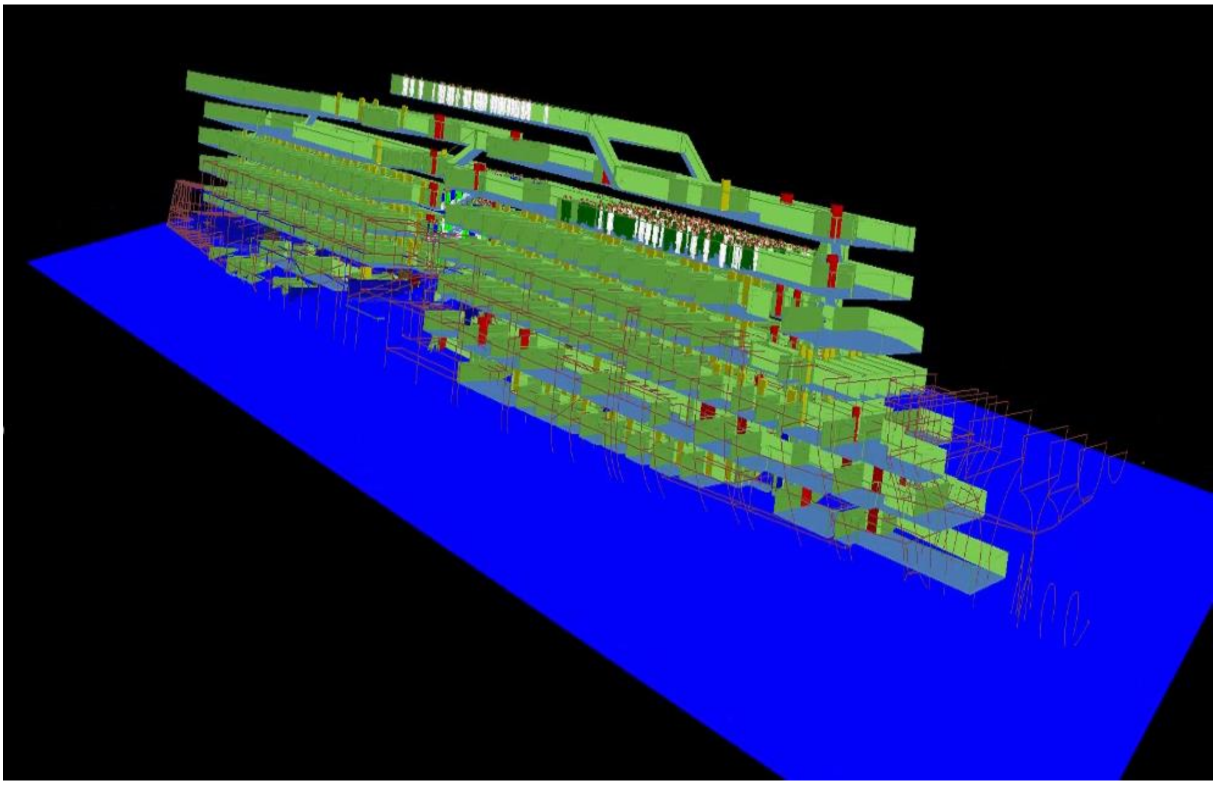


Figure 36 EVI snapshot of a simulation case – Ship #5

3.3 Results of the evacuation simulations

The results of the evacuation analysis permitted to generate the diagrams with the numbers of persons evacuated versus the time (Figure 37). Entering within these diagrams with the TTC it is possible to calculate for each case the number of persons evacuated before the ship capsizes.

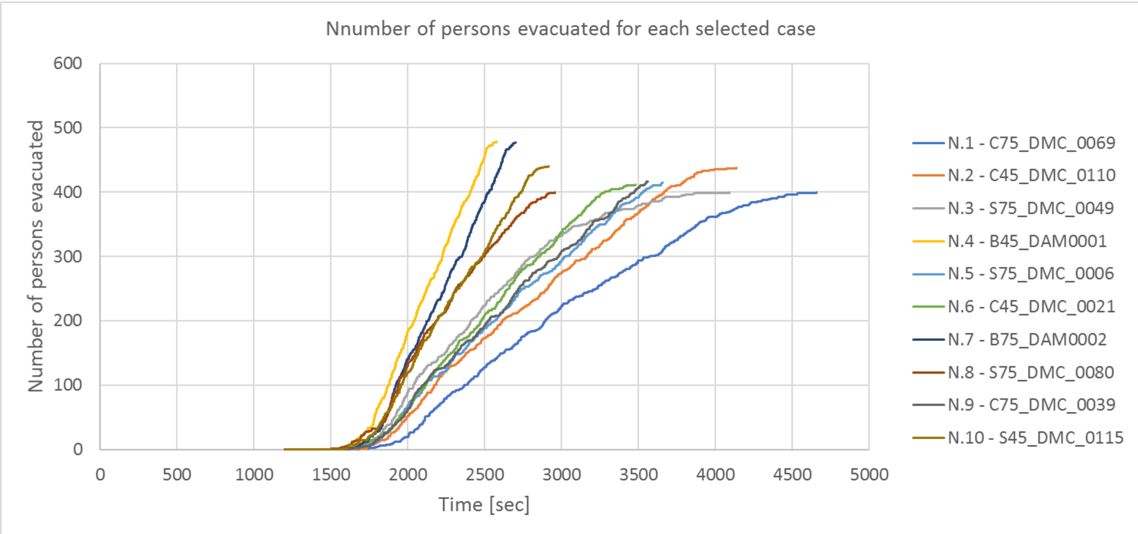


Figure 37 diagrams of the evacuations for the selected flooding scenarios – Ship #5

With the values for the persons evacuated in each scenario the fatality rate is available now and therefore it is possible to compare this to the fatality rate calculated with the simplified formula (PLL level 2.1). In the Figure 38 such comparison is summarised for these ten selected flooding scenarios.

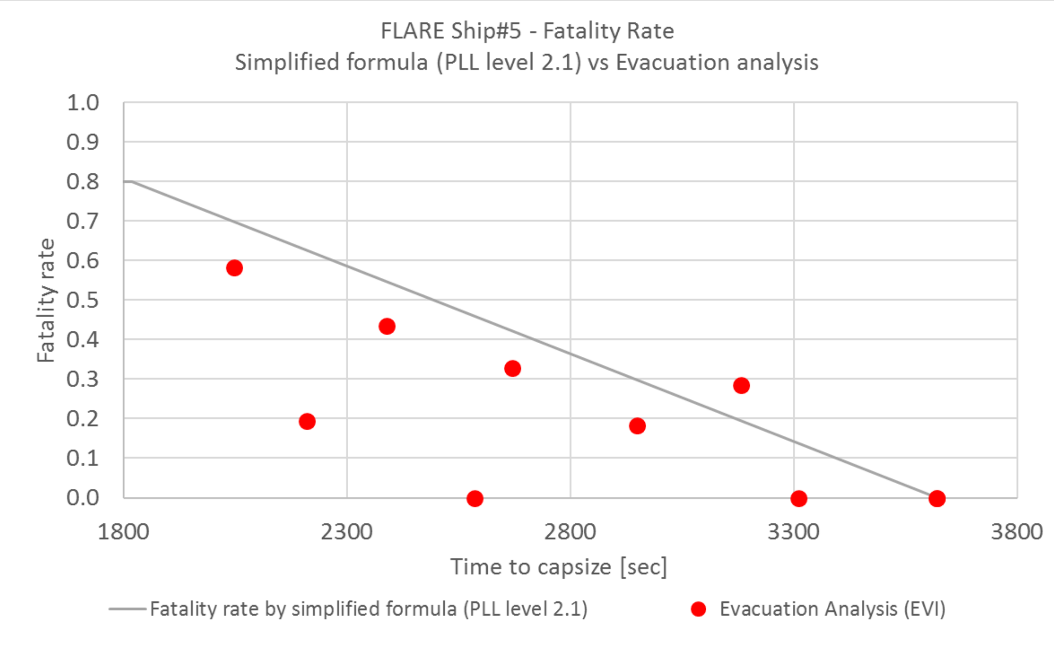


Figure 38 Comparison of evacuation analysis vs simplified formula – Ship #5

For seven cases, which have been simulated, the fatality rate is lower than the value calculated by the simplified formula (PLL level 2.1). It can be observed that for the two bottom grounding cases a fatality rate much lower than the calculated values has been obtained.

For the two cases where the simplified formula resulted into zero fatalities, such result has been confirmed by evacuation analysis and just one case resulted in a fatality rate higher than the calculated value.

Hence it is confirmed that the simplified approach for the fatality rate calculated as a linear function of the TTC (PLL level 2.1) is conservative.

3.4 Calculation of PLL level 2.2

Using the fatality rate that has been obtained from the evacuation analysis, the PLL level 2.2 has been calculated. In Table 13 the overview of the results obtained at different PLL levels is reported.

Table 13 PLL level 2.2 – Ship #5

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	5.08	5.2	5.08	5.2	5.08	5.2	
PLL L1 (1/ship year) (static assessment)	6.41E-02	6.16E-02	3.77E-02	3.39E-02	2.35E-02	2.46E-02	0.2454
	0.1257		0.0716		0.0481		
PLL L2.1 (1/ship year) (dynamic assessment)	5.15E-02	5.08E-02	2.38E-02	2.15E-02	2.33E-02	2.45E-02	0.1955
	0.1023		0.0454		0.0478		
PLL L2.1 vs L1 (variation percentage)	-18.7%		-36.6%		-0.5%		-20.4%
PLL L2.2 (1/ship year) (evacuation analysis)	**5.15E-02**	**5.08E-02**	**2.38E-02**	**2.15E-02**	**2.33E-02**	**2.45E-02**	**0.1953**
	0.1022		**0.0453**		**0.0477**		
PLL L2.2 vs L2.1 (variation percentage)	**-0.1%**		**-0.2%**		**-0.2%**		**-0.1%**

As expected, the impact of the evacuation analysis on the PLL is negligible (-0.1%).

4 CONCLUSIONS

The complete procedure for calculation of Risk has been applied on Ship 5 and the results obtained demonstrated that the procedure is coherent with the multi-level approach. In fact, the PLL has been reduced from 0.2454 (level 1) to 0.1953 (level 2.2)

The PLL Level 1 procedure appears conservative, while it seems to be more robust than PLL calculated by EMSA3 Risk Model as the fast/slow sinking node has not been used in the FLARE procedure.

The Dynamic analysis in level 2 leaded to a reduction of the PLL by about 20% with the simulation of 500 breaches. Such reduction of the PLL is essentially based on the fact that about 60% of cases with Sfac =0 in the static analysis, have been found to survive in the dynamic analysis .

Furthermore, a sensitivity analysis demonstrated that the impact on the PLL level 2.1 by even a large deviation of the fatality rate (calculated with the simplified formula) is negligible.

The flooding simulations showed a percentage of 91% of fast capsize cases (TTC < 30 min) and 9% only for slow capsize cases (TTC > 30 min). This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model for which only 18% fast capsizing rate was used.

With the aim to check if the simplified formula for the fatality rate (applied for cases with TTC > 30 min) is conservative, 10 cases have been selected for the evacuation analysis and PLL Level 2.2 has been calculated accordingly. In such a way the PLL obtained after flooding simulation has been reduced by further 0.1% only.

The results obtained from the evacuation analysis showed that in general the simplified formula for the fatality rate (PLL level 2.1) is conservative, but it can be applied, when an evacuation model is not available. In fact, the preparation of the EVI model for the evacuation analysis is a time consuming activity which may be avoided considering the low impact on the PLL for this ship.

ANNEX 7 – Calculation of the flooding Risk for Ship n.6

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a small Ro-Pax ship design. As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1). The refined model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

1 STATIC ASSESSMENT

1.1 Main data

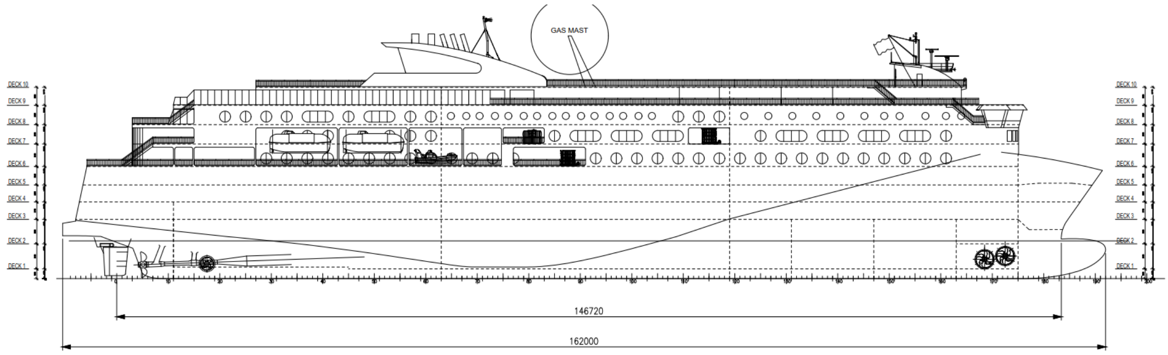


Figure 1 Profile view – Ship #6

Ship #6 is a small day ferry with a roro deck for trucks and trailers and a garage deck for cars. The cargo handling for trucks and trailers is based on a drive-through concept with large stern ramps and a bow door and ramp on the bulkhead deck. There is no lower cargo hold.

Table 1 Main characteristics – Ship #6

Length over all	~162 m
Length between perpendiculars	146.72 m
Subdivision length	160.96 m
Breadth	28.0 m
Subdivision draught	6.3 m
Height of bulkhead deck	9.20 m
Number of passengers	1900
Number of crew	100
Gross tonnage	28500 GT
Deadweight	3800 t
No of cabins (crew)	91
Lane meter for trailers	abt 800
Lane meter for cars	abt 1060
Service speed	17 knots

The business model and detailed description of the vessel are included in deliverable D.2.1.6.

Here following the Attained and Required Index according to SOLAS 2020 ch.II-1:

Number of persons	POB = 2000
Required subdivision index	R = 0.8611
Attained subdivision index	A = 0.8892

1.2 Static calculations with new draughts and permeabilities

The following diagram is showing the draughts and the calculated GM for this vessel based on paragraph. 2.1 of the main report.

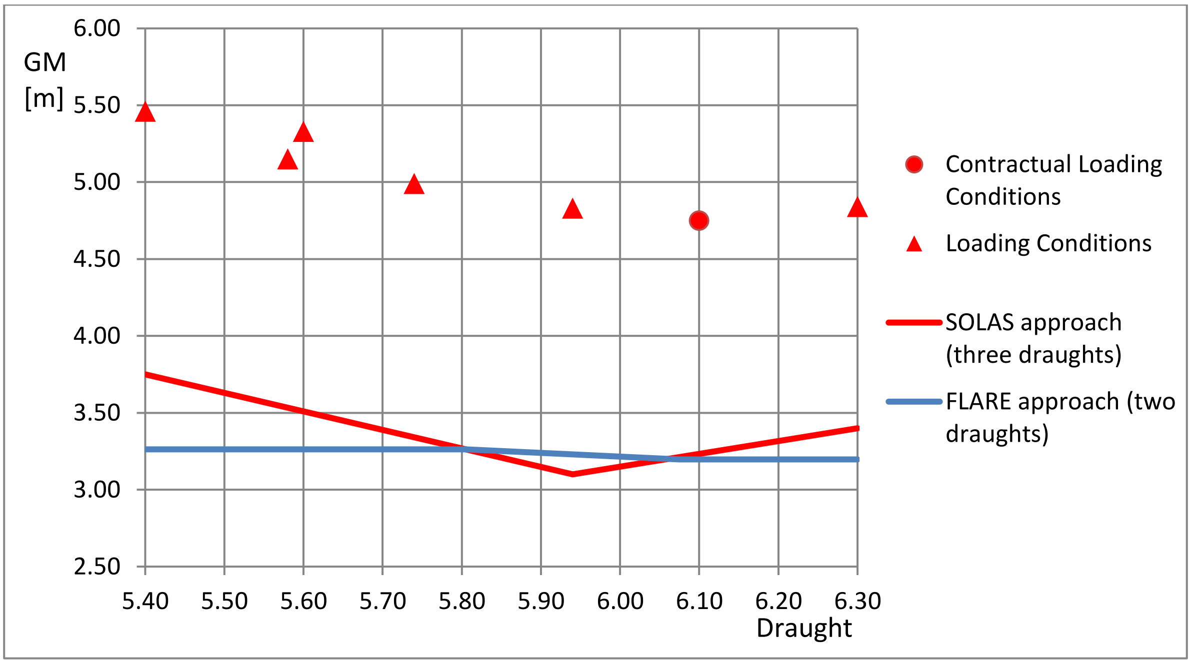


Figure 2 GM limiting curve with new FLARE draughts – Ship #6

1.2.1 Static calculations with new draughts and permeabilities same model as used in WP2

Calculation has been executed with the software NAPA rel.2020.2 generating damages up to 5 adjacent zones.

These parameters led to an attained index A = 0.9427 (with reference to the SOLAS A index +6,0 %). The difference is mostly caused by the changes in permeabilities (+ 5 %). In particular, the reduction of the heeling tank permeability makes a big impact.

Table 2 Static results with new draughts and permeabilities – Ship #6

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	5.805	3.263	0.9520	0.5	0.4760	0.9427
T0.75	6.075	3.197	0.9335	0.5	0.4667	

1.2.2 Static calculations with new draughts and permeabilities & void spaces divided in CL

SOLAS2020 calculations are based on the separate verification of instantaneous cross-flooding within 60 seconds through the crossduct on the other side of the void space.

According to FLARE modelling guidelines, (Annex 1) U-void spaces shall be divided in centre line. In small dayferry the volume of void spaces is quite big compared to the size of the ship. This will have remarkable impact on the attained index. However, it can be assumed, that despite the modelling guidelines for simulation the compliance according SOLAS will be based on instantaneous flooding of the voids.

These observations led to an attained index A = 0.8879 (with reference to the SOLAS A index + 0.8892).

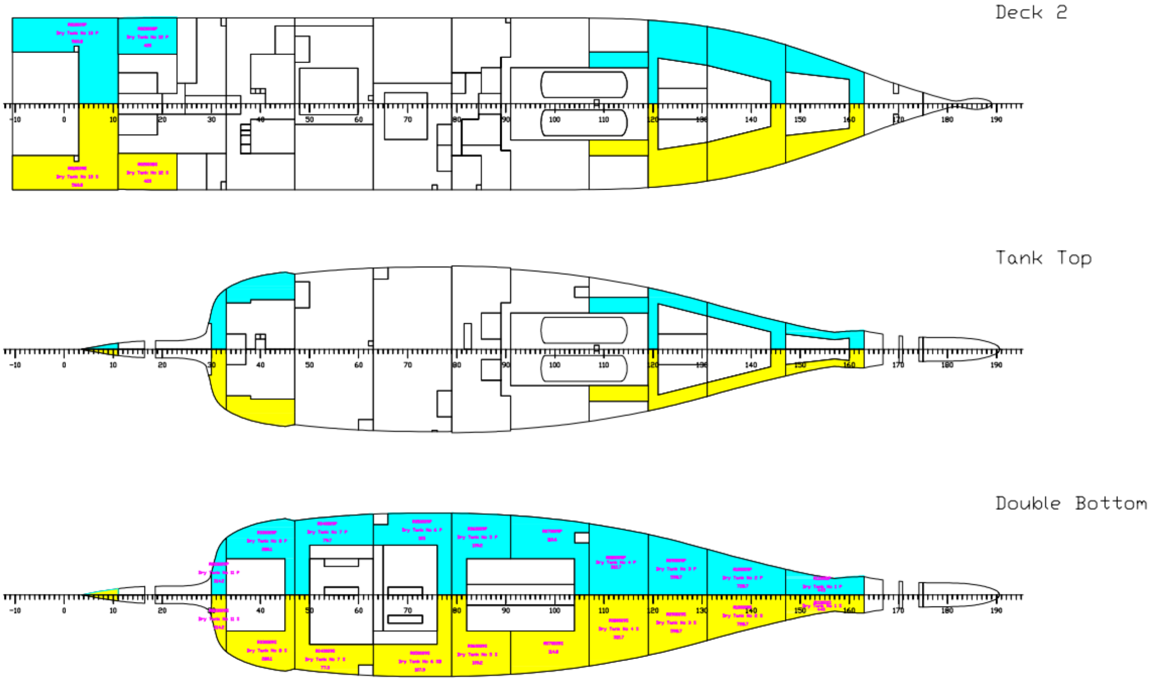


Figure 3 Divided U-void spaces – Ship #6

Table 3 Static results with new draughts, permeabilities and divided void spaces – Ship #6

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	5.805	3.263	0.9070	0.5	0.4535	0.8879
T0.75	6.075	3.197	0.8689	0.5	0.4344	

1.2.3 Static calculations with new draughts and permeabilities, U-void spaces divided in CL and car deck assumed watertight

By assuming car deck (=bulkhead deck) watertight in case, when U-void spaces are divided in CL the increase in the attained index 0.9091 is 2.4%.

In RoRo ships car deck is easy to assume watertight, because accesses below the deck to be located minimum 2.4 m above the deck.

This option is assumed as basic to carry out non-zonal static calculations.

Table 4 Static results with new draughts and permeabilities, U-void spaces divided in CL and car deck assumed watertight – Ship #6

	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	5.805	3.263	0.9249	0.5	0.4624	0.9091
T0.75	6.075	3.197	0.8933	0.5	0.4467	

1.3 Non-zonal static analysis

For the non-zonal static analysis, the car deck was divided into five parts. This modification was implemented to enable for a more accurate dynamic model as Proteus software cannot take into account the compartments in the middle of the car deck (such as staircases and engine casings). The implementation of this modification had to be done already before the non-zonal static analysis because the dynamic analysis uses that as input information.

With the refined model according to the FLARE modelling guidelines (Annex 1) an increased number of rooms and connections has been generated (see Table 5). Spaces inside DAMHULL are quite simple and the number of rooms is quite small. Further SOLAS2020 calculations are based on spaces corresponding the real general arrangement.

Table 5 Comparison between simplified model and refined model – Ship #6

Description	Before modelling	After modelling
Damhull volume	49 723 m^3	49 723 m^3
Rooms number	154	175
Connections number	57	142

Once the geometrical model has been updated according to the modeling guidelines, static damage stability has been calculated again.

The updated model is provided between the parts of U-shaped voids below the car deck. Because the original ship model is based on real spaces and stairs are defined as one space the number of rooms increases only with 21 new spaces in the simulation model.

The subdivision table is also affected by minor changes in order to consider also the damage cases that involve new rooms.

However, all the differences in how to set up the geometrical model determine a slightly different result in A-index +0.0002 (0.9091 => 0.9093).

Table 6 Static results with refined model – Ship #6

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	5.805	3.263	0.9249	0.5	0.4624	0.9093
T0.75	6.075	3.197	0.8937	0.5	0.4469	

1.3.1 Non-damage area

Internal watertight integrity is based on the fact that a "NON-DAMAGE AREA" was not assumed in the central part of the ship. Progressive flooding is prevented with remote control valves or by routing the pipes in the same watertight compartment above the most severe waterline and range of residual stability before routing longitudinally.

1.4 Calculation of PLL level 1

For this vessel, breaches for collision, side and bottom grounding have been generated according to Ch. 3.2 of the main report and the grouping of breaches, leading to the same sets of flooded rooms, permitted to reduce the damage cases to be calculated by abt. 76% for collision, abt. 79% for bottom grounding, and by abt. 86% for side grounding.

With the results of the static calculation, the PLL level 1 was calculated according to procedure described in Ch.2 of the main report. In particular, in Table 7 below, the non-zonal results are showed and in Table 8, the PLL (Potential loss of life) calculation is reported.

Table 7 Non-zonal static analysis results – Ship #6

Damage Type	Collision		Side Grounding		Bottom Grounding	
Init condition	D45	D75	D45	D75	D45	D75
Draught	5.805m	6.075m	5.805m	6.075m	5.805m	6.075m
Breaches	10000	10000	10000	10000	10000	10000
Number of Empty cases	12	6	169	152	340	355
Number of Unique damage cases	2347	2354	1396	1398	2176	2109
Partial Index	0.9334	0.9022	0.9196	0.9165	0.9422	0.9280
Total Attained Subdivision Index A_i	**0.9178**		**0.9180**		**0.9351**	

Table 8 PLL level 1 – Ship #6

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		4.33E-03
Relative frequency	0.388		0.328		0.284		1.000
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	5.805	6.075	5.805	6.075	5.805	6.075	
Attained Index	0.9334	0.9022	0.9196	0.9165	0.9422	0.9280	0.9228
$\sum pfac$ (for cases with s=1)	0.9177	0.8761	0.9108	0.9083	0.9409	0.9265	0.9115
$\sum pfac \cdot (1 - sfac)$	0.0666	0.0978	0.0804	0.0835	0.0578	0.0720	0.0772
PLL level 1 (1/ship year)	8.94E-02	1.31E-01	9.14E-02	9.48E-02	5.68E-02	7.09E-02	**0.5348**
	0.2209		**0.1862**		**0.1277**		

Even though the PLL is eventually the parameter to be used as a risk metric in by FLARE, the Combined Attained Index is also shown in Table 8 for information only. These values are calculated by using the relative frequency for collision, Side grounding and Bottom Grounding, which are based on the updated damage statistics of FLARE (WP2).

1.5 Filtering of static results and selecting cases for dynamic simulations

The screening of the static result according to filtering criteria identified within Ch. 3.4 permitted to select 500 cases for the dynamic simulations. In the following table, a summary of the filtered breaches is reported.

Table 9 Filtering results – Ship #6

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	5.805	6.075	5.805	6.075	5.805	6.075	
Number of filtered damage cases	97	174	81	71	29	48	500
$\sum pfac$ (for the filtered damage cases)	0.0275	0.0529	0.0416	0.0422	0.0147	0.0252	0.0350
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0273	0.0514	0.0415	0.0415	0.0147	0.0252	0.0345
Potential PLL (if the ships would not capsize for all selected cases)	5.28E-02	6.25E-02	4.42E-02	4.78E-02	4.24E-02	4.61E-02	0.2956
	0.1152		0.0920		0.0884		
Potential PLL reduction (if the ships would not capsize for all selected cases)	47.8%		50.6%		30.7%		44.7%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. In particular, for this ship the PLL would be reduced by about 44% if none of the cases to be simulated lead to capsizing.

In the following diagrams, some typical damage parameters of the selected breaches are presented in non-dimensional form.

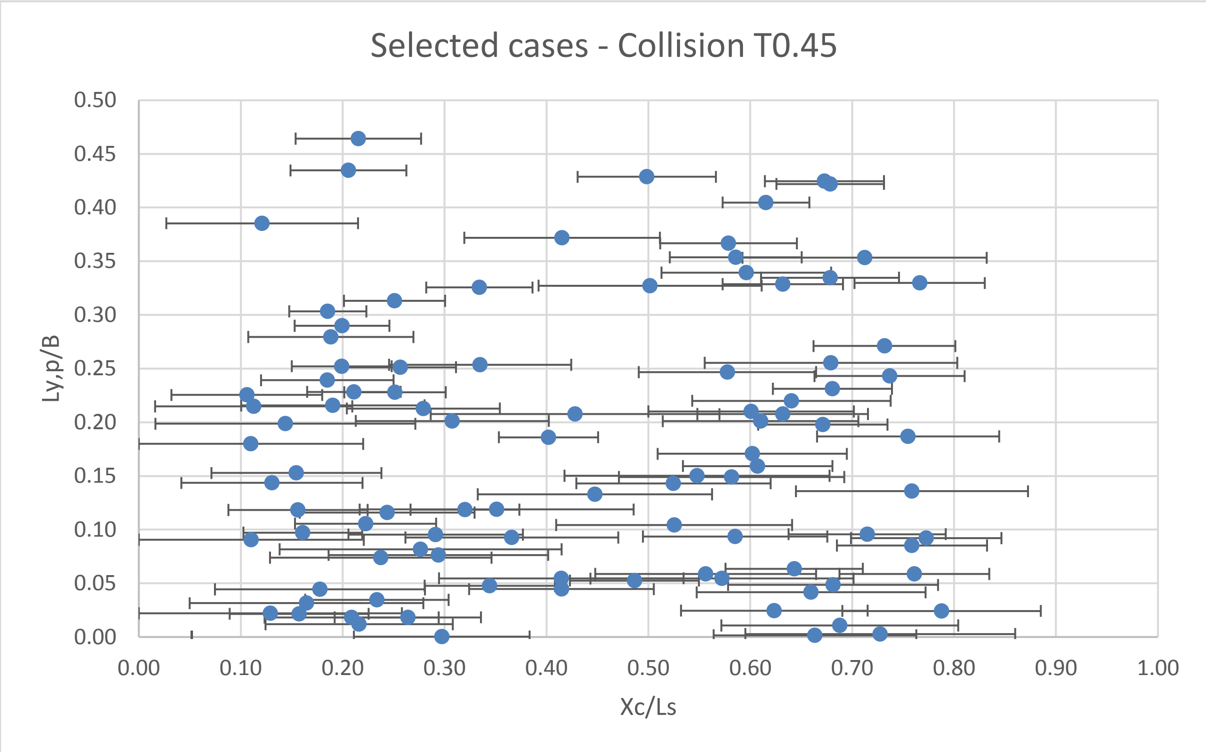


Figure 4 Selected collision breaches T0.45 – Ship #6

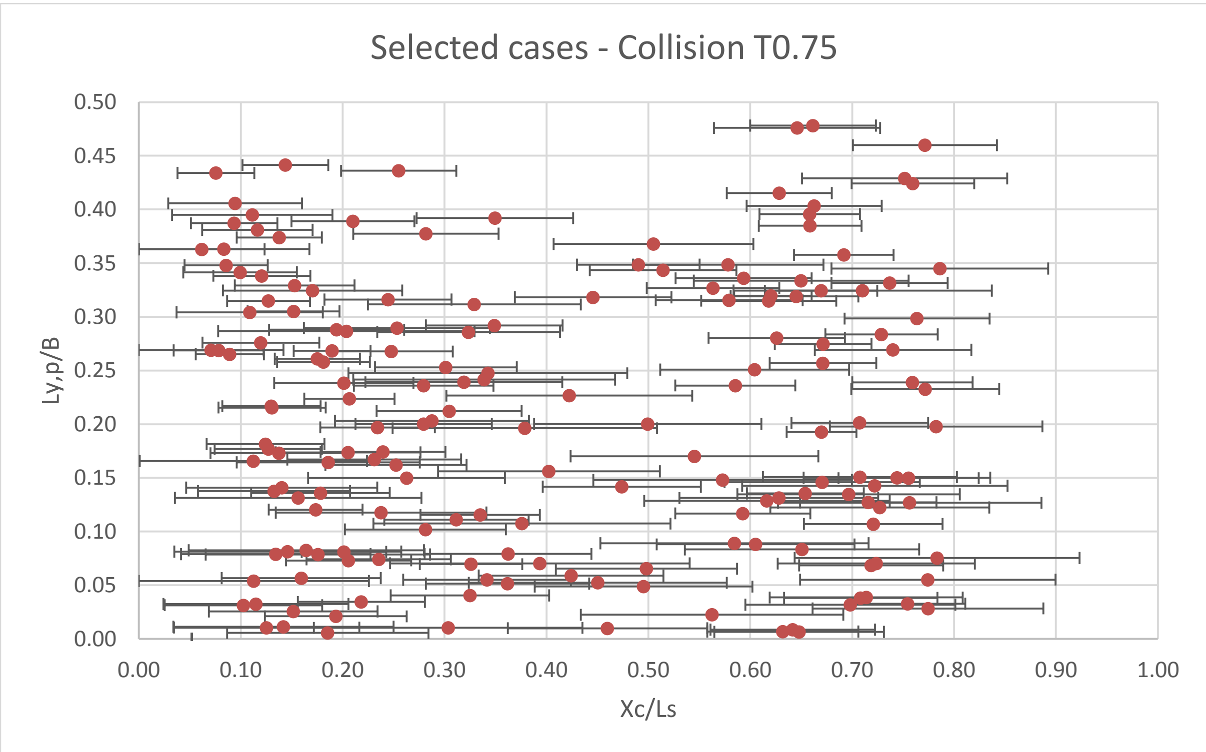


Figure 5 Selected collision breaches T0.75 – Ship #6

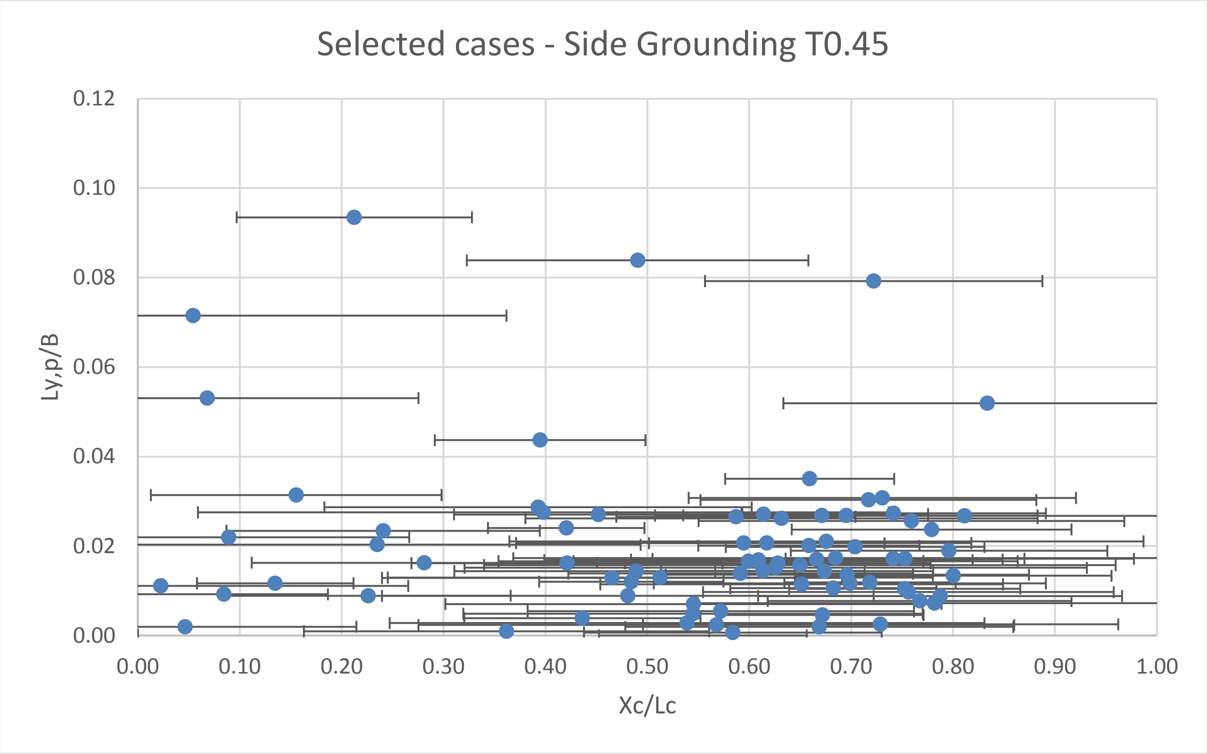


Figure 6 Selected side grounding breaches T0.45 – Ship #6

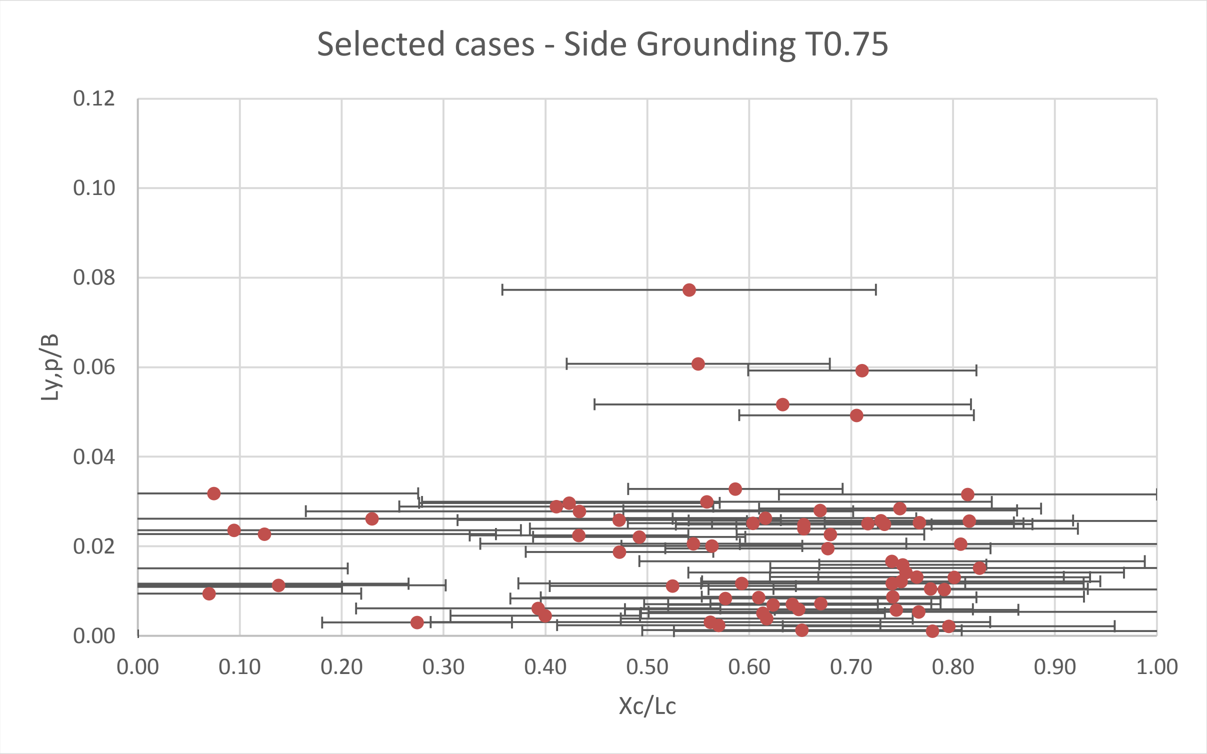


Figure 7 Selected side grounding breaches T0.75 – Ship #6

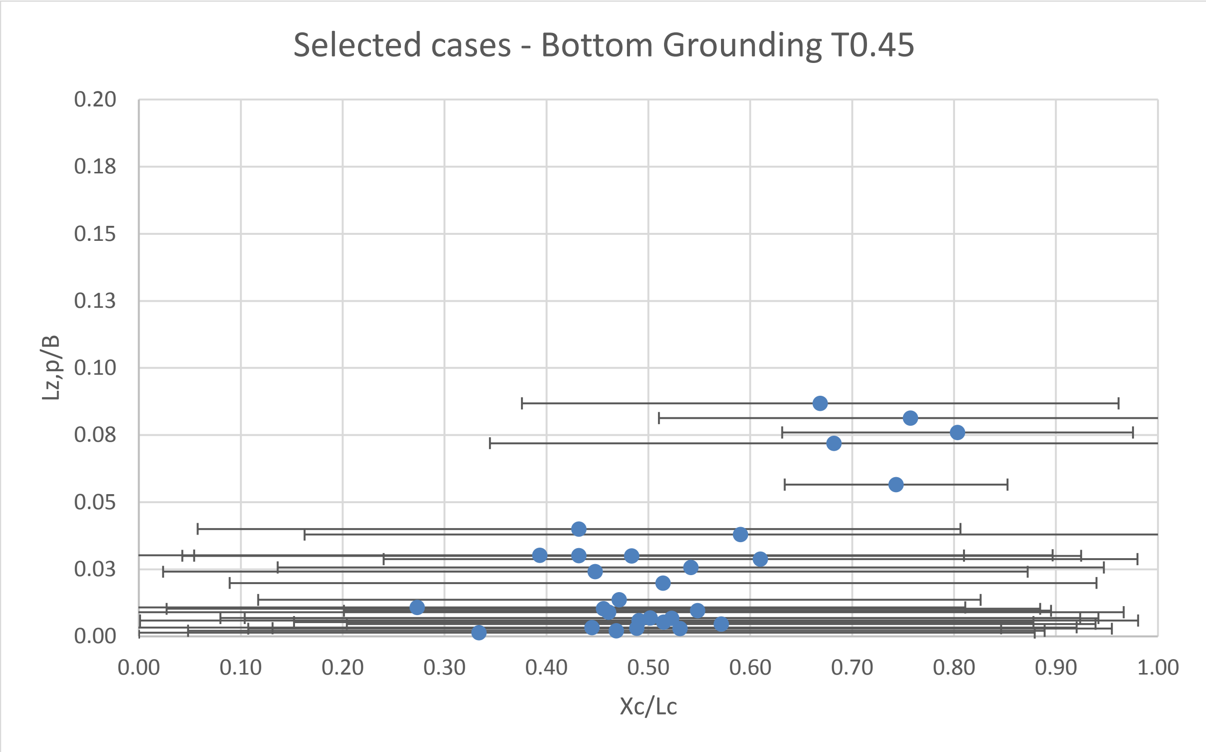


Figure 8 Selected bottom grounding breaches T0.45 – Ship #6

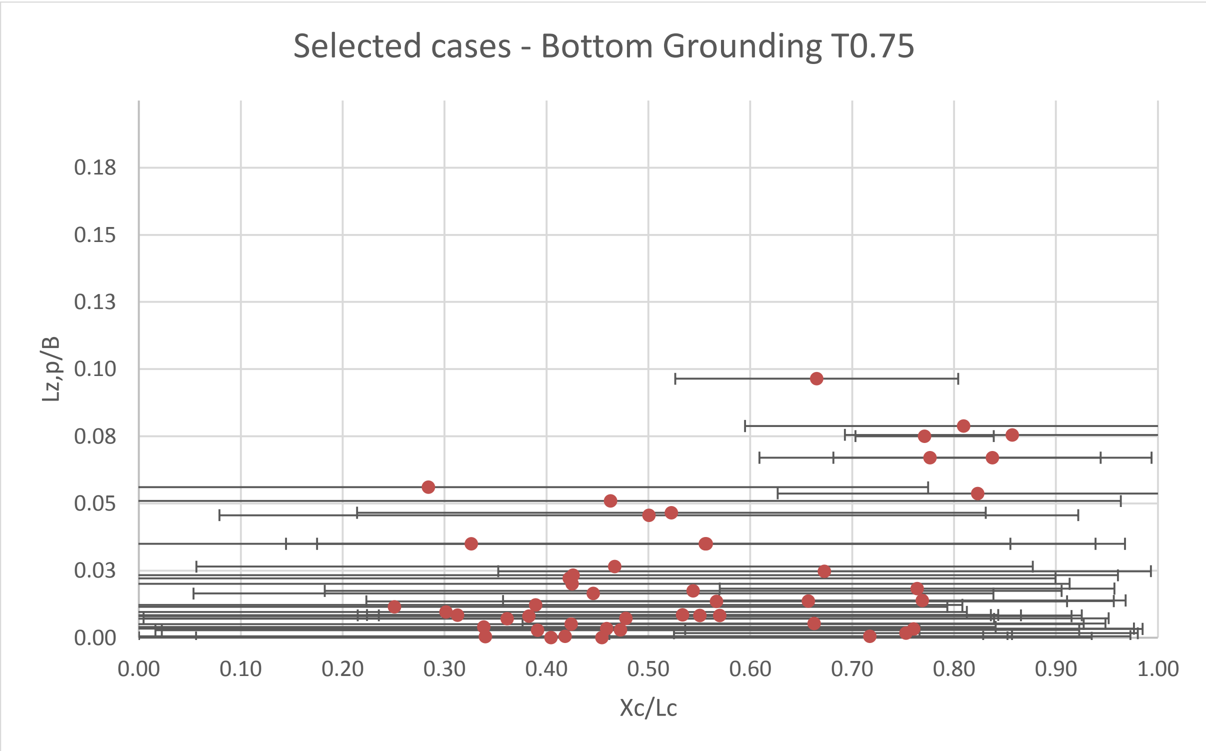


Figure 9 Selected bottom grounding breaches T0.75 – Ship #6

For collision damages, areas of interest can be identified: the shoulder regions. Filtered side grounding damages are concentrated mostly on the fore part of the vessel, whereas the bottom grounding damages are mostly extremely long, longitudinally penetrating the whole double ship. There are also a few deep bottom grounding cases that penetrate the double bottom. These damages are located at the forward shoulder region.

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with s-factor equal to zero and failure modes for cases with s-factor between 0 and 1, are showed in the following tables.

Table 10 Breakdown of failure mode for Sfac=0 cases – Ship #6

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	87	144	9	16	0	0	**256**
Heeling Angle (>15 deg)	4	7	48	34	0	0	**93**
Smom=0	0	3	2	1	0	0	**6**
Opening immersion	2	10	21	19	29	48	**129**
Sfac=0 - Total cases	**93**	**164**	**80**	**70**	**29**	**48**	**484**

Table 11 Breakdown of failure mode for 0<Sfac<1 cases – Ship #6

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	0	0	0	0	0	0	**0**
Insufficient Range	0	0	0	0	0	0	**0**
Heeling Angle (>7 deg)	0	0	0	1	0	0	**1**
Insufficient Restoration (GZmax) + Range	4	10	1	0	0	0	**15**
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	**0**

Insufficient Range + Excessive Heel	0	0	0	0	0	0	**0**
Insufficient Restoration (GZmax) + Range + Excessive Heel	0	0	0	0	0	0	**0**
0<Sfac<1 - Total cases	**4**	**10**	**1**	**1**	**0**	**0**	**16**

A remarkably large percentage of captured cases resulted into Sfac = 0 (484 cases over 500) and about 70% of the captured cases had a failure mode corresponding to either a capsize or heeling angle greater than 15 degrees.

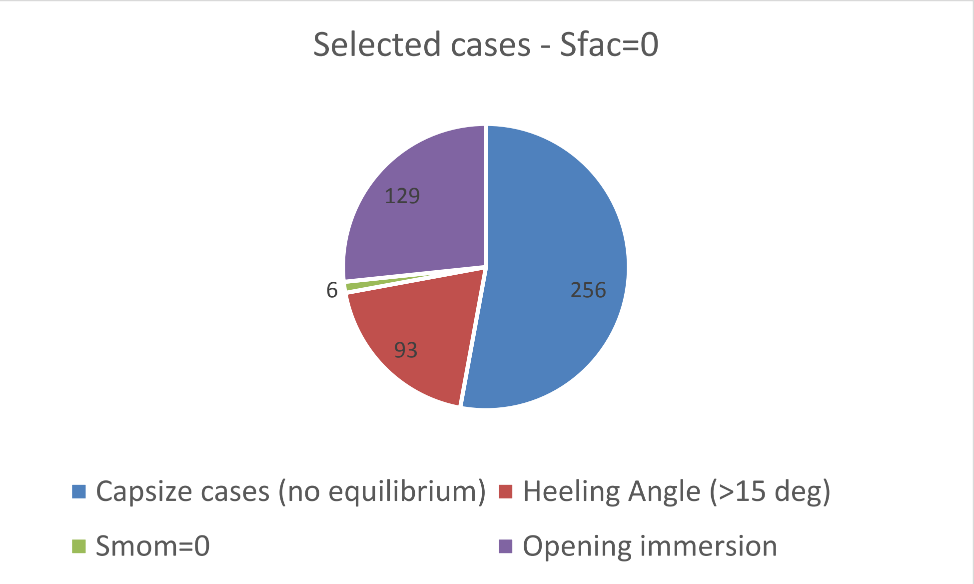


Figure 10 Diagram of failure mode for Sfac=0 cases – Ship #6

Only a few cases (6) with Smom = 0 were found and 129 cases have been identified due to the immersion of openings. These cases are very important to be selected too as it is expected that the outcome of the dynamic simulation should be quite different. In fact, the approach for connections and openings definition is completely different between static and dynamic calculation.

Only 16 damage cases with 0 < Sfac < 1 has been selected and almost all (15) of these cases resulted in an insufficient GZmax + range. The remaining one case was found to be resulting in a heeling angle larger than 7 degrees.

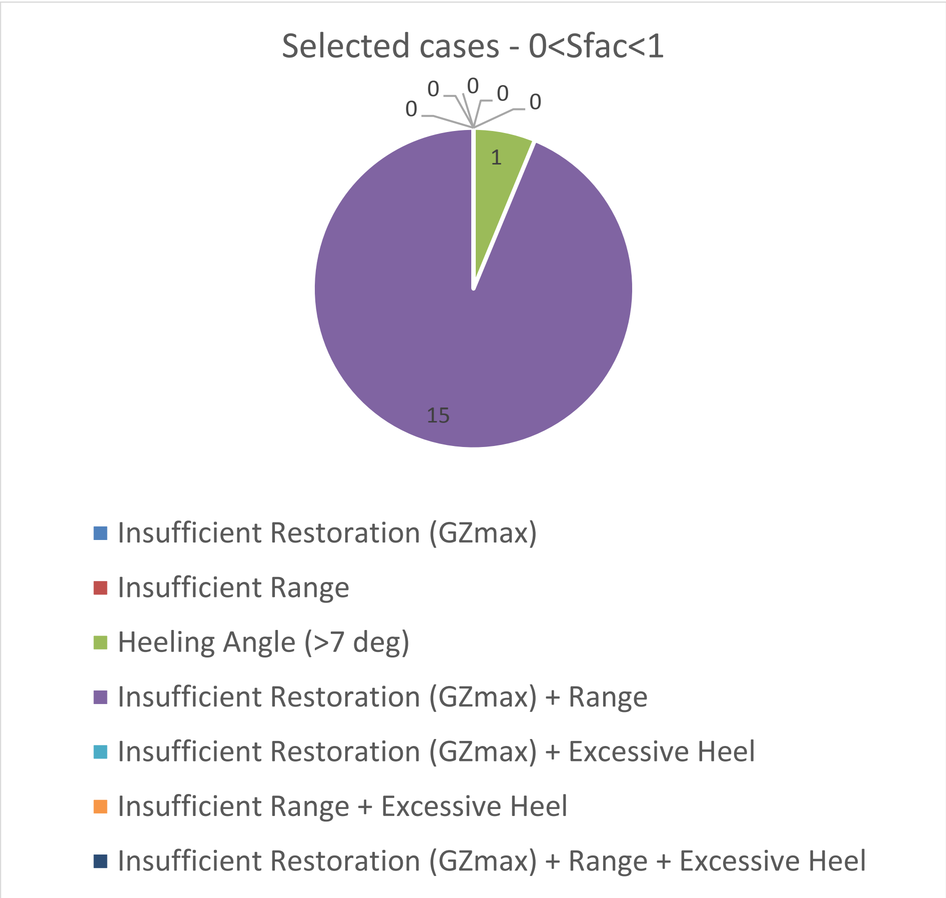


Figure 11 Diagram of failure mode for 0 < Sfac < 1 cases – Ship #6

2 DYNAMIC ASSESSMENT

2.1 Preparation of the PROTEUS model

The dynamic analysis has been carried out by use of the *PROTEUS* software (last release distributed in November 2021). In particular, for the preparation of the model the tool Proteus Manager has been used.

To generate in the *Proteus Manager* the loading conditions defined in NAPA and corresponding to the two calculation draughts at 45% and 75%, the following lightships have been generated:

$T_1 = 5.805$ m → LIG_1 [Δ=15462.8 t ; CG (68.010 , 0 , 13.75) m]

$T_2 = 6.075$ m → LIG_2 [Δ=16437.0 t ; CG (67.726 , 0 , 13.60) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at five different deck slices:

DB = 0.1m ; D1 = 3.6m ; D2 = 6.1m ; D3 = 9.3m ; D4 = 12m

For this ropax ship, 158 openings have been defined in the dynamic simulation model. Horizontal openings have been defined on the higher deck of the model to capture the down-flooding through engine casings, stair trunks, vertical escape and lifts.

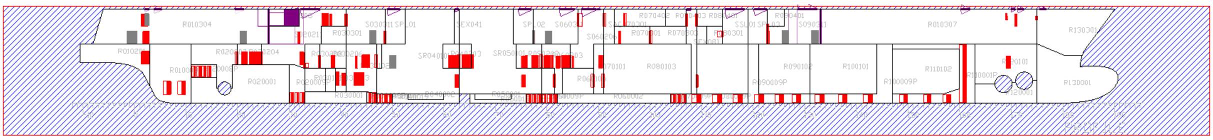


Figure 12 – Openings imported in Proteus Project (longitudinal section) – Ship #6

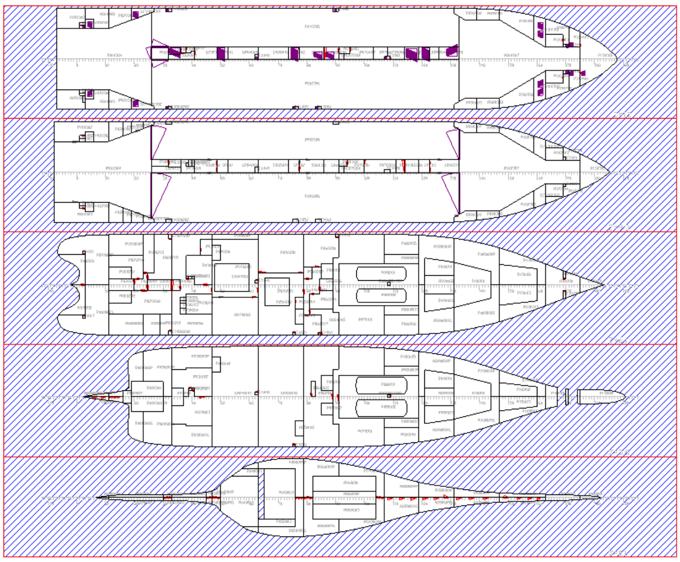


Figure 13 – Openings imported in Proteus Project (horizontal section) – Ship #6

Table 12 – Opening types in Proteus Manager – Ship #6

TYPE	Leak Area Ratio 1 to 2	Leak Area Ratio 2 to 1	Collapse Pressure 1 to 2 [meters]	Collapse Pressure 2 to 1 [meters]	Leak Height [meters]	Gap Height [meters]	Effective Height HEff Switch	Open At Time [seconds]	Close At Time [seconds]
CONNECTION	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
B-CLASS-JOINER	0.03000	0.03000	1.50	1.50	0.000	0.000	True	0	999999
FDOOR-A-HINGED	0.03000	0.02000	2.50	2.50	0.000	0.000	True	999999	0
FDOOR-A-SLIDING	0.03000	0.02000	1.00	1.00	0.000	0.000	True	999999	0
FDOOR-A-DOUBLELEAF	0.02500	0.02500	2.00	2.00	0.000	0.000	True	999999	0
COLDROOM-DOOR	0.00000	0.03000	3.50	3.50	0.000	0.000	False	0	999999
LIFT-DOOR	0.00000	0.00000	1.50	1.50	0.000	0.000	False	0	999999
SWT-DOOR	0.01000	0.01000	10.00	10.00	8.000	0.000	False	0	999999
WT-DOOR	0.00100	0.00100	100.00	100.00	99.000	0.000	True	999999	0
WT-DOOR_LBHD	0.00100	0.00100	100.00	100.00	99.000	0.000	True	999999	0
SHELL-DOOR_LARGE	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
SHELL-DOOR_NORMAL	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999

Since in Proteus the discharge coefficient for the flow through openings is set to a constant value of 0.6 and it may be not changed, the area of the cross-flooding openings has been partly reduced in order to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation sets have been created and the comparison of the geometric and hydrostatic data between NAPA and Proteus showed that the differences are negligible in general (from Figure 14 to Figure 20 and Table 13).

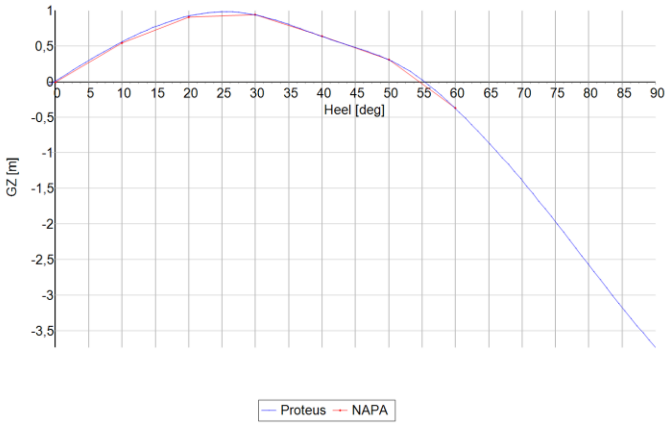


Figure 14 – GZ comparison between NAPA and Proteus – Ship #6

Table 13 – Floating Position comparison between NAPA and Proteus – Ship #6

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	5.805	5.808	-0.003	-0.052
TA [m]	5.804	5.816	-0.012	-0.207
TF [m]	5.806	5.800	0.006	0.103
Trim [deg]	0.002	0.016	-0.014	-87.500
Heel [deg]	0.142	0.142	0.000	0.000
KM [m]	17.003	16.993	0.010	0.059
KG [m]	13.750	13.750	0.000	0.000
GM0 [m]	3.253	3.243	0.010	0.307
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	3.253	3.243	0.010	0.307

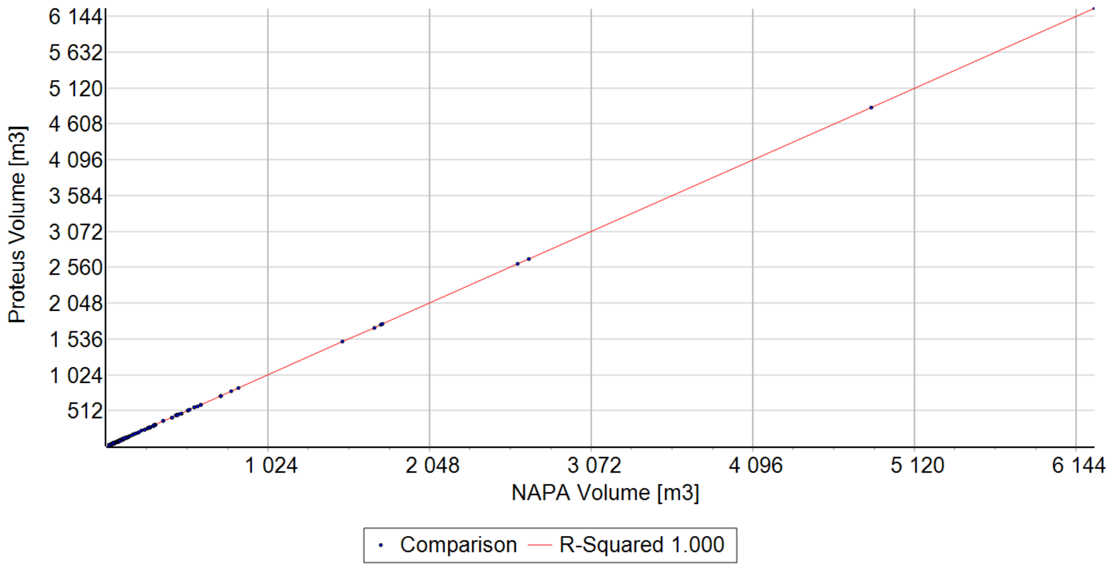


Figure 15 – Hull volume comparison between NAPA and Proteus – Ship #6

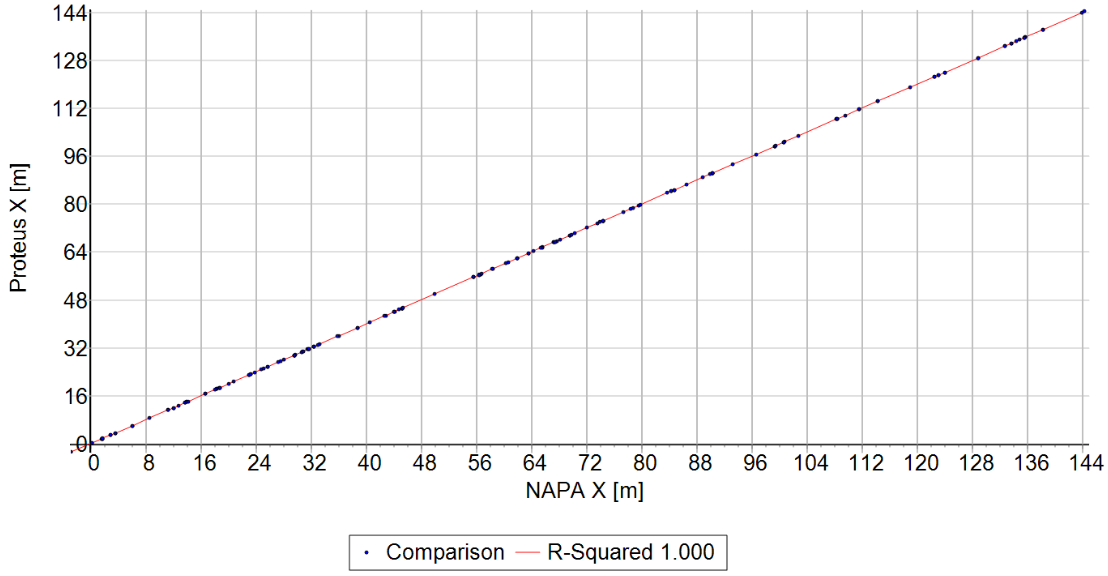


Figure 16 – Hull LCB comparison between NAPA and Proteus – Ship #6

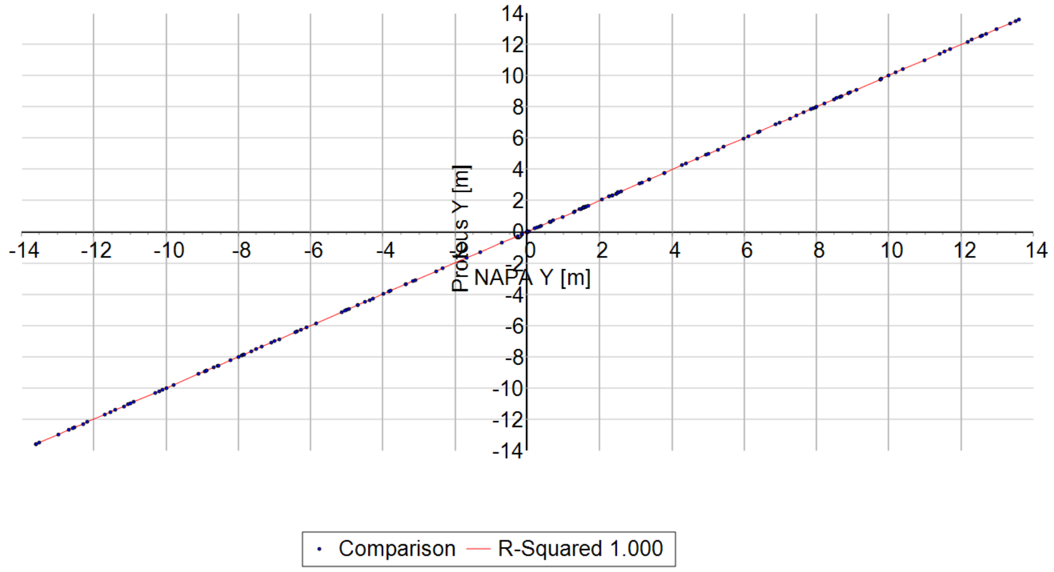


Figure 17 – Hull TCB comparison between NAPA and Proteus – Ship #6

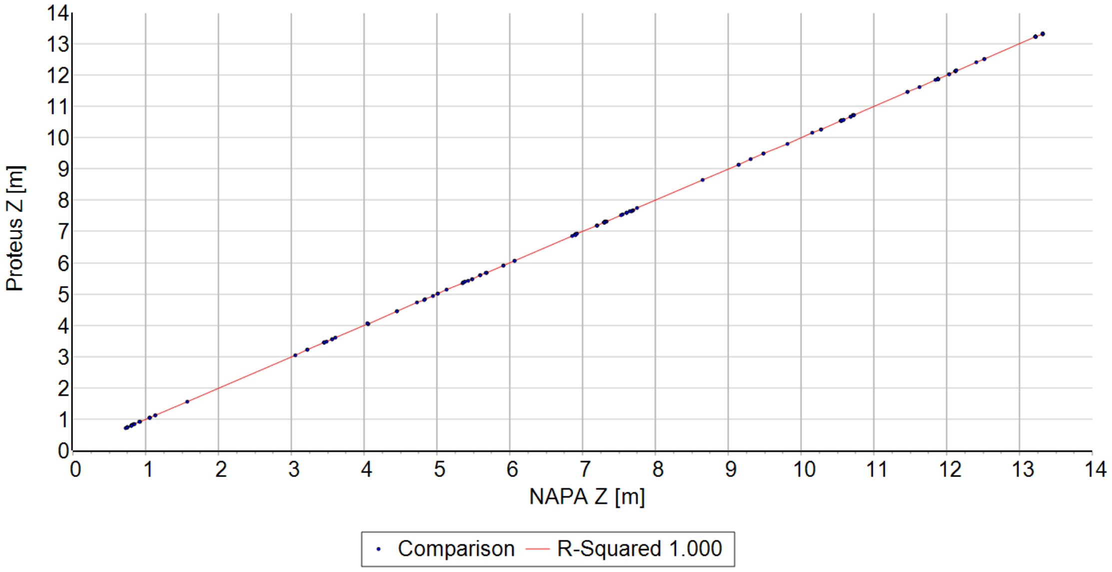
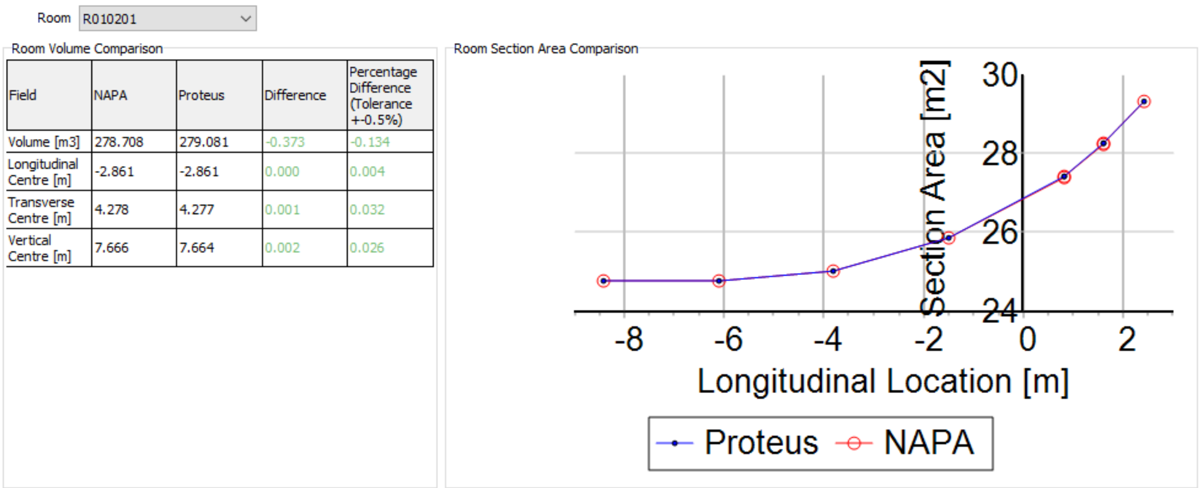


Figure 18 – Hull VCB comparison between NAPA and Proteus – Ship #6



Room R010201

Room Volume Comparison

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	278.708	279.081	-0.373	-0.134
Longitudinal Centre [m]	-2.861	-2.861	0.000	0.004
Transverse Centre [m]	4.278	4.277	0.001	0.032
Vertical Centre [m]	7.666	7.664	0.002	0.026

Figure 19 – Aftpeak comparison between NAPA and Proteus – Ship #6

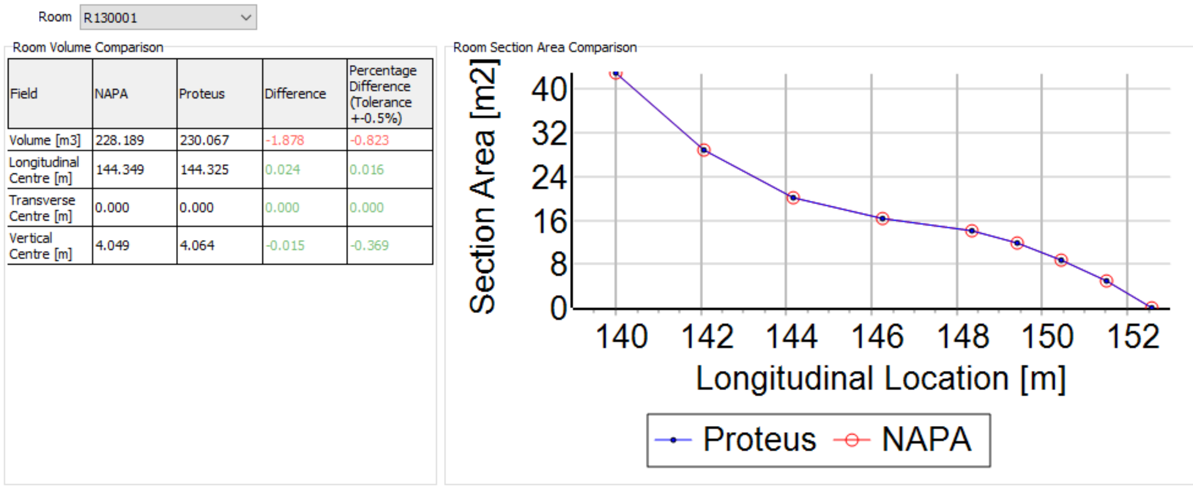


Figure 20 – Forepeak comparison between NAPA and Proteus – Ship #6

2.2 Results of dynamic simulations

In the first round of dynamic simulations by Proteus, all the 500 breaches have been simulated up to 30 minutes, then for 60 breaches a second simulation round has been executed up to 90 minutes, as these were found with progressive flooding still occurring at the end of the first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1 = capsize 0 = not capsize) and TTC for cases where a capsize occurred. In the following graphs, the results for each hazard and the global results of simulations are presented.

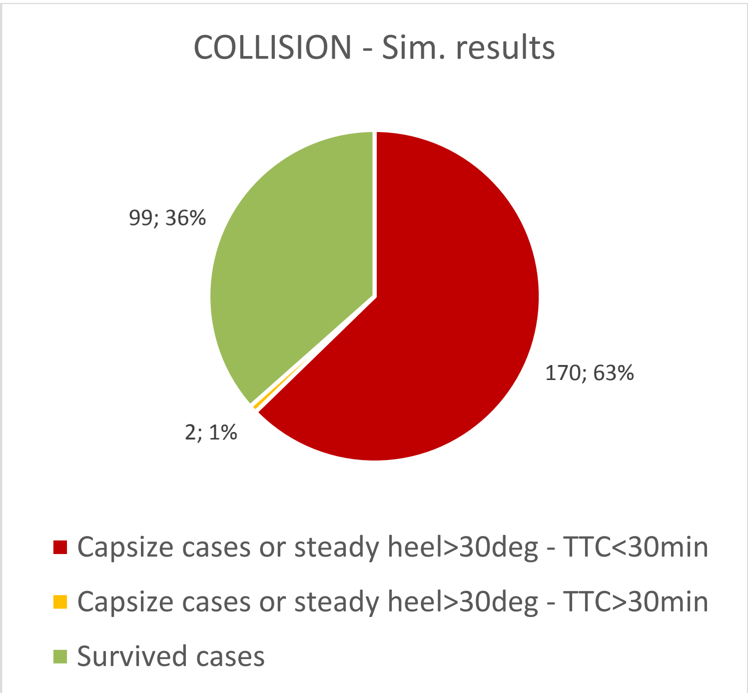


Figure 21 – Dynamic simulation results for collision – Ship #6

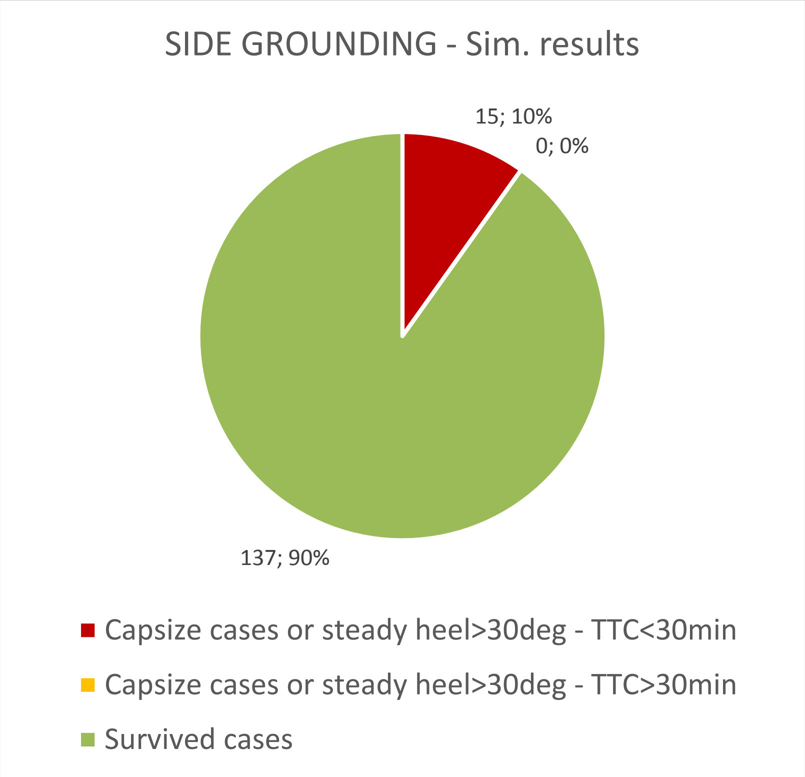


Figure 22 – Dynamic simulation results for side grounding – Ship #6

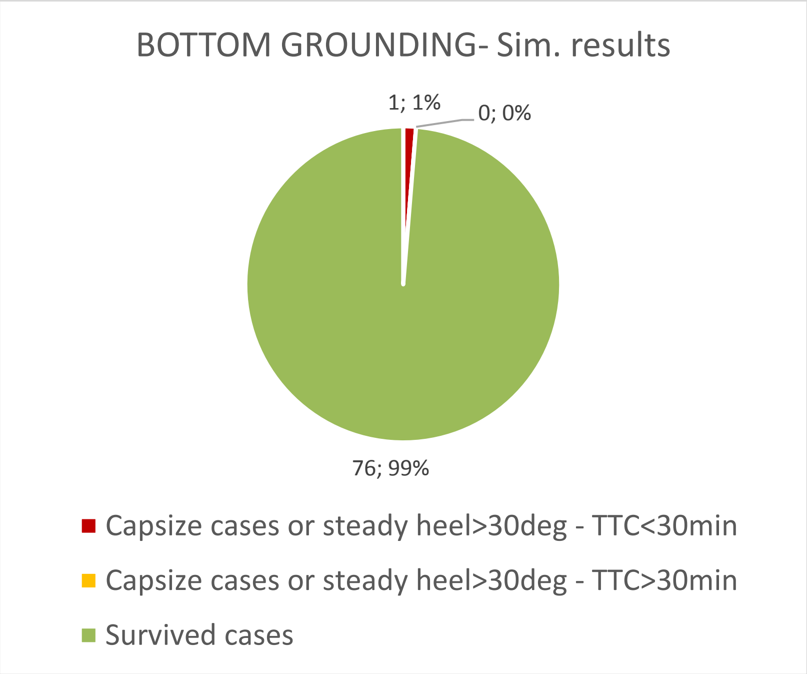


Figure 23 – Dynamic simulation results for bottom grounding – Ship #6

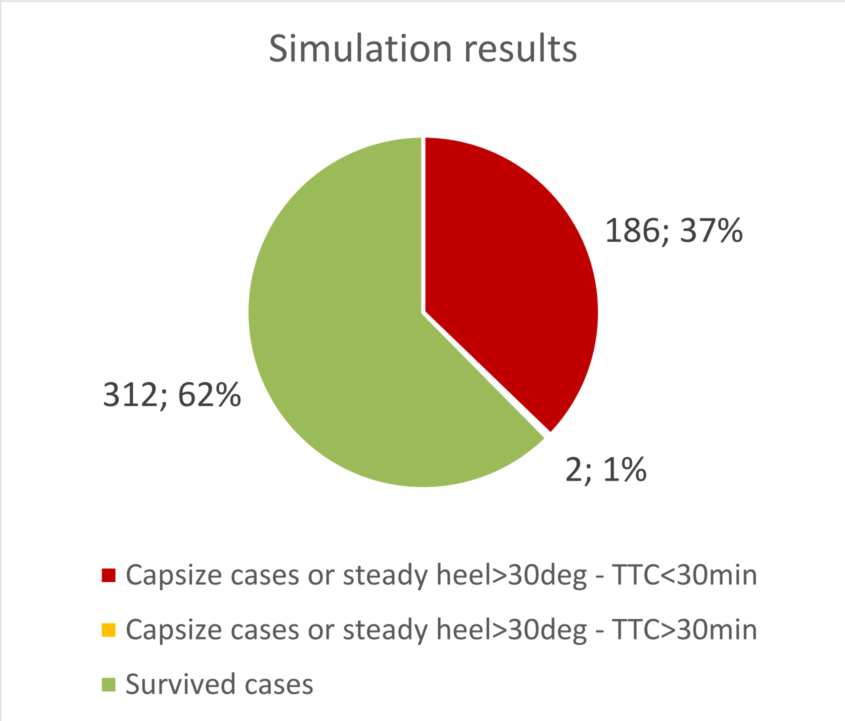


Figure 24 – Global dynamic simulation results for the 500 filtered breaches – Ship #6

The results obtained clearly show that the ship did not capsize in most of the cases. This confirms that the static results are conservative as almost all of those case had an sfac = 0 in the static analysis. The results also reveal that most of the capsizes in the dynamic analysis come from the collision cases (about 91%)

Almost all capsize cases (99%) are considered fast capsizes as the TTC is less than 30 minutes. For these cases, there is no sufficient time to orderly evacuate persons.

2.3 Calculation of PLL level 2.1

The results of the flooding simulations permit to get the TTC too, therefore the fatality rate may be estimated for the cases with TTC > 30 min according to the procedure for calculation of Risk (Level 2.1).

Table 14 PLL level 2.1 – Ship #6

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	5.805	6.075	5.805	6.075	5.805	6.075	
PLL L1 (1/ship year) (static assessment)	**8.94E-02**	**1.31E-01**	**9.14E-02**	**9.48E-02**	**5.68E-02**	**7.09E-02**	**0.5348**
	0.2209		**0.1862**		**0.1277**		
Number of filtered damage cases	97	174	81	71	29	48	500
Capsize cases or steady heel>30deg - TTC<30min	61	109	5	10	0	1	186
Capsize cases or steady heel>30deg - TTC>30min	1	1	0	0	0	0	2
Survived cases	35	62	76	61	29	47	312
PLL L2.1 (1/ship year) (dynamic assessment)	**7.38E-02**	**1.04E-01**	**4.61E-02**	**5.25E-02**	**4.24E-02**	**4.65E-02**	**0.3649**
	0.1775		**0.0985**		**0.0888**		
PLL L2.1 vs L1 (variation percentage)	**-19.6%**		**-47.1%**		**-30.4%**		**-31.8%**

In Table 14, the details of the results obtained by static and dynamic simulations are reported. It can be observed that the PLL from the static calculation has been reduced by nearly 32% from 0.5348 (Level 1) to 0.3649 (Level 2.1) when using dynamic simulation.

In the following figures, the diagrams for the characteristics of the breaches which lead to capsize after dynamic simulations are reported.

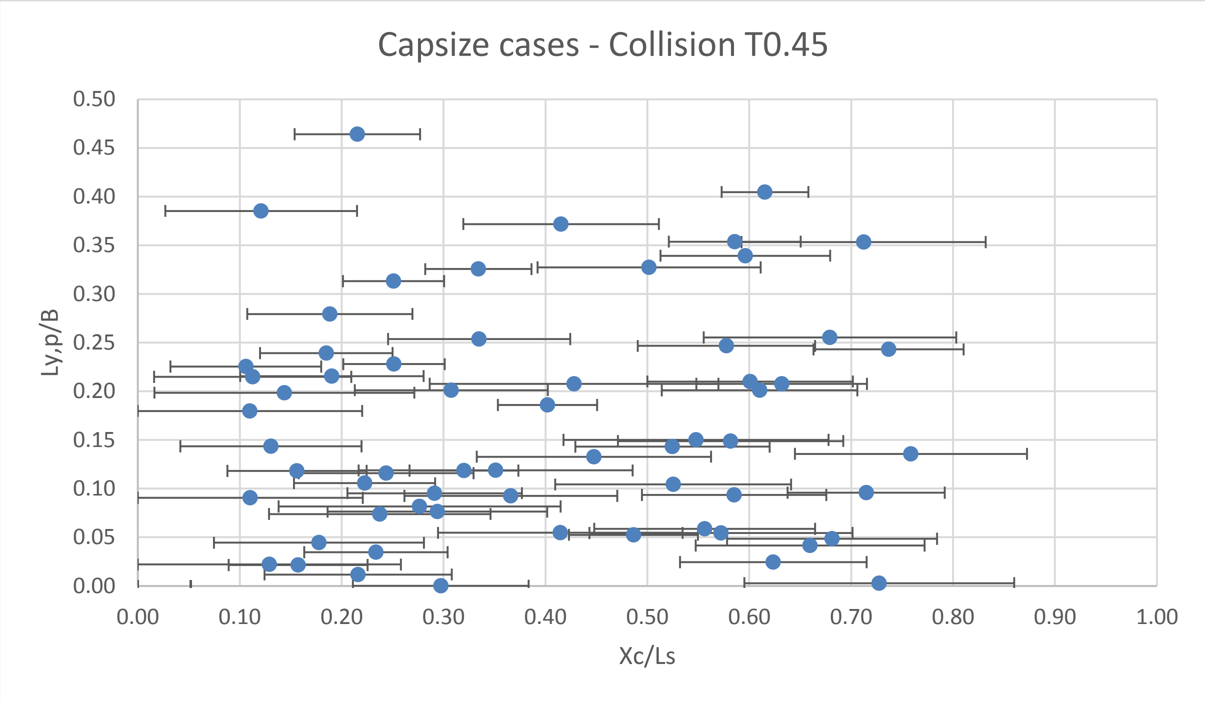


Figure 25 Collision characteristics leading to capsize T0.45 – Ship #6

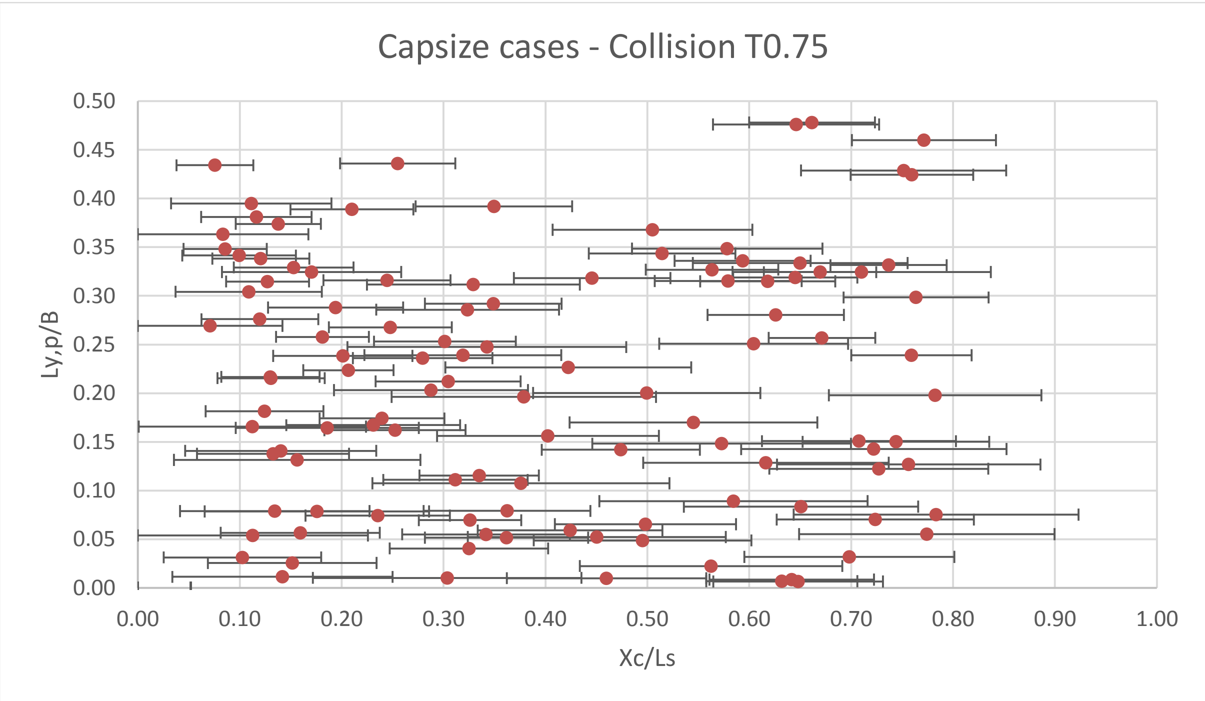


Figure 26 Collision characteristics leading to capsize T0.75 – Ship #6

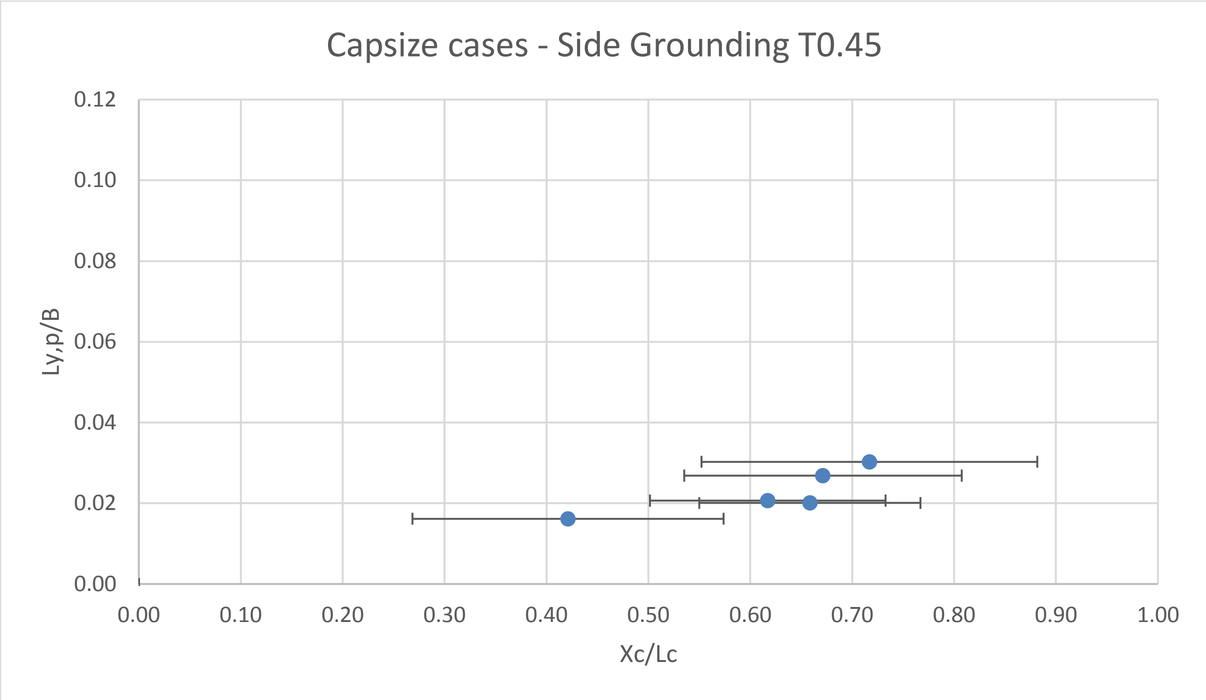


Figure 27 Side grounding characteristics leading to capsize T0.45 – Ship #6

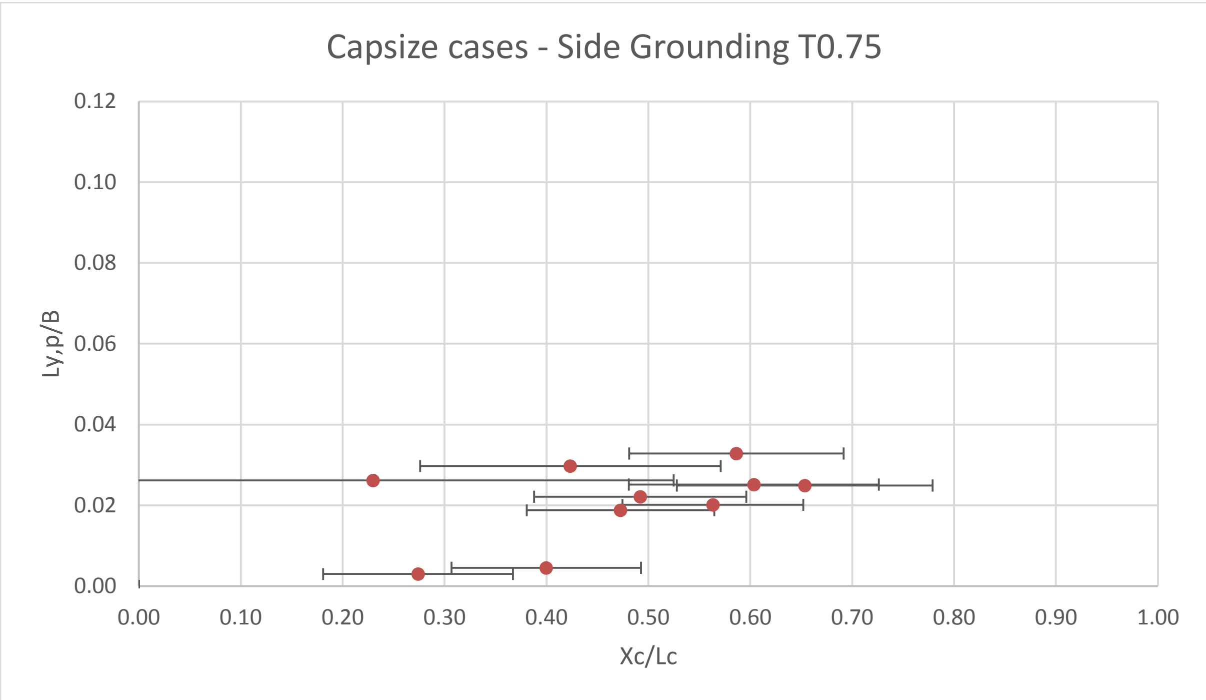


Figure 28 Side grounding characteristics leading to capsize T0.75 – Ship #6

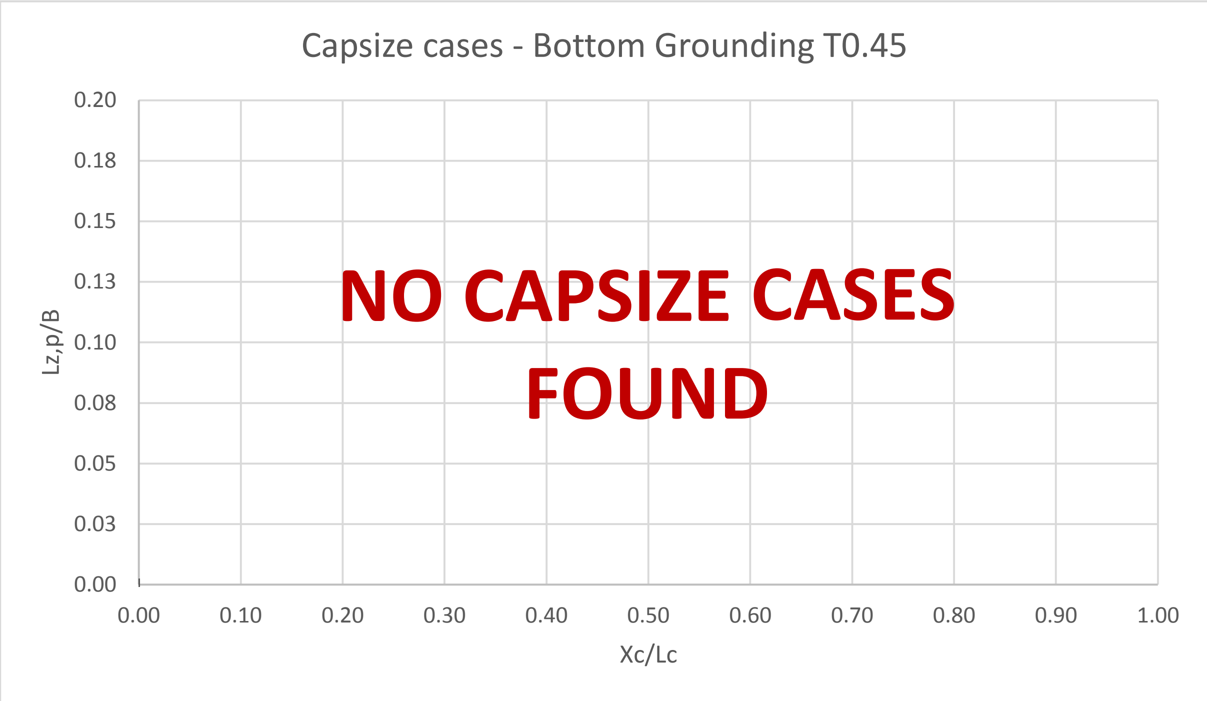


Figure 29 Bottom grounding characteristics leading to capsize T0.45 – Ship #6

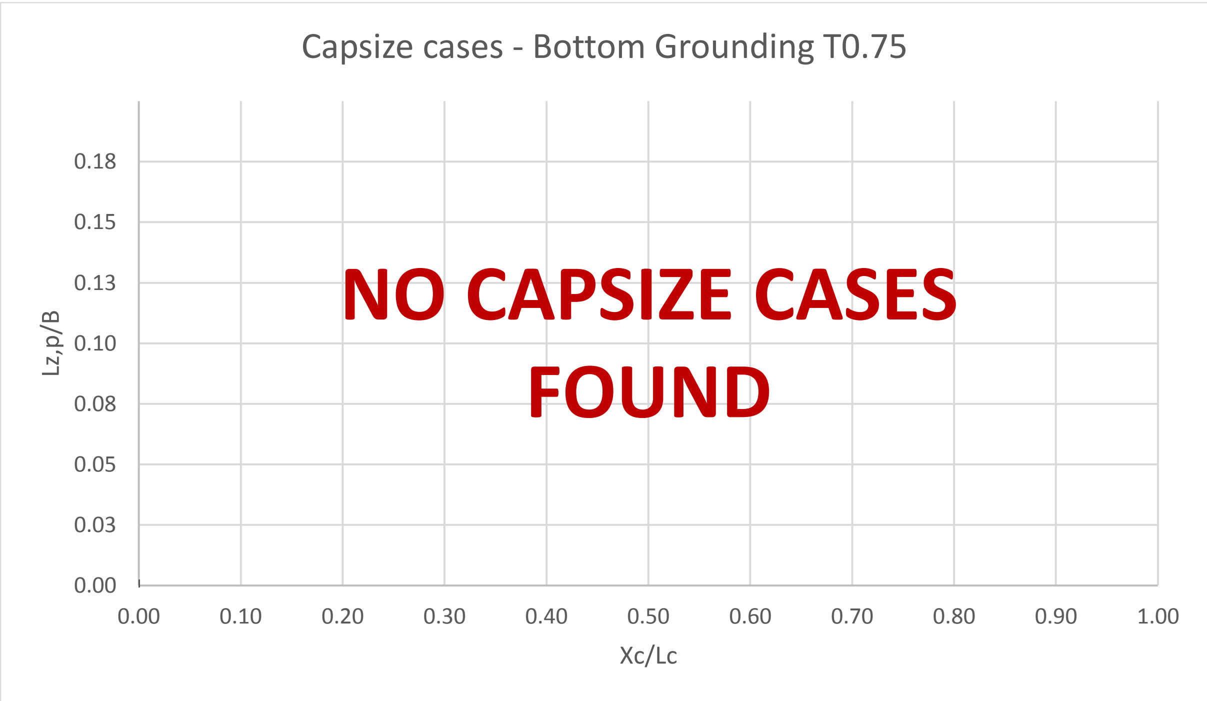


Figure 30 Bottom grounding characteristics leading to capsize T0.75 – Ship #6

The identified capsizal cases showed from the Figure 25 to Figure 30 may be investigated in WP7.2, when Risk Control Options are to be implemented.

2.4 Sensitivity analysis of the fatality rate

From the dynamic simulation results, it has been observed that 2 cases resulted into a TTC greater than 30 minutes but lower than 60 minutes. For those cases, linear Interpolation between 0% and 80% has been used for the estimation of the fatality rates. Furthermore, there are further 11 cases where progressive flooding is still occurring after 60min and for these cases, no fatality has been assumed (Figure 31).

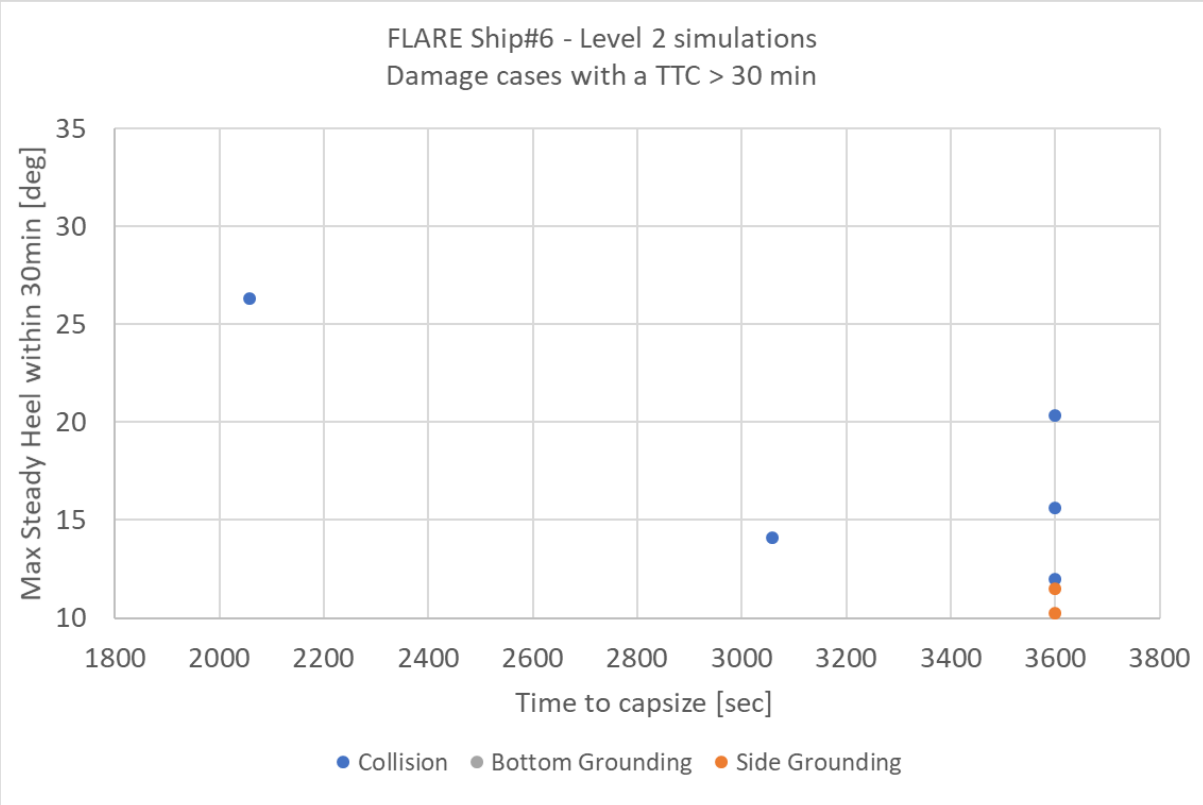


Figure 31 Cases with TTC > 30 min or progressive flooding still occurring after 60min – Ship #6

In order to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out for the total 13 cases (with TTC > 30 min or progressive flooding still occurring after 60 min). For this, the impact on the PLL has been evaluated in case of variation of the fatality rate by ± 30% of the POB.

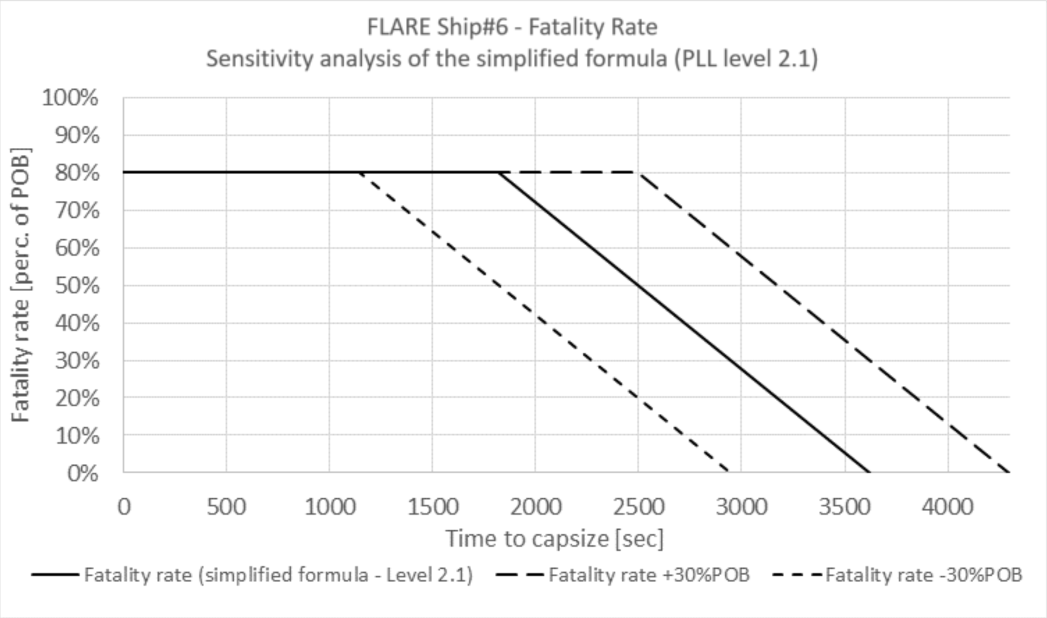


Figure 32 Sensitivity analysis of simplified formula for fatality rate calculation – Ship #6

As the amount of damages considered in this sensitivity analysis is so small, the variation in the sensitivity function practically did not affect the PLL. The calculation with +30% in the fatality rate increased the PLL be 0.05% whereas the -30% calculation resulted in a decrease of 0.05%.

3 CONCLUSIONS

The complete procedure for calculation of Risk has been applied on Ship #6 and the results obtained demonstrated that the procedure is coherent with the multi-level approach. In fact, the PLL has been reduced from 0.5348 (level 1) to 0.3651 (level 2.1).

The PLL Level 1 procedure appears conservative, while it seems to be more robust than PLL calculated by EMSA3 Risk Model, as the fast/slow sinking node has not been used in the FLARE procedure.

The Dynamic analysis in level 2 leaded to a reduction of the PLL by about 32% with the simulation of 500 breaches. Such reduction of the PLL is essentially based on the fact that about 62% of cases have been found to survive in the dynamic analysis while they had sfac = 0 in the static analysis.

Furthermore, a sensitivity analysis demonstrated that the impact on the PLL level 2.1 by even a large deviation of the fatality rate (calculated with the simplified formula) is negligible.

The flooding simulations showed that 99% of the capsizes were fast capsize cases (TTC < 30 min) and a mere 1% were discovered slow capsize cases (TTC > 30 min). This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model for which 50% fast capsize rate was used.

ANNEX 8 – Calculation of the flooding Risk for Ship n.7

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

Duration: 36 months - Project Start: 01/06/2019 - Project End: 31/05/2022

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a large cruise ferry design. As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1). The refined model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

1 STATIC ASSESSMENT

1.1 Main data

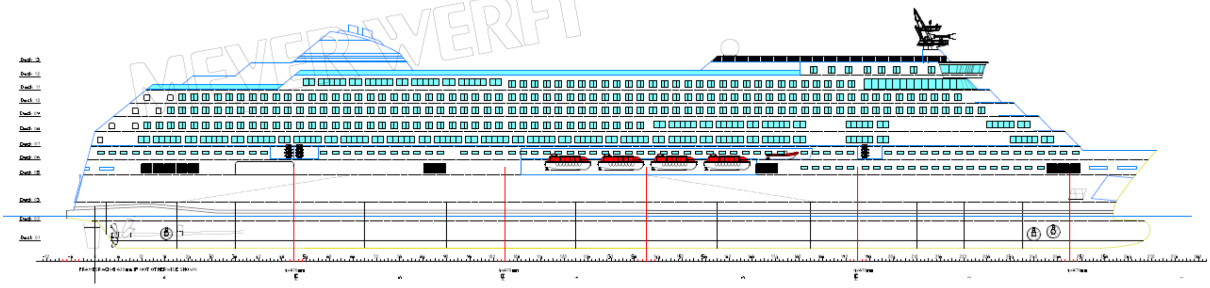


Figure 1 Profile view – Ship #7

Ship #7 is a large modern cruise ferry with a roro deck for trucks and trailers, a large lower hold for cars and an additional car deck within the super structure, designed as an overnight ferry. Here following the main characteristics:

Table 1 Main characteristics – Ship #7

Length over all	Approx. 229 m
Length between perpendiculars	214.32 m
Subdivision length	227.97 m
Breadth	33.2 m
Subdivision draught	6.7 m
Height of bulkhead deck	9.7 m
Number of passengers	3300
Number of crew	200
Gross tonnage	70000 GT
Deadweight	6900 t
No of cabins	1000
Lanemeter	1500
No of cars	1000
Service speed	21.5 knots

The business model and detailed description of the vessel are included in deliverable D.2.1.5.

Here following the Attained and Required Index according to SOLAS 2020 ch.II-1:

Number of persons	POB = 3496
Required subdivision index	R = 0.881
Attained subdivision index	A = 0.89475

1.2 Static calculations with new draughts and permeabilities

The following diagram is showing the draughts and the calculated GM for this vessel based on Ch. 3.1 of the main report.

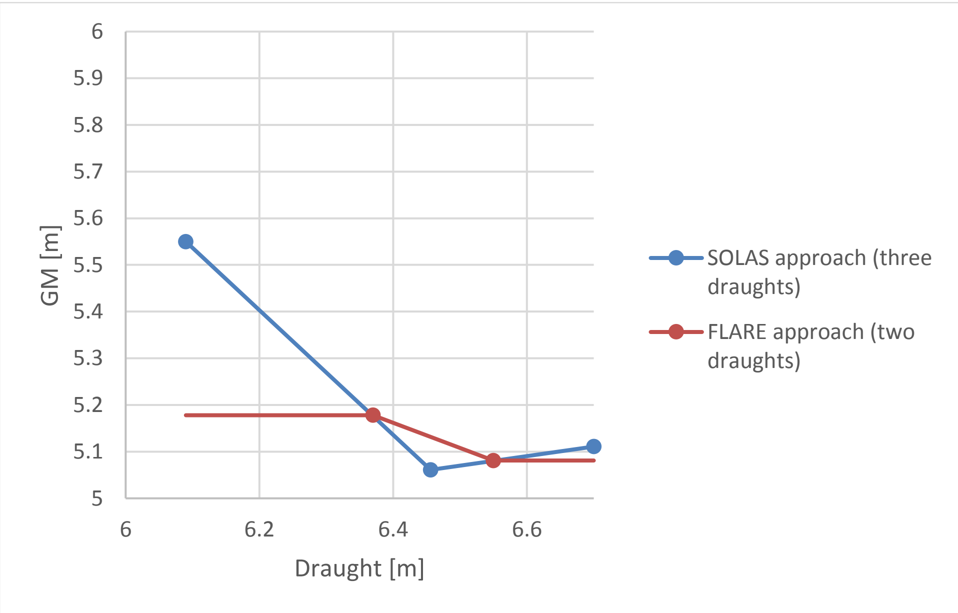


Figure 2 GM limiting curve with new FLARE draughts – Ship #7

The calculation has been executed with the software NAPA rel.2020.2-1, using the NEI approach for A-Class bulkheads and generating damages up to 5 adjacent zones.

These observations led to an attained index A = 0.8609 (with reference to the SOLAS A index -3.9%). The reason for this significant drop in index can be assumed to be the selection of GM values, as the rather high GM for the lightest service draught according SOLAS is not considered anymore.

Table 2 Static results with new draughts and permeabilities acc. to FLARE – Ship #7

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	6.37	5.178	0.8772	0.25	0.2193	0.8609
T0.75	6.55	5.081	0.8446	0.25	0.2112	

1.3 Non-zonal static analysis

With the refined model according to the FLARE modelling guidelines (Annex 1) an increase of number of rooms and connections has been generated (see Table 3).

Table 3 Comparison between simplified model and refined model – Ship #7

Description	Before modelling	After modelling
Damhull volume	90163 m^3	90163 m^3
Rooms number	118	119
Connections number	53	58

For this ships the U-shaped void spaces within the DB were already subdivided in the CL with cross-flooding opening defined, hence there was no change for these void spaces in the new model.

The updated model includes new direct connections between cabin areas and corridors (for B-class boundaries) and between the parts of U-shaped voids above the double bottom. Moreover, new smaller A-class spaces that would impact the flooding have been modelled and provided with A-class connections accordingly.

The subdivision table is also affected by minor changes in order to consider also the damage cases that involve new rooms.

However, considering the refined model and using NAPA, a slightly different value for the Attained Index (+4.2%) resulted.

Table 4 Static results with refined model – Ship #7

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	6.37	5.178	0.90589	0.25	0.2265	0.89734
T0.75	6.55	5.081	0.88879	0.25	0.2222	

1.3.1 Non-damage area

In the reference subdivision table, used for the zonal calculation, a “NON-DAMAGE AREA” was defined in the central part of the ship. This is used to route pipes generating progressive flooding that may not be controlled by remote control valves

Since the non-zonal analysis does not take into account the subdivision table, it is very important to define a virtual room to simulate that “NON-DAMAGE AREA”.

That room is assumed having a permeability equal to zero and an unprotected opening in connection with the DAMHULL room in its lowest point at frame #18 has been defined too. The purpose of this definition is to make sure that every time a breach from collision or side/bottom grounding involves the “NON-DAMAGE AREA”, such opening should be considered relevant by the used NAPA software and therefore the Sfac is set to zero.

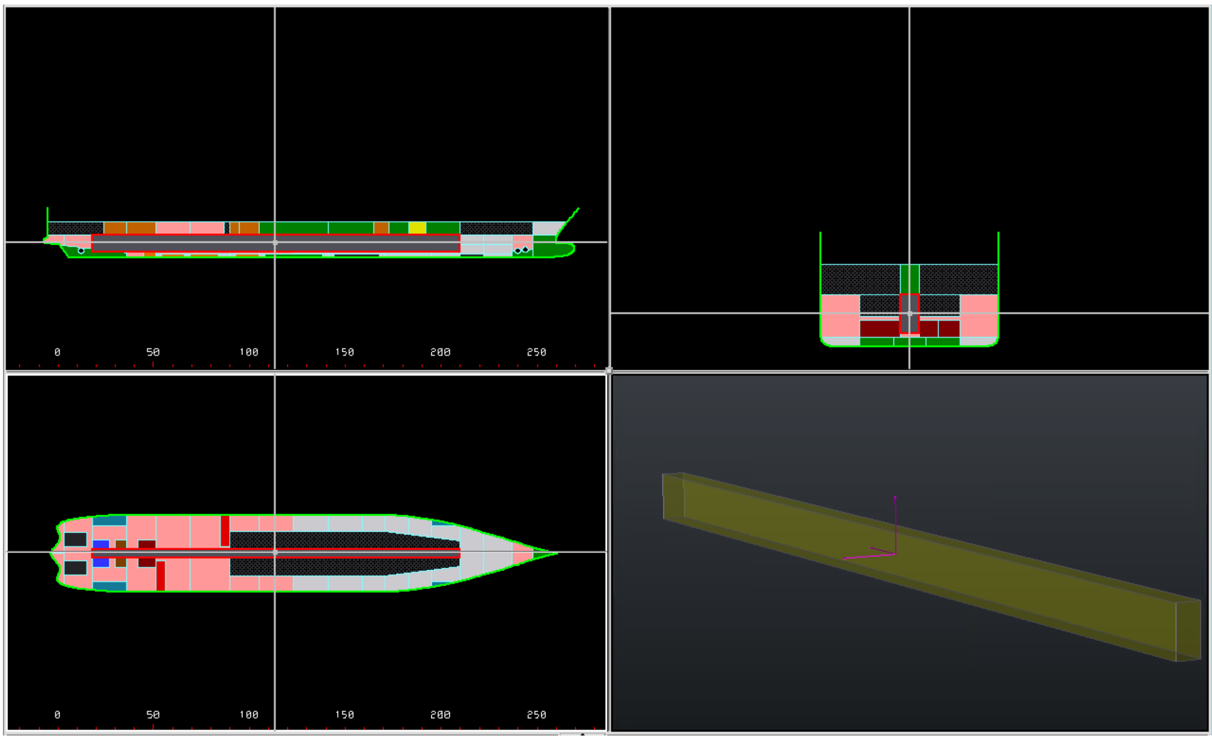


Figure 3 Defined room for NON-DAMAGE AREA in the non-zonal approach by NAPA – Ship #7

1.4 Calculation of PLL level 1

For this vessel breaches for collision, side and bottom grounding have been generated according to Ch. 3.2 of the main report and the grouping of breaches, leading to the same sets of flooded rooms, permitted to reduce the damage cases to be calculated by abt. 77% for collision and bottom grounding, and by abt. 87% for side grounding.

With the results of the static calculation for the attained index in hand, the PLL level 1 was calculated according to procedure described in Ch.2.4-2.5 of the main report. In particular in the Table 5 the non-zonal results are showed and in Table 6 the PLL (Potential loss of life) calculation is reported.

Table 5 Non-zonal static analysis results – Ship #7

<table>
<tr><th>Damage Type</th><th colspan="2">Collision</th><th colspan="2">Side Grounding</th><th colspan="2">Bottom Grounding</th></tr>
<tr><td>Initial condition</td><td>T0.45</td><td>T0.75</td><td>T0.45</td><td>T0.75</td><td>T0.45</td><td>T0.75</td></tr>
<tr><td>Draught</td><td>6.37m</td><td>6.55m</td><td>6.37m</td><td>6.55m</td><td>6.37m</td><td>6.55m</td></tr>
<tr><td>Breaches</td><td>10000</td><td>10000</td><td>10000</td><td>10000</td><td>10000</td><td>10000</td></tr>
<tr><td>Number of Empty cases</td><td>12</td><td>8</td><td>79</td><td>87</td><td>171</td><td>133</td></tr>
<tr><td>Number of Unique damage cases</td><td>2235</td><td>2191</td><td>1336</td><td>1312</td><td>2309</td><td>2324</td></tr>
<tr><td>Partial Index</td><td>0.9205</td><td>0.9084</td><td>0.9770</td><td>0.9766</td><td>0.965</td><td>0.9663</td></tr>
<tr><td>Total Attained Subdivision Index A_i</td><td colspan="2">0.9144</td><td colspan="2">0.9768</td><td colspan="2">0.9656</td></tr>
</table>

Table 6 PLL level 1 – Ship #7

<table>
<tr><th>Damage Type</th><th colspan="2">Collision</th><th colspan="2">Side Grounding</th><th colspan="2">Bottom Grounding</th><th>TOTAL</th></tr>
<tr><td>Frequency (1/ship-year)</td><td colspan="2">1.68E-03</td><td colspan="2">1.42E-03</td><td colspan="2">1.23E-03</td><td>4.33E-03</td></tr>
<tr><td>Relative frequency</td><td colspan="2">0.388</td><td colspan="2">0.328</td><td colspan="2">0.284</td><td>1.000</td></tr>
<tr><td>Initial condition</td><td>T0.45</td><td>T0.75</td><td>T0.45</td><td>T0.75</td><td>T0.45</td><td>T0.75</td><td></td></tr>
<tr><td>Draught</td><td>6.37m</td><td>6.55m</td><td>6.37m</td><td>6.55m</td><td>6.37m</td><td>6.55m</td><td></td></tr>
<tr><td>Attained Index</td><td>0.9205</td><td>0.9084</td><td>0.9770</td><td>0.9766</td><td>0.9650</td><td>0.9663</td><td>0.9494</td></tr>
<tr><td>$\sum pfac$ (for cases with s=1)</td><td>0.8288</td><td>0.7898</td><td>0.9698</td><td>0.9678</td><td>0.9650</td><td>0.9663</td><td>0.9060</td></tr>
<tr><td>$\sum pfac \cdot (1 - sfac)$</td><td>0.0795</td><td>0.0916</td><td>0.0230</td><td>0.0234</td><td>0.0350</td><td>0.0337</td><td>0.0506</td></tr>
<tr><td rowspan="2">PLL level 1 (1/ship year)</td><td>1.87E-01</td><td>2.15E-01</td><td>4.57E-02</td><td>4.66E-02</td><td>6.03E-02</td><td>5.81E-02</td><td rowspan="2">0.6132</td></tr>
<tr><td colspan="2">0.4025</td><td colspan="2">0.0923</td><td colspan="2">0.1184</td></tr>
</table>

Even if the PLL is the parameter to be used for the risk measurement in Table 6 the Combined Attained Index is showed too for information only. That value is calculated by using the relative frequency for collision, Side grounding and Bottom Grounding.

1.5 Filtering of static results and selecting cases for dynamic simulations

The screening of the static result according to filtering criteria identified within Ch. 3.4 of the main report permitted to select 500 cases for the dynamic simulations. In the following table a summary of the filtered breaches is reported.

Table 7 Filtering results – Ship #7

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Initial condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	6.37m	6.55m	6.37m	6.55m	6.37m	6.55m	
Number of filtered damage cases	175	239	19	67	0	0	500
$\sum pfac$ (for the filtered damage cases)	0.0367	0.0539	0.0041	0.0091	0.0000	0.0000	0.0198
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0260	0.0395	0.0040	0.0089	0.0000	0.0000	0.0148
Potential PLL (if the ships would not capsize for all selected cases)	1.26E-01	1.22E-01	3.77E-02	2.89E-02	6.03E-02	5.81E-02	0.4335
	0.2485		0.0666		0.1184		
Potential PLL reduction (if the ships would not capsize for all selected cases)	38.3%		27.8%		0.0%		29.3%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. In particular for this ship the PLL would be reduced by about 29% if all the cases to be simulated are not capsizing.

In the following diagrams some typical damage parameters of the selected breaches are presented in non-dimensional form.

It is very interesting to note that for collision there are two vulnerable areas, the engine room damages and breaches leading to flooding of the large lower hold, while the majority of selected breaches for side grounding has a huge length therefore they affect a high number of compartments.

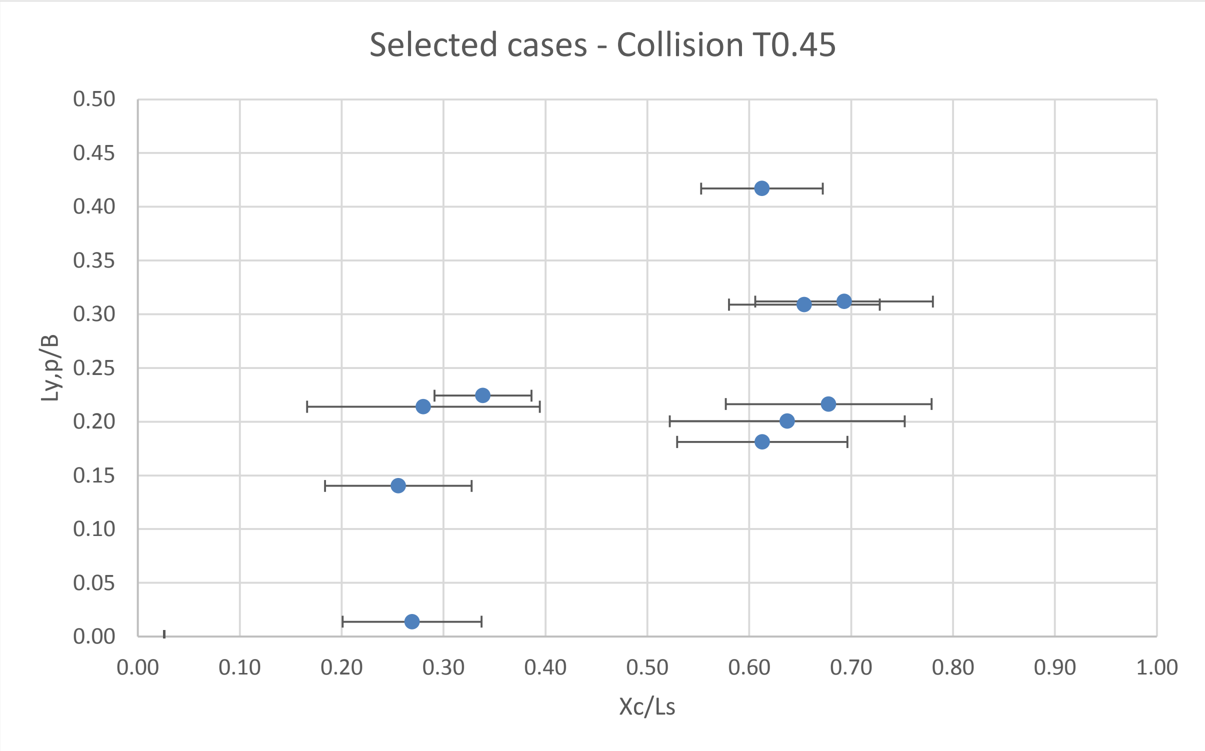


Figure 4 Selected collision breaches T0.45 – Ship #7

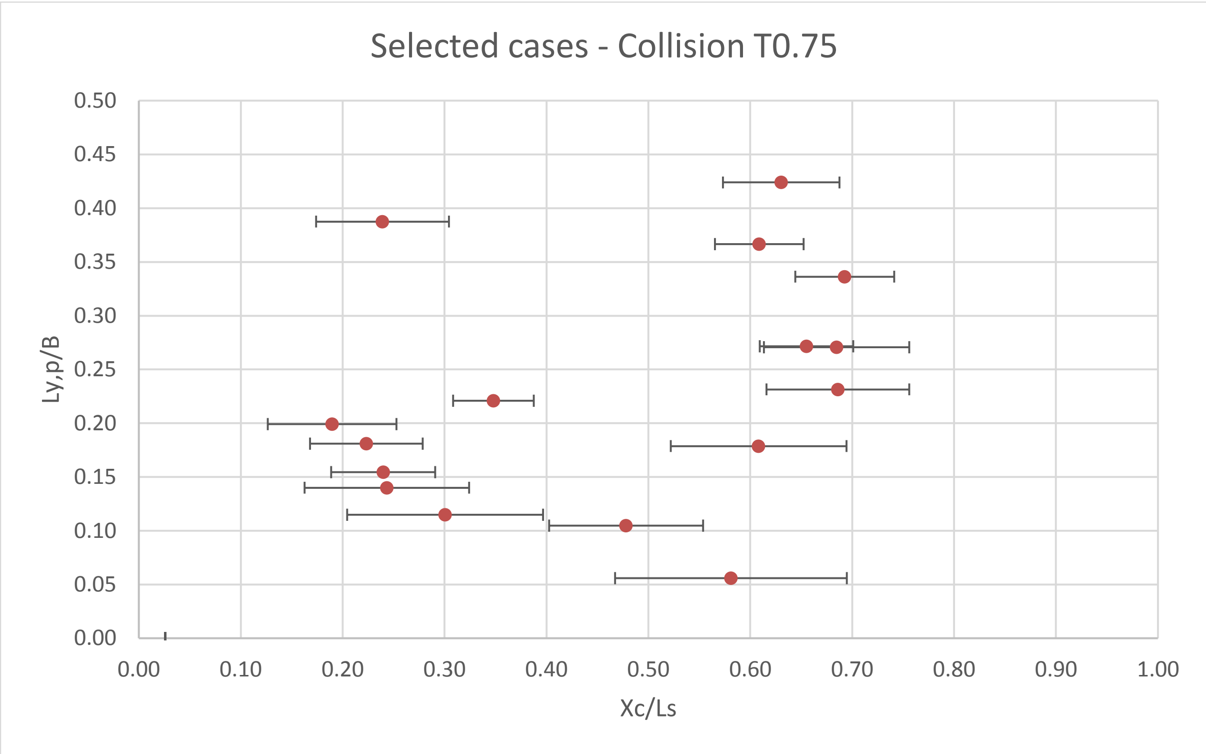


Figure 5 Selected collision breaches T0.75 – Ship #7

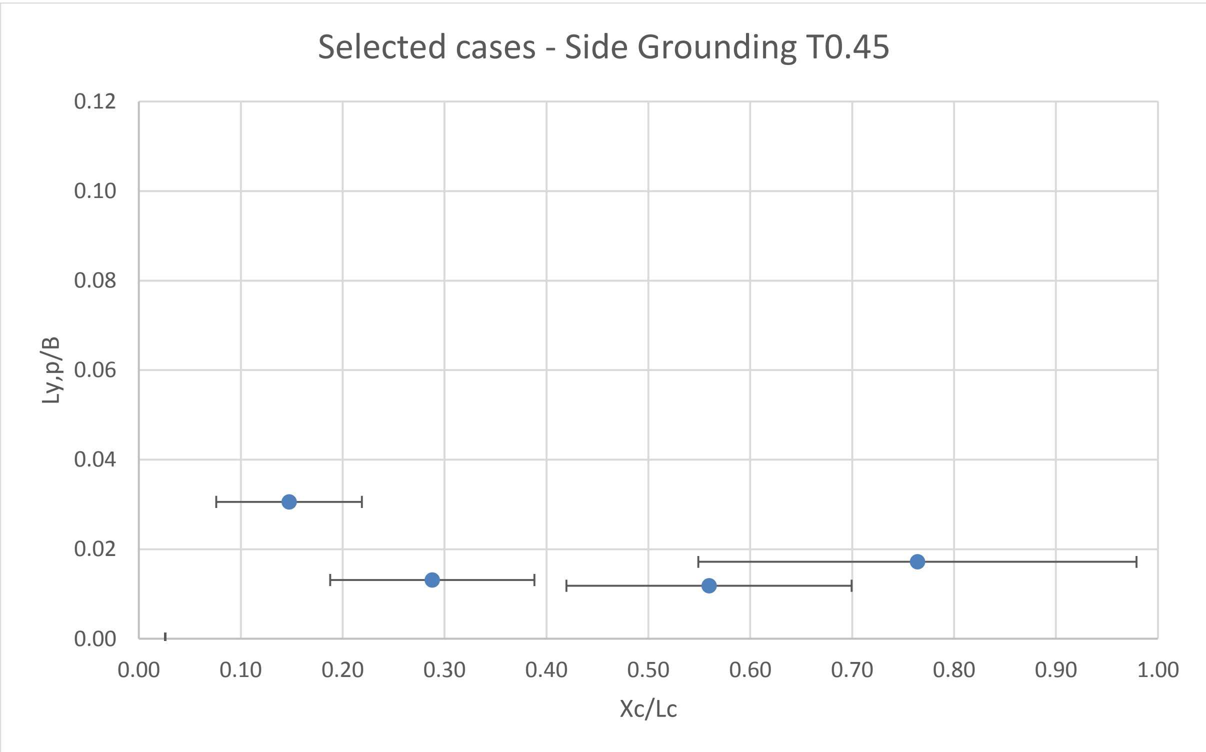


Figure 6 Selected side grounding breaches T0.45 – Ship #7

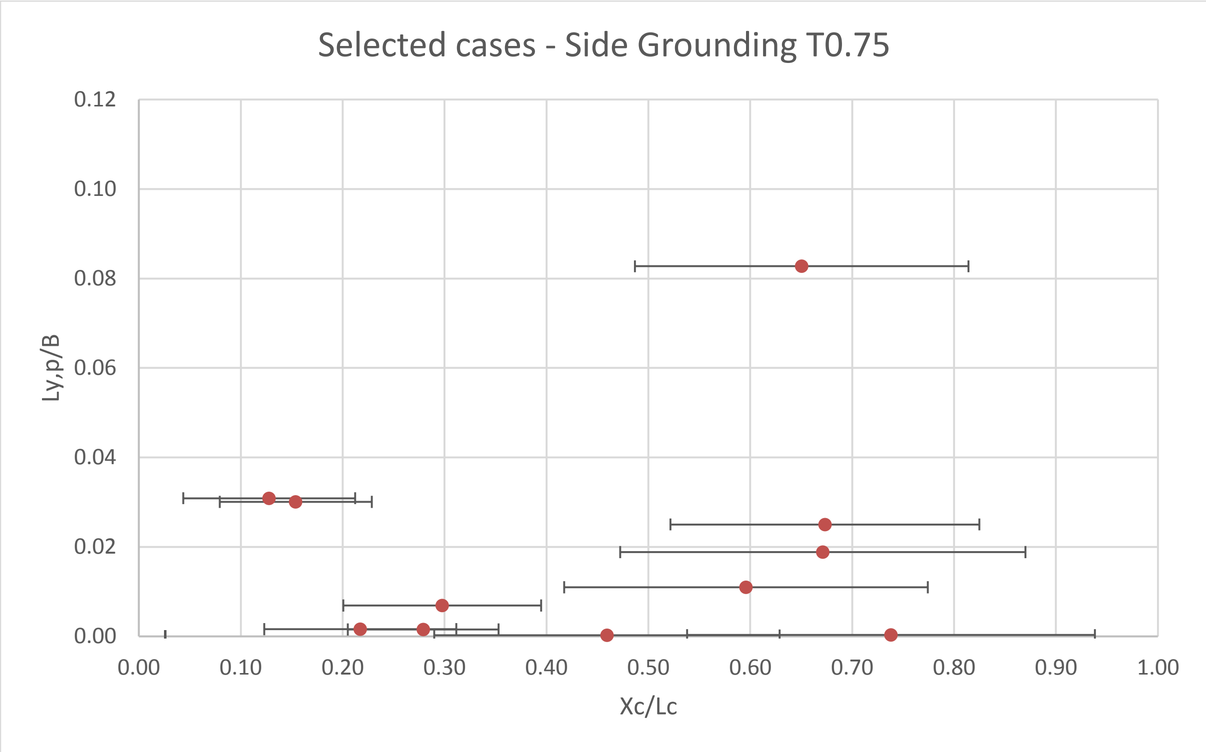


Figure 7 Selected side grounding breaches T0.75 – Ship #7

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with Sfac = 0 and failure modes for cases with 0 < Sfac < 1, are showed in the following tables.

Table 8 Breakdown of failure mode for Sfac=0 cases – Ship #7

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Initial condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	156	205	17	65	0	0	443
Heeling Angle (>15 deg)	0	0	0	0	0	0	0
Smom=0	2	6	0	0	0	0	8
Opening immersion	0	0	0	0	0	0	0
Sfac=0 - Total cases	**158**	**211**	**17**	**65**	**0**	**0**	**451**

Table 9 Breakdown of failure mode for 0<Sfac<1 cases – Ship #7

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Initial condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	0	0	0	0	0	0	0
Insufficient Range	4	5	0	0	0	0	9
Heeling Angle (>7 deg)	0	0	0	0	0	0	0
Insufficient Restoration (GZmax) + Range	13	23	2	2	0	0	40
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	0
Insufficient Range + Excessive Heel	0	0	0	0	0	0	0
Insufficient Restoration (GZmax) + Range + Excessive Heel	0	0	0	0	0	0	0
0<Sfac<1 - Total cases	**17**	**28**	**2**	**2**	**0**	**0**	**49**

A large percentage of captured cases resulted into Sfac = 0 (451 cases over 500) but none of the captured cases had a failure mode corresponding to a heeling angle greater than 15 deg.

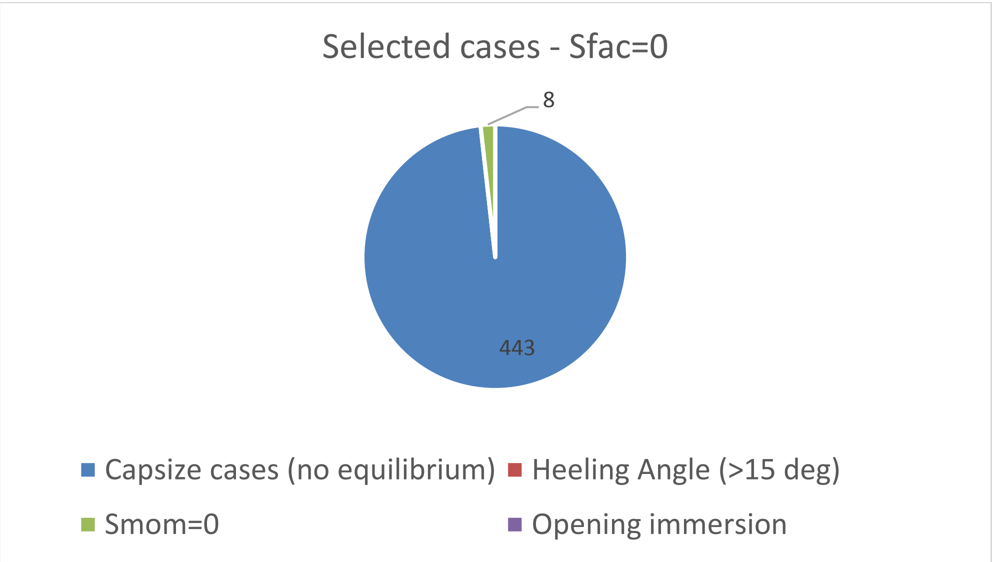


Figure 8 Diagram of failure mode for Sfac = 0 cases – Ship #7

Only 8 damage cases with Smom = 0 have been found too while the equilibrium was not reached in the static calculation for 443 cases.

In the majority of the cases where equilibrium was not achieved the failure was found at the first stage of flooding when the cross-flooding is not started yet. That stage is not used to calculate the survivability factor s but it is requested by the explanatory notes of SOLAS Ch.II-1 that a positive GZ is achieved at that stage in order to calculate the cross-flooding time. It will be very important to assess those cases by dynamic simulations so that the real physics of the phenomenon will be investigated.

Finally, 0 cases have been identified due to the immersion of openings. These cases are very important to be selected too as it is expected that the outcome of the dynamic simulation should be quite different. In fact, the approach for connections and openings definition is completely different between static and dynamic calculation.

A limited number of damage cases with 0 < Sfac < 1 has been selected and the majority of these cases resulted in an insufficient GZmax and excessive Range, then eight cases resulted in an insufficient Range and excessive heeling angle too.

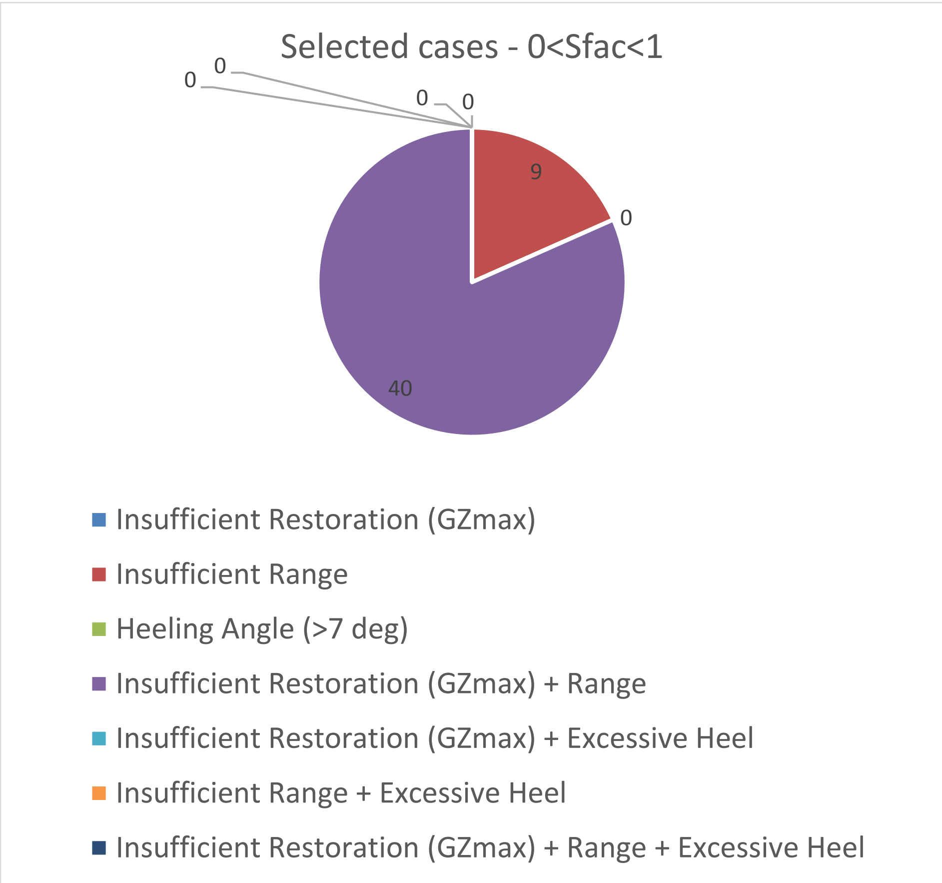


Figure 9 Diagram of failure mode for 0 < Sfac < 1 cases – Ship #7

2 DYNAMIC ASSESSMENT

2.1 Preparation of the PROTEUS model

The dynamic analysis has been carried out by use of the software *PROTEUS* (last release distributed in November 2021). In particular for the preparation of the model the tool Proteus Manager has been used.

To generate in the Proteus Manager the loading conditions defined in NAPA and corresponding to the two calculation draughts at 45% and 75%, the following ship weights have been generated:

T_1 = 6.37 m → LIG_1 [Δ=30,564 t ; CG (98.47 , 0 , 15.43) m]

T_2 = 6.55 m → LIG_2 [Δ=31,709 t ; CG (98.27 , 0 , 15.24) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at five different deck slices:

DB =1.69 m ; D1 =1.71 m ; D2 =6.71 m ; D3 =9.71 m ; D4 =12.61 m

For this roro passenger ship a total of 53 openings have been defined. Horizontal openings have been defined on the higher deck of the model to capture the down-flooding through engine casings, stair trunks, vertical escape and lifts.

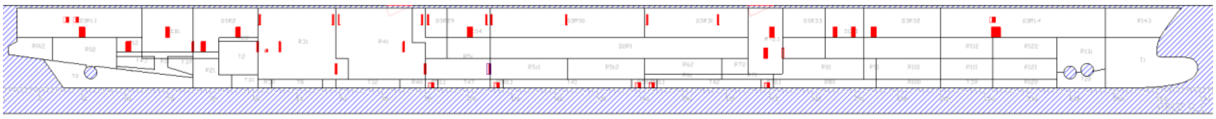


Figure 10 – Openings imported in Proteus Project (longitudinal section)– Ship #7

Table 10 Opening Types in Proteus Manager

	Leak Area Rat	Leak Area Rat	Collapse Pressu	Collapse Pressu	Leak Heigh	Gap Heigh	Effective Heigl	Open At Tir	Close At Tim
TYPE	1 to 2	2 to 1	1 to 2 [meters]	2 to 1 [meters]	[meters]	[meters]	HEff Switch	[seconds]	[seconds]
CONNECTION	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
B-CLASS-JOINER	0.00000	0.00000	1.50	1.50	0.000	0.000	False	0	999999
FDOOR-A-HINGED	0.00000	0.00000	2.50	2.50	0.000	0.000	False	0	999999
FDOOR-A-SLIDING	0.00000	0.00000	1.00	1.00	0.000	0.000	False	0	999999
FDOOR-A-DOUBLELEAF	0.00000	0.00000	2.00	2.00	0.000	0.000	False	0	999999
COLDROOM-DOOR	0.00000	0.00000	3.50	3.50	0.000	0.000	False	0	999999
LIFT-DOOR	0.00000	0.00000	1.50	1.50	0.000	0.000	False	0	999999
SWT-DOOR	0.00000	0.00000	10.00	10.00	8.000	0.000	False	0	999999
WT-DOOR	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
WT-DOOR_LBHD	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
SHELL-DOOR_LARGE	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999
SHELL-DOOR_NORMAL	0.00000	0.00000	100.00	100.00	99.000	0.000	False	0	999999

Since in Proteus the discharge coefficient for the holes is set to 0.6 and it may be not changed, the area of the cross-flooding openings has been reduced in order to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation sets have been created and the comparison of the geometric and hydrostatic data between NAPA and Proteus showed that the differences are negligible in general (from Figure 11 to Figure 17 and Table 11).

To be noted that the ship was originally defined with left-handed coordinate system in NAPA but then it has been changed into right-handed when the model has been imported in Proteus. This generated some false warning when checking the tolerance in the differences for trim and TCG between NAPA and Proteus.

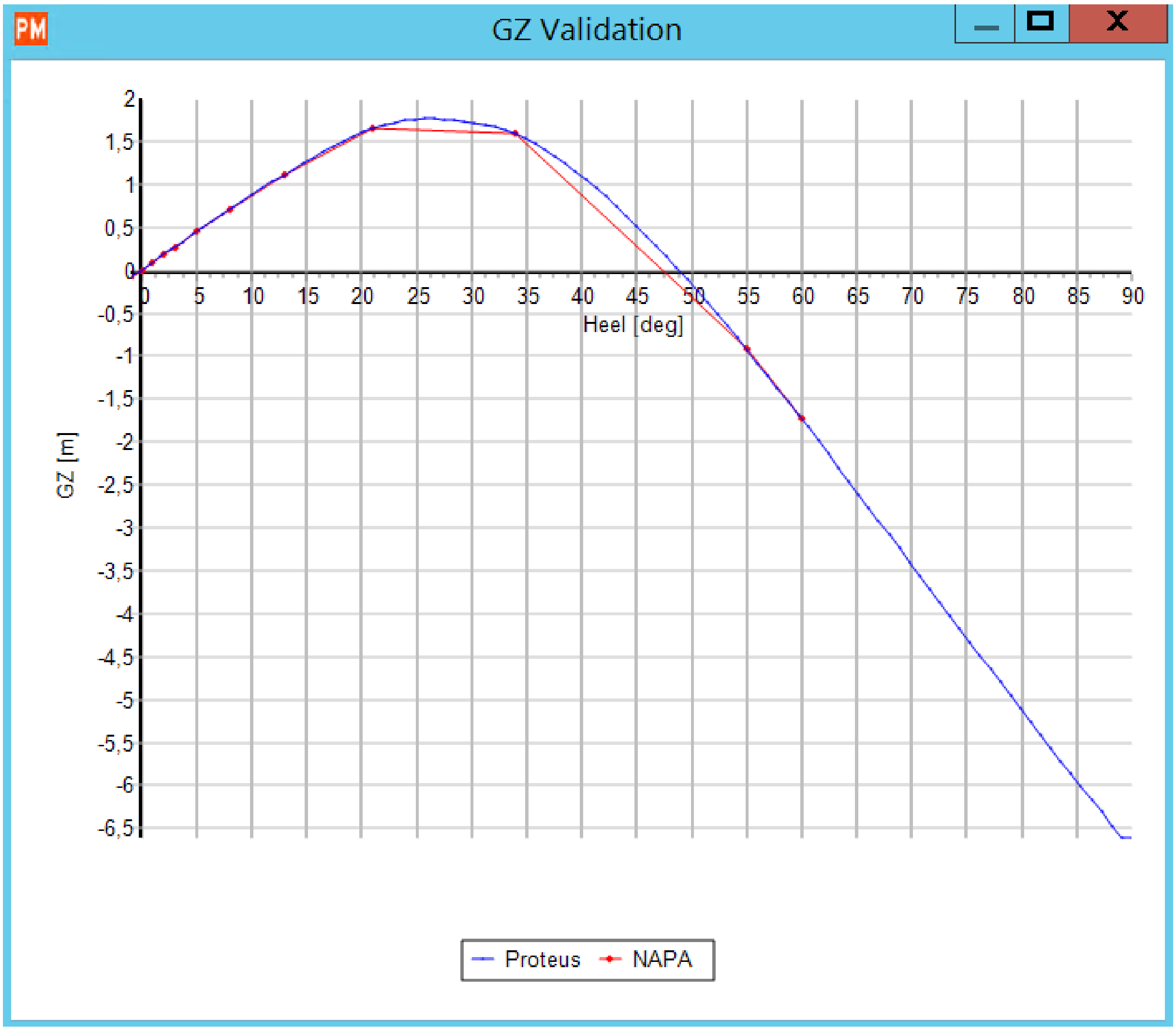


Figure 11 – GZ comparison between NAPA and Proteus – Ship #7

Table 11– Floating Position comparison between NAPA and Proteus – Ship #7

Loadcase Validation

GZ Curve | Floating Position | Volume and CGs | Section Areas

Floating Position

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	6.370	6.373	-0.003	-0.047
TA [m]	6.370	6.373	-0.003	-0.047
TF [m]	6.370	6.373	-0.003	-0.047
Trim [deg]	0.000	0.000	0.000	0.000
Heel [deg]	0.000	0.000	0.000	0.000
KM [m]	20.607	20.720	-0.113	-0.548
KG [m]	15.432	15.430	0.002	0.013
GM0 [m]	5.175	5.288	-0.113	-2.184
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	5.175	5.288	-0.113	-2.184

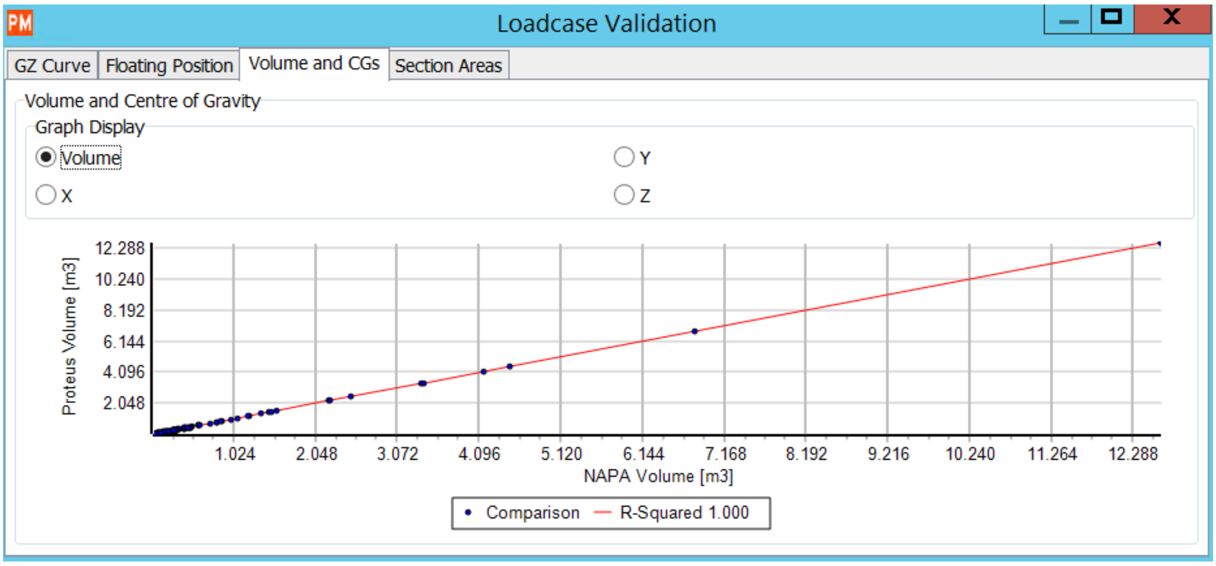


Figure 12 – Hull volume comparison between NAPA and Proteus – Ship #7

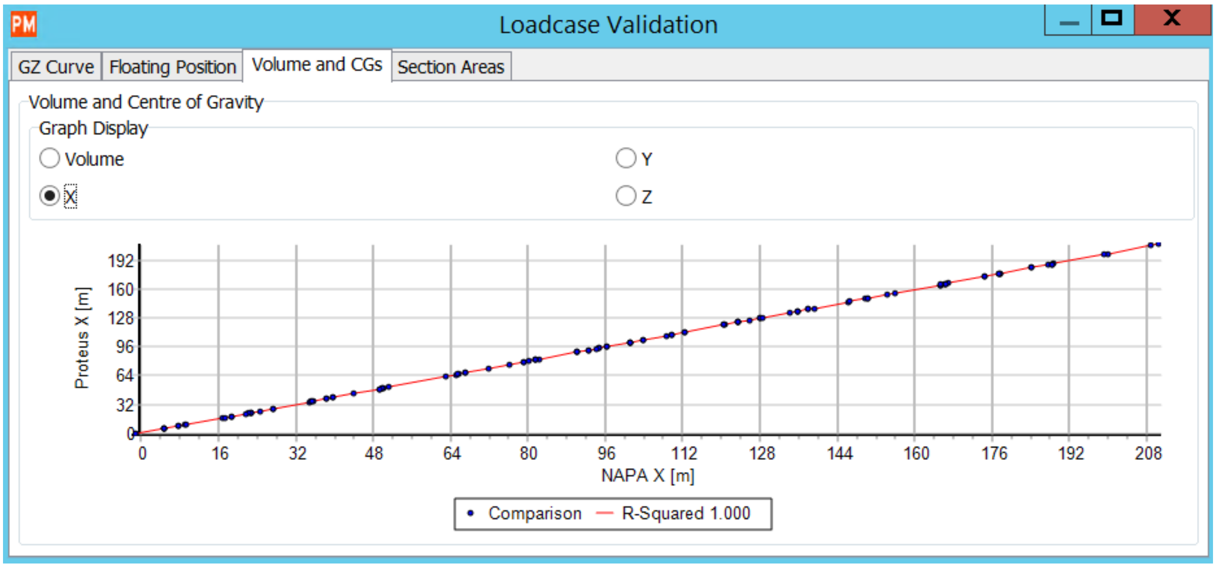


Figure 13 – Hull LCB comparison between NAPA and Proteus – Ship #7

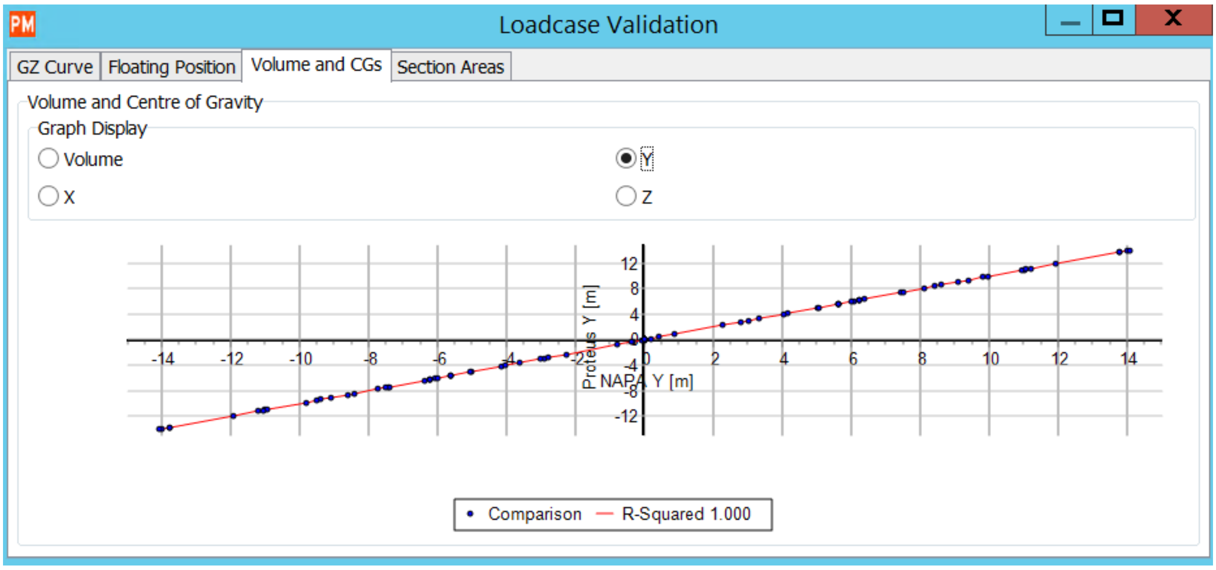


Figure 14 – Hull TCB comparison between NAPA and Proteus – Ship #7

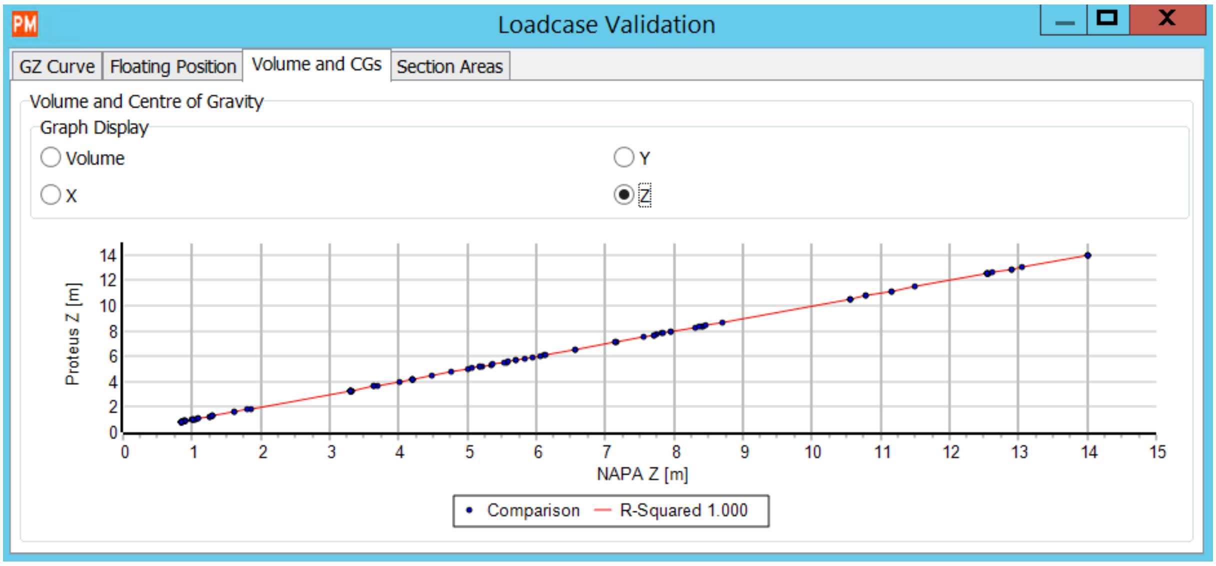


Figure 15 – Hull VCB comparison between NAPA and Proteus – Ship #7

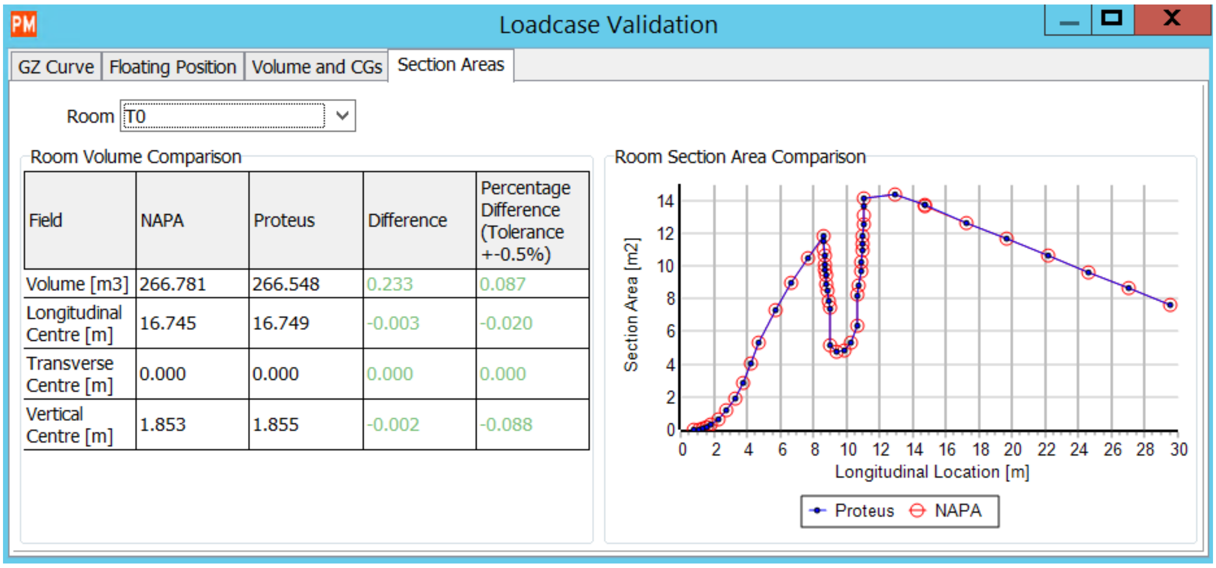
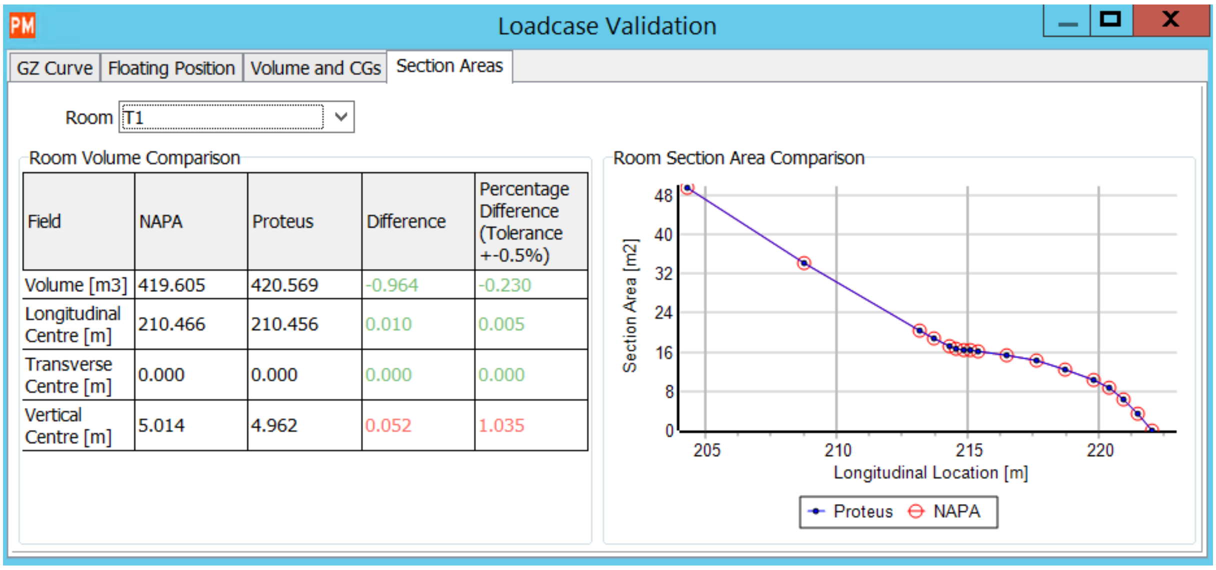


Figure 16 – Aftpeak comparison between NAPA and Proteus – Ship #7



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	419.605	420.569	-0.964	-0.230
Longitudinal Centre [m]	210.466	210.456	0.010	0.005
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	5.014	4.962	0.052	1.035

Figure 17 – Forepeak comparison between NAPA and Proteus – Ship #7

2.2 Results of dynamic simulations

In the first round of simulations all the 500 breaches have been simulated up to 30 minutes, then for 26 breaches a second simulation round has been executed up to 60 minutes, as these were found with progressive flooding still occurring at the end of first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1 = capsize 0 = not capsize) and TTC for cases where a capsize was found. In the following graphs the results for each hazard and the global results of simulations are presented.

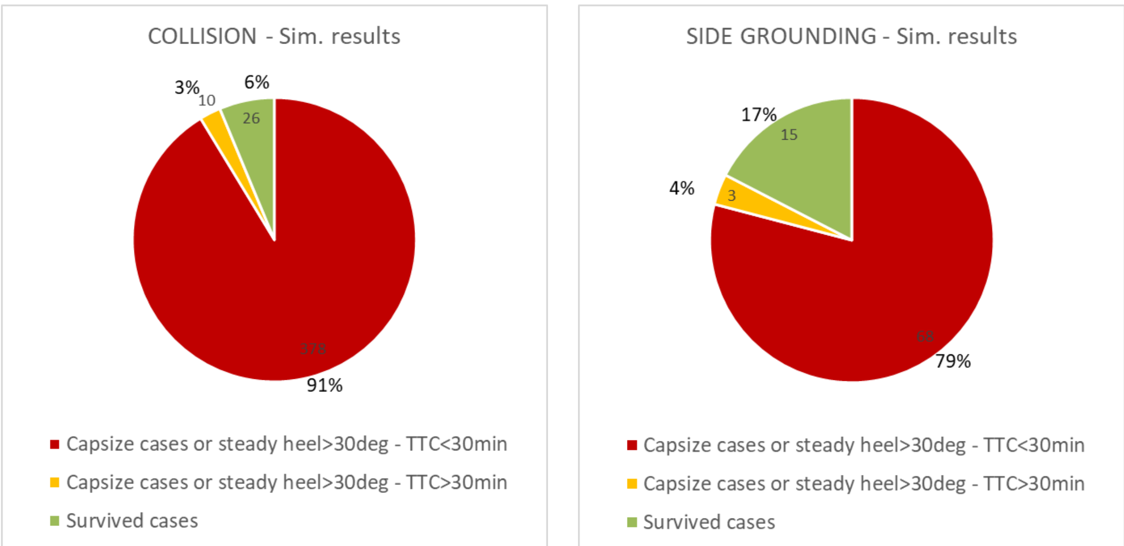


Figure 18 – Simulation results for collision and side grounding – Ship #7

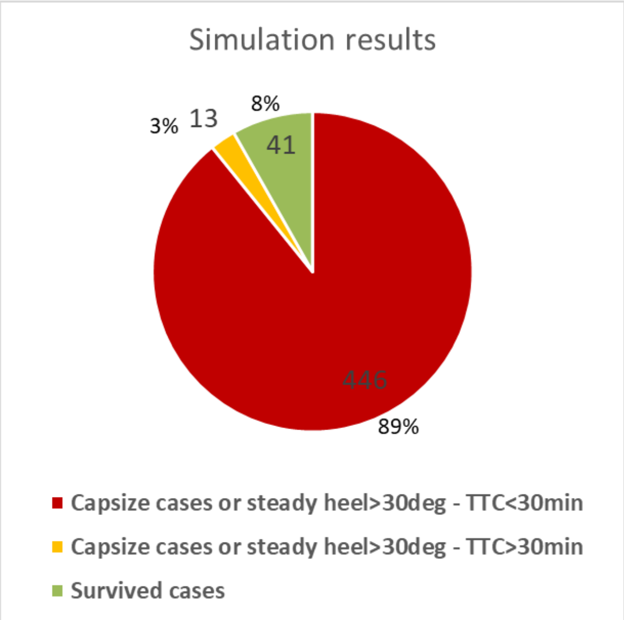


Figure 19 – Global simulation results for the 500 filtered breaches – Ship #7

The results obtained clearly show that there is a minority of cases which did not results in the capsize of the ship.

Furthermore it is equally clear that a great majority of the capsize cases (89%) are to be considered fast capsize as the TTC is less than 30 minutes therefore there is no sufficient time to evacuate persons in such cases.

2.3 Calculation of PLL level 2.1

The results of the flooding simulations permit to get the TTC too, therefore the fatality rate may be estimated for the cases with TTC > 30min according to the procedure for calculation of Risk (Level 2.1).

Table 12 PLL level 2.1 – Ship #7

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Initial condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	6.37	6.55	6.37	6.55	6.37	6.55	
PLL L1 (1/ship year) (static assessment)	**1.87E-01**	**2.15E-01**	**4.57E-02**	**4.66E-02**	**6.03E-02**	**5.81E-02**	**0.6132**
	0.4025		**0.0923**		**0.1184**		
Number of filtered damage cases	175	239	19	67	0	0	500
Capsize cases or steady heel>30deg - TTC<30min	161	217	13	55	0	0	446
Capsize cases or steady heel>30deg - TTC>30min	4	6	2	1	0	0	13
Survived cases	10	16	4	11	0	0	41
PLL L2.1 (1/ship year) (dynamic assessment)	**1.88E-01**	**2.22E-01**	**4.32E-02**	**4.36E-02**	**6.03E-02**	**5.81E-02**	**0.6154**
	0.4102		**0.0868**		**0.1184**		
PLL L2.1 vs L1 (variation percentage)	**1.9%**		**-6.0%**		**0.0%**		**0.4%**

In the Table 12 the details of the results obtained are reported and it can be noted that the PLL has been slightly increased from 0.6132 (Level 1) to 0.6154 (Level 2.1).

In the following figures the diagrams of the breaches which lead to capsize after dynamic simulations are reported.

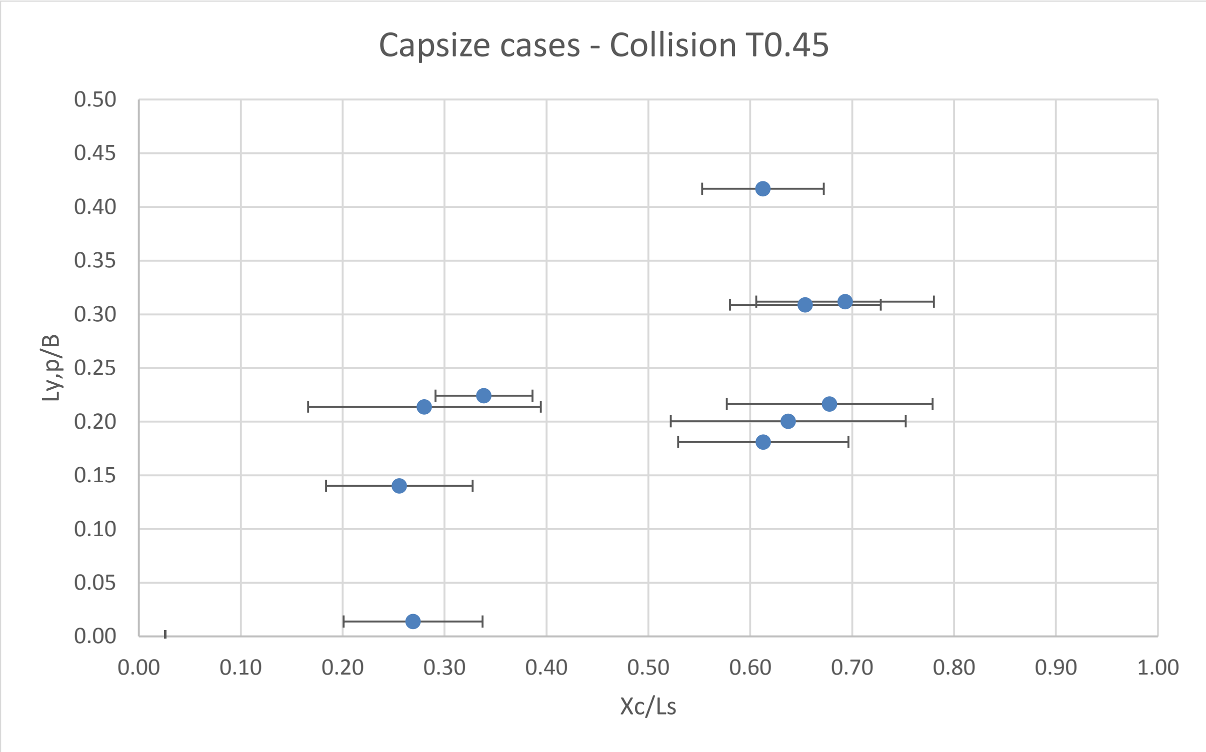


Figure 20 Collision leading to capsize T0.45 – Ship #7

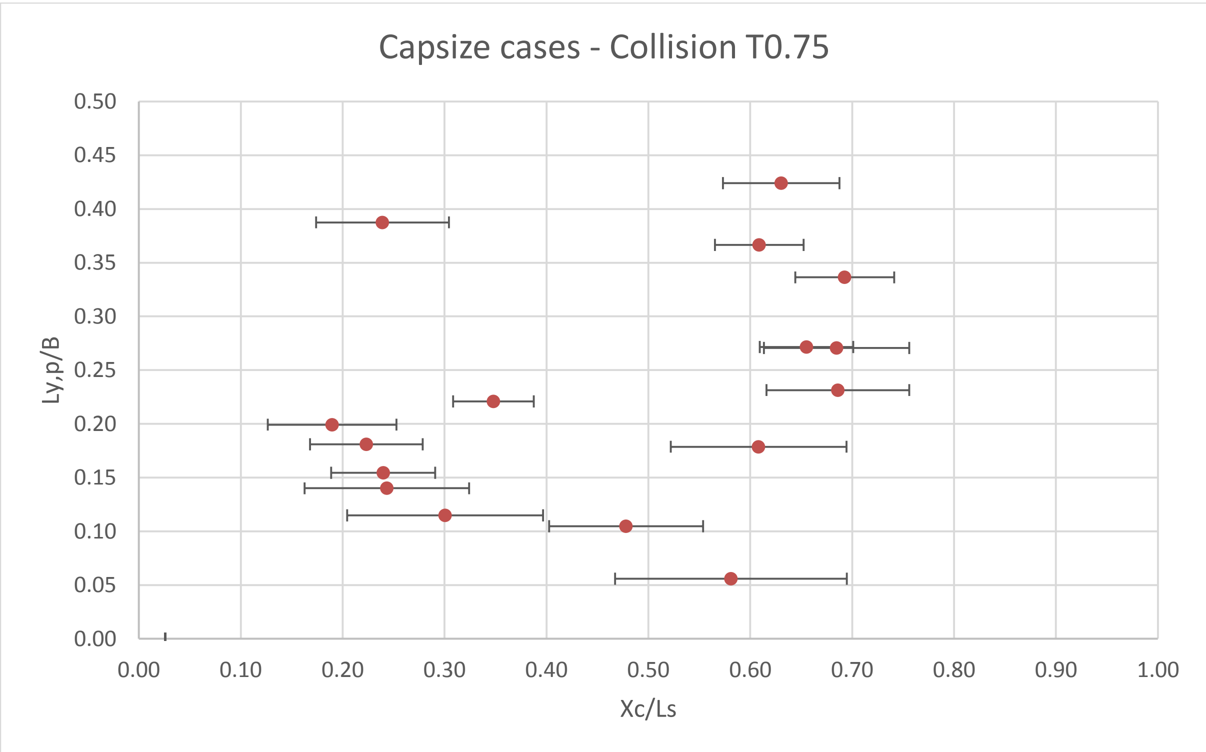


Figure 21 Collision leading to capsize T0.75 – Ship #7

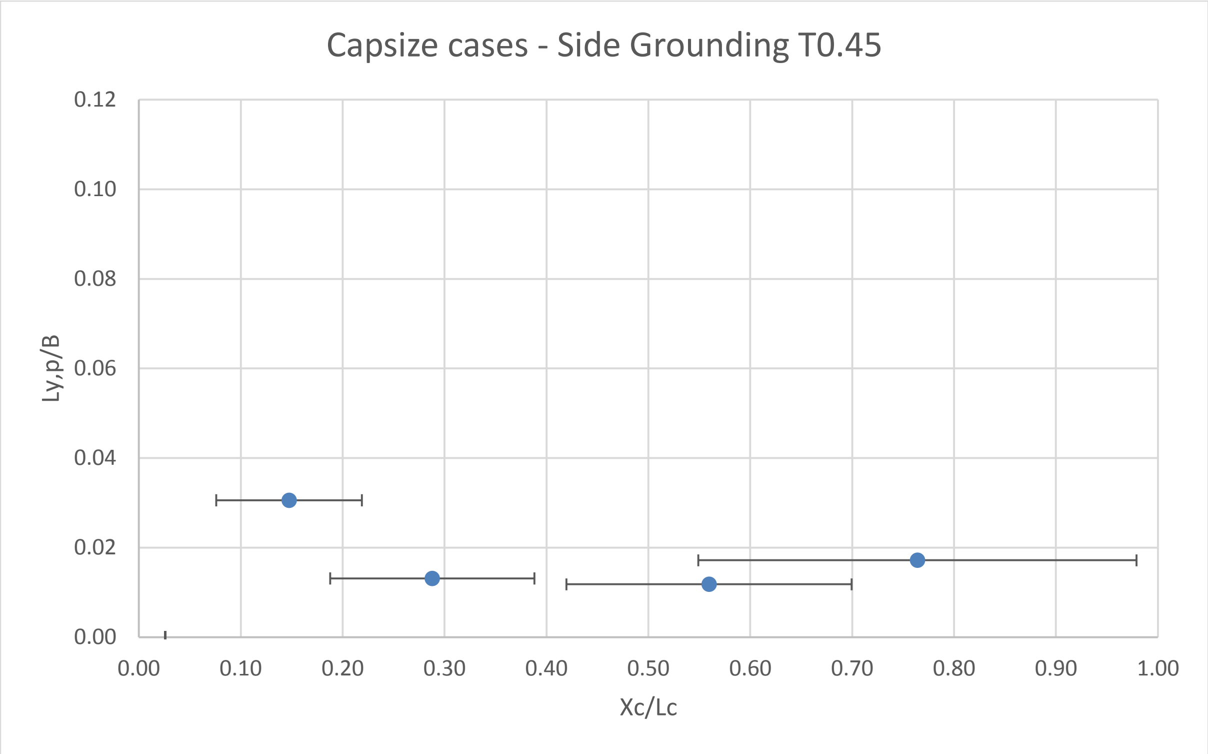


Figure 22 Side grounding breaches leading to capsize T0.45 – Ship #7

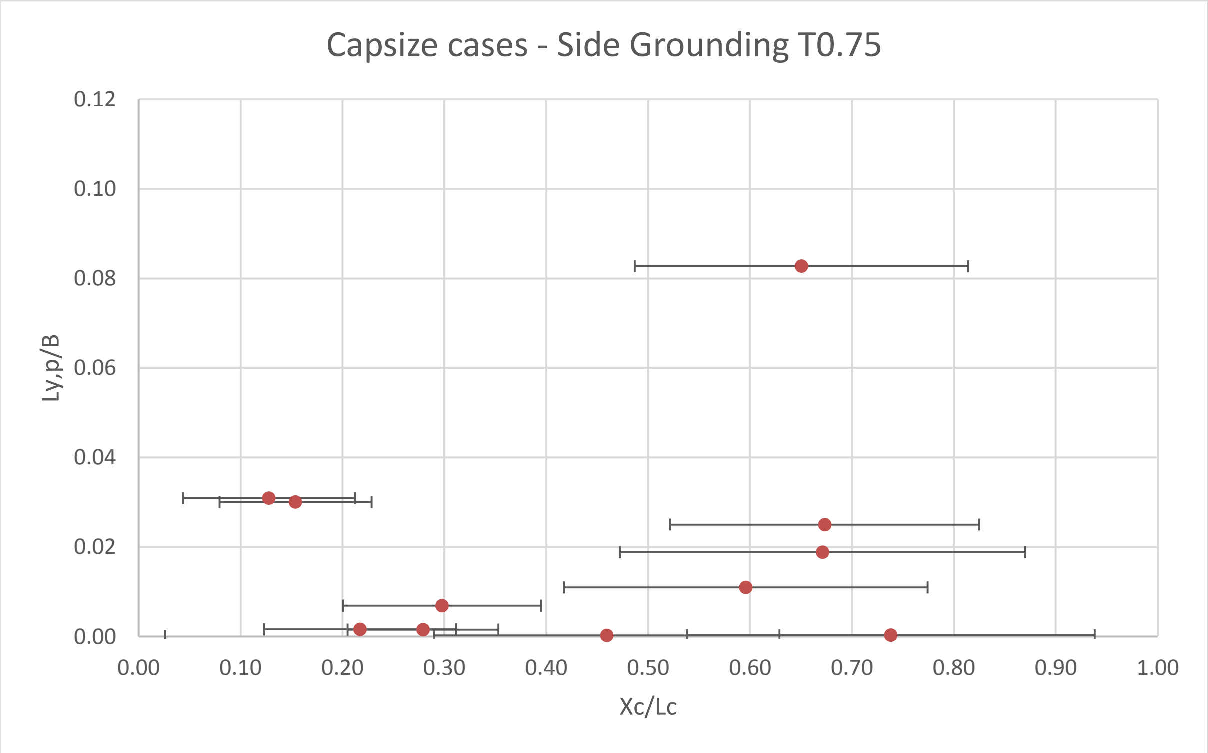


Figure 23 Side grounding breaches leading to capsize T0.75 – Ship #7

The cases showed from the Figure 20 to Figure 23 may be investigated in WP7.2 when Risk Control Options are to be implemented.

2.4 Sensitivity analysis of the fatality rate

With the aim to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out on the total 13 cases (with TTC > 30min or progressive flooding still occurring after 60 min). For such purpose, the impact on the PLL has been evaluated in case of variation of the fatality rate by ± 30% of the POB.

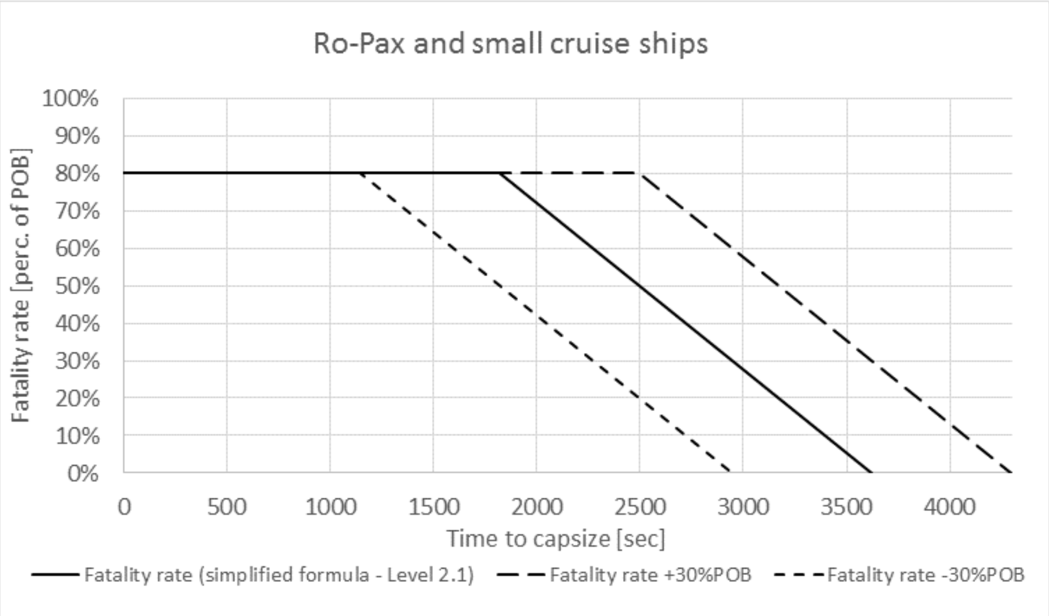


Figure 24 Sensitivity analysis of simplified formula for fatality rate calculation

The calculation with +30% in the fatality rate resulted into a PLL of 0.619 (+0.6% compared to the reference PLL) while the calculation with -30% for the fatality rate resulted into a PLL of 0.6151 (-0.1% compared to the reference PLL). These values demonstrated that for this ship the simplified formula to derive the fatality rate used in the calculation of risk (Level 2.1) has a low impact on the PLL, because PLL is mainly based, for this ship, by the scenarios leading to fast capsize.

3 CONCLUSIONS

The complete procedure for calculation of risk has been applied on Ship #7 and an insignificant variation has been observed for the PLL. In fact, the PLL has been slightly increased from 0.6132 (level 1) to 0.6154 (level 2.1)

The results obtained for this ship showed that the PLL Level 1 is more robust than PLL calculated by EMSA3 Risk Model as the fast/slow sinking node has not been used in the FLARE procedure.

Furthermore, a sensitivity analysis demonstrated that the impact on the PLL level 2.1 by even a large deviation of the fatality rate (calculated with the simplified formula) is negligible.

The flooding simulations showed a percentage of 97% of fast capsize cases (TTC < 30min) and 3% only for slow capsize cases (TTC > 30min). This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model for which 50% fast capsize rate was used.

For this ship the flooding simulations generate a change of next to 0% of the PLL but the results are consistent with static analysis. A great majority of the breaches, selected for the dynamic analysis were also capsize cases (no equilibrium) in the static analysis.

ANNEX 9 – Calculation of the flooding Risk for Ship n.8

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a medium Ro-Pax ship design. As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1). The refined model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

1 STATIC ASSESSMENT

1.1 Main data

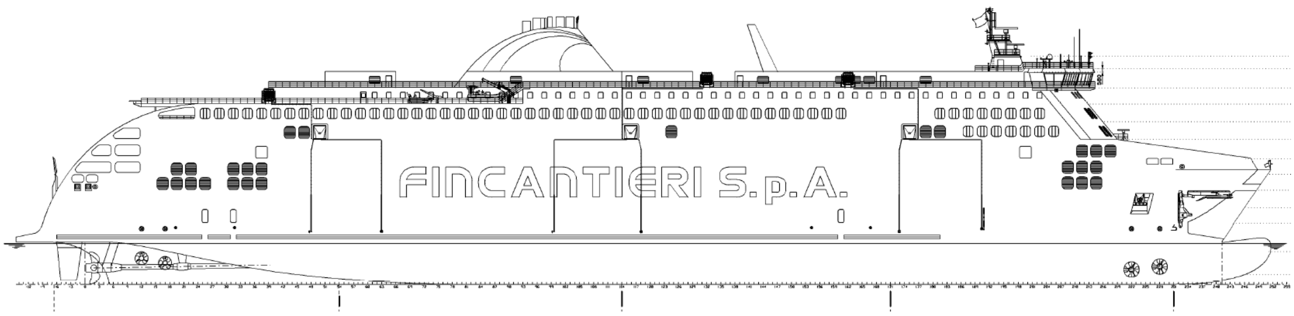


Figure 1 Profile view – Ship #8

Ship #8 is a RO-PAX for short international voyages with the following main characteristics:

Table 1 Main characteristics – Ship #8

Length over all	~213.6 m
Length between perpendiculars	195.4 m
Subdivision length	213.0 m
Breadth	31.5 m
Subdivision draught	7.10 m
Height of bulkhead deck	10.3 m
Number of passengers	2617
Number of crew	183
Gross tonnage	50000 GT
Deadweight	5300 t
No of pax cabins	145
No of cars	852
Trial speed	26.9 knots

The business model and detailed description of the vessel are included in deliverable D.2.1.8.

Here following the Attained and Required Index according to SOLAS 2020 ch.II-1:

Number of persons	POB = 2800
Required subdivision index	R = 0.87304
Attained subdivision index	A = 0.88248

1.2 Static calculations with new draughts and permeabilities

The following diagram is showing the draughts and the calculated GM for this vessel based on Ch. 3.1 of the main report.

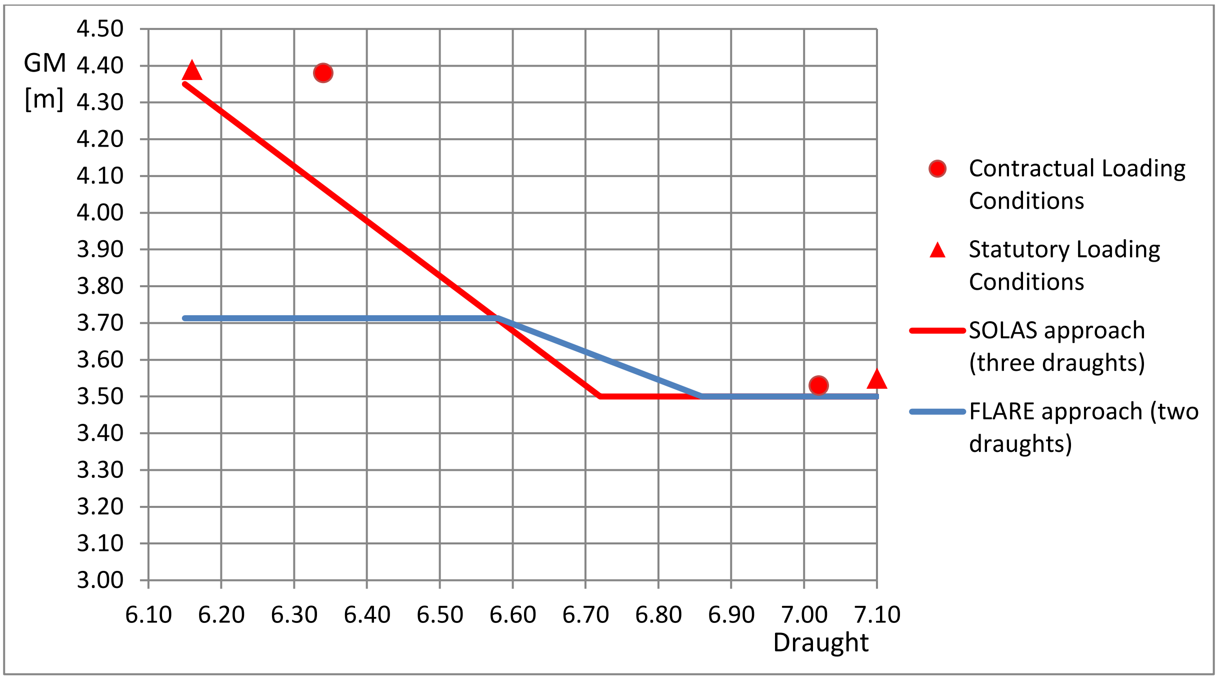


Figure 2 GM limiting curve with new FLARE draughts – Ship #8

The calculation has been executed with the software NAPA rel.2020.2, using the NEI approach for A-Class bulkheads and generating damages up to 5 adjacent zones.

These parameters led to an attained index A = 0.8897 (with reference to the SOLAS A index +0.8%).

Table 2 Static results with new draughts and permeabilities acc. to FLARE – Ship #8

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	6.58	3.713	0.9116	0.5	0.4558	0.8897
T0.75	6.86	3.500	0.8678	0.5	0.4339	

1.3 Non-zonal static analysis

With the refined model according to the FLARE modelling guidelines (Annex 1) an increased number of rooms and connections has been generated (see Table 3).

Table 3 Comparison between simplified model and refined model – Ship #8

Description	Before modelling	After modelling
Damhull volume	106,044 m^3	106,307 m^3
Rooms number	135	238
Connections number	45	277

For this ship the U-shaped void spaces within the DB were already subdivided in the CL with cross-flooding openings defined, hence there was no change for these void spaces in the new model.

The updated model includes new direct connections between cabin areas and corridors (for B-class boundaries) and between the parts of U-shaped voids above the double bottom. Moreover, new smaller A-class spaces that would impact the flooding have been modelled and provided with A-class connections accordingly.

However, considering the refined model and using NAPA, a slightly lower value for the Attained Index (-0.1%) was found.

Table 4 Static results with refined model – Ship #8

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	6.58	3.713	0.9082	0.5	0.4541	0.8892
T0.75	6.86	3.500	0.8702	0.5	0.4351	

1.3.1 Non-damage area

In the reference subdivision table, used for the zonal calculation, a "NON-DAMAGE AREA" was defined in the central part of the ship. This is used to route pipes generating progressive flooding that may not be controlled by remote control valves.

Since the non-zonal analysis does not consider the subdivision table, it is very important to define a virtual room to simulate that "NON-DAMAGE AREA".

That room is assumed having a permeability equal to zero and an unprotected opening in connection with the DAMHULL room in its lowest point at frame #100 has been defined too. The purpose of this definition is to make sure that every time a breach from collision or side/bottom grounding involves the "NON-DAMAGE AREA", such opening should be considered relevant by the used NAPA software and therefore the Sfac is set to zero.

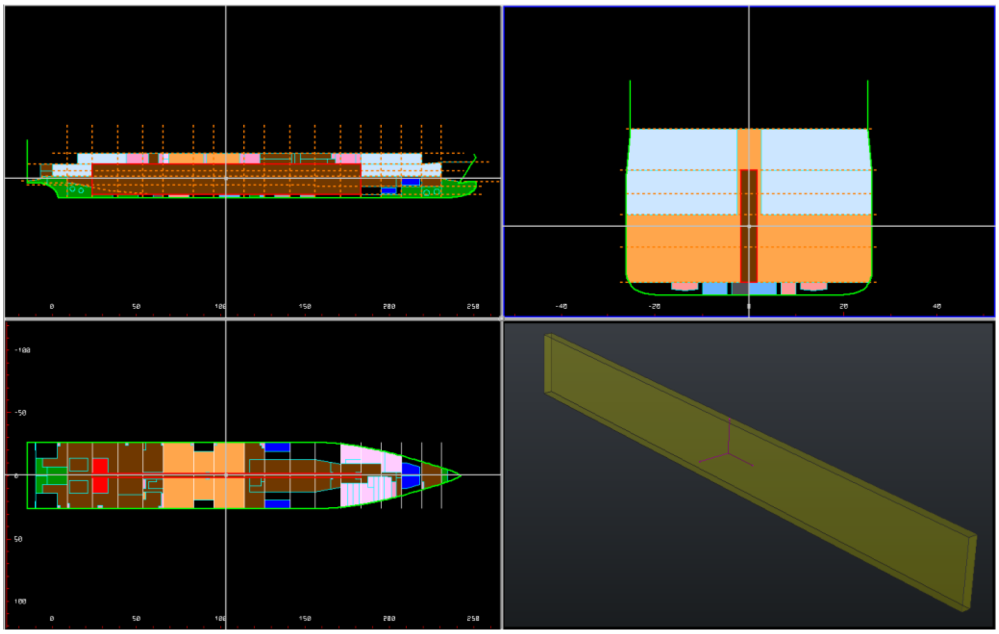


Figure 3 Defined room for *NON-DAMAGE AREA* in the non-zonal approach by NAPA– Ship #8

1.4 Calculation of PLL level 1

For this vessel breaches for collision, side and bottom grounding have been generated according to Ch. 3.3 of the main report, and the grouping of breaches, leading to the same sets of flooded rooms, permitted to reduce the damage cases to be calculated by abt. 59% for collision, by abt. 81% bottom grounding, and by abt. 71% for side grounding.

With the results of the static calculation for the attained index in hand, the PLL level 1 was calculated according to procedure described in Ch.2.4-2.5 of the main report. In particular, in the below Table 5 the non-zonal results are showed and in Table 6 the PLL (Potential Loss of Life) calculation is reported.

Table 5 Non-zonal static analysis results – Ship #8

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**	
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75
Draught	6.58 m	6.86 m	6.58 m	6.86 m	6.58 m	6.86 m
Breaches	10000	10000	10000	10000	10000	10000
Number of Empty cases	8	5	21	26	106	104
Number of Unique damage cases	4052	4147	1865	1939	2902	2931
Partial Index	0.8800	0.8424	0.9114	0.9035	0.9092	0.9072
Total Attained Subdivision Index A_i	**0.8612**		**0.9074**		**0.9082**	

Table 6 PLL level 1 – Ship #8

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		4.33E-03
Relative frequency	0.388		0.328		0.284		1.000
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	6.58 m	6.86 m	6.58 m	6.86 m	6.58 m	6.86 m	
Attained Index	0.8800	0.8424	0.9114	0.9035	0.9092	0.9072	0.8897
$\sum pfac$ (for cases with s=1)	0.7276	0.6639	0.8510	0.8456	0.8951	0.8947	0.8023
$\sum pfac \cdot (1 - sfac)$	0.1200	0.1576	0.0886	0.0965	0.0895	0.0928	0.1103

PLL level 1 (1/ship year)	**2.26E-01**	**2.97E-01**	**1.41E-01**	**1.54E-01**	**1.25E-01**	**1.28E-01**	**1.0698**
	0.5224		**0.2945**		**0.2529**		

Even though the PLL is eventually the parameter to be used as a risk metric by FLARE, the Combined Attained Index is also shown in Table 6 for information only. These values are calculated by using the relative frequency (Eq. 7 of the main report) for Collision, Side Grounding and Bottom Grounding, which are based on the updated damage statistics of FLARE (WP2).

1.5 Filtering of static results and selecting cases for dynamic simulations

The screening of the static results, according to filtering criteria identified within Ch. 3.4 of the Main Report, allowed to select 500 cases for the dynamic simulations. In the following table a summary of the filtered breaches is reported.

Table 7 Filtering results for dynamic simulation – Ship #8

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	6.58 m	6.86 m	6.58 m	6.86 m	6.58 m	6.86 m	
Number of filtered damage cases	89	149	102	148	5	7	500
$\sum pfac$ (for the filtered damage cases)	0.0271	0.0525	0.0387	0.0537	0.0019	0.0021	0.0312
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0233	0.0431	0.0373	0.0459	0.0019	0.0021	0.0271
Potential PLL (if the ship would not capsize for all selected cases)	1.82E-01	2.15E-01	8.17E-02	8.06E-02	1.22E-01	1.25E-01	0.8069
	0.3973		0.1623		0.2473		
Max PLL reduction (if the ship would not capsize for all selected cases)	23.9%		44.9%		2.2%		24.6%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. For this ship the PLL would be reduced by 24.6% if all the cases to be simulated were not capsizals.

In the following diagrams some typical damage parameters of the selected breaches are presented in non-dimensional form.

It is interesting to note that for collision, almost all the selected breaches are located in the parallel middle body, whereas a large majority of the selected breaches for side grounding has a huge length, therefore they affect a high number of compartments.

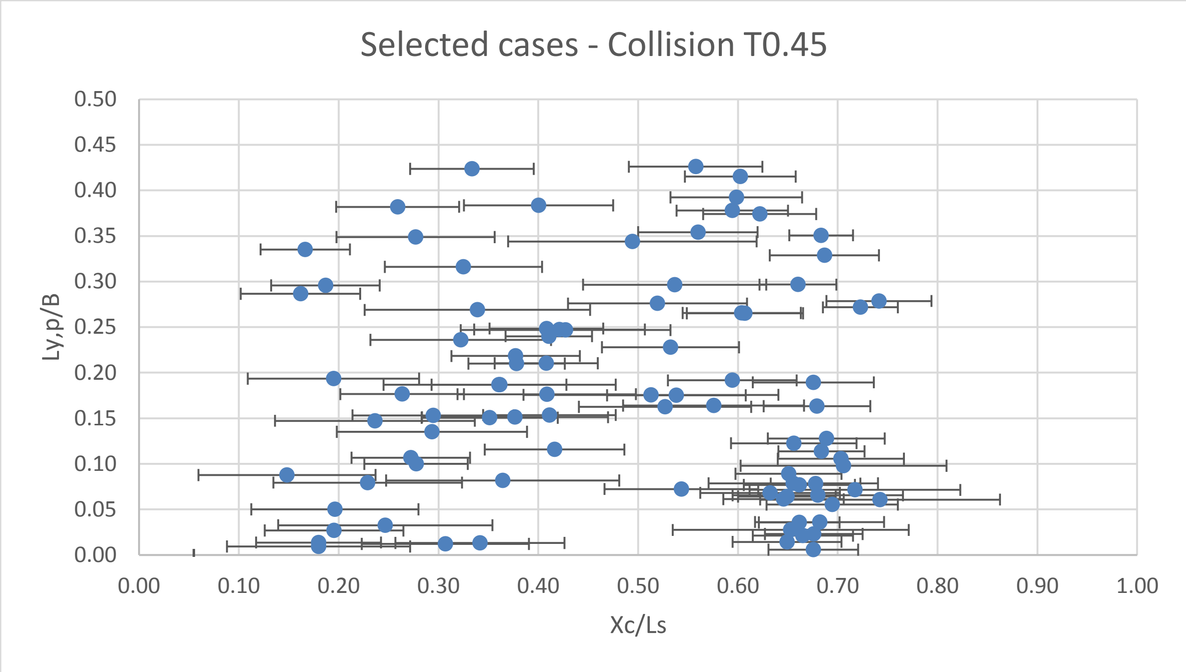


Figure 4 Selected collision breaches T0.45 – Ship #8

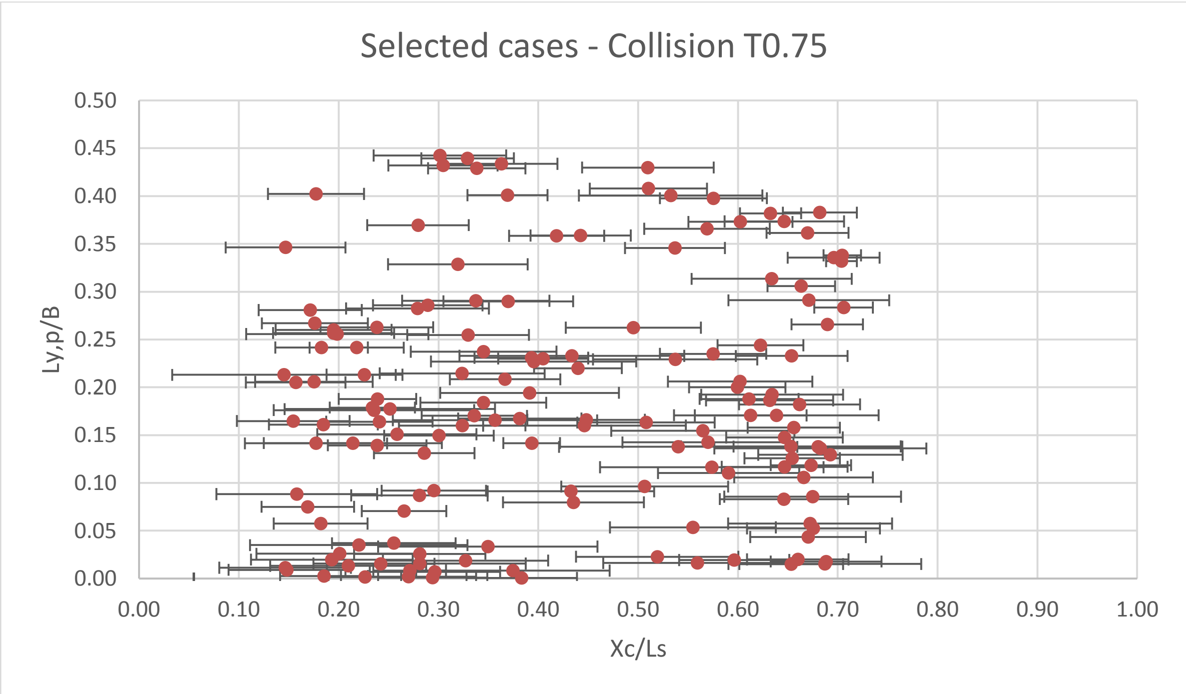


Figure 5 Selected collision breaches T0.75 – Ship #8

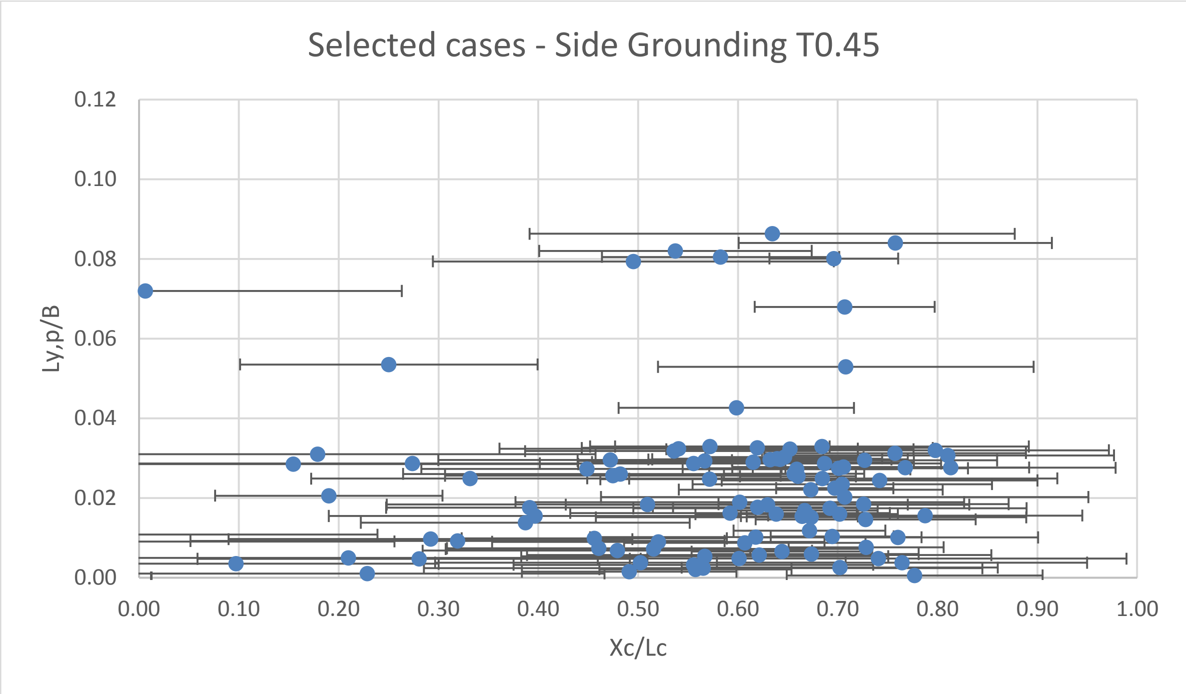


Figure 6 Selected side grounding breaches T0.45 – Ship #8

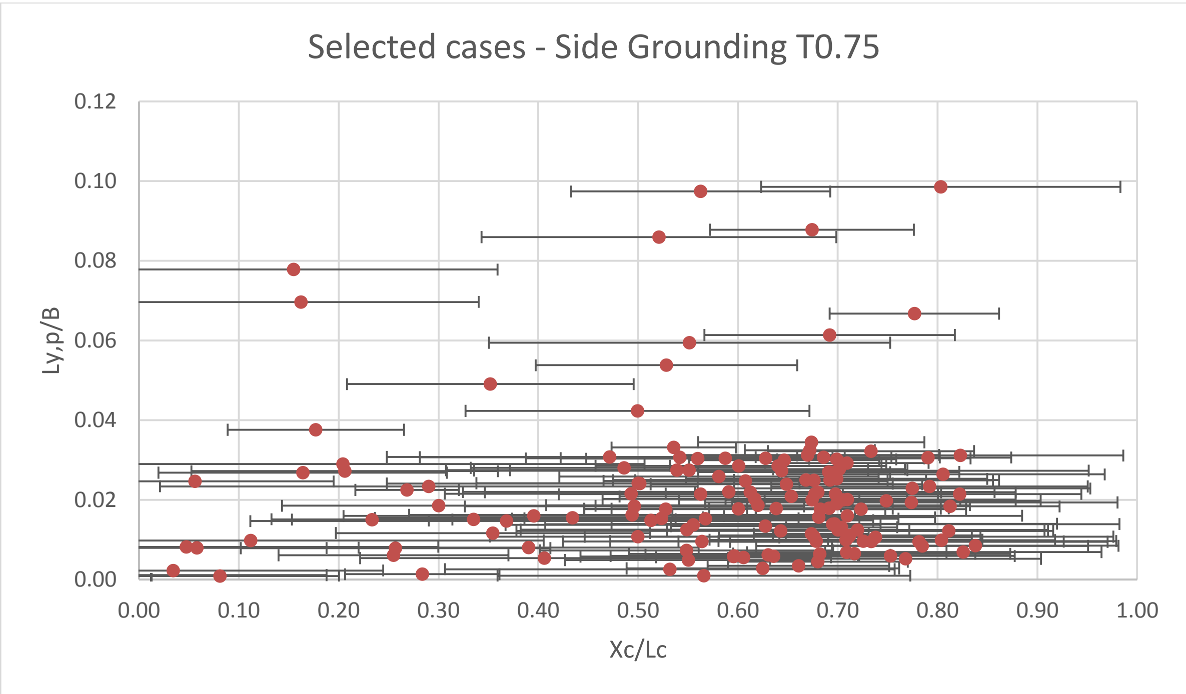


Figure 7 Selected side grounding breaches T0.75 – Ship #8

For the bottom grounding, instead, are just few filtered breaches, this is due to the fact that the ship survives when only the double bottom is affected by flooding. Hence only those case with a vertical penetration higher than the double bottom height and with a high value *freq*pfac*(1-sfac)* are selected.

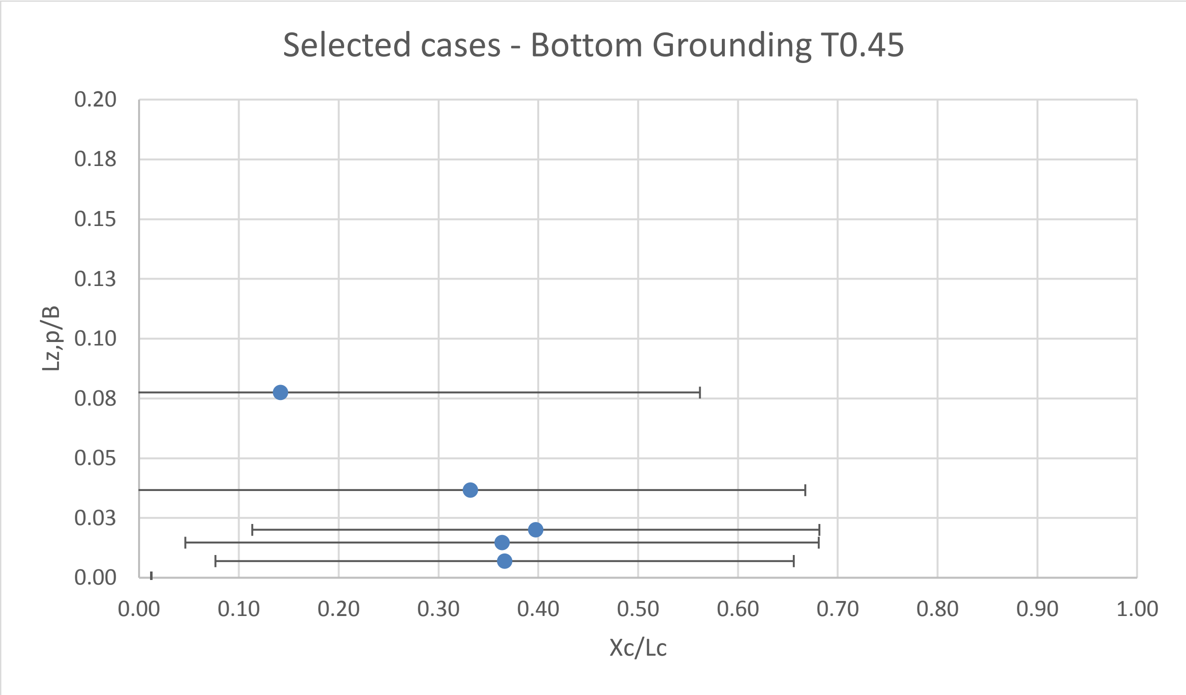


Figure 8 Selected bottom grounding breaches T0.45 – Ship #8

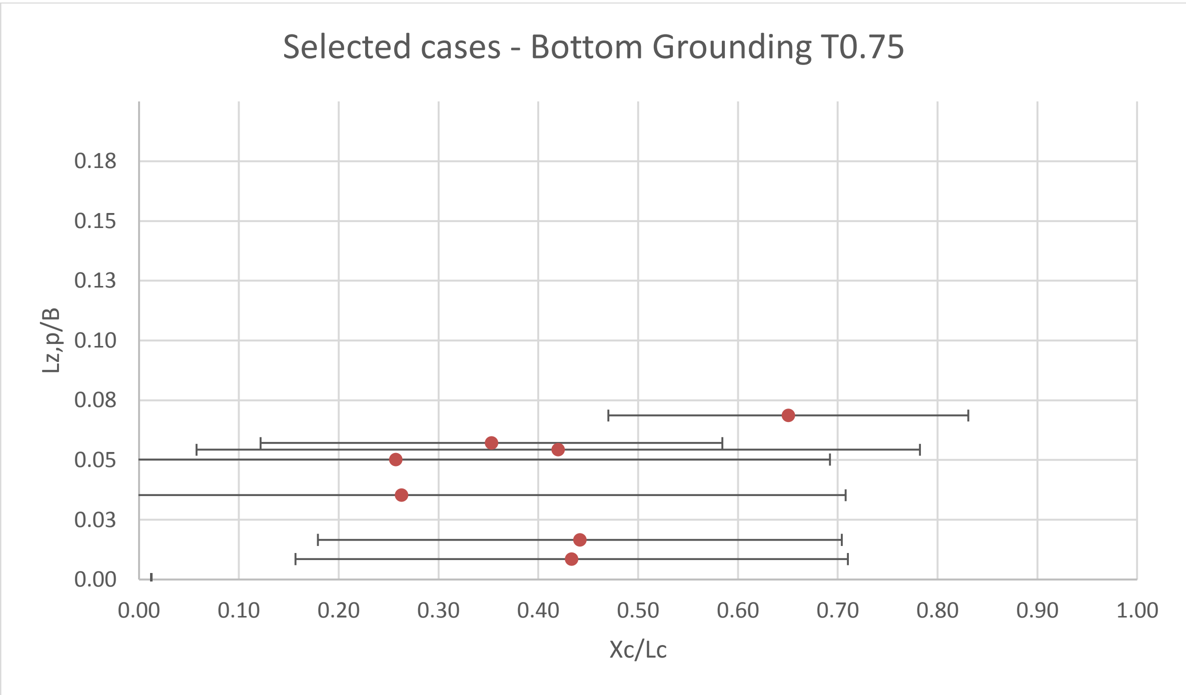


Figure 9 Selected bottom grounding breaches T0.75 – Ship #8

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with Sfac = 0 and failure modes for cases with 0 < Sfac < 1, are showed in the following tables.

Table 8 Breakdown of failure mode for Sfac=0 cases – Ship #8

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	59	109	39	68	0	0	**275**
Heeling Angle (>15 deg)	5	1	45	56	5	5	**117**
Smom=0	12	12	7	4	0	0	**35**
Opening immersion	3	1	7	11	0	2	**24**
Sfac=0 - Total cases	**79**	**123**	**98**	**139**	**5**	**7**	**451**

Table 9 Breakdown of failure mode for 0<Sfac<1 cases – Ship #8

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	0	0	0	0	0	0	**0**
Insufficient Range	0	3	0	1	0	0	**4**
Heeling Angle (>7 deg)	0	0	1	1	0	0	**2**
Insufficient Restoration (GZmax) + Range	3	10	0	1	0	0	**14**
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	**0**
Insufficient Range + Excessive Heel	0	1	3	4	0	0	**8**
Insufficient Restoration (GZmax) + Range + Excessive Heel	7	12	0	2	0	0	**21**
0<Sfac<1 - Total cases	**10**	**26**	**4**	**9**	**0**	**0**	**49**

A large percentage of captured cases resulted into Sfac = 0 (451 cases over 500) and more than 50% of the captured cases had a failure mode corresponding to capsize cases (no equilibrium).

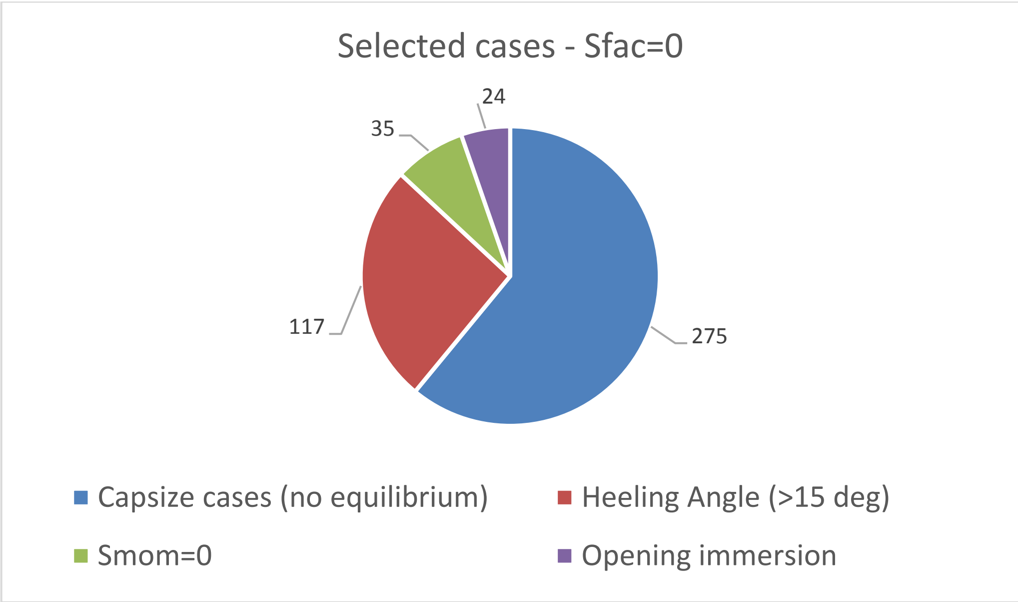


Figure 10 Diagram of failure mode for Sfac = 0 cases – Ship #8

A lot of damage cases (n.117) with Heeling Angle > 15° have been found too, while Smom = 0 was found in the static calculation for 35 cases.

Finally, 24 cases have been identified due to the immersion of openings. These cases are very important to be selected as it is expected that the outcome of the dynamic simulation should be quite different. In fact, the approach for connections and openings definition is completely different between static and dynamic calculation.

A limited number of damage cases with 0 < Sfac < 1 has been selected and most of these cases resulted in an Insufficient GZmax + Range + Excessive Heeling, and Insufficient GZmax + Range.

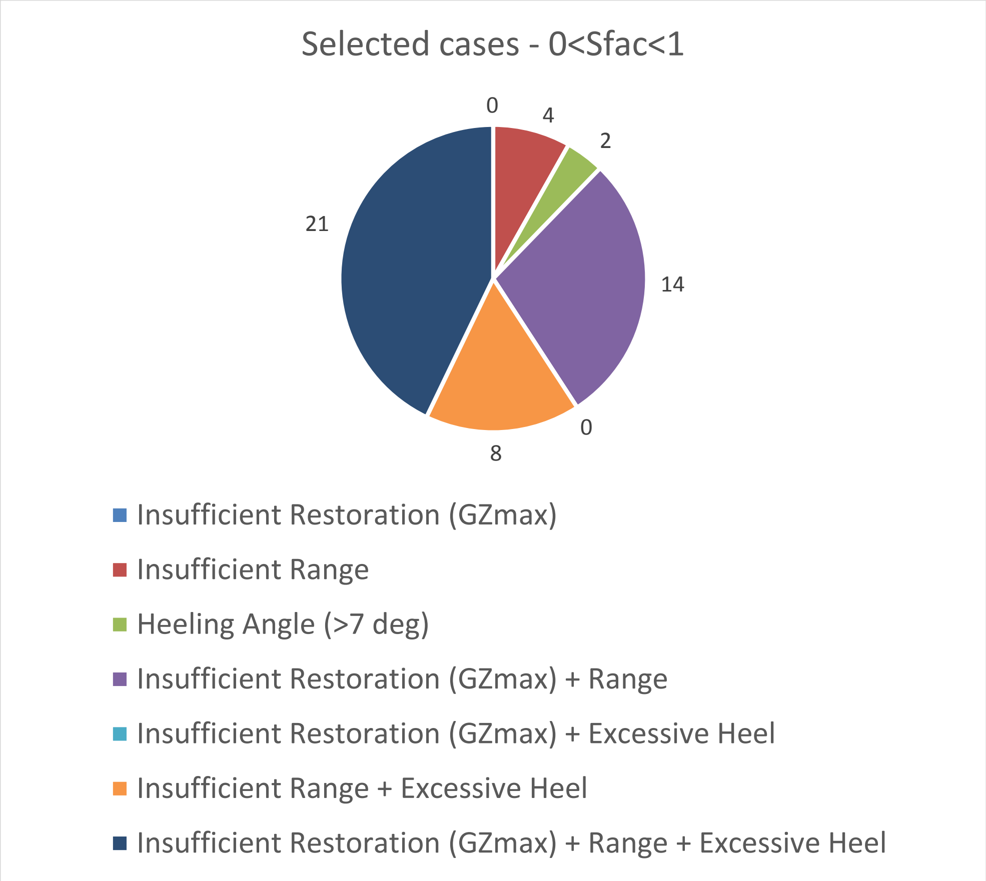


Figure 11 Diagram of failure mode for 0 < Sfac < 1 cases – Ship #8

2 DYNAMIC ASSESSMENT

2.1 Preparation of the PROTEUS model

The dynamic assessment has been carried out by use of the software *PROTEUS* (last release distributed in November 2021). For the preparation of the model the tool *Proteus Manager* has been used.

To generate in the *Proteus Manager* the loading conditions defined in NAPA and corresponding to the two selected calculation draughts at 45% and 75%, the following lightship values have been generated:

$T_1 = 6.58$ m → LIG_1 [Δ=24937 t; CG (89.131, 0.031, 3.713) m]

$T_2 = 6.86$ m → LIG_2 [Δ=26365 t; CG (88.887, 0.029, 3.5) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at twenty different deck slices:

D1 = 0.801; D2 = 1.001; D3 = 1.326; D4 = 1.601; D5 = 1.801; D6 = 1.901; D7 = 2.001; D8 = 4.551;

D9 = 5.501; D10 = 5.601; D11 = 6.101; D12 = 6.501; D13 = 6.601; D14 = 10.301; D15 = 12.951;

D16 = 13.951; D17 = 15.951; D18 = 16.951; D19 = 18.601; D20 = 21.25

For this RO-PAX ship a total of 210 openings have been defined. Horizontal openings have been defined on the higher deck of the model to capture the down-flooding through engine casings, stair trunks, vertical escape and lifts.

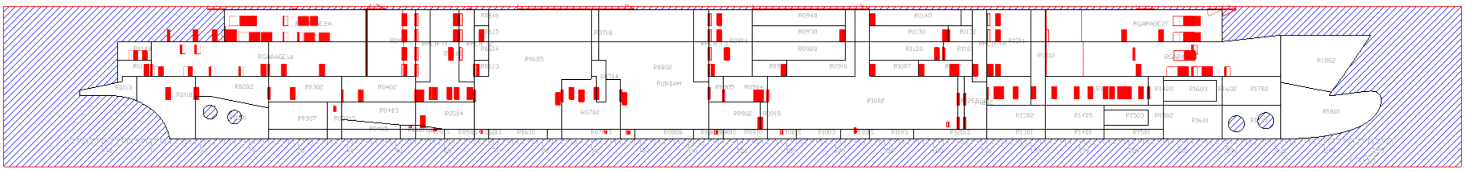
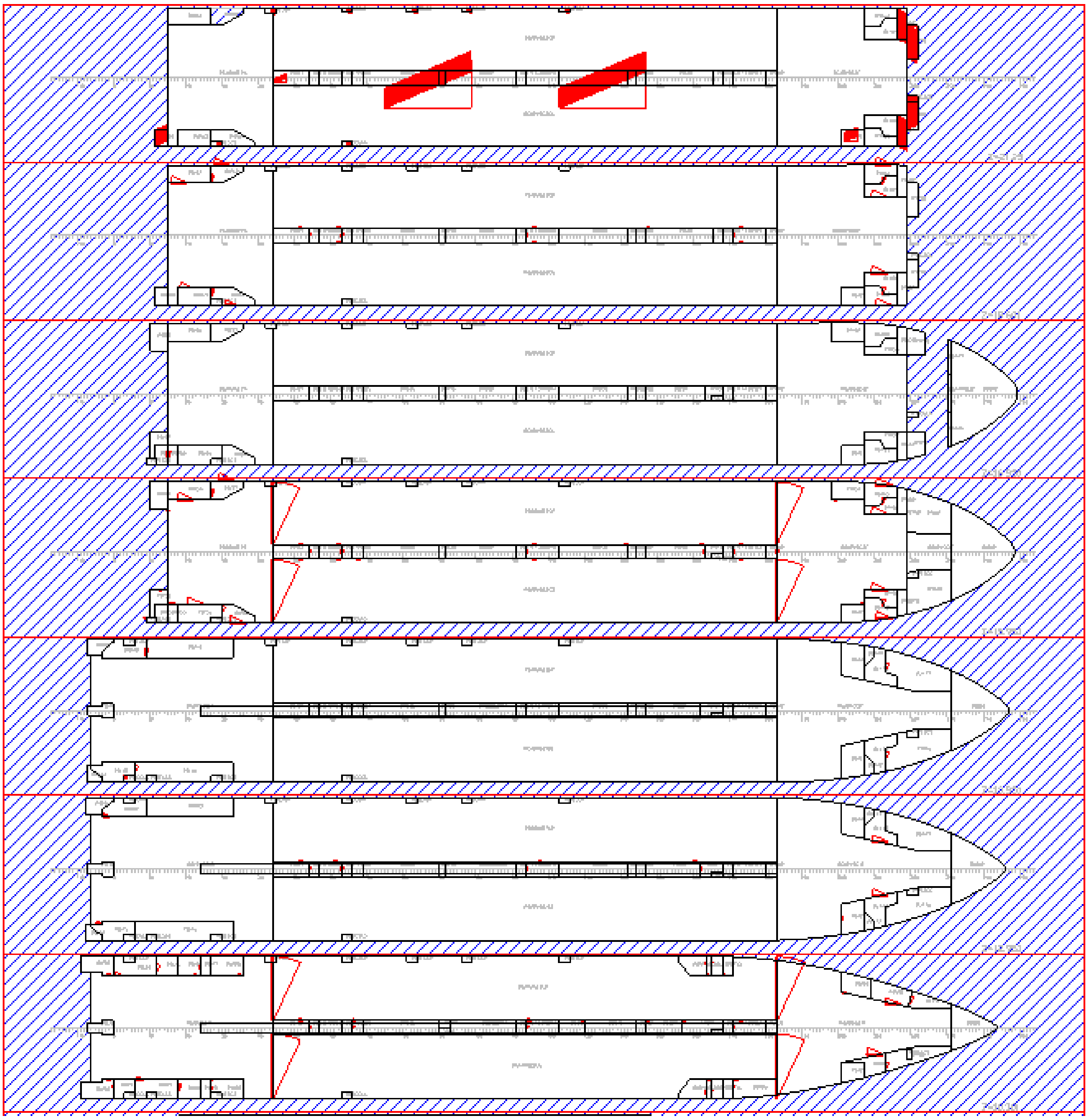
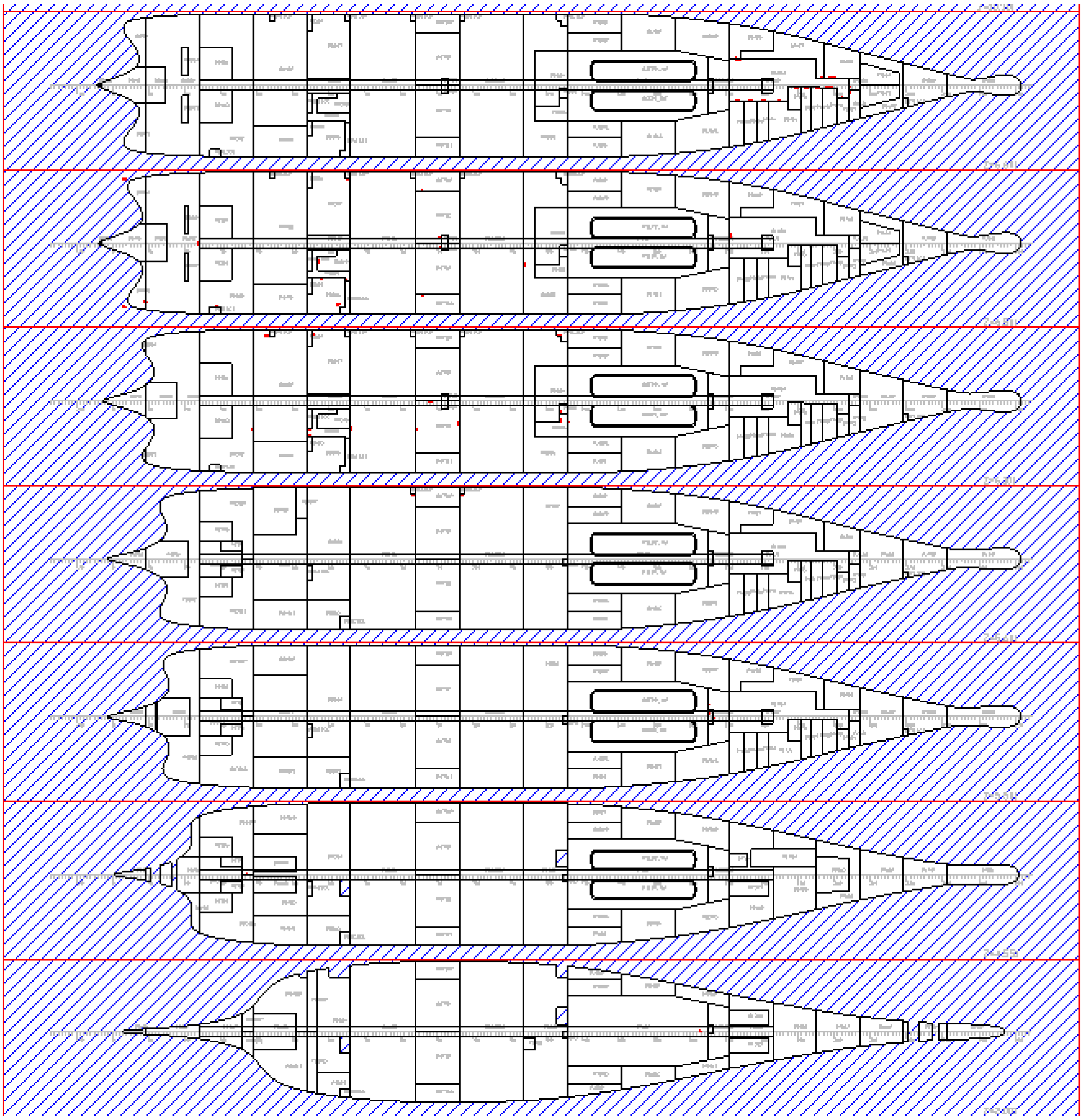


Figure 12 – Openings imported in Proteus Project (longitudinal section)– Ship #8





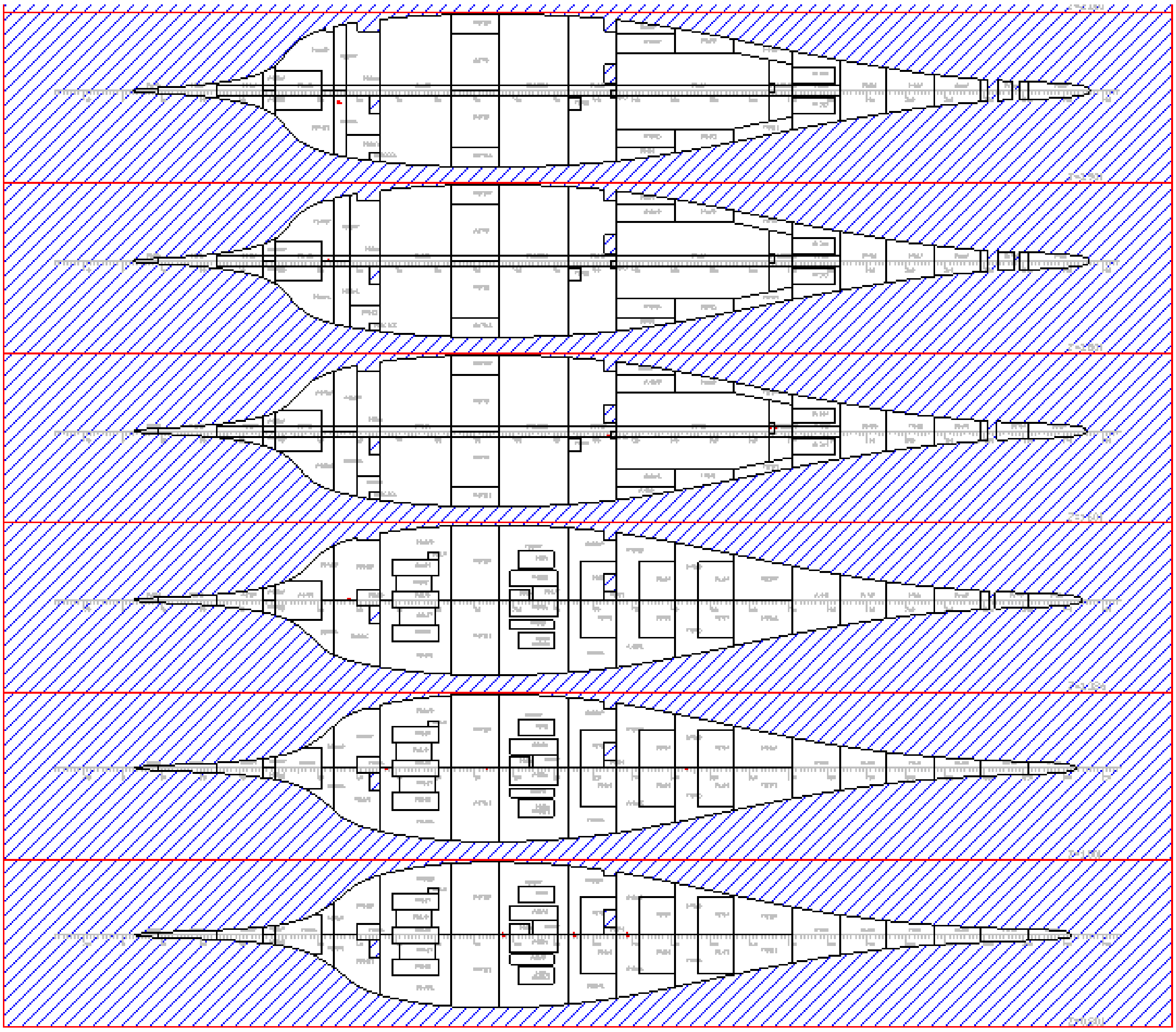


Figure 13 – Openings imported in Proteus Project (horizontal sections at deck levels)– Ship #8

Table 10 Opening Types in Proteus Manager

TYPE	Leak Area Ratio 1 to 2	Leak Area Ratio 2 to 1	Collapse Pressure 1 to 2 [meters]	Collapse Pressure 2 to 1 [meters]	Leak Height [meters]	Gap Height [meters]	Effective Height HEff Switch	Open At Time [seconds]	Close At Time [seconds]
FDOOR-A-SLIDING	0.02500	0.02500	1.00	1.00	0.000	0.000	True	999999	0
FDOOR-A-HINGED	0.03000	0.02000	2.50	2.50	0.000	0.000	True	999999	0
CONNECTION	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
LIFT-DOOR	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
FDOOR-A-DOUBLELEAF	0.02500	0.02500	2.00	2.00	0.000	0.000	True	999999	0
B-CLASS-JOINER	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
WT-DOOR	0.00100	0.00100	100.00	100.00	99.000	0.000	True	999999	0

Since in Proteus the discharge coefficient for the flow through openings is set to a constant value of 0.6 and it may be not changed, the area of the cross-flooding openings has been partly reduced to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation set have been created and the comparison of the geometric and hydrostatic data between NAPA and Proteus showed that the differences are negligible in general (from Figure 14 to Figure 20 and Table 11).

To be noted that the ship was originally defined with a lefthanded coordinate system in NAPA, but values were transformed to a righthanded system when the model has been imported in Proteus (Proteus does not accept lefthanded coordinate system).

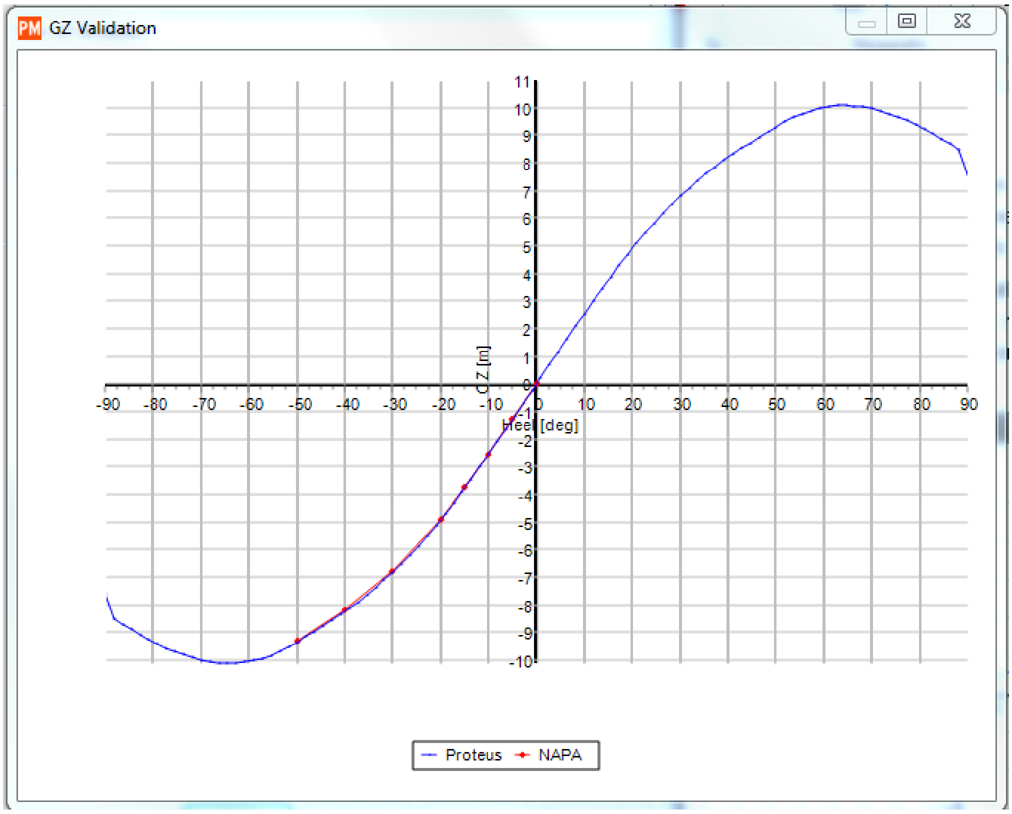


Figure 14 – GZ comparison between NAPA and Proteus – Ship #8

Table 11 Floating Position comparison between NAPA and Proteus – Ship #8

Loadcase Validation

GZ Curve | Floating Position | Volume and CGs | Section Areas

Floating Position

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	6.580	6.583	-0.003	-0.046
TA [m]	6.580	6.583	-0.003	-0.046
TF [m]	6.580	6.583	-0.003	-0.046
Trim [deg]	0.000	0.000	0.000	0.000
Heel [deg]	0.000	0.001	-0.001	0.000
KM [m]	18.310	18.342	-0.032	-0.175
KG [m]	3.713	3.710	0.003	0.081
GM0 [m]	14.597	14.629	-0.032	-0.219
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	14.597	14.629	-0.032	-0.219

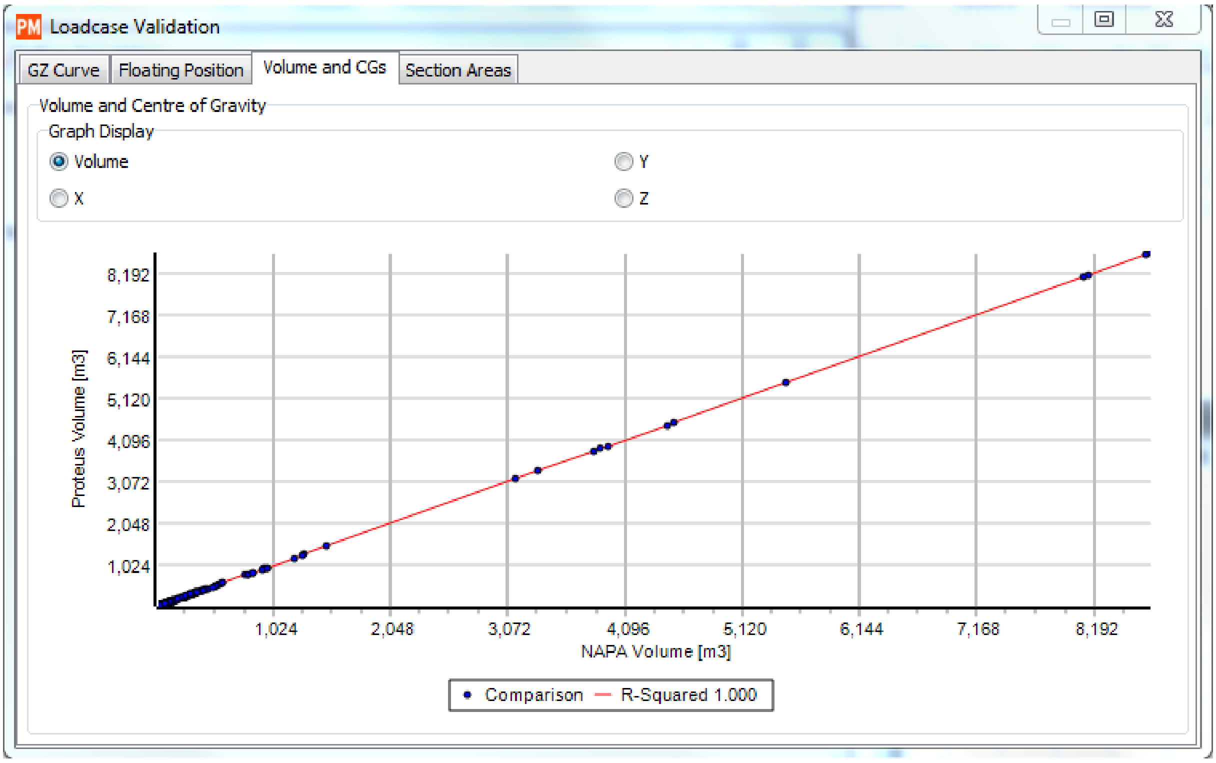


Figure 15 – Hull volume comparison between NAPA and Proteus – Ship #8

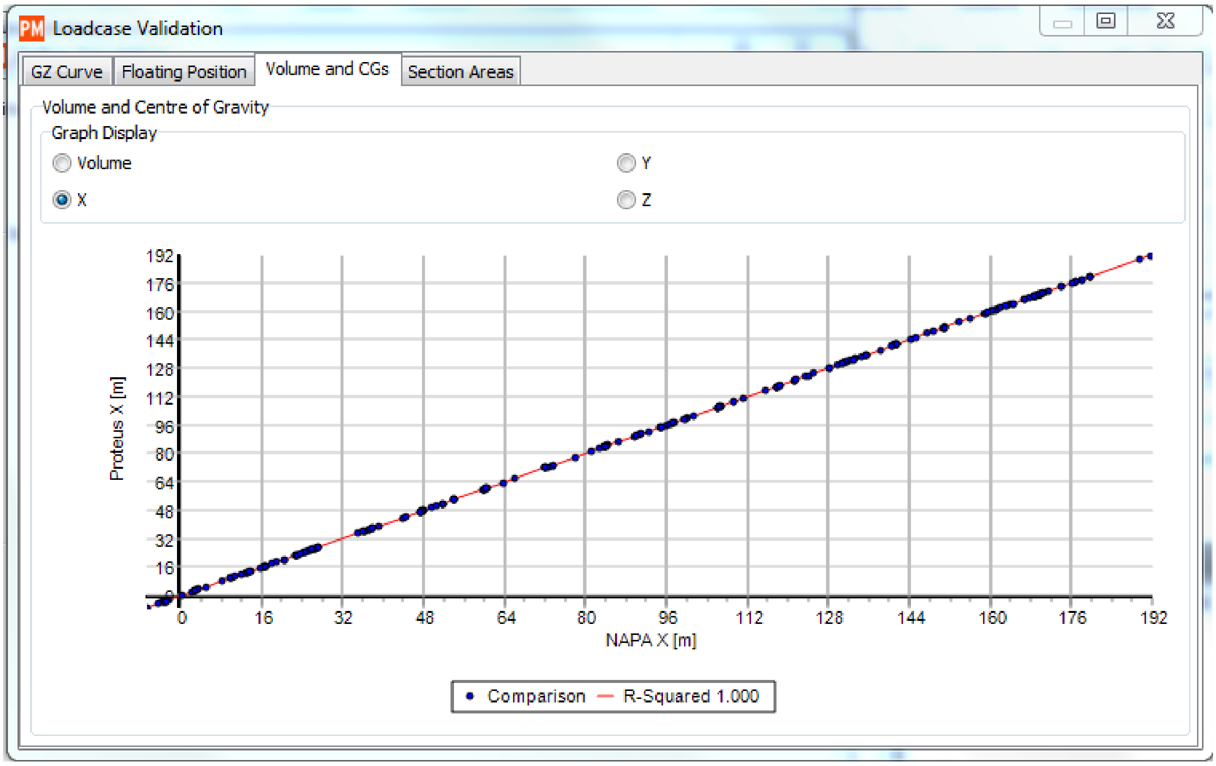


Figure 16 – Hull LCB comparison between NAPA and Proteus – Ship #8

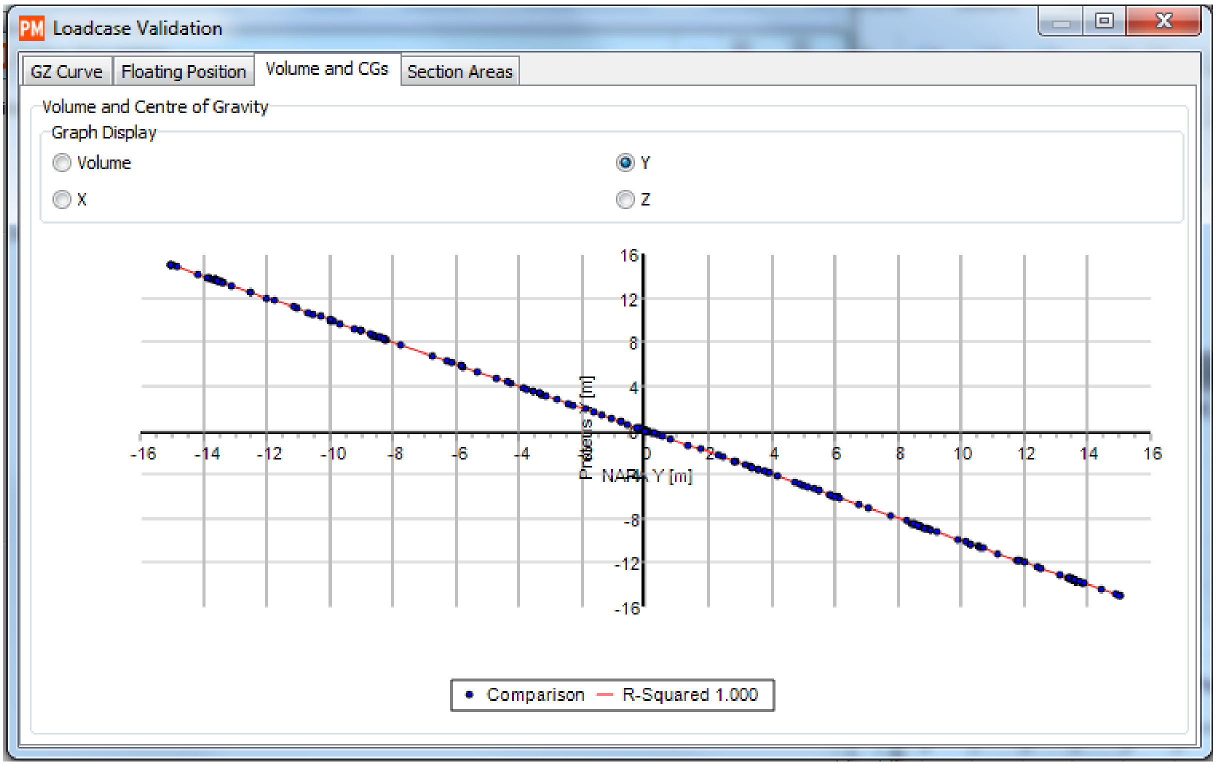


Figure 17 – Hull TCB comparison between NAPA and Proteus – Ship #8

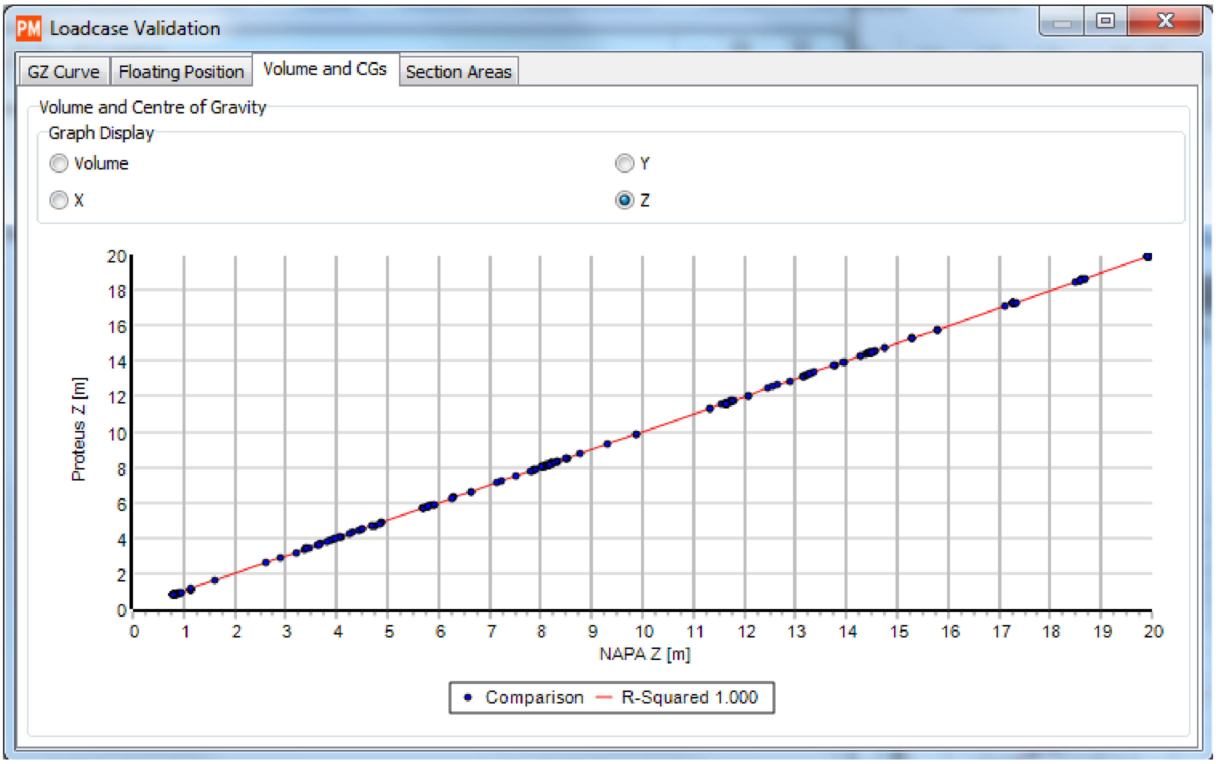
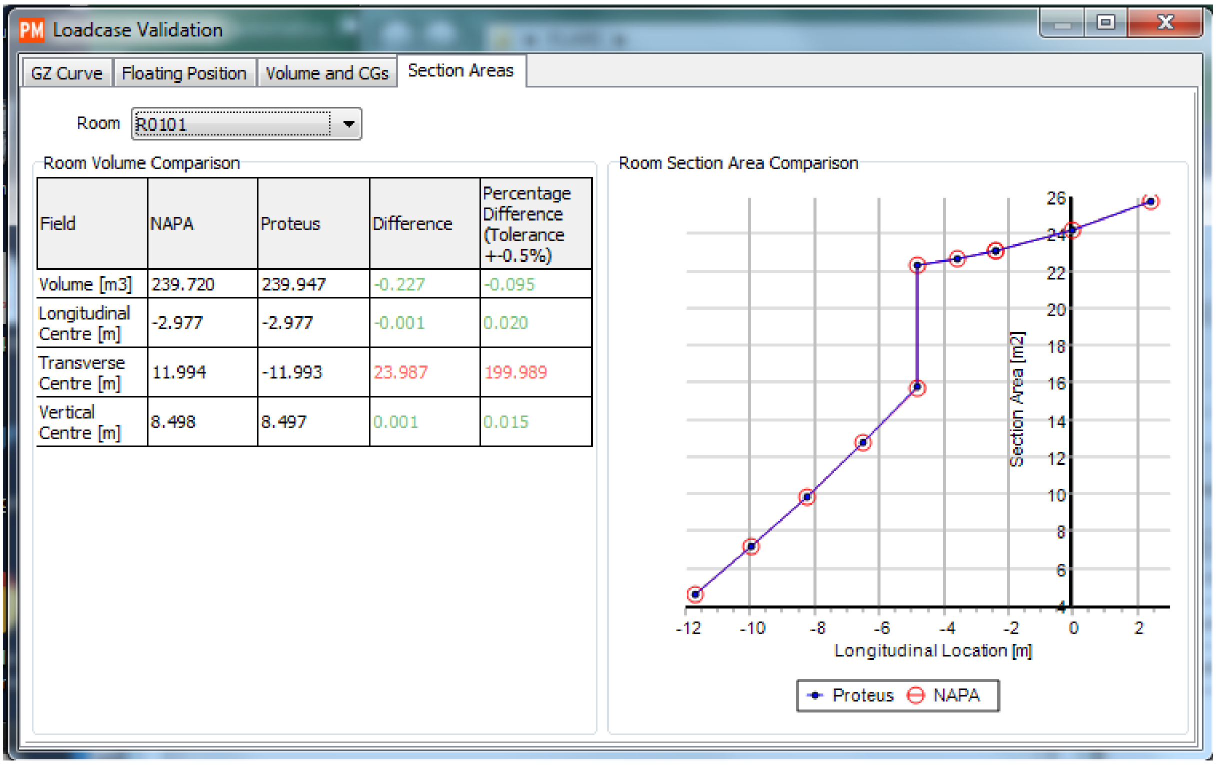
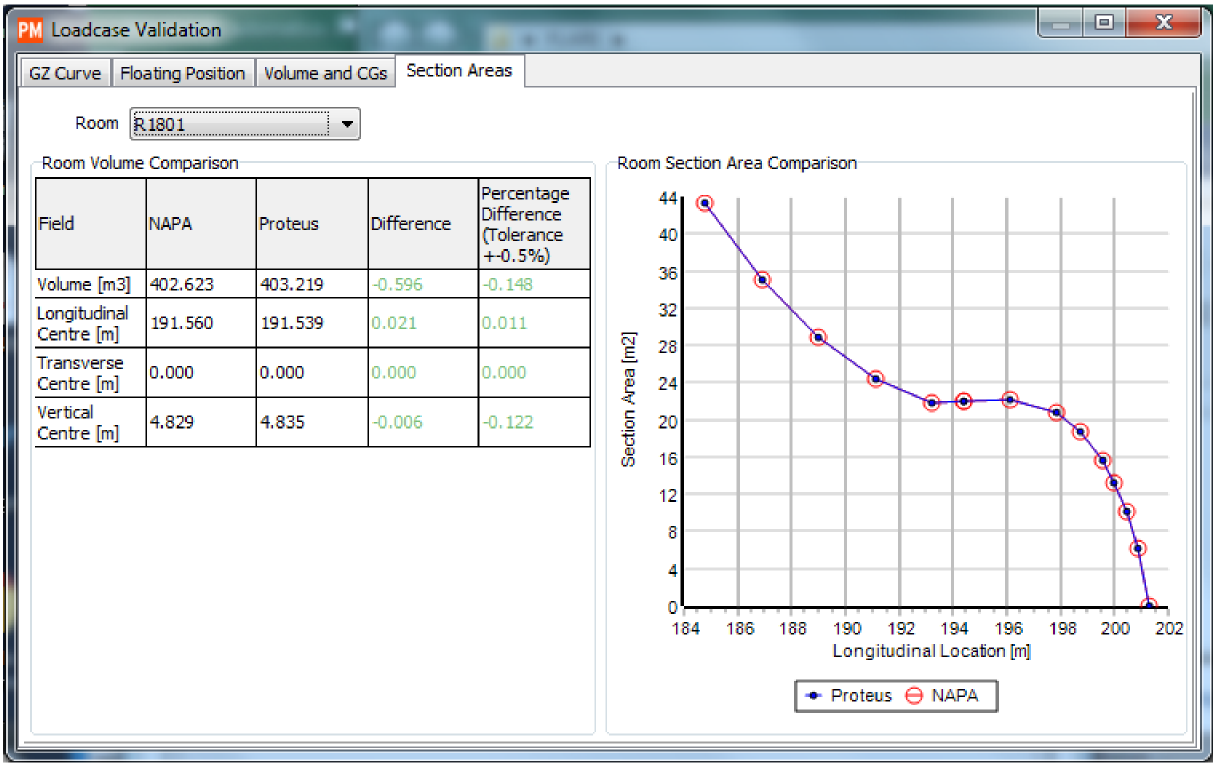


Figure 18 – Hull VCB comparison between NAPA and Proteus – Ship #8



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	239.720	239.947	-0.227	-0.095
Longitudinal Centre [m]	-2.977	-2.977	-0.001	0.020
Transverse Centre [m]	11.994	-11.993	23.987	199.989
Vertical Centre [m]	8.498	8.497	0.001	0.015

Figure 19 – Aftpeak comparison between NAPA and Proteus – Ship #8



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	402.623	403.219	-0.596	-0.148
Longitudinal Centre [m]	191.560	191.539	0.021	0.011
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	4.829	4.835	-0.006	-0.122

Figure 20 – Forepeak comparison between NAPA and Proteus – Ship #8

2.2 Results of dynamic simulations

In the first round of dynamic simulations by Proteus, all the 500 breaches have been simulated up to 30 minutes, then for 154 breaches a second simulation round has been executed up to 60 minutes, as these were found with progressive flooding still occurring at the end of the first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1 = capsize 0 = not capsize) and TTC for cases where a capsize was found. In the following graphs the results for each hazard and the global results of simulations are presented.

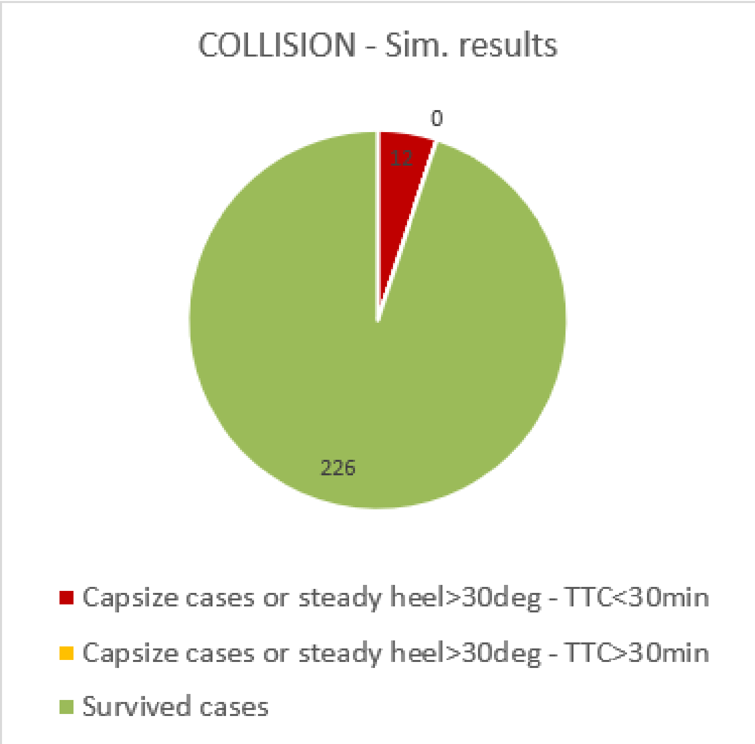


Figure 21 – Simulation results for collision – Ship #8

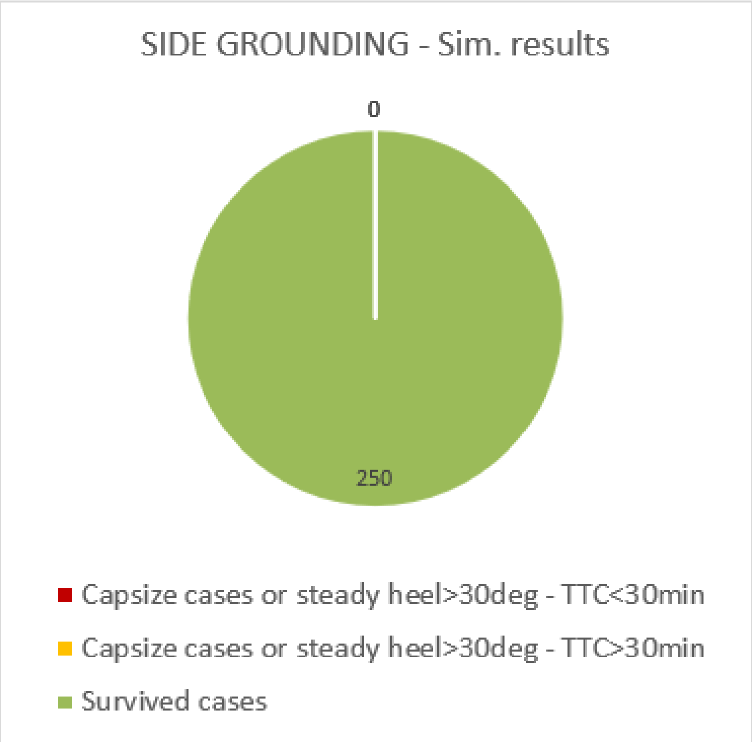


Figure 22 – Simulation results for side grounding – Ship #8

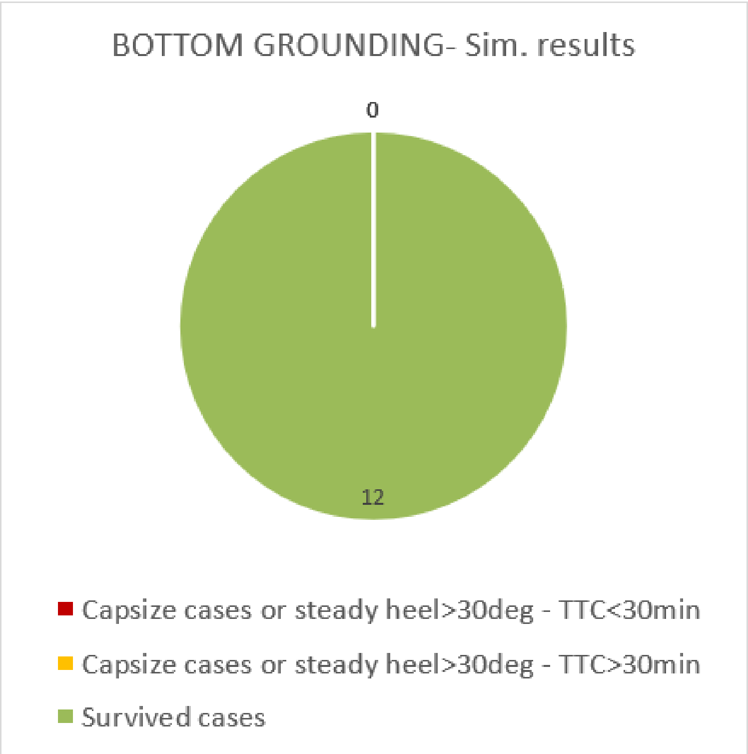


Figure 23 – Simulation results for bottom grounding – Ship #8

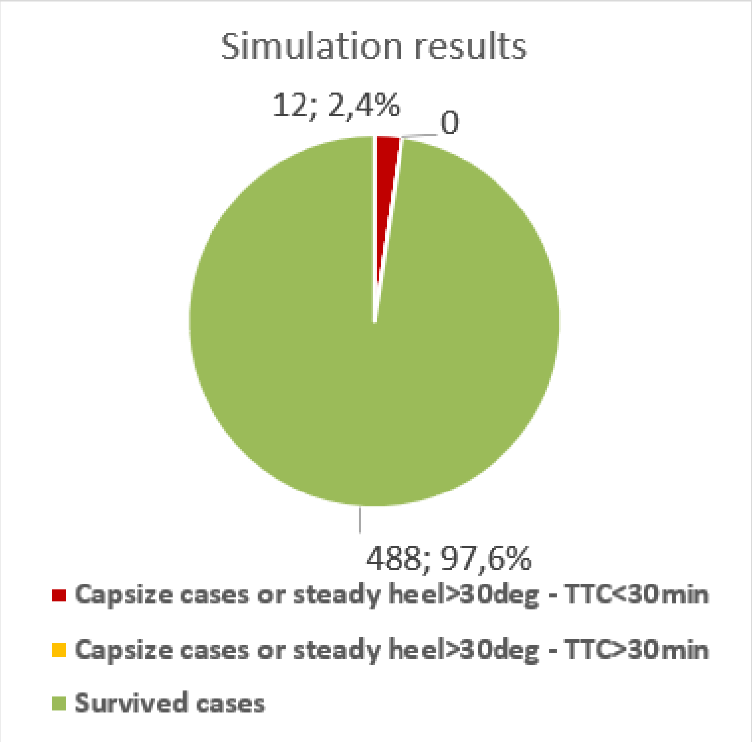


Figure 24 – Global simulation results for the 500 filtered breaches – Ship #8

The results obtained clearly show that there is a great majority of cases which did not result in the capsize of the ship; this confirms that the static results are conservative as almost all these cases had a Sfac = 0 in the static analysis.

2.3 Calculation of PLL level 2.1

The results of the flooding simulations allow to get the TTC too, therefore the fatality rate may be estimated for the cases with TTC>30min according to the procedure for calculation of Risk (Level 2.1).

In Table 12 the details of the results obtained by static and dynamic simulations are reported. It can be observed that the PLL from the static calculation has been reduced by nearly 13% from 1.0698 (Level 1) to 0.9313 (Level 2.1) when using dynamic simulation.

Table 12 PLL level 2.1 – Ship #8

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	6.58	6.86	6.58	6.86	6.58	6.86	
PLL L1 (1/ship year)	**2.26E-01**	**2.97E-01**	**1.41E-01**	**1.54E-01**	**1.25E-01**	**1.28E-01**	**1.0698**

(Static assessment)	0.5224		0.2945		0.2529		
Number of filtered damage cases	89	149	102	148	5	7	500
Capsize cases or steady heel>30deg - TTC<30min	3	9	0	0	0	0	12
Capsize cases or steady heel > 30deg – TTC > 30min	0	0	0	0	0	0	0
Survived cases	86	140	102	148	5	7	488
PLL L2.1 (1/ship year) **(Dynamic assessment)**	**1.58E-01**	**2.68E-01**	**1.25E-01**	**1.30E-01**	**1.24E-01**	**1.27E-01**	**0.9313**
	0.4254		**0.2547**		**0.2512**		
PLL L2.1 vs L1 **(Variation percentage)**	**-18.6%**		**-13.5%**		**-0.7%**		**-12.9%**

In the following figures the diagrams for the characteristics of the breaches which lead to capsize after dynamic simulations are reported.

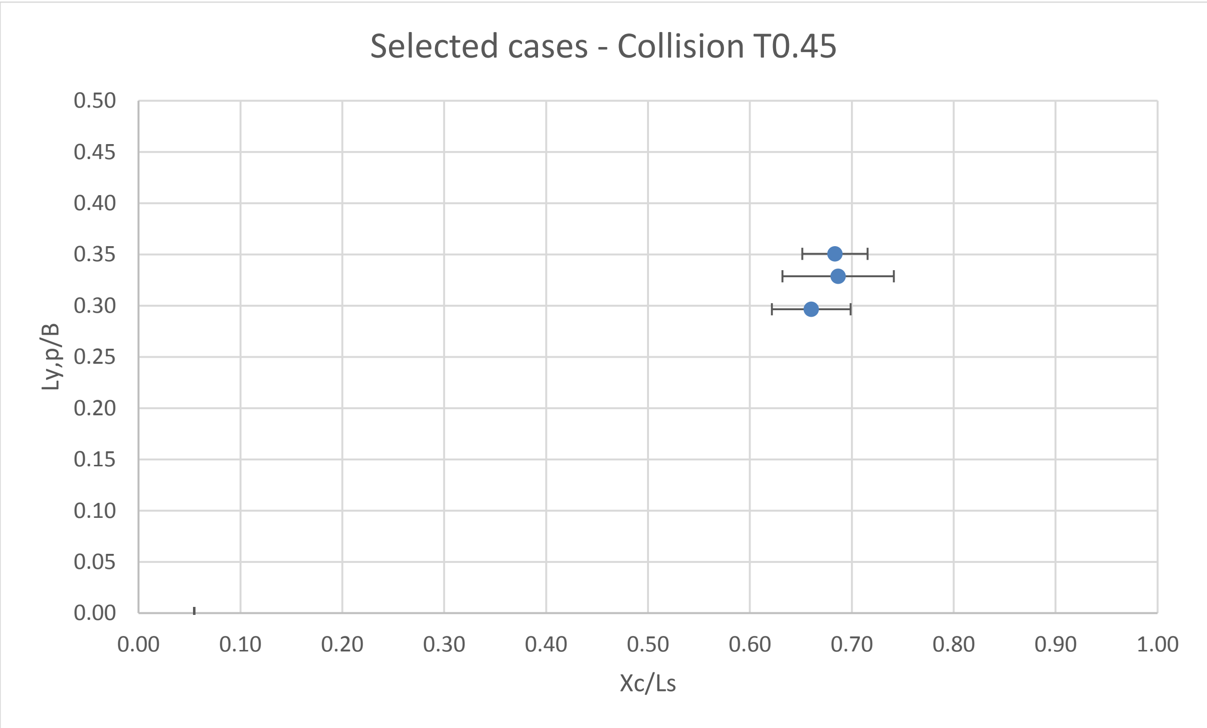


Figure 25 Characteristics of collision breaches leading to capsize T0.45 – Ship #8

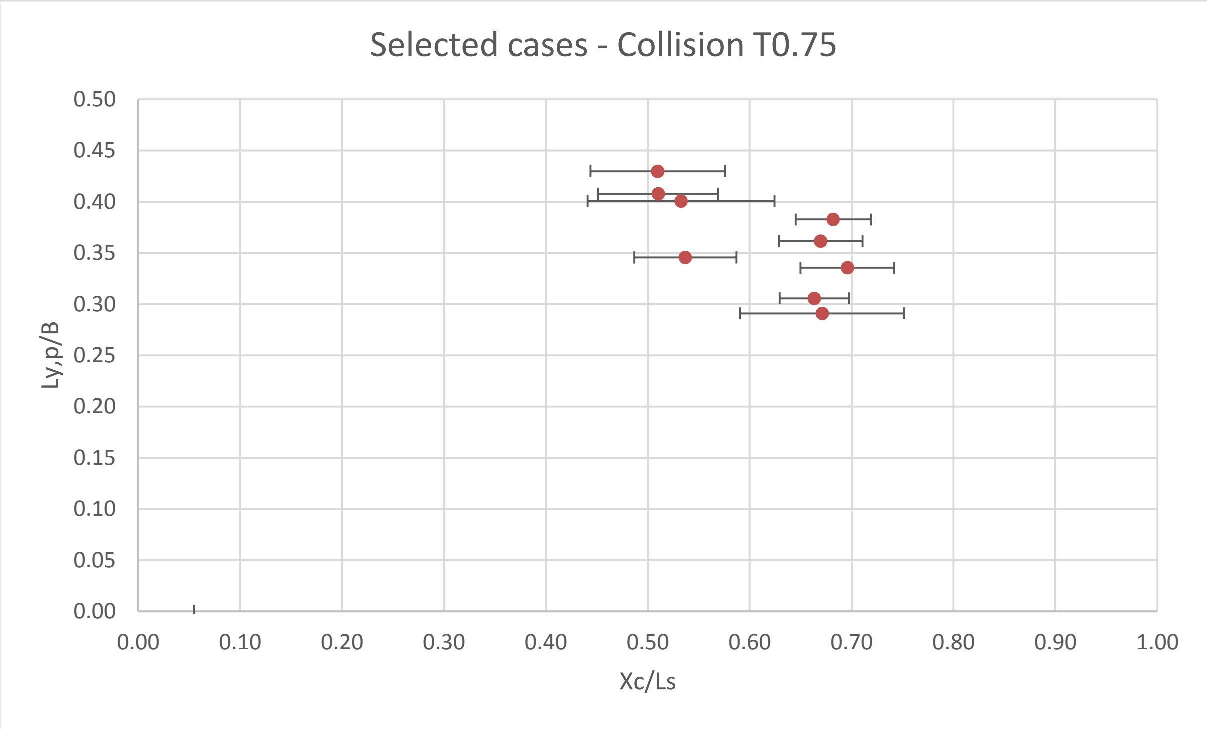


Figure 26 Characteristics of collision breaches leading to capsize T0.75 – Ship #8

The identified capsizal cases showed in Figure 25-26 may be investigated in WP7.2, when Risk Control Options are to be implemented.

2.4 Sensitivity analysis of the fatality rate

From the dynamic simulation results it has been observed that 47 cases ended with progressive flooding still occurring after 60 min simulation; for these cases no fatality has been assumed (Figure 27). No cases of capsizing/sinking after 30 min and before 60 min have been detected.

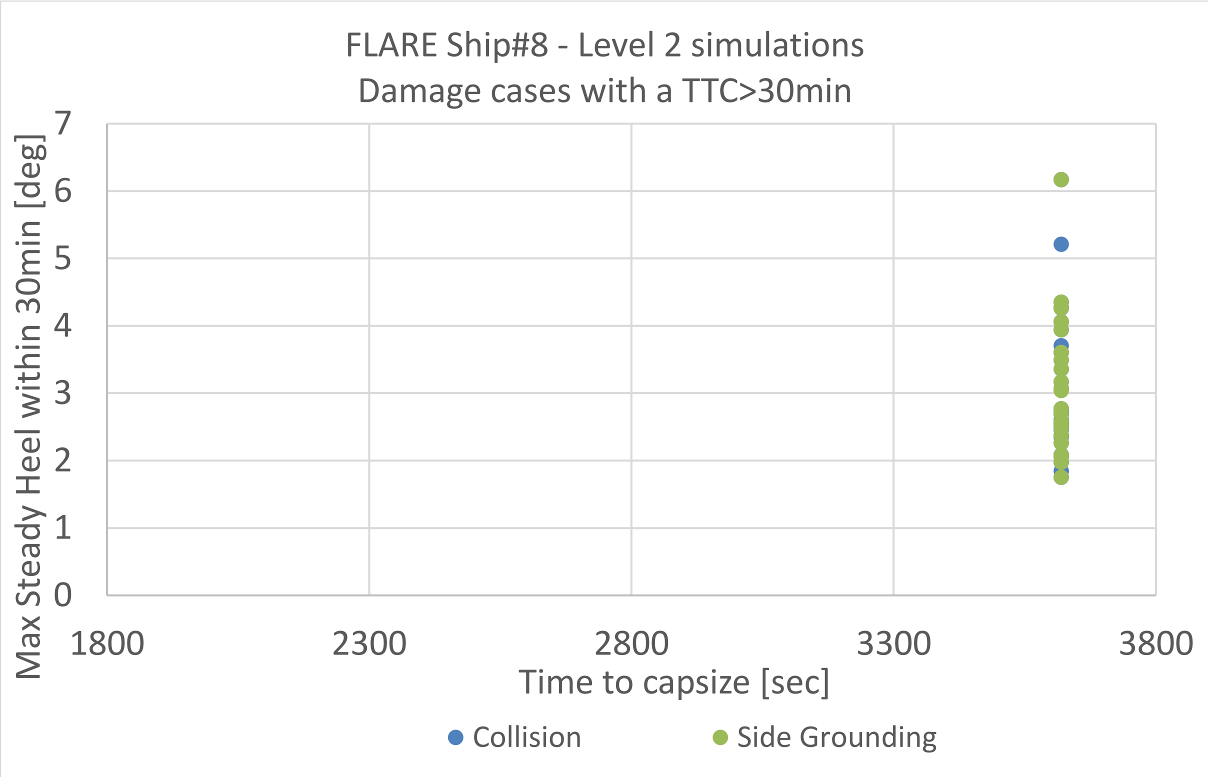


Figure 27 Cases with TTC>30min or progressive flooding still occurring after 60min – Ship #8

In order to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out for the total 47 cases (with TTC > 30min or progressive flooding still occurring after 60 min). For this, the impact on the PLL has been evaluated by use of the simplified formula (Eq. 5 of the Main Report) but assuming a variation of the fatality rate by ± 30% of the POB.

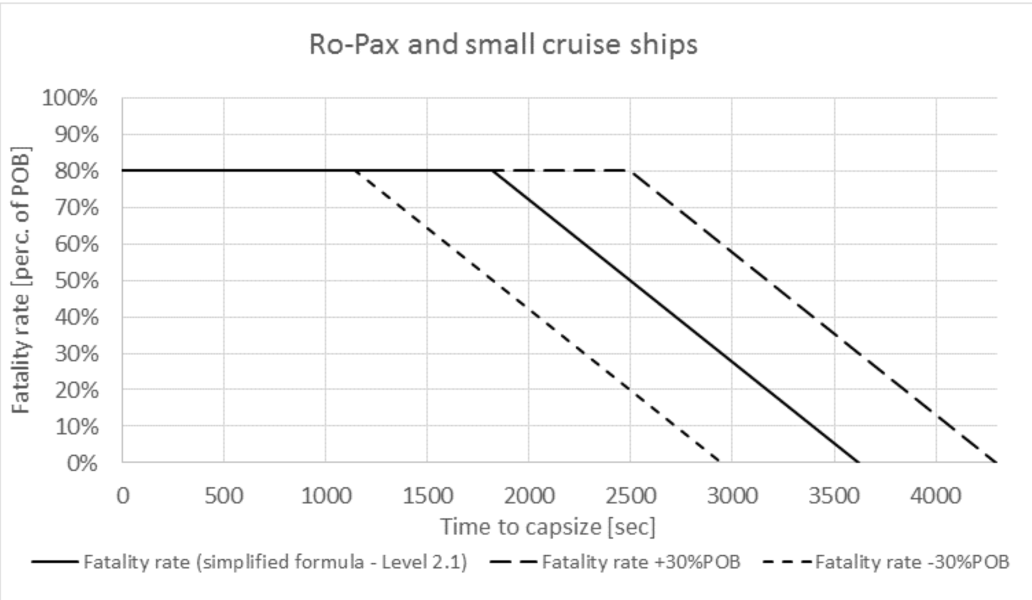


Figure 28 Sensitivity analysis of simplified formula for fatality rate calculation – Ship #8

The calculation with +30% in the fatality rate resulted into a PLL of 0.9379 (+0.7% compared to the reference PLL) while the calculation with -30% for the fatality rate resulted into a PLL of 0.9313 (-0.00% compared to the reference PLL). These values demonstrated that for this ship the simplified formula to derive the fatality rate used in the calculation of risk (Level 2.1) is insensitive with respect to the PLL.

3 CONCLUSIONS

Since the sensitivity analysis has shown that the impact on the PLL level 2.1 is negligible, when a large deviation of the fatality rate is assumed, an evacuation analysis would have been ineffective for this ship, therefore the PLL level 2.2 has not been calculated. Nonetheless, the implementation of the procedure from Level 1 to Level 2.1demonstrated that the procedure still is coherent with use of the multi-level approach. In fact, the PLL has been reduced from 1.0698 (Level 1) to 0.9313 (Level 2.1)

The PLL Level 1 is procedure appears conservative, while it seems to be more robust than PLL calculated by EMSA3 Risk Model, as the fast/slow sinking node has not been used in the FLARE procedure.

The Dynamic analysis in level 2 led to a reduction of the PLL by about 13% with the simulation of 500 breaches. Such reduction of the PLL is essentially based on the fact that about 80% of cases with Sfac = 0 in the static analysis have been found to survive in the dynamic analysis.

The flooding simulations showed that all the capsizals detected were fast capsize cases (TTC < 30 min), while no cases of slow capsize cases (TTC > 30 min) were encountered. This could be justified considering the typical compartmentation of a Ro-Pax characterized by large rooms which, in a damage case, intuitively either lead to a fast capsize or to an equilibrium/survival condition. This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model for which 50% fast capsize rate was used.

ANNEX 10 – Calculation of the flooding Risk for Ship n.9

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

Duration: 36 months - Project Start: 01/06/2019 - Project End: 31/05/2022

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a medium size cruise ship, built according the deterministic stability rule SOLAS'90. As a first step, the SOLAS'90 required GM curve has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1).

With that the SOLAS'90 required GM curve has been updated again and the SOLAS2020 Attained Subdivision Index has been calculated using the refined model. This model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

1 STATIC ASSESSMENT

1.1 Main data

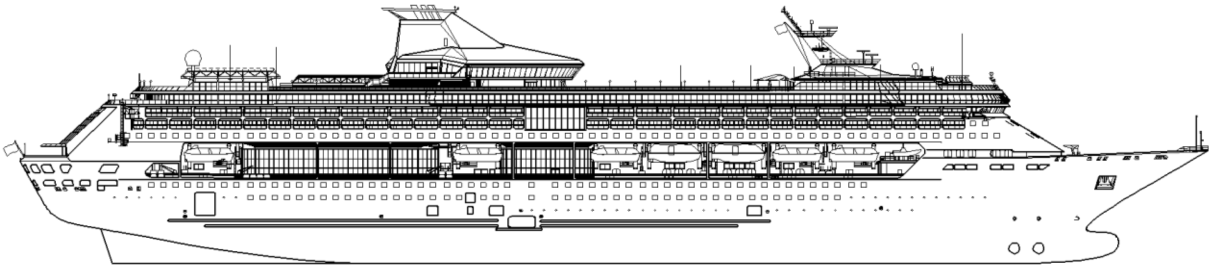


Figure 1 Profile view – Ship #9

Ship#9 is a medium size cruise vessel, designed according to the deterministic stability rule SOLAS'90, to accommodate on long international voyage 2800 persons, 2074 passengers and 726 crew members.

The main characteristics are described below as a reminder.

Table 1 Main characteristics – Ship #9

Length over all	~264 m
Length between perpendiculars	221.5 m
Subdivision length	251.4 m
Breadth	32.0 m
Subdivision draught	7.8 m
Height of bulkhead deck	10.45 m
Number of persons on board (POB)	2800
Number of passengers	2074
Number of crew	726
Gross tonnage	69490 GT
Deadweight	6324 t
No of pax cabins	902
Service speed	24 knots
Installed propulsion power	40500 kW
Installed power of main engines	58500 kW

1.2 Static calculations with new draughts and permeabilities

The first step of FLARE damage stability analysis starts with a static damage calculation in accordance to SOLAS90 but using new draughts 0.45 / 0.75 as per deliverable D2.2 and new permeability as per deliverable D2.3. The following diagram shows the evolution of the required GM :

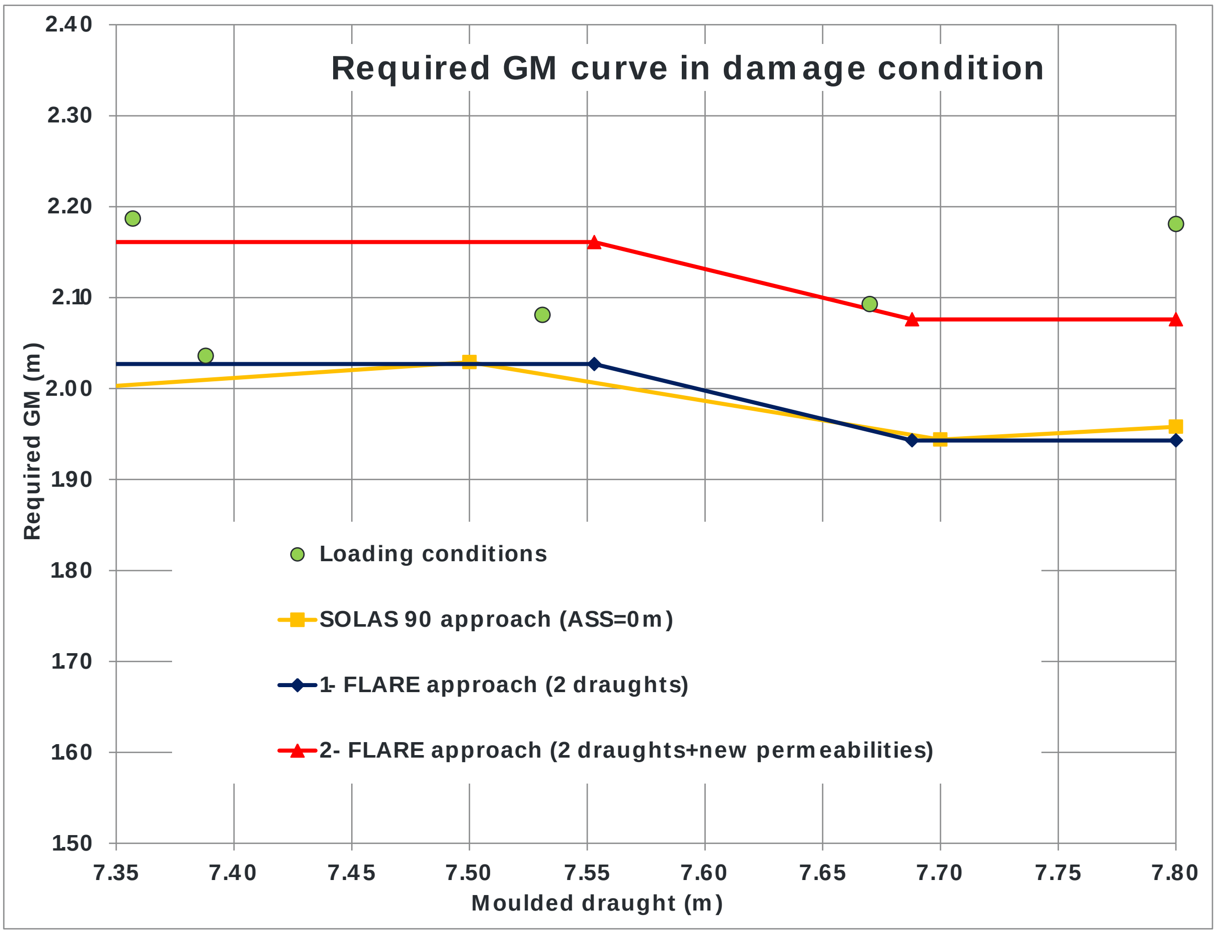


Figure 2 GM limiting curve with new FLARE draughts and permeabilities – Ship #9

The calculation has been executed with the software NAPA rel.2020.2.

Considering the outcome of D.2.3, the permeability values shown in the last two columns of following table have been used:

Table 2 Permeability – Ship #9

Rooms	**SOLAS perm.**	**FLARE perm. T0.45**	**FLARE perm. T0.75**
Engine rooms	0.85	0.90	0.90
Auxiliary machinery spaces	0.95	0.90	0.90
Stores	0.60	0.90	0.90
Accommodation (cabin areas, galleys, offices, work shops etc)	0.95	0.90	0.90
Public spaces, crew mess, corridors, stair cases	0.95	0.95	0.95
Marine Gas Oil, Lube Oil, Potable Water, Waste Water, Technical water, Water ballast, Misc.	0.95	0.540	0.507
RoRo spaces, Car Deck	0.95/0.90	0.91	0.90
Heeling tanks	0.95	0.51	0.51
Void Spaces	0.95	0.95	0.95

1.3 Static calculations with refined model

Subsequently the geometry model used for calculations has been updated according to the FLARE modelling guidelines [8].

The refined model reflects as close as possible the geometry of the physical ship or its design and the following items have been refined or added:

- Staircases and lifts
- U-shaped compartments above double bottom
- Void space below tank top

Adding the above modifications generates a significant increase of the number of rooms and connections:

Table 3 Comparison between simplified model and refined model – Ship #9

Description	Before modelling	After modelling
Damhull volume	89,033 m^3	108,564 m^3
Rooms number	134	490
Connections number	14	410

For this ship, the U-shaped void spaces within the double bottom were not splitted in two parts with cross-flooding opening defined, hence these void spaces are divided in centreline in the new model. There is no impact on the SOLAS90 damage calculations results.

The new required GM curves from the damage calculation on the refined model are given in the figure 3:

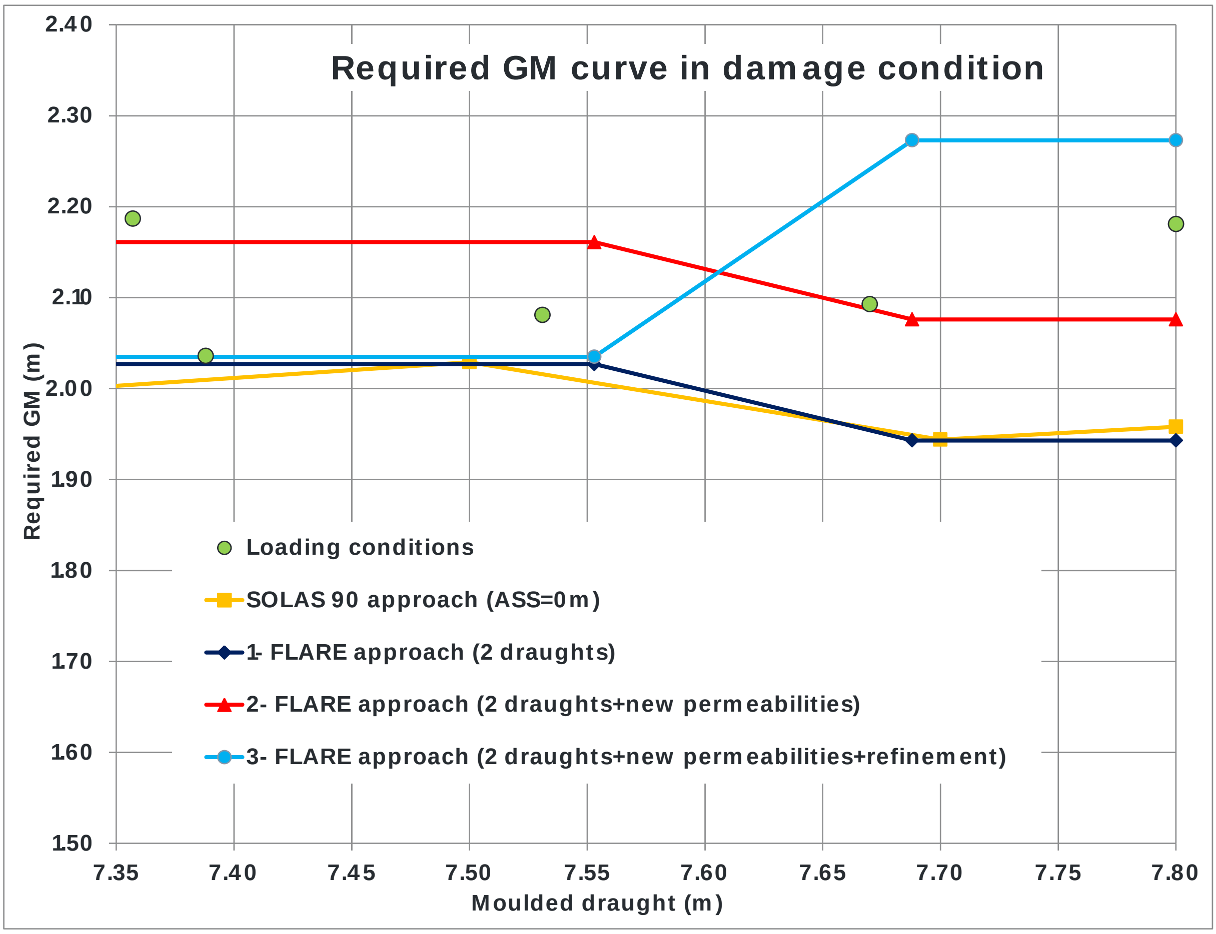


Figure 3 GM limiting curve with new FLARE model refinement – Ship #9

The model refinement led to an increase of the required GM for T0.75 and a decrease of the required GM for T0.45, due to the variation on the damage asymmetry at the different flooding stages.

For the following calculations (static zonal probabilistic, static non-zonal, and dynamic), the initial conditions correspond to the required GM with the model refinement:

Table 4 Initial conditions for calculations – Ship #9

Name	Moulded draught (m)	GM (m)
T0.45	7.553	2.035
T0.75	7.688	2.273

1.4 Static calculations with refined model (probabilistic method)

Subdivision and connections table have been defined to run a damage calculation with the actual probabilistic method (SOLAS 2020 ch.II-1).

Calculation has been executed with the software NAPA rel.2020.2 generating damages up to 6 adjacent zones. Here following the Attained and Required Index.

Number of persons POB = 2800
Required subdivision index R = 0.8730
Attained subdivision index A = 0.7691

Table 5 Static results with refined model (probabilistic method) – Ship #9

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	(m)	(m)				
PS						
T0.75	7.688	2.273	0.77482	0.5	0.38741	0.76575
T0.45	7.553	2.035	0.75667	0.5	0.37834	
SB						
T0.75	7.688	2.273	0.78204	0.5	0.39102	0.77236
T0.45	7.553	2.035	0.76268	0.5	0.38134	

1.5 Non-zonal static analysis

In addition to the zonal stability results for collision, the attained index following the non-zonal approach has been calculated for collision, bottom grounding and side grounding/contact.

For that purpose the outcome of eSAFE project has been used [1].

1.5.1 Non-damage area

There is no "non-damage area" for this ship calculated and designed with previous deterministic method for damage stability calculation.

1.5.2 Breach generations and results

In total, 10000 breaches have been generated with NAPA tool using the Monte Carlo method. Then frequencies and damage cases to be calculated are obtained by grouping breaches leading to the same sets of flooded rooms.

The following results have been obtained:

Table 6 Non-zonal static analysis results – Ship #9

Damage Type	Collision		Side Grounding		Bottom Grounding	
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75
Draught	7.553m	7.688m	7.553m	7.688m	7.553m	7.688m
Breaches	10000	10000	10000	10000	10000	10000
Number of Empty cases	325	461	86	84	131	154
Number of Unique damage cases	6448	6944	3109	3097	3326	3326
Partial Index	0.7671	0.7892	0.8633	0.8732	0.9421	0.9371
Total Attained Subdivision Index Ai	**0.7781**		**0.8683**		**0.9396**	

For this vessel breaches for collision, side and bottom grounding have been generated according to Ch. 3.2 of the main report and the grouping of breaches, leading to the same sets of flooded rooms, permitted to reduce the damage cases to be calculated by 33% for collision, 69% for side grounding and 67% for bottom grounding.

1.6 Calculation of PLL level 1

With the results of the static calculation for the attained index in hand, the PLL level 1 was calculated according to the procedure described in Ch.2.4-2.5 of the main report. In the Table 7 the PLL (Potential loss of life) calculation is reported.

Table 7 PLL level 1 – Ship #9

Damage Type	**Collision**		**Side Grouding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		4.33E-03
Relative frequency	0.388		0.328		0.284		1.000
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	7.553m	7.688m	7.553m	7.688m	7.553m	7.688m	
Attained Index	0.7671	0.7892	0.8633	0.8732	0.9421	0.9371	0.8536
$\sum pfac$ (for cases with s=1)	0.5229	0.4839	0.6915	0.6762	0.7665	0.7574	0.6360
$\sum pfac \cdot (1 - sfac)$	0.2329	0.2108	0.1367	0.1268	0.0579	0.0629	0.1464
PLL level 1 (1/ship year)	4.38E-01	3.97E-01	2.17E-01	2.02E-01	7.98E-02	8.66E-02	**1.4204**
	0.8349		0.4190		0.1664		

Even though the PLL is eventually the parameter to be used as a risk metric by FLARE, the Combined Attained Index is also shown in Table 7 for information only. These values are calculated by using the relative frequency (equation 7 of the main report) for collision, Side grounding and Bottom Grounding, which are based on the updated damage statistics of FLARE (WP2).

1.7 Filtering of static results and selecting cases for dynamic simulations

The screening of the static result according to filtering criteria identified within Ch. 3.4 of the main report permitted to select 500 cases for the dynamic simulations. In the following table a summary of the filtered breaches is reported.

Table 8 Filtering results for dynamic simulation – Ship #9

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	7.553m	7.688m	7.553m	7.688m	7.553m	7.688m	
Number of filtered damage cases	128	97	128	110	21	16	500
$\sum pfac$ (for the filtered damage cases)	0.0345	0.0179	0.0505	0.0414	0.0054	0.0034	0.0265
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0275	0.0171	0.0305	0.0256	0.0045	0.0034	0.0190
Potential PLL (if the ship would not capsize for all selected cases)	3.87E-01	3.64E-01	1.69E-01	1.61E-01	7.37E-02	8.20E-02	1.2364
	0.7510		0.3298		0.1556		
Potential PLL reduction (if the ship would not capsize for all selected cases)	-10.1%		-21.3%		-6.5%		-12.9%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. In particular for this ship the PLL would be reduced by about 13% if all the cases to be simulated are not capsizals.

In the following diagrams some typical damage parameters of the selected breaches are presented in non-dimensional form.

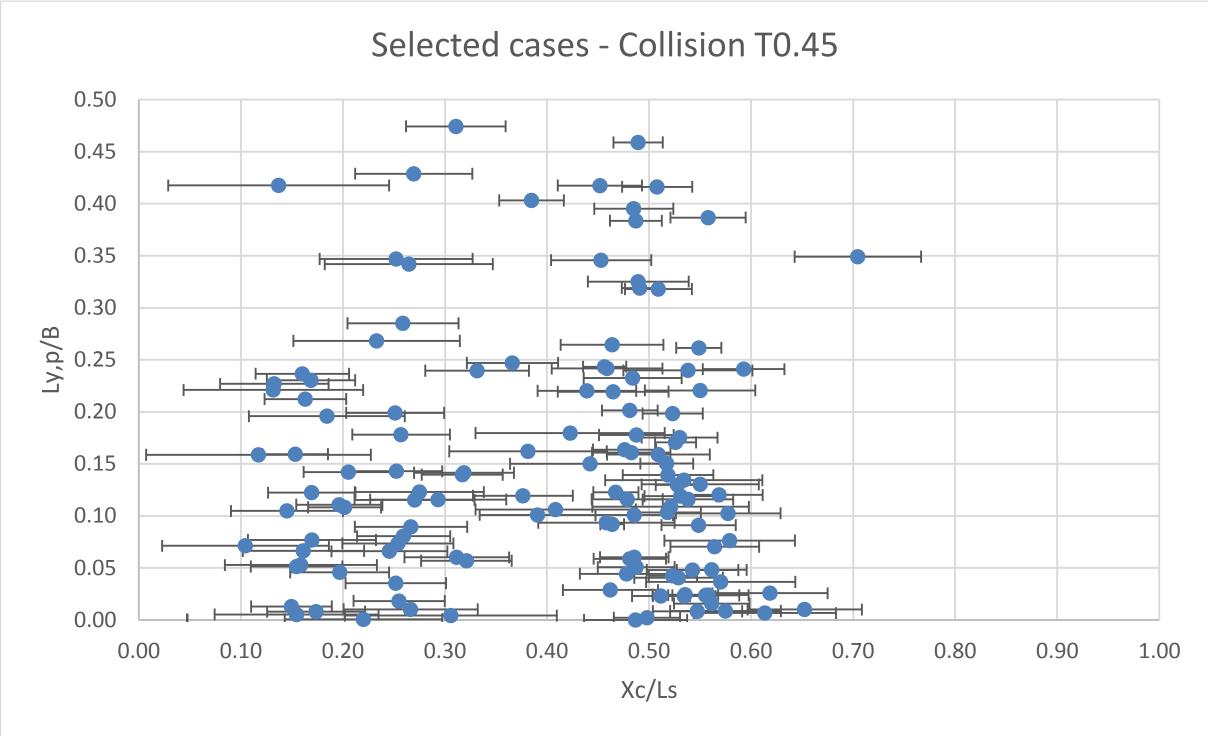


Figure 4 Characteristics of selected collision breaches T0.45 – Ship #9

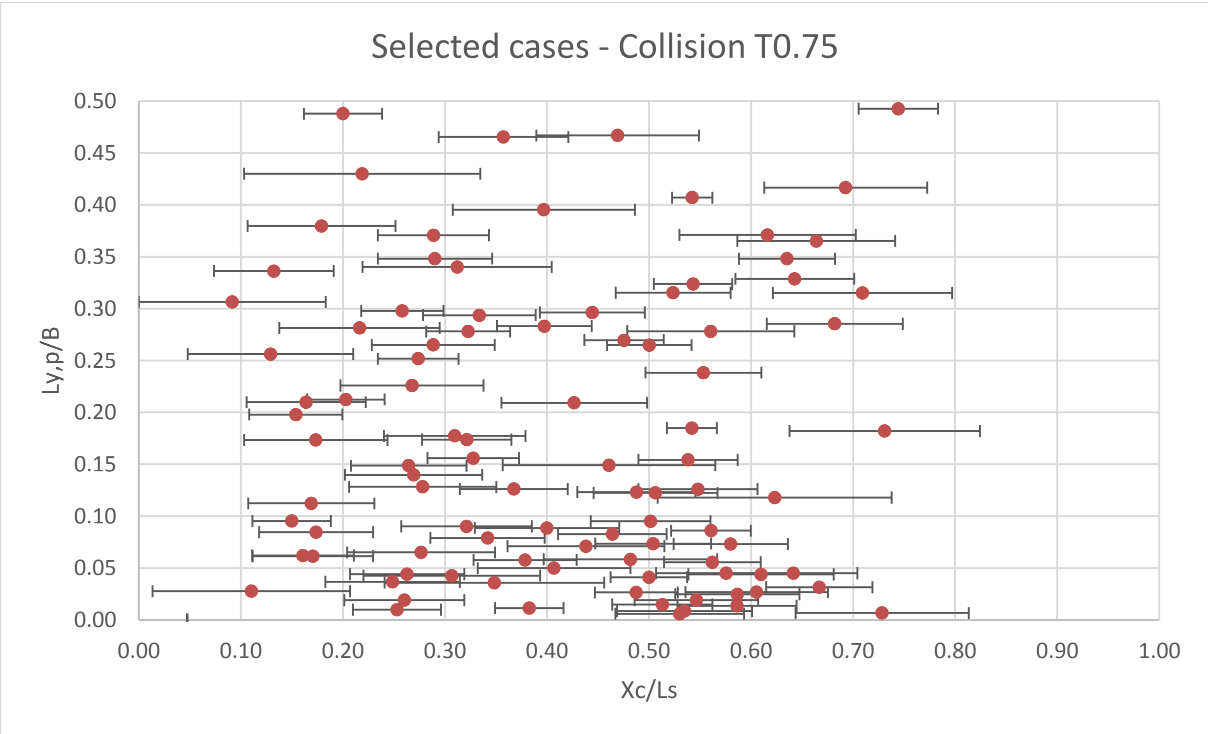


Figure 5 Characteristics of selected collision breaches T0.75 – Ship #9

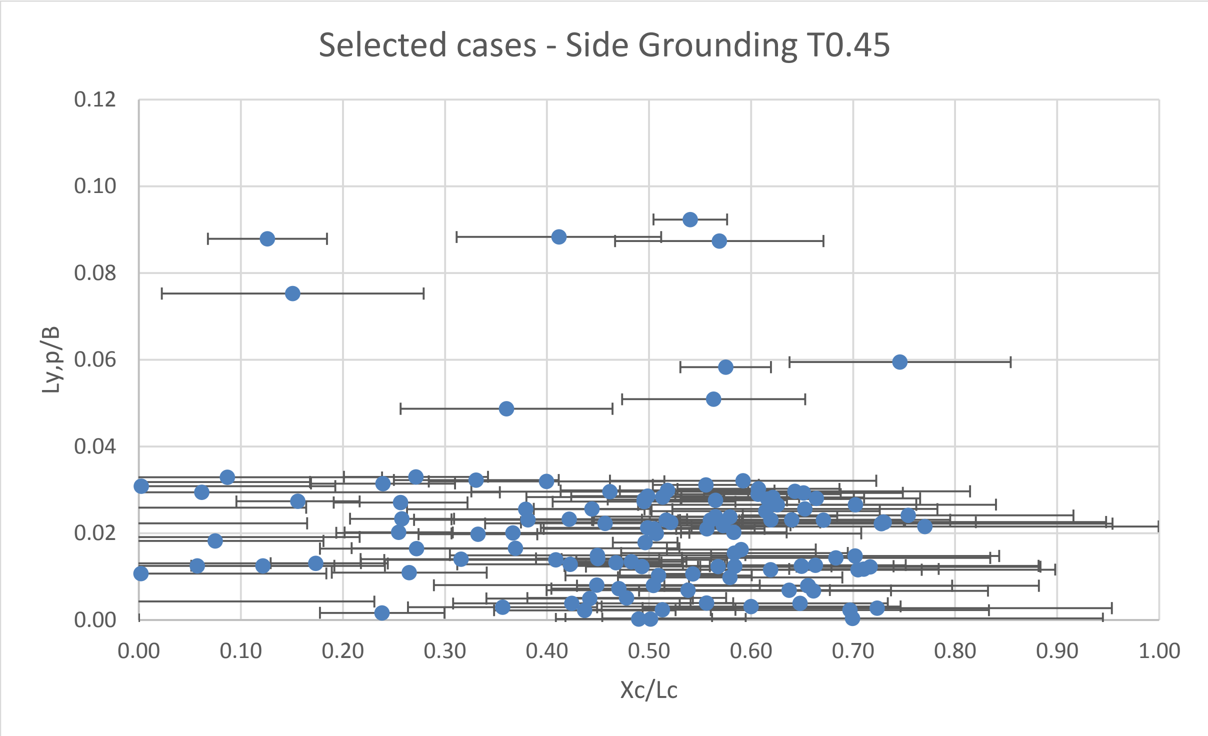


Figure 6 Characteristics of selected side grounding breaches T0.45 – Ship #9

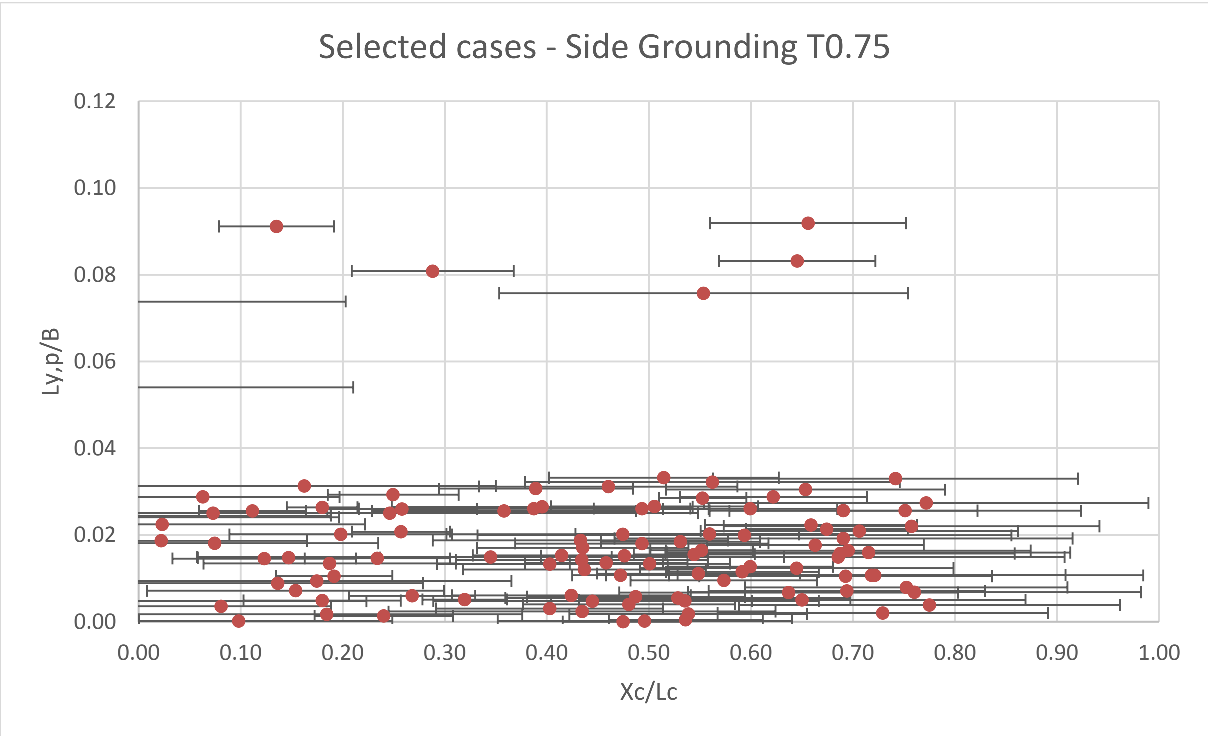


Figure 7 Characteristics of selected side grounding breaches T0.75 – Ship #9

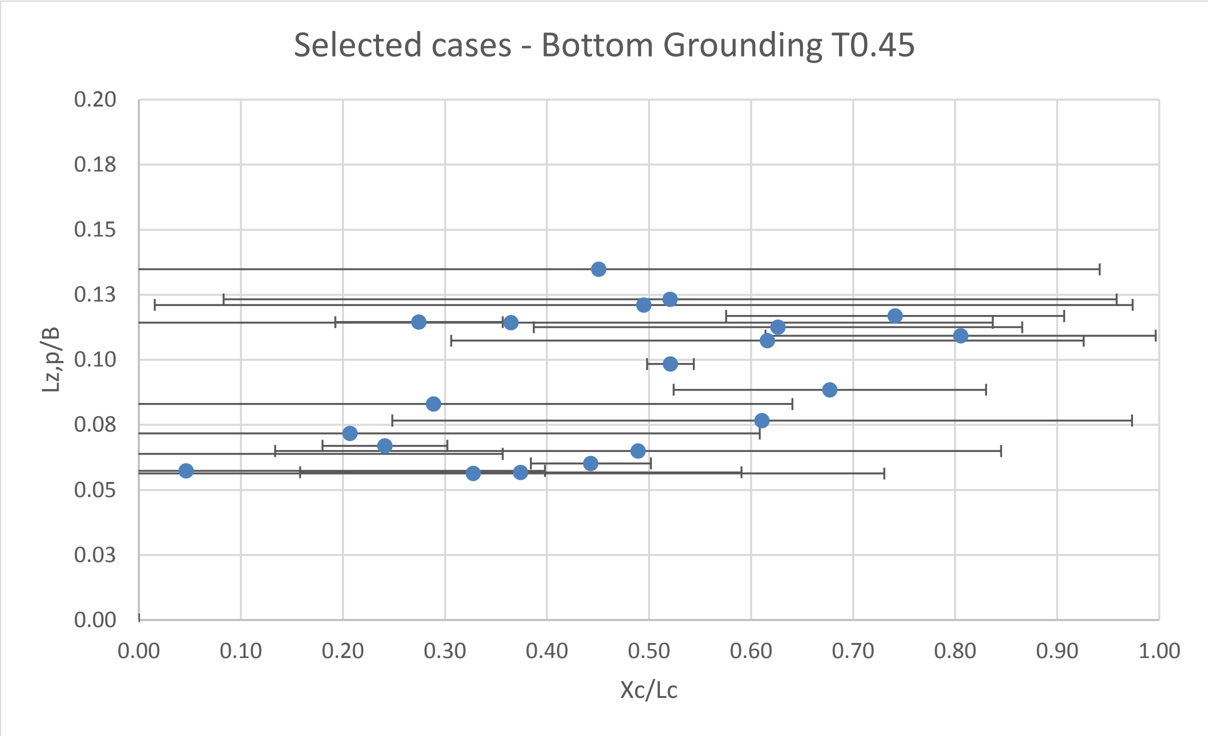


Figure 8 Characteristics of selected bottom grounding breaches T0.45 – Ship #9

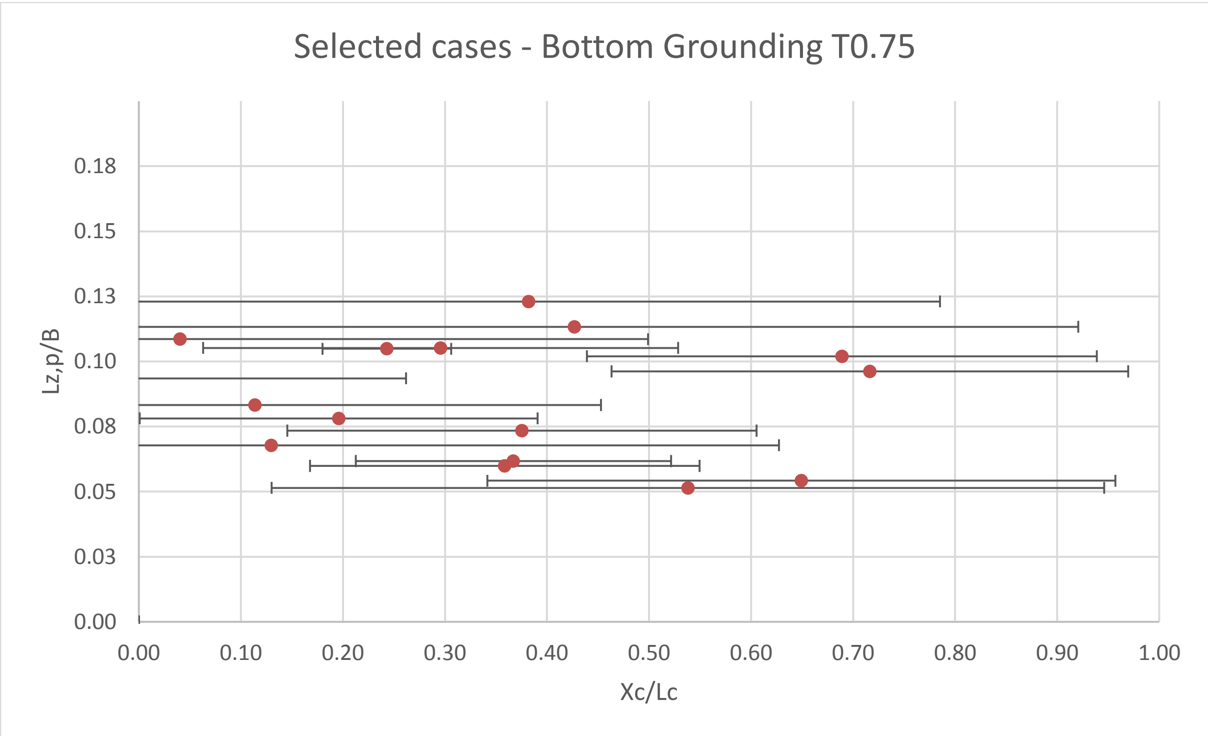


Figure 9 Characteristics of selected bottom grounding breaches T0.75 – Ship #9

From these graphs, it can be noted that:

- For collision breaches there is two vulnerable area : the compartments at the aft of the main engine rooms (in the static deterministic calculation according to "SOLAS90", this zone is the most critical one as damages in this area are driving the required GM) and the compartments just forward the main engine rooms
- For side grounding breaches there is almost the same vulnerable area forward the main engine rooms
- For the bottom grounding breaches there are less filtered breaches. This is due to the fact the ship does not capsize when just the double bottom is affected by flooding.

1.8 Breakdown of failure modes

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with Sfac=0 and failure modes for cases with 0<Sfac<1, are showed in the following tables.

Table 9 Breakdown of failure mode for Sfac=0 cases – Ship #9

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	4	2	0	0	0	0	**6**
Heeling Angle (>15 deg)	41	27	18	6	0	0	**92**
Smom=0	40	57	61	79	18	16	**271**
Opening immersion	2	2	3	1	0	0	**8**
Sfac=0 - Total cases	**87**	**88**	**82**	**86**	**18**	**16**	**377**

Table 10 Breakdown of failure mode for 0<Sfac<1 cases – Ship #9

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	0	0	0	0	0	0	**0**
Insufficient Range	0	0	3	2	0	0	**5**
Heeling Angle (>7 deg)	0	0	0	0	0	0	**0**
Insufficient Restoration (GZmax) + Range	5	4	7	4	1	0	**21**
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	**0**
Insufficient Range + Excessive Heel	24	4	24	12	2	0	**66**
Insufficient Restoration (GZmax) + Range + Excessive Heel	12	1	12	6	0	0	**31**
0<Sfac<1 - Total cases	**41**	**9**	**46**	**24**	**3**	**0**	**123**

A large percentage of captured cases resulted into Sfac=0 (377 cases over 500) and about 72% of the selected cases with Sfac=0 had a failure mode corresponding to the heel due to the moment of the crowding of passengers.

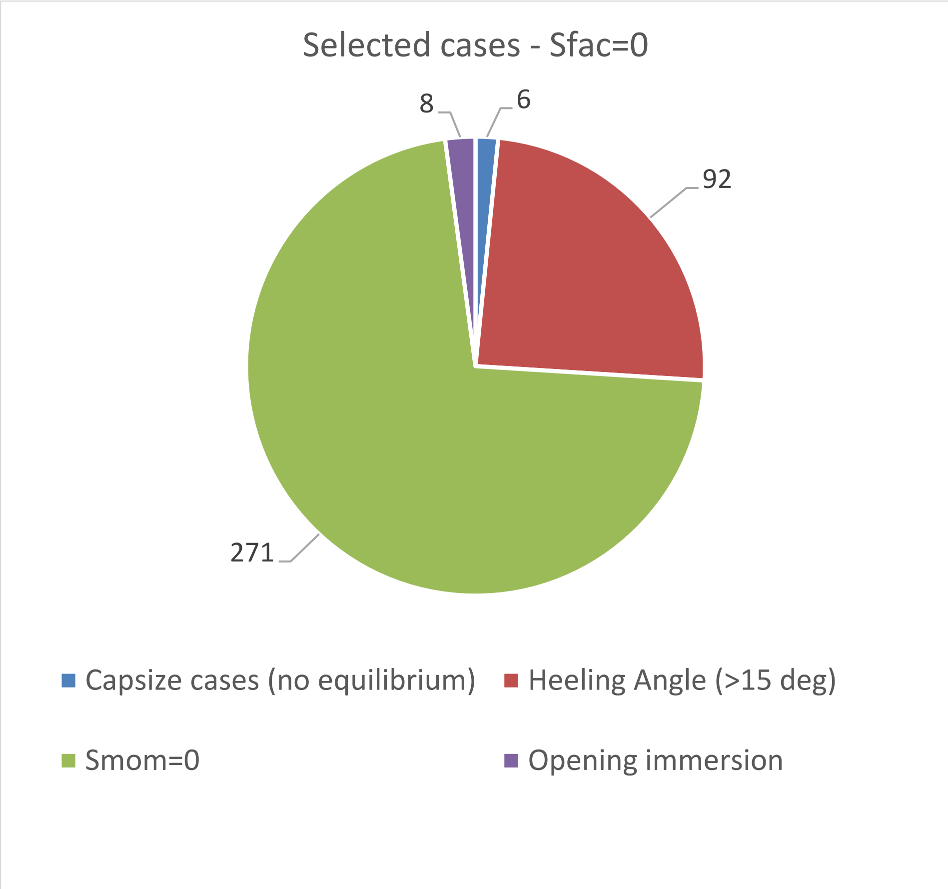


Figure 10 Diagram of failure mode for Sfac=0 cases – Ship #9

A majority of damage cases (n.271) with Smom=0 have been found too while the equilibrium was not reached in the static calculation for only 6 cases.

In the majority of the cases where equilibrium was not achieved the cause was found at the progressive stage of flooding after the cross-flooding. It is interesting to assess those cases by dynamic simulations so that the real physics of the phenomenon will be investigated because it is possible that the progressive flooding may begin during the cross-flooding stage.

Finally, only 8 cases have been identified due to the immersion of openings. These cases are very important to be selected too as it is expected that the outcome of the dynamic simulation should be quite different. In fact the approach for connections and openings definition is completely different between static and dynamic calculation.

123 damage cases with 0<Sfac<1 have been selected. The majority of these cases (66) resulted in an insufficient range+excessive heel, then 31 cases resulted in an insufficient restoration (GZmax)+range+excessive heel.

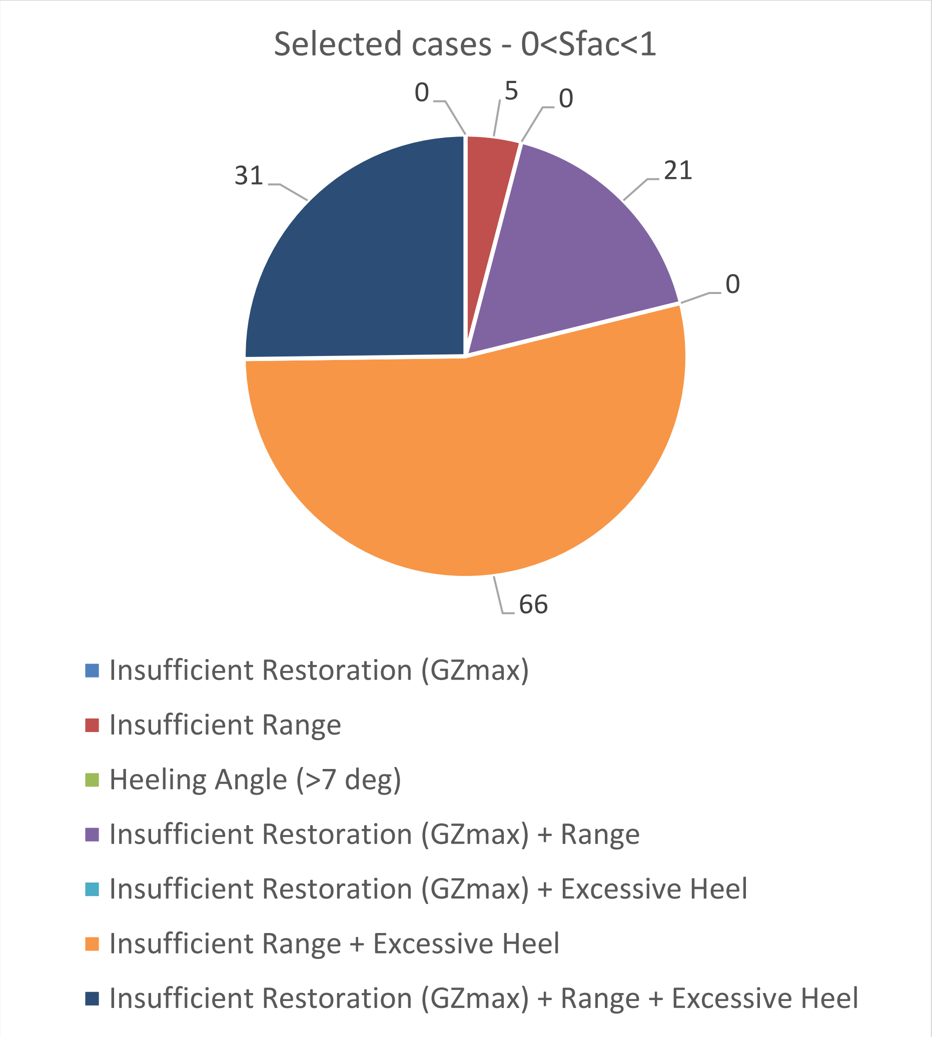


Figure 11 Diagram of failure mode for 0<Sfac<1 cases – Ship #9

2 DYNAMIC ASSESSMENT

2.1 Preparation of the PROTEUS model

The dynamic analysis has been carried out by use of the software *PROTEUS* [12]. In particular for the preparation of the model the tool Proteus Manager has been used.

To generate in the Proteus Manager the loading conditions defined in NAPA and corresponding to the two calculation draughts at 45% and 75%, the following lightships have been generated:

T_1 = 7.553 m → LIG_1 [Δ=33962 t ; CG (100.42 , 0 , 15.16) m]

T_2 = 7.688 m → LIG_2 [Δ=34757 t ; CG (100.37 , 0 , 14.72) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at seven different deck slices:

TT-=1.59m ; TT+=2.41m ; TD=4.36m ; D0=8.4m ; D1=11m ; D2=13.5m ; D3=17.1m

For this medium cruise ship a total of 754 openings have been defined. Horizontal openings have been defined on the higher deck of the model to capture the down-flooding through engine casings, stair trunks, vertical escape and lifts.

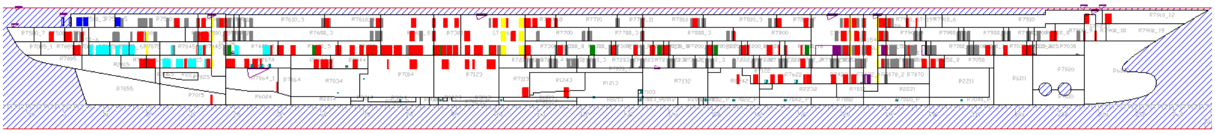


Figure 12 – Openings imported in Proteus Project (longitudinal section)– Ship #9

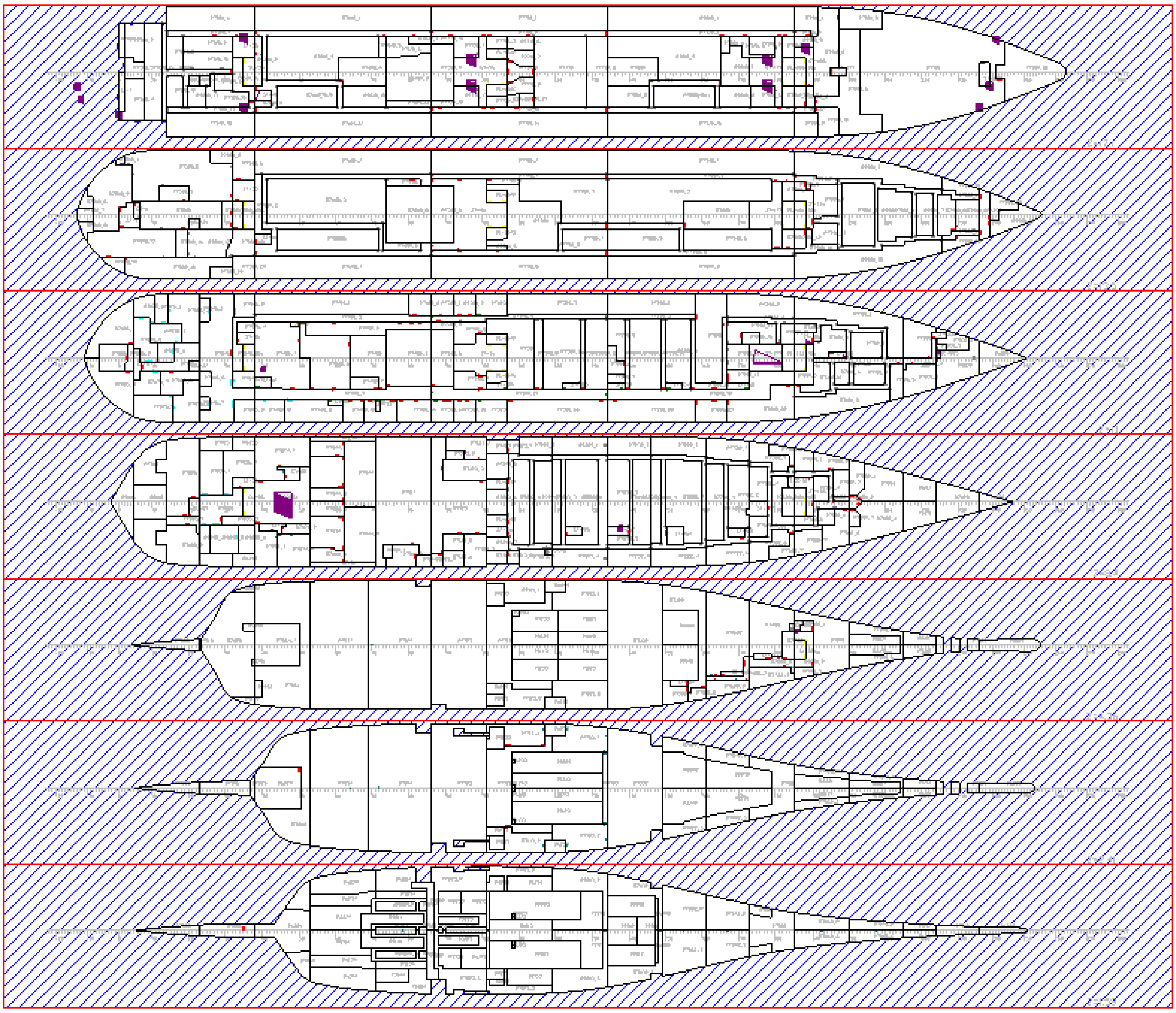


Figure 13 – Openings imported in Proteus Project (horizontal section)– Ship #9

Table 11 Opening Types in Proteus Manager

	Leak Area Ratio	Leak Area Ratio	Collapse Pressure	Collapse Pressure	Leak Height	Gap Height	Effective Height	Open At Time	Close At Time
TYPE	1 to 2	2 to 1	1 to 2 [meters]	2 to 1 [meters]	[meters]	[meters]	HEff Switch	[seconds]	[seconds]
CONNECTION	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
WT-DOOR-LWD	0.02500	0.02500	2.60	2.60	0.000	0.000	False	0	999999
WT-DOOR-SWD	0.02500	0.02500	2.60	2.60	0.000	0.000	False	0	999999
ESCAPE_HATCH	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
ESCAPE_DOOR	0.03000	0.02000	2.50	2.50	0.000	0.000	False	0	999999
FDOOR-HINGED	0.03000	0.02000	2.50	2.50	0.000	0.000	False	0	999999
FDOOR-HINGED-DOUBLE	0.02500	0.02500	2.00	2.00	0.000	0.000	False	0	999999
FDOOR-SLIDING	0.02500	0.02500	1.00	1.00	0.000	0.000	False	0	999999
COLDROOM-DOOR-SLIDING	0.03000	0.03000	3.50	3.50	0.000	0.000	False	0	999999
COLDROOM-DOOR-HINGED	0.03000	0.02000	3.50	3.50	0.000	0.000	False	0	999999
COLD-DOOR-HINGED-DOUBLE	0.02500	0.02500	3.50	3.50	0.000	0.000	False	0	999999
CABINS-DOOR	0.03000	0.03000	1.50	1.50	0.000	0.000	False	0	999999
LIFT-SLIDING_DOOR	0.03000	0.03000	1.50	1.50	0.000	0.000	False	0	999999
EXTERNAL-DOOR	0.00100	0.00100	100.00	100.00	99.000	0.000	False	0	999999
FREE-OPENING	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
CROSS_FLOODING-PIPE	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
CROSS_FLOODING-HATCH	0.00000	0.00000	0.50	0.50	0.000	0.000	False	0	999999

Since in Proteus the discharge coefficient for the flow through openings is set to a constant value of 0.6 and it may be not changed, the area of the cross-flooding openings has been partly reduced in order to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation set have been created and the comparison of the geometric and hydrostatic data between NAPA and Proteus showed that the differences are negligible in general (from Figure 14 to Figure 21).

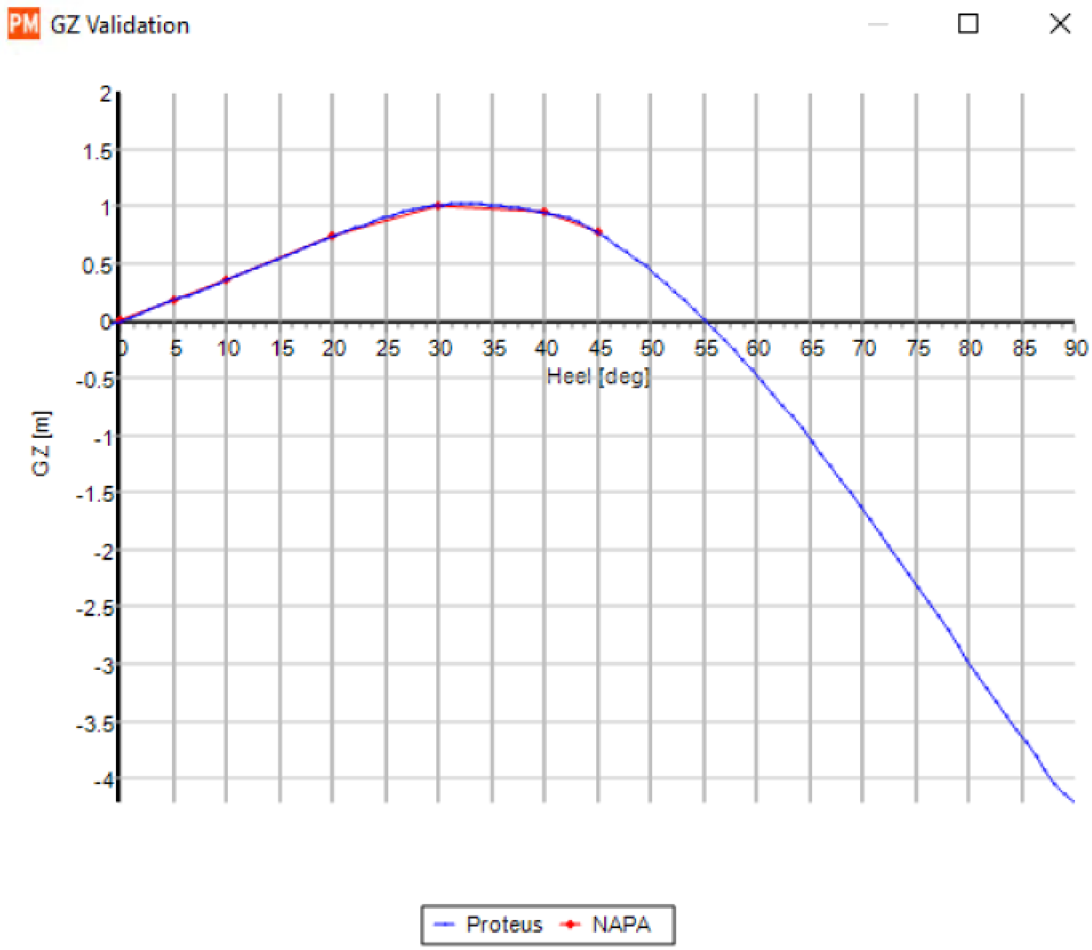


Figure 14 – GZ comparison between NAPA and Proteus – Ship #9

Loadcase Validation

GZ Curve | Floating Position | Volume and CGs | Section Areas

Floating Position

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	7.550	7.553	-0.003	-0.040
TA [m]	7.549	7.557	-0.008	-0.106
TF [m]	7.550	7.550	0.000	0.000
Trim [deg]	0.001	0.007	-0.006	0.000
Heel [deg]	0.000	0.011	-0.011	-100.000
KM [m]	17.197	17.200	-0.003	-0.017
KG [m]	15.163	15.160	0.003	0.020
GM0 [m]	2.034	2.037	-0.003	-0.147
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	2.034	2.037	-0.003	-0.147

Loadcase Validation

GZ Curve | Floating Position | Volume and CGs | Section Areas

Floating Position

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	7.684	7.688	-0.004	-0.052
TA [m]	7.684	7.691	-0.007	-0.091
TF [m]	7.684	7.685	-0.001	-0.013
Trim [deg]	0.000	0.006	-0.006	0.000
Heel [deg]	0.000	0.010	-0.010	0.000
KM [m]	16.998	17.033	-0.035	-0.206
KG [m]	14.719	14.720	-0.001	-0.007
GM0 [m]	2.279	2.314	-0.035	-1.536
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	2.279	2.314	-0.035	-1.536

Figure 15 – Floating Position comparison between NAPA and Proteus – Ship #9

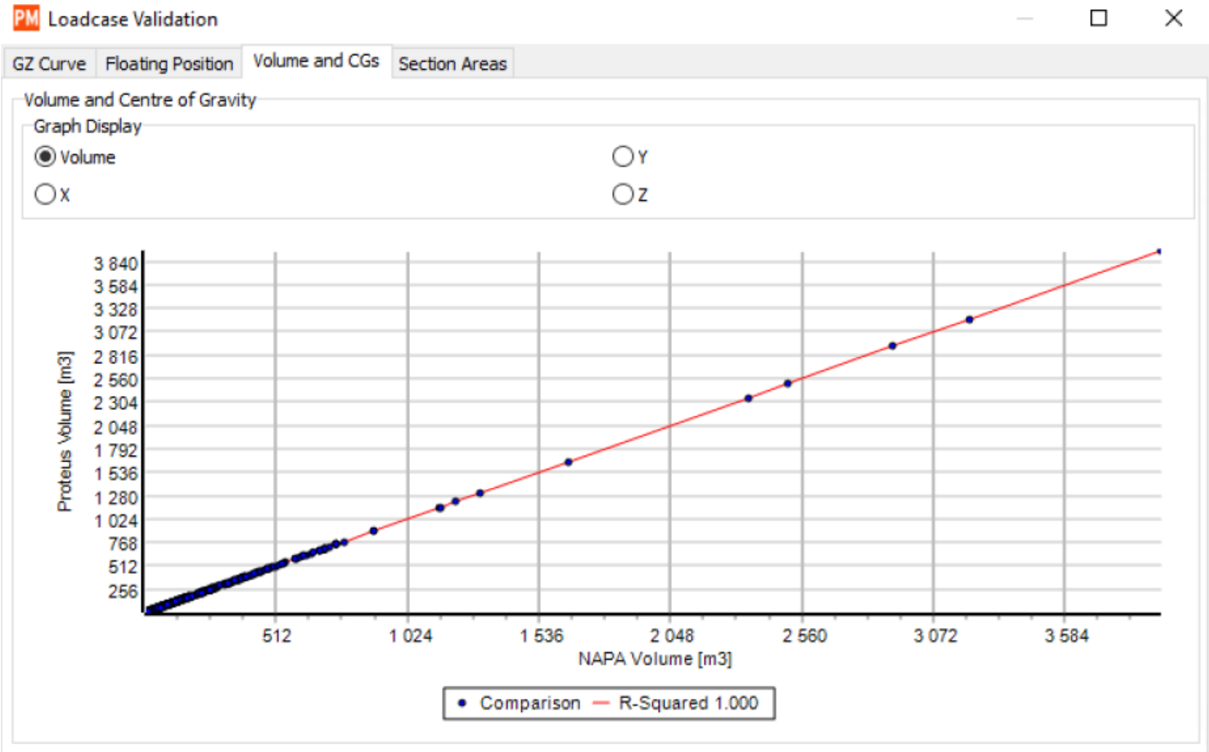


Figure 16 – Hull volume comparison between NAPA and Proteus – Ship #9

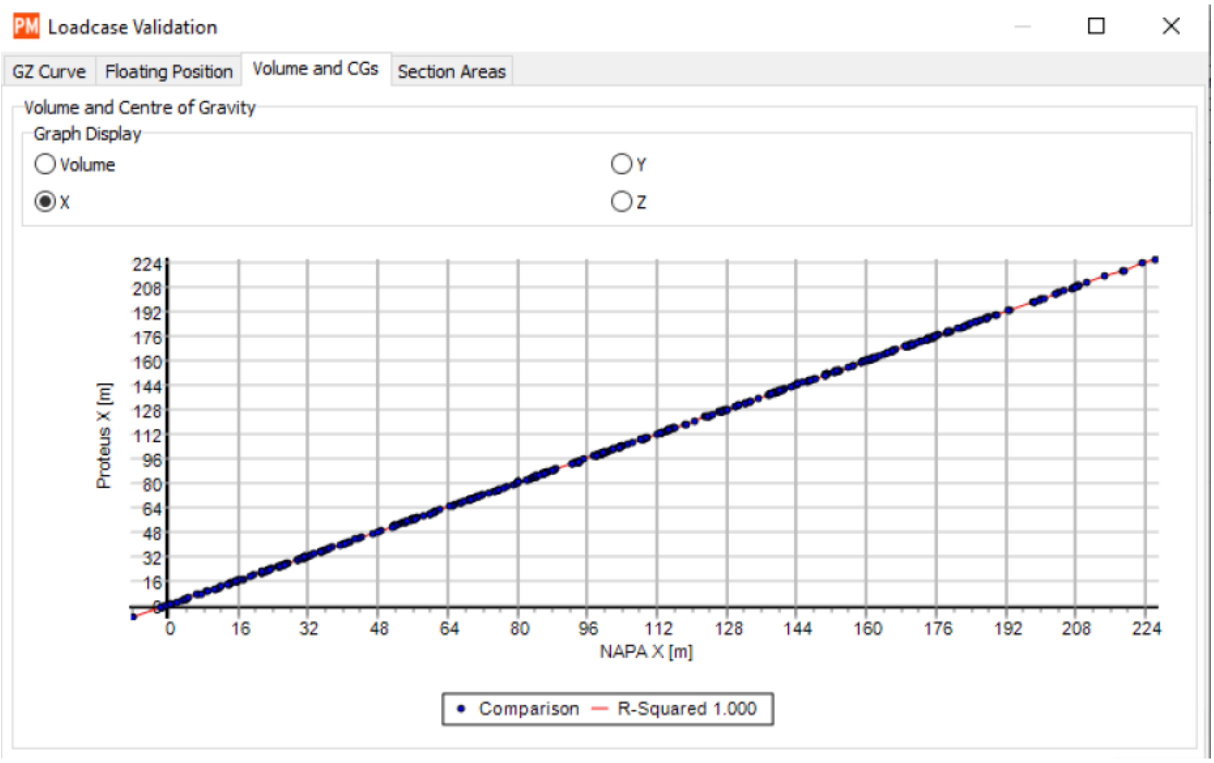


Figure 17 – Hull LCB comparison between NAPA and Proteus – Ship #9

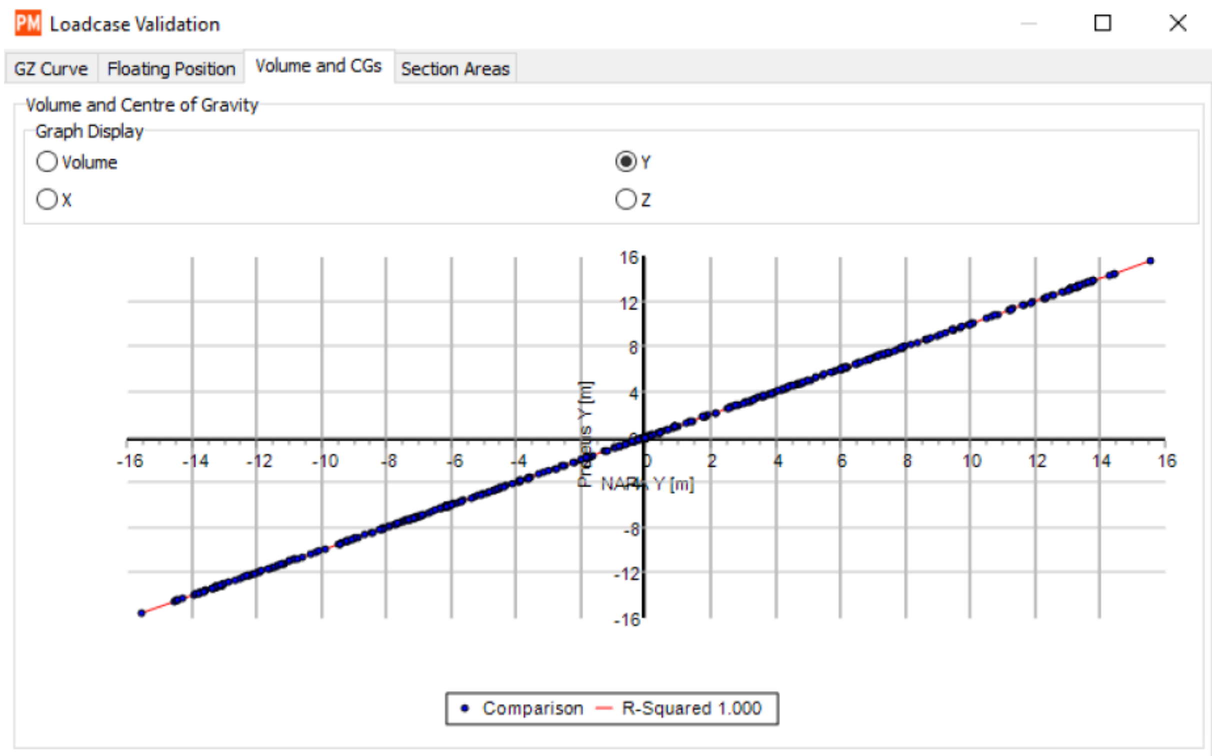


Figure 18 – Hull TCB comparison between NAPA and Proteus – Ship #9

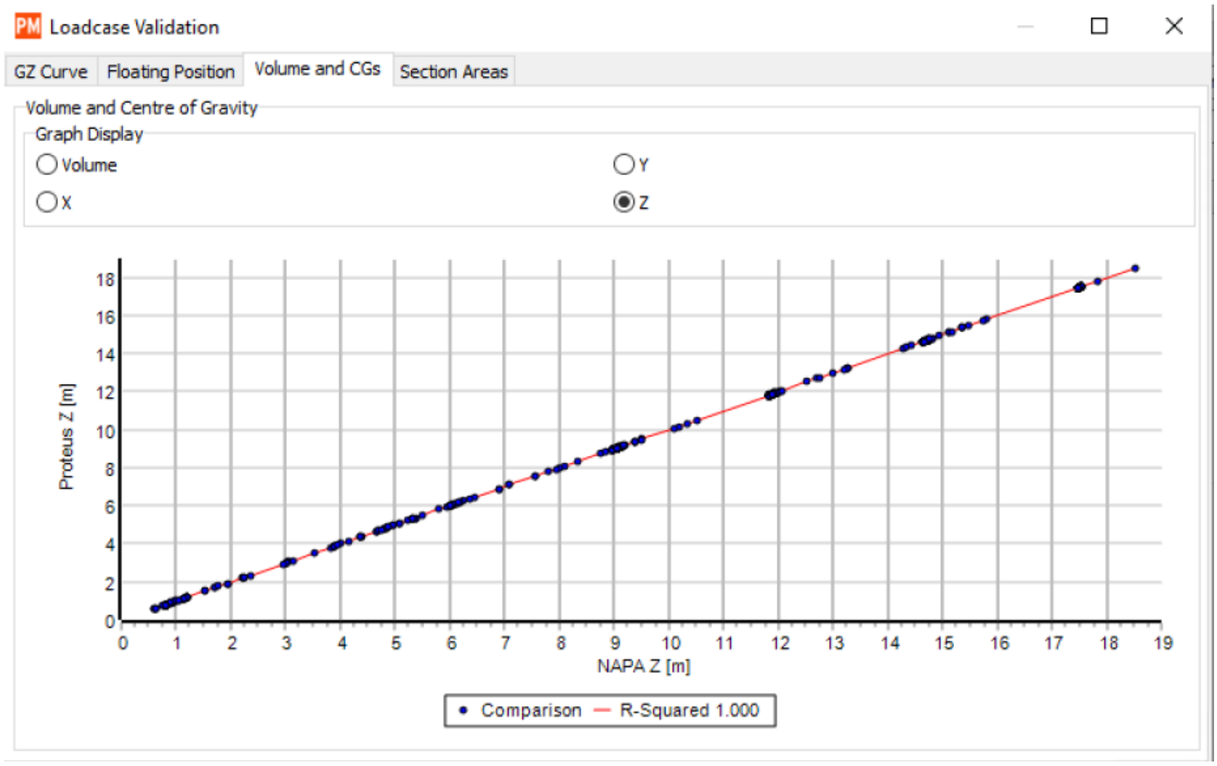
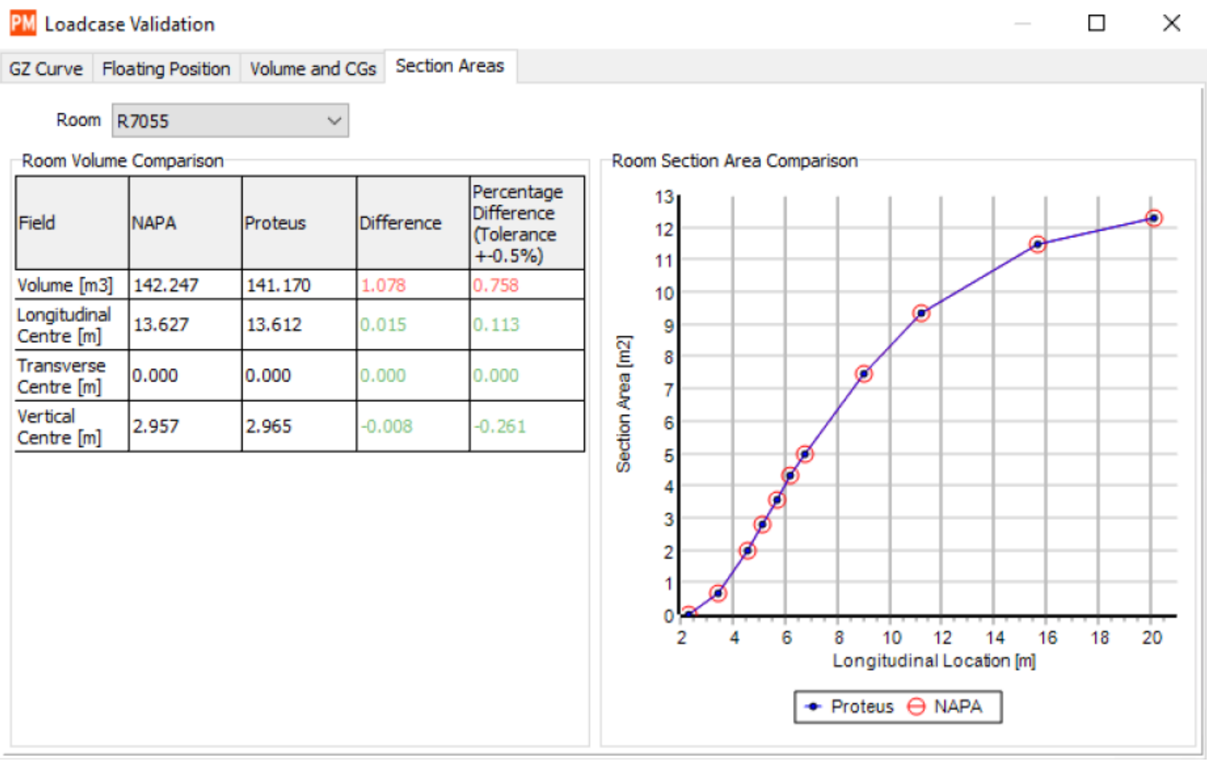
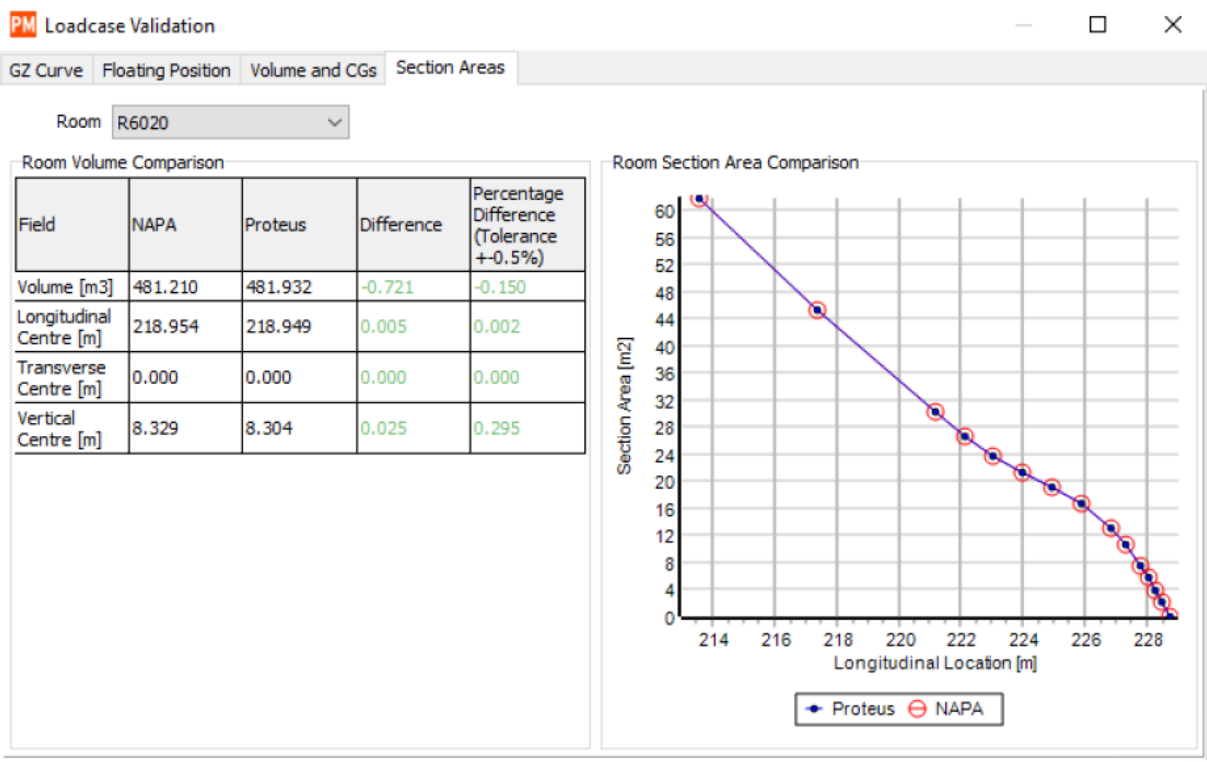


Figure 19 – Hull VCB comparison between NAPA and Proteus – Ship #9



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	142.247	141.170	1.078	0.758
Longitudinal Centre [m]	13.627	13.612	0.015	0.113
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	2.957	2.965	-0.008	-0.261

Figure 20 – Aftpeak comparison between NAPA and Proteus – Ship #9



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	481.210	481.932	-0.721	-0.150
Longitudinal Centre [m]	218.954	218.949	0.005	0.002
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	8.329	8.304	0.025	0.295

Figure 21 – Forepeak comparison between NAPA and Proteus – Ship #9

2.2 Results of dynamic simulations

In the first round of dynamic simulations by Proteus all the 500 breaches have been simulated up to 30 minutes, then for 182 breaches a second simulation round has been executed up to 80 minutes (cruise ship with 6 MVZ main vertical zone), as these were found with progressive flooding still occurring at the end of the first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1=capsize 0=not capsize) and TTC for cases where a capsize was found. In the following graphs the results for each hazard and the global results of simulations are presented.

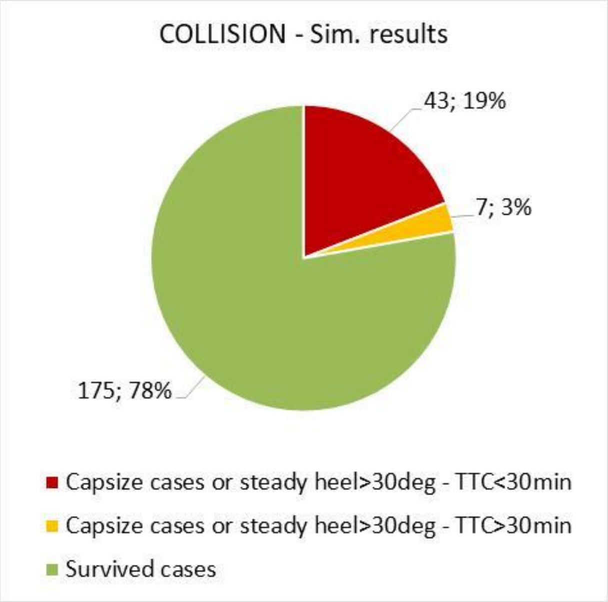


Figure 22 – Simulation results for collision – Ship #9

Figure 23 – Simulation results for side grounding – Ship #9

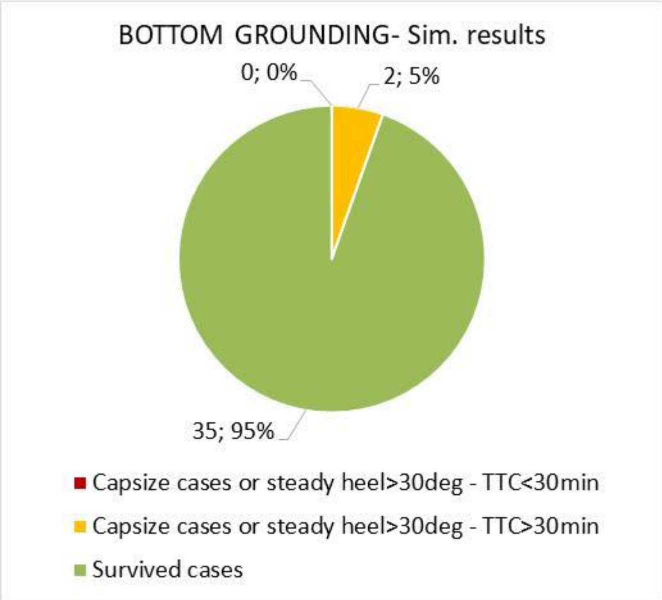


Figure 24 – Simulation results for bottom grounding – Ship #9

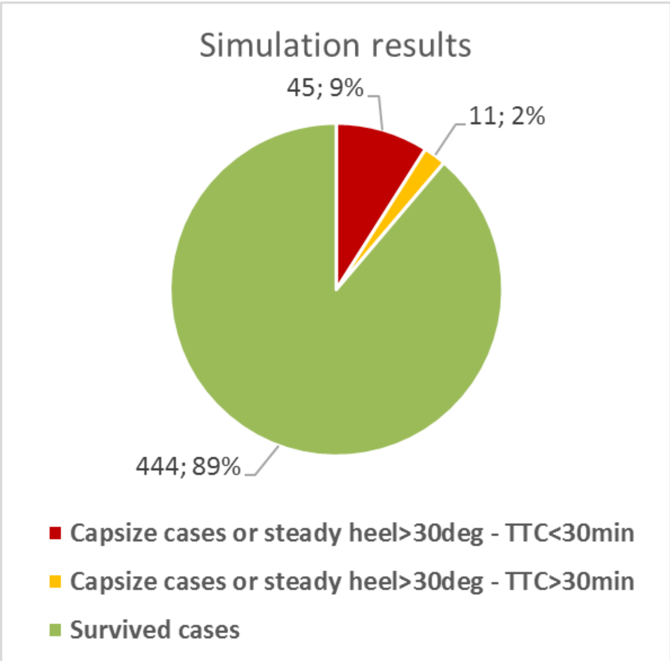


Figure 25 – Global simulation results for the 500 filtered breaches – Ship #9

The results obtained clearly show that for most of cases (89%) the ship did not capsize, which confirmed that the static results are conservative as almost all of these case have had a Sfac=0 in the static analysis.

Furthermore, the last graph shows that 80% of the capsize cases are fast capsize cases. For those cases, there is no sufficient time to orderly evacuate as the TTC is less than 30 minutes.

2.3 Calculation of PLL level 2.1

The results of the flooding simulations permit to get the TTC, therefore the fatality rate may be estimated for the cases with TTC>30min according to the procedure for calculation of Risk (Level 2.1).

In the Table 12 the details of the results obtained by static and dynamic simulations are reported. It can be observed that the PLL from the static calculation has been reduced by nearly 12% from 1.4204 (Level 1) to 1.2542 (Level 2.1) when using dynamic simulation.

Table 12 PLL level 2.1 – Ship #9

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	7.553	7.688	7.553	7.688	7.553	7.688	
PLL L1 (1/ship year) (static assessment)	**4.38E-01**	**3.97E-01**	**2.17E-01**	**2.02E-01**	**7.98E-02**	**8.66E-02**	**1.4204**
	0.8349		**0.4190**		**0.1664**		
Number of filtered damage cases	128	97	128	110	21	16	500
Capsize cases or steady heel>30deg - TTC<30min	22	21	2	0	0	0	45
Capsize cases or steady heel>30deg - TTC>30min	3	4	1	1	1	1	11
Survived cases	103	72	125	109	20	15	444
PLL L2.1 (1/ship year) (dynamic assessment)	**3.97E-01**	**3.71E-01**	**1.70E-01**	**1.61E-01**	**7.37E-02**	**8.22E-02**	**1.2542**
	0.7677		**0.3306**		**0.1559**		
PLL L2.1 vs L1 (variation percentage)	**-8.1%**		**-21.1%**		**-6.3%**		**-11.7%**

In the following figures the diagrams of the breaches which lead to capsize after dynamic simulations are reported.

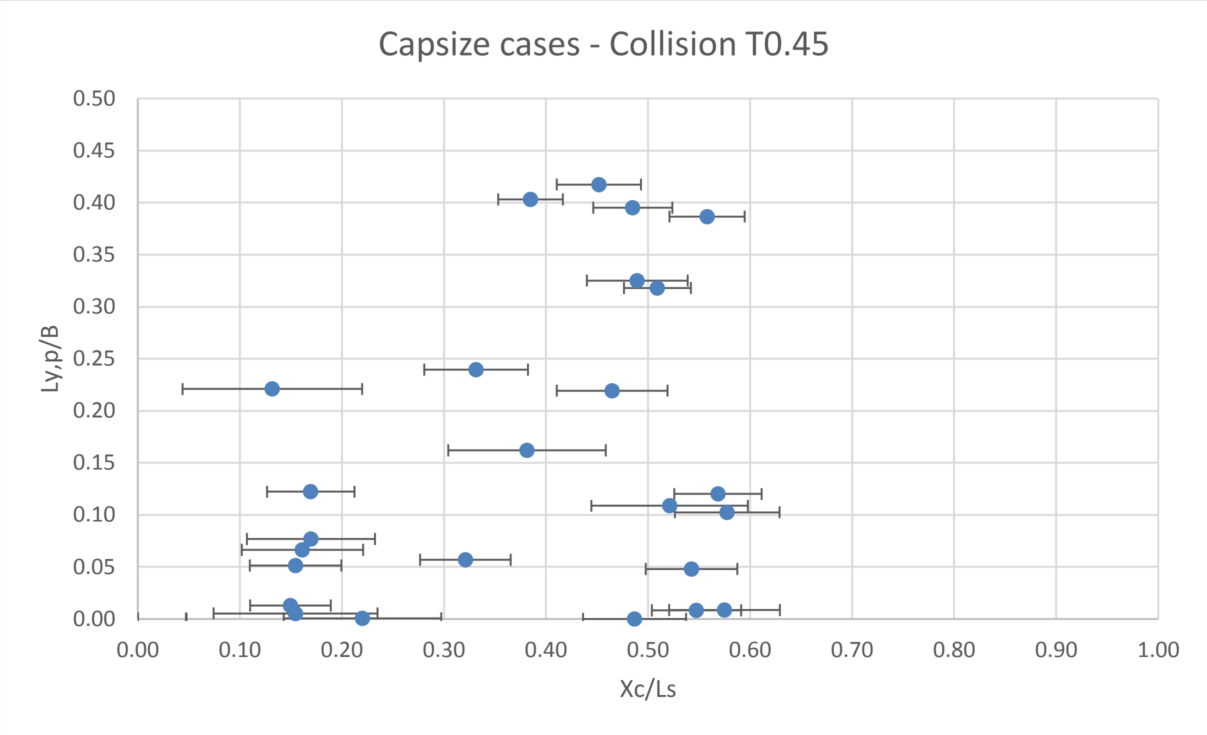


Figure 26 Characteristics of collision breaches leading to capsize T0.45 – Ship #9

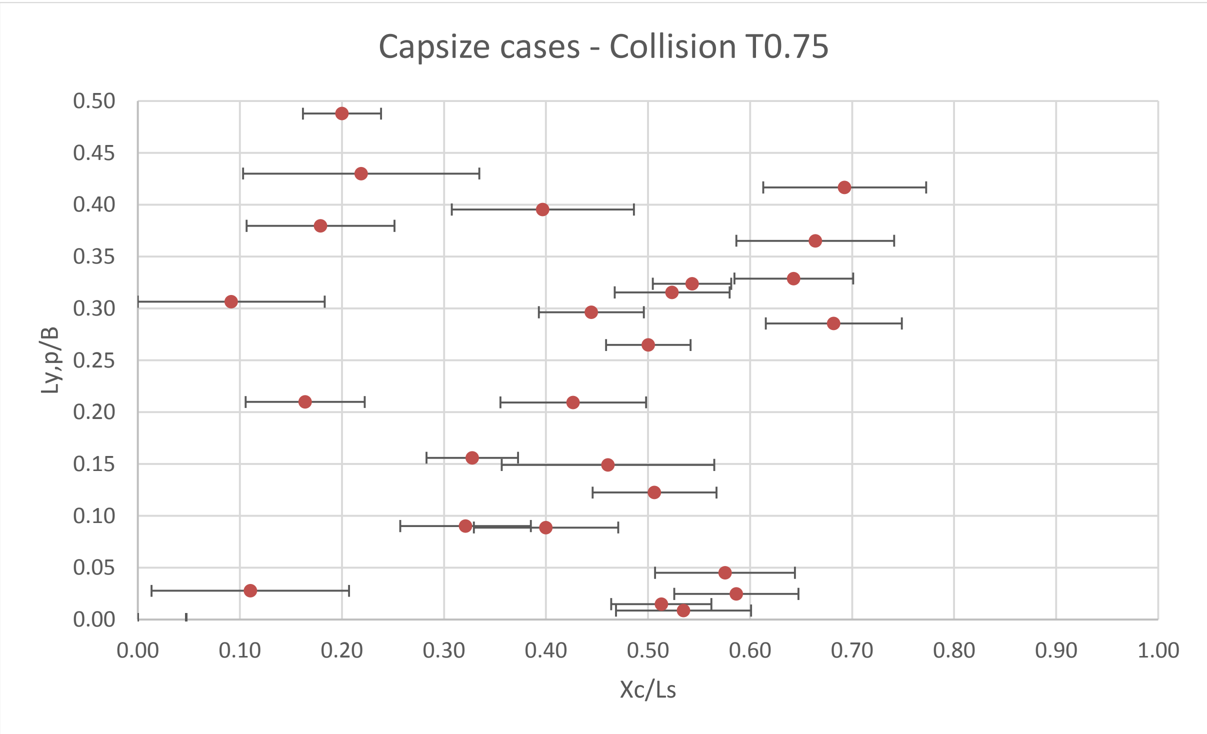


Figure 27 Characteristics of collision breaches leading to capsize T0.75 – Ship #9

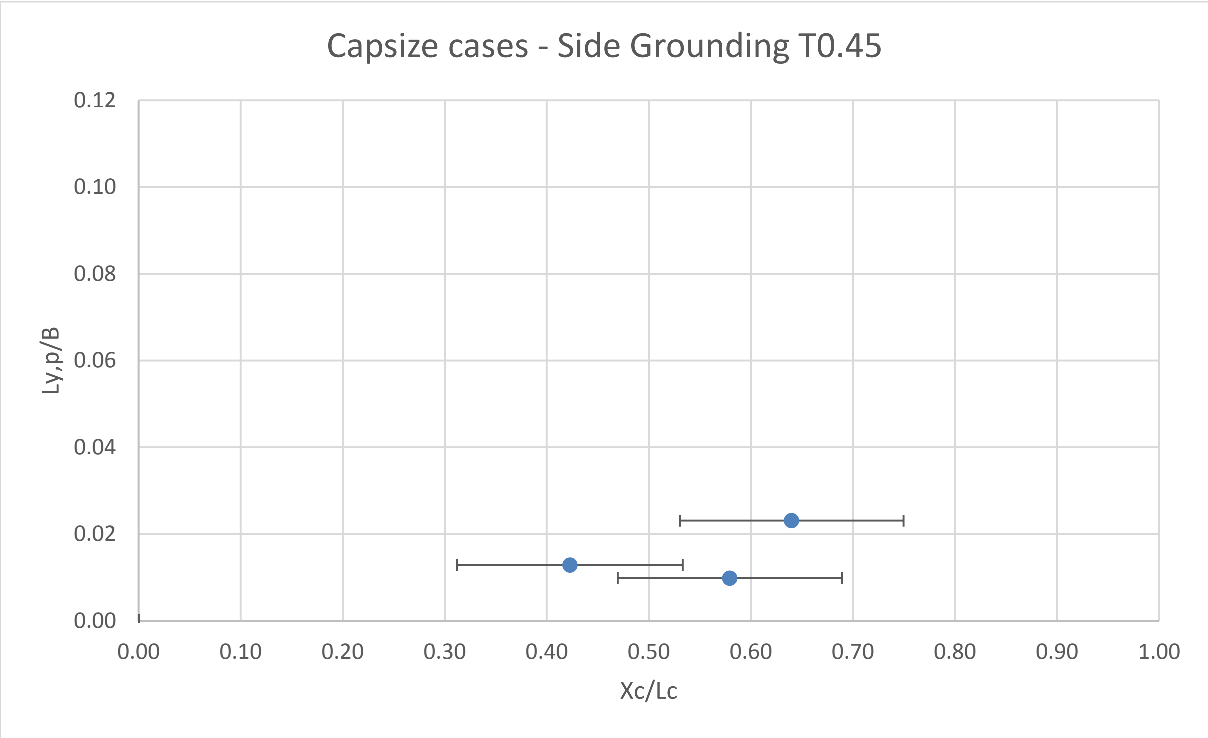


Figure 28 Characteristics of side grounding breaches leading to capsize T0.45 – Ship #9

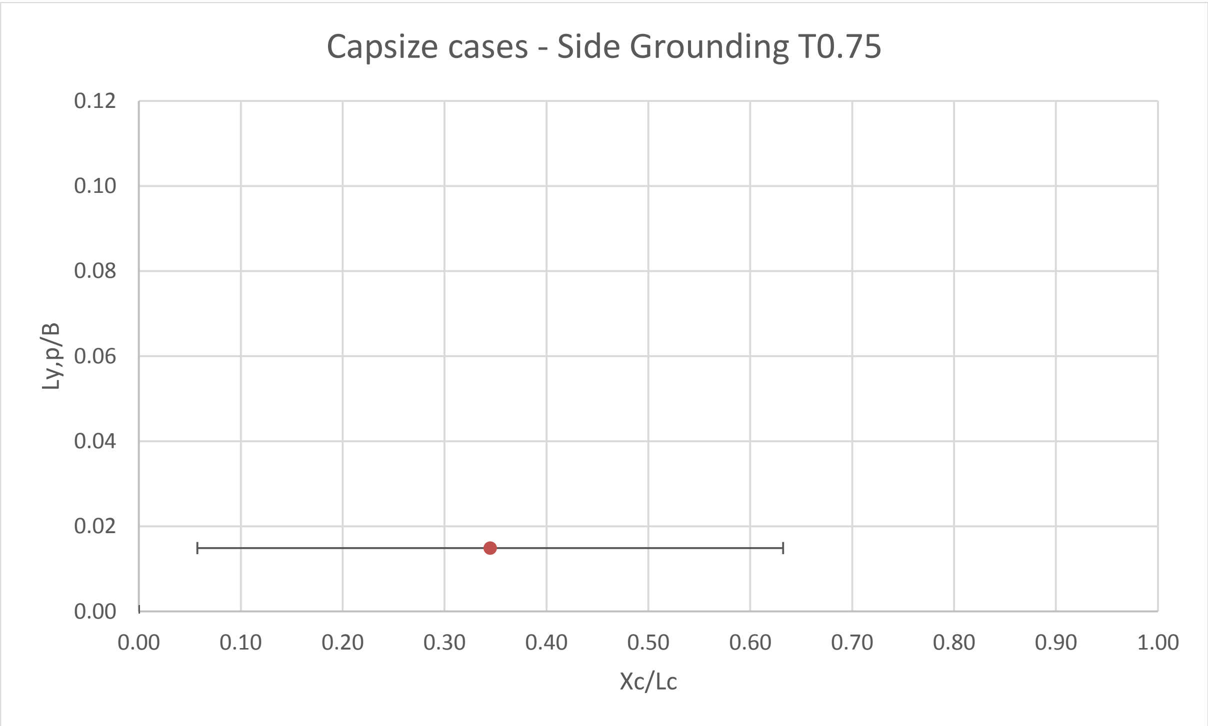


Figure 29 Characteristics of side grounding breaches leading to capsize T0.75 – Ship #9

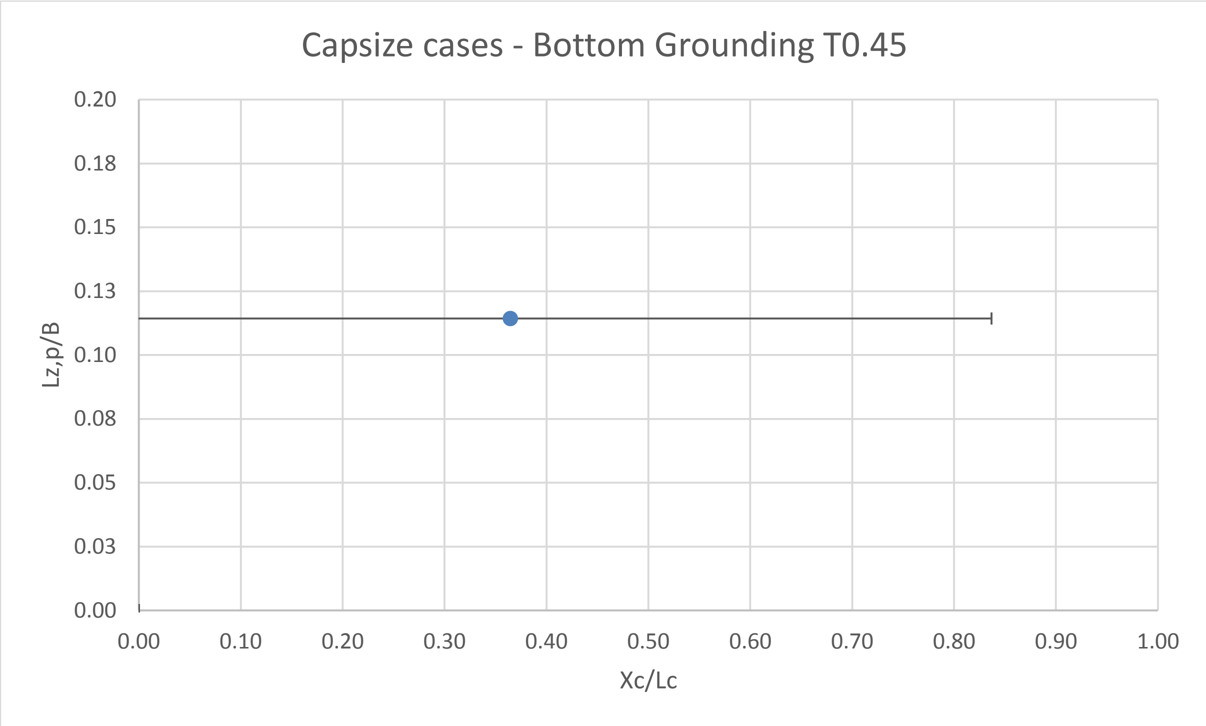


Figure 30 Characteristics of bottom grounding breaches leading to capsize T0.45 – Ship #9

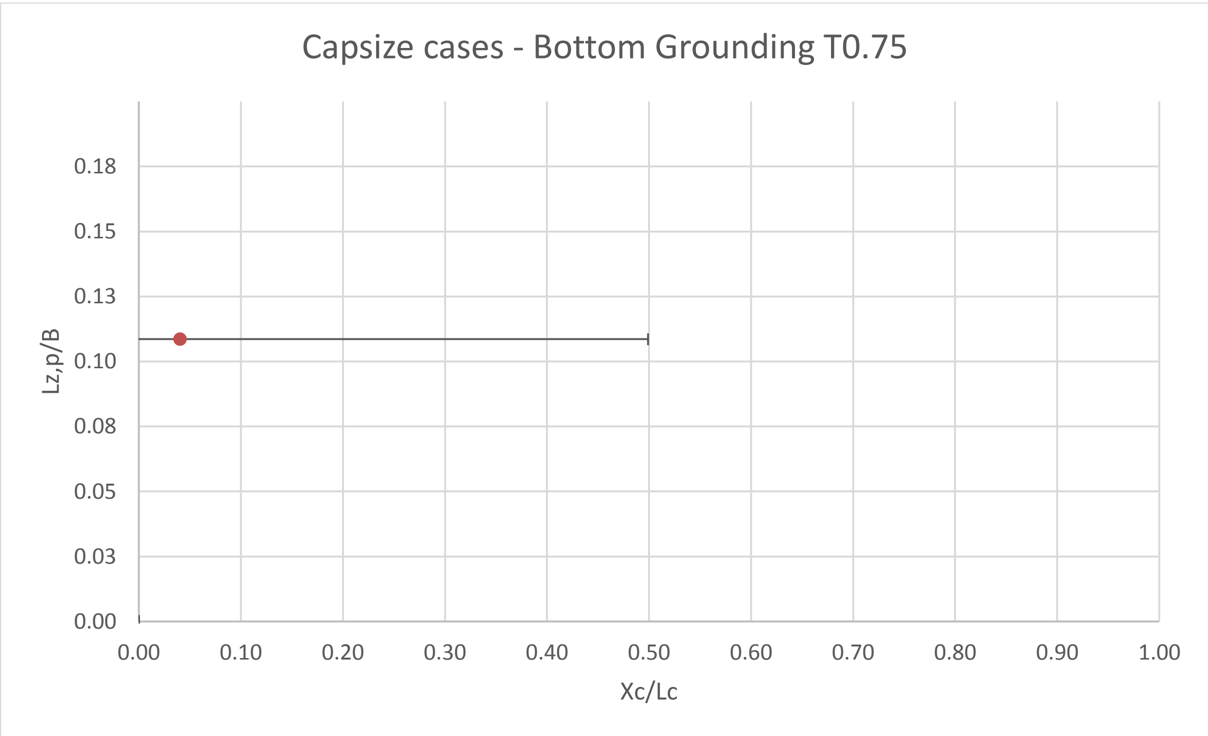


Figure 31 Characteristics of bottom grounding breaches leading to capsize T0.75 – Ship #9

The identified capsizal cases showed in the Figure 26 to Figure 31 may be investigated in WP7.2 when Risk Control Options are to be implemented.

2.4 Sensitivity analysis of the fatality rate

From the dynamic simulation results it has been observed that 11 cases resulted into a TTC greater than 30 min but lower than 80 min simulation. For those cases linear Interpolation between 0% and 80% has been used for the estimation of the fatality rates (equation 5 of the main report). Furthermore, there are further 65 cases where progressive flooding is still occurring after 80 min and for these cases no fatality has been assumed (Figure 32).

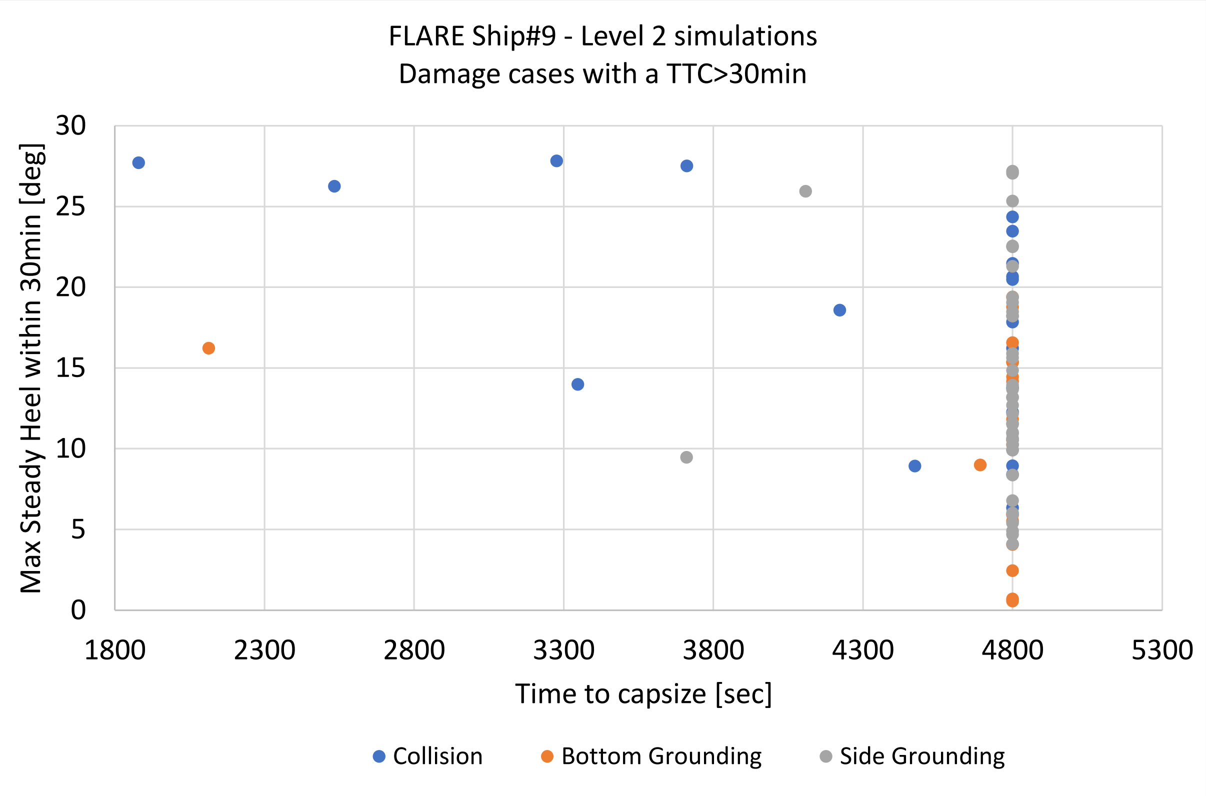


Figure 32 Cases with TTC>30min or progressive flooding still occurring after 80min – Ship #9

In order to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out for the total 76 cases (with TTC>30 min or progressive flooding still occurring after 80 min). For this, the impact on the PLL has been evaluated by use of the simplified formula (main report equation 5) but assuming a variation of the fatality rate by ± 30% of the POB.

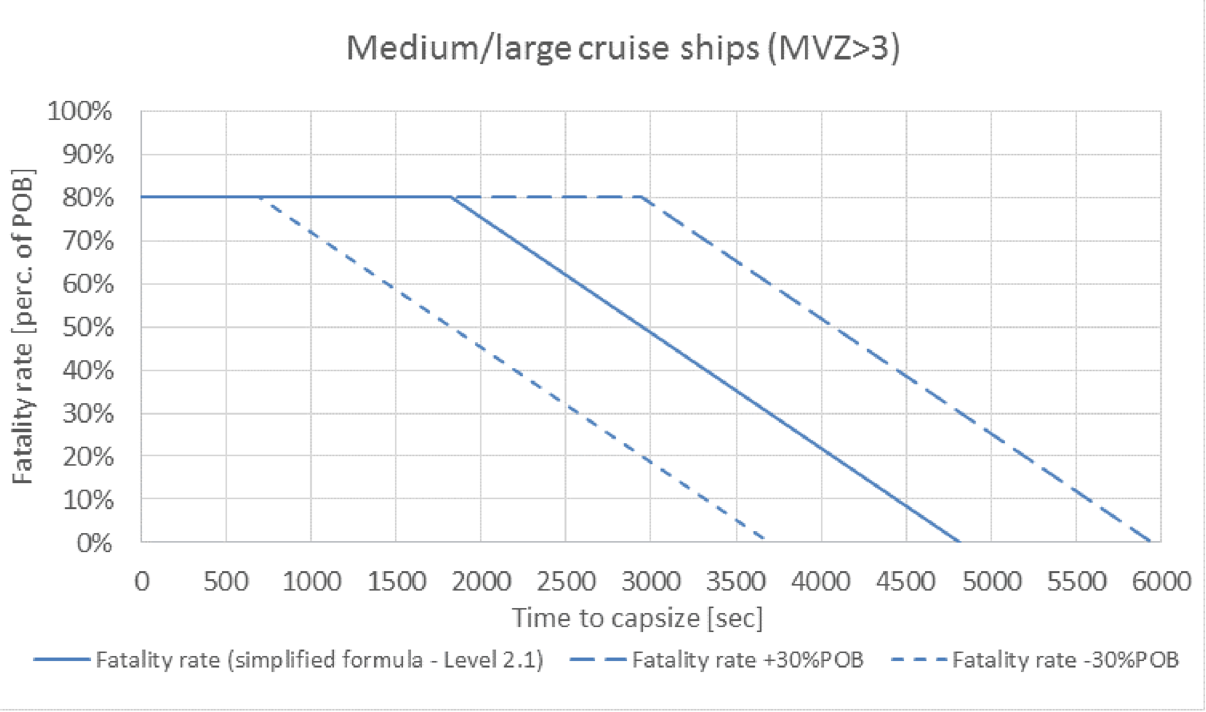


Figure 33 Sensitivity analysis of simplified formula for fatality rate calculation – Ship #9

Table 13 PLL level 2.1 variation of fatality rate – Ship #9

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	7.553	7.688	7.553	7.688	7.553	7.688	
PLL L1 (1/ship year) (static assessment)	4.38E-01	3.97E-01	2.17E-01	2.02E-01	7.98E-02	8.66E-02	**1.4204**
	0.8349		0.4190		0.1664		
PLL L2.1 (1/ship year) (dynamic assessment)	3.97E-01	3.71E-01	1.70E-01	1.61E-01	7.37E-02	8.22E-02	**1.2542**
	0.7677		0.3306		0.1559		
PLL L2.1 vs L1 (variation percentage)	-8.1%		-21.1%		-6.3%		**-11.7%**
PLL L2.1 (1/ship year) with fatality rate increased by 30%	3.98E-01	3.72E-01	1.72E-01	1.64E-01	7.46E-02	8.32E-02	**1.2636**
	0.7700		0.3358		0.1578		
	+0.3%		+1.2%		+1.2%		**+0.7%**
PLL L2.1 (1/ship year) with fatality rate reduced by 30%	3.96E-01	3.71E-01	1.70E-01	1.61E-01	7.37E-02	8.21E-02	**1.2532**
	0.7670		0.3305		0.1558		
	-0.1%		-0.0%		-0.1%		**-0.1%**

The calculation with +30% in the fatality rate resulted into a PLL of 1.2636 (+0.7% compared to the reference PLL) while the calculation with -30% for the fatality rate resulted into a PLL of 1.2532 (-0.1% compared to the reference PLL). These values demonstrated that for this ship the simplified formula to derive the fatality rate used in the calculation of risk (Level 2.1) gives a reasonable accuracy. An evacuation simulation assessing the Time to evacuate and therefore refining the fatality rate would not bring any added value.

3 CONCLUSIONS

The complete procedure for calculation of Risk has been applied on Ship 9 and the results obtained demonstrated that the procedure is coherent with the multi-level approach. In fact the PLL has been reduced from 1.4204 (level 1) to 1.2542 (level 2.1)

The PLL Level 1 procedure appears conservative, while it seems to be more robust than PLL calculated by EMSA3 Risk Model as the fast/slow sinking node has not been used in the FLARE procedure.

The dynamic analysis in level 2 led to a reduction of the PLL by about 12% with the simulation of 500 breaches. Such reduction of the PLL is essentially based on the fact that about 89% of cases with Sfac =0 in the static analysis have been found to survive in the dynamic analysis. Moreover, although we have calculated the most efficient 500 breaches in term of PLL reduction, it is expected that the dynamic simulation applied on a higher sample of breaches would allow reducing more the PLL for our ship #9. The goal of this task was to demonstrate the process and it could be applied and extended in order to optimize further the result.

The flooding simulations showed a percentage of 80% of fast capsize cases (TTC<30min) and 20% for slow capsize cases (TTC>30min). This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model for which only 18% fast capsizing rate was used.

Furthermore a sensitivity analysis demonstrated that the impact on the PLL level 2.1 by even a large deviation of the fatality rate (calculated with the simplified formula) is negligible (between +0.7% and -0.1%). This in turn shows that an evacuation analysis allowing assessing the time to evacuate would not bring any added value for our ship.

ANNEX 11 – Calculation of the flooding Risk for Ship n.10

CONTENTS

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

Duration: 36 months - Project Start: 01/06/2019 - Project End: 31/05/2022

ABSTRACT

The two-level procedure to calculate the flooding risk of a passenger ship has been applied to a fast Ro-Pax ship, built according the deterministic stability rule SOLAS'90 and Stockholm Agreement, but fulfilling the SOLAS 2009 requirements as well. As a first step, the SOLAS Attained Index has been re-calculated using draughts and permeabilities obtained from WP2.

After this, the ship model has been refined according to the modelling guidelines (Annex 1). The refined model has then been used for the two-level flooding risk is calculation process.

On the basis of the results of EMSA3 [1] and eSAFE project [2] regarding grounding calculation and the non-zonal approach, the probabilistic indices for collision, side grounding/contact and bottom grounding have been calculated. Then, the first level of flooding risk has been calculated using static methods for A-Index and semi-empirical results for the remaining parameters.

Results obtained from Level 1 have been filtered and dynamic simulations have been executed for the selected cases (level 2.1).

The assumptions made for the fatality rate in the calculation for level 2.1 have been validated by an evacuation analysis carried out for the selected scenarios (level 2.2).

1 STATIC ASSESSMENT

1.1 Main data

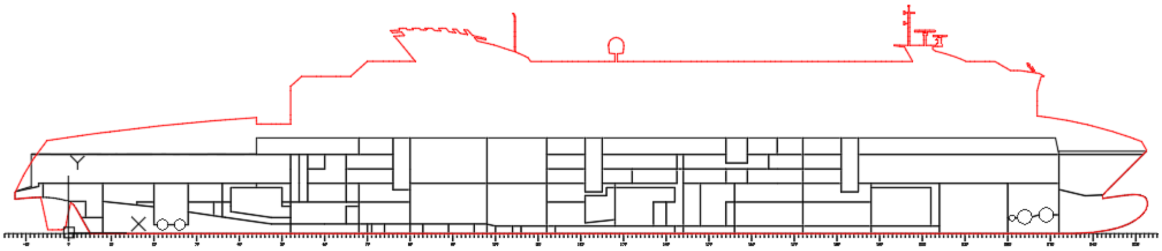


Figure 1 Profile view – Ship #10

Ship #10 is an existing fast RoPax ferry built in 2008. Here are the main characteristics:

Table 1 Main characteristics – Ship #10

Length overall	~211.30 m
Length between perpendiculars	195.3 m
Subdivision length	212.25 m
Breadth	25.8 m
Subdivision draught	6.70 m
Height of bulkhead deck	9.40 m
Number of passengers	2315
Number of crew	85
Gross tonnage	36822 GT

As a late addition to FLARE, a business model and detailed description of the vessel are not included in deliverable D.2.1.

Here following the Attained and Required Index according to SOLAS ch.II-1:

Number of persons	POB = 2400
Required subdivision index (SOLAS 2009)	R = 0.8015
Required subdivision index (SOLAS 2020)	R = 0.8675
Attained subdivision index	A = 0.8142

1.2 Static calculations with new draughts and permeabilities

The following diagram shows the draughts and the calculated GM for this vessel based on Ch. 3.1 of the main report.

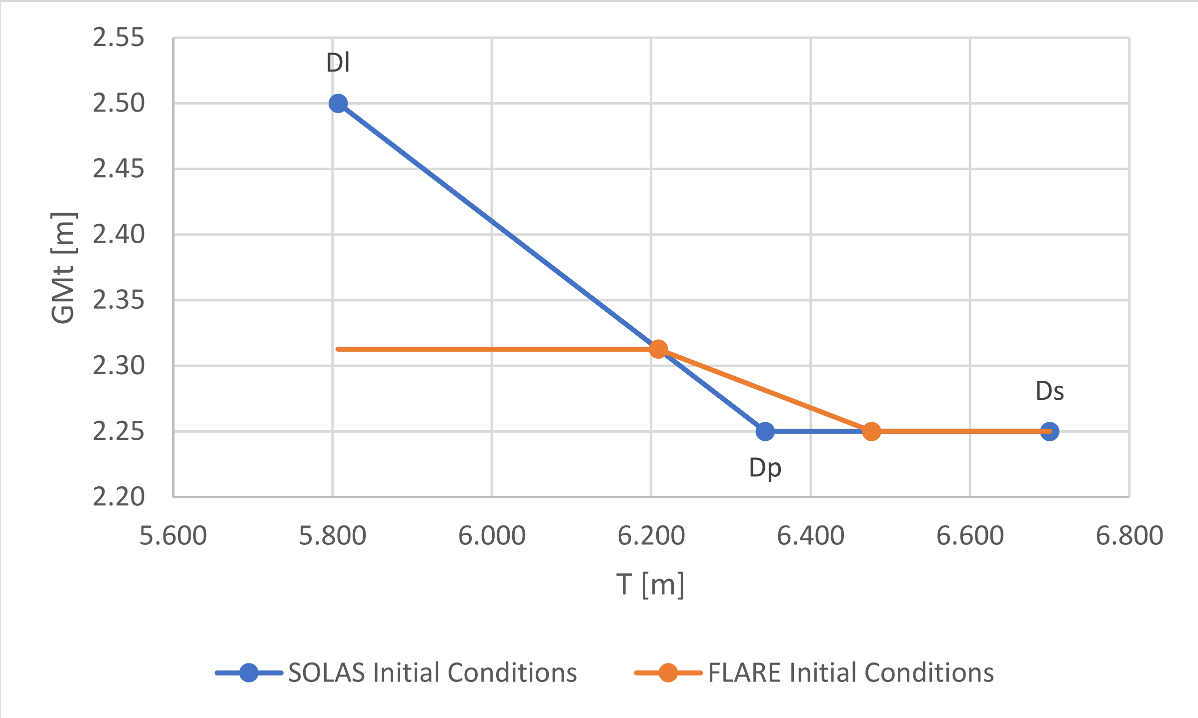


Figure 2 GM limiting curve with new FLARE draughts – Ship #10

The calculation has been executed with the software NAPA rel.2020.2, using the NEI approach for A-Class bulkheads (eSAFE project) and generating damages up to 5 adjacent zones.

These observations led to an attained index A = 0.8399 (with reference to the SOLAS A index +3.2%).

Table 2 Static results with new draughts and permeabilities acc. to FLARE – Ship #10

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	6.209	2.313	0.8606	0.5	0.4303	0.8399
T0.75	6.477	2.250	0.8193	0.5	0.4097	

1.3 Non-zonal static analysis

With the refined model according to the FLARE modelling guidelines (Annex 1) an increase of number of rooms and connections has been generated (see Table 3).

Table 3 Comparison between simplified model and refined model – Ship #10

Description	Before modelling	After modelling

Damhull volume	59,673 m^3	71,697 m^3
Rooms number	189	219
Connections number	86	234

The main addition to the new model is the addition of two decks, Deck 5 and Deck 6, incorporating additional car deck spaces. Furthermore, additional longitudinal subdivision has been added within the double bottom in way of the cross-flooding arrangements. Finally, additional geometry changes were made to reflect the arrangement of vertical escape and vent trunks.

However, considering the refined model and using NAPA, a slightly higher value for the Attained Index (+0.7%) resulted.

Table 4 Static results with refined model – Ship #10

INIT	T	GM	A	WCOEF	A*WCOEF	Attained Index
	m	m				
T0.45	6.209	2.313	0.8662	0.5	0.4331	0.8454
T0.75	6.477	2.250	0.8246	0.5	0.4123	

1.3.1 Non-damage area

No "NON-DAMAGE AREA" was defined for this vessel.

1.4 Calculation of PLL level 1

For this vessel breaches for collision, side and bottom grounding have been generated according to Ch. 3.2 of the main report and the grouping of breaches, leading to the same sets of flooded rooms, permitted to reduce the damage cases to be calculated by abt. 75% for collision and bottom grounding, and by abt. 83% for side grounding.

With the results of the static calculation for the attained index in hand, the PLL level 1 was calculated according to procedure described in Ch.2.4-2.5 of the main report. In particular, in Table 5 the non-zonal results are shown and in

Table 6 the PLL (Potential loss of life) calculation is reported.

Table 5 Non-zonal static analysis results – Ship #10

Damage Type	Collision		Side Grounding		Bottom Grounding	
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75
Draught	6.209m	6.477m	6.209m	6.477m	6.209m	6.477m
Breaches	10000	10000	10000	10000	10000	10000
Number of Empty cases	6	0	35	34	115	100
Number of Unique damage cases	2517	2505	1644	1628	2323	2314
Partial Index	0.9183	0.8701	0.9463	0.9361	0.9863	0.9835
Total Index	**0.8942**		**0.9412**		**0.9849**	

Table 6 PLL level 1 – Ship #10

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		4.33E-03
Relative frequency	0.388		0.328		0.284		1.000
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	6.209	6.477	6.209	6.477	6.209	6.477	
Attained Index	0.9183	0.8701	0.9463	0.9361	0.9863	0.9835	0.9354
$\sum pfac$ (for cases with s=1)	0.8015	0.6479	0.9154	0.8769	0.9679	0.9624	0.8492
$\sum pfac \cdot (1 - sfac)$	0.0817	0.1299	0.0537	0.0639	0.0137	0.0165	0.0646
PLL level 1 (1/ship year)	1.32E-01	2.09E-01	7.32E-02	8.71E-02	1.62E-02	1.95E-02	**0.5372**
	0.3412		**0.1603**		**0.0357**		

Even though the PLL is eventually the parameter to be used as a risk metric by FLARE, the Combined Attained Index is also shown in

Table 6 for information only. These values are calculated by using the relative frequency (equation 7 of the main report) for collision, side grounding and bottom grounding, which are based on the updated damage statistics of FLARE (WP2).

1.5 Filtering of static results and selecting cases for dynamic simulations

The screening of the static result according to filtering criteria identified within Ch. 3.4 of the main report permitted to select 500 cases for the dynamic simulations. In the following table a summary of the filtered breaches is reported.

Table 7 Filtering results for dynamic simulation – Ship #10

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	6.209m	6.477m	6.209m	6.477m	6.209m	6.477m	
Number of filtered damage cases	106	193	92	108	0	1	500
$\sum pfac$ (for the filtered damage cases)	0.0534	0.0995	0.0332	0.0438	0.0000	0.0004	0.0424
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0381	0.0733	0.0306	0.0371	0.0000	0.0004	0.0328
Potential PLL (if the ships would not capsize for all selected cases)	7.03E-02	9.13E-02	3.15E-02	3.65E-02	1.62E-02	1.90E-02	0.2648
	0.1616		0.0680		0.0352		
Potential PLL reduction (if the ships would not capsize for all selected cases)	52.6%		57.6%		1.3%		50.7%

The criterion applied to filter the breaches permitted to select those breaches with higher potential impact on the PLL in case they are found to survive in the dynamic simulations. In particular for this ship the PLL would be reduced by about 51% if all the cases to be simulated are not capsizals.

In the following diagrams some typical damage parameters of the selected breaches are presented in non-dimensional form.

It is interesting to note that for collision and, to a lesser extent, side grounding, there are two vulnerable areas, forward and aft in way of areas with high asymmetry below the bulkhead deck.

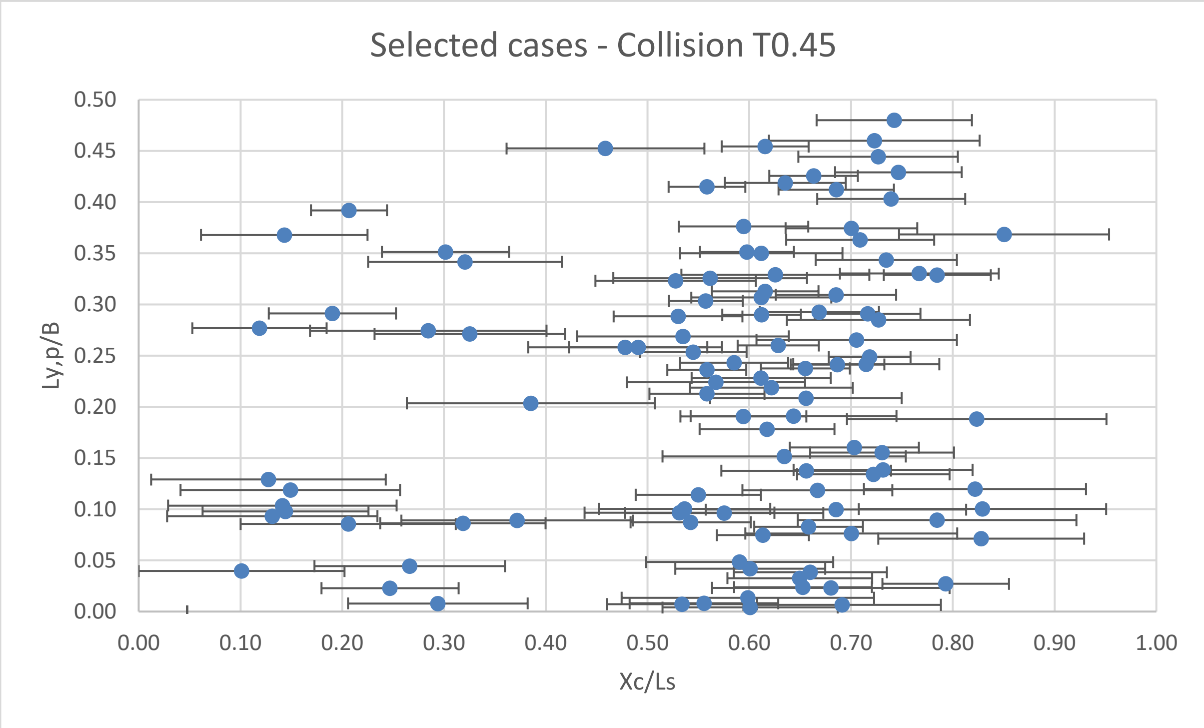


Figure 3 Selected collision breaches T0.45 – Ship #10

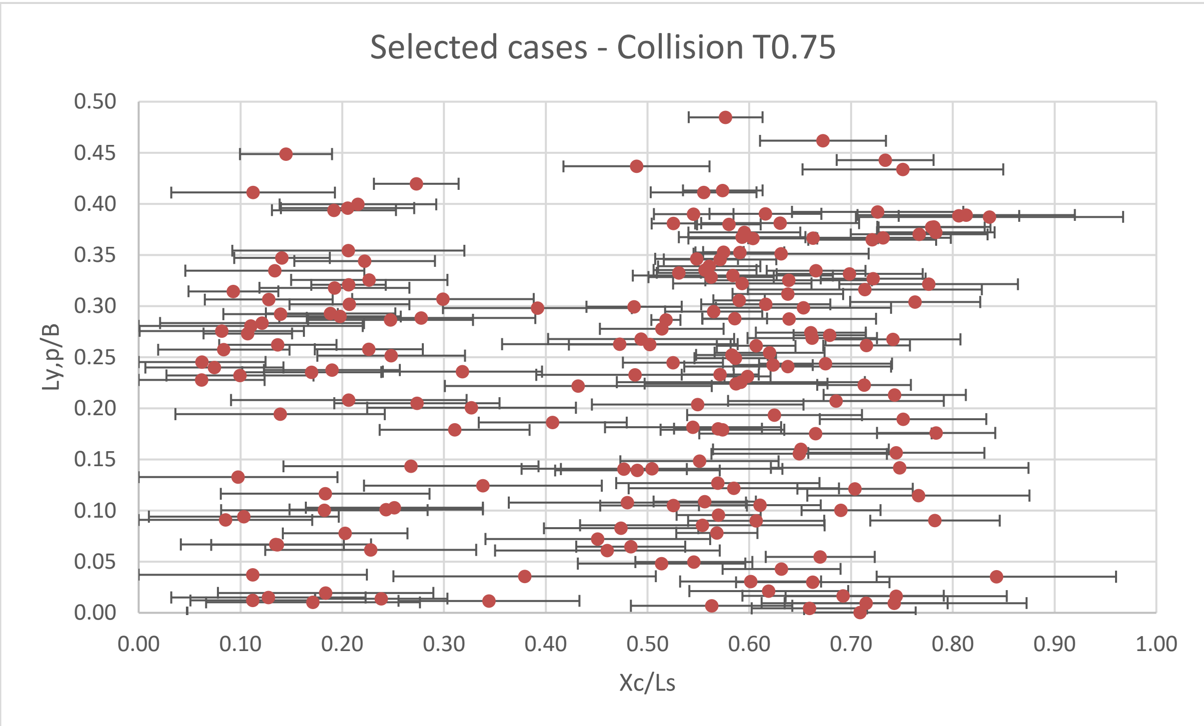


Figure 4 Selected collision breaches T0.75 – Ship #10

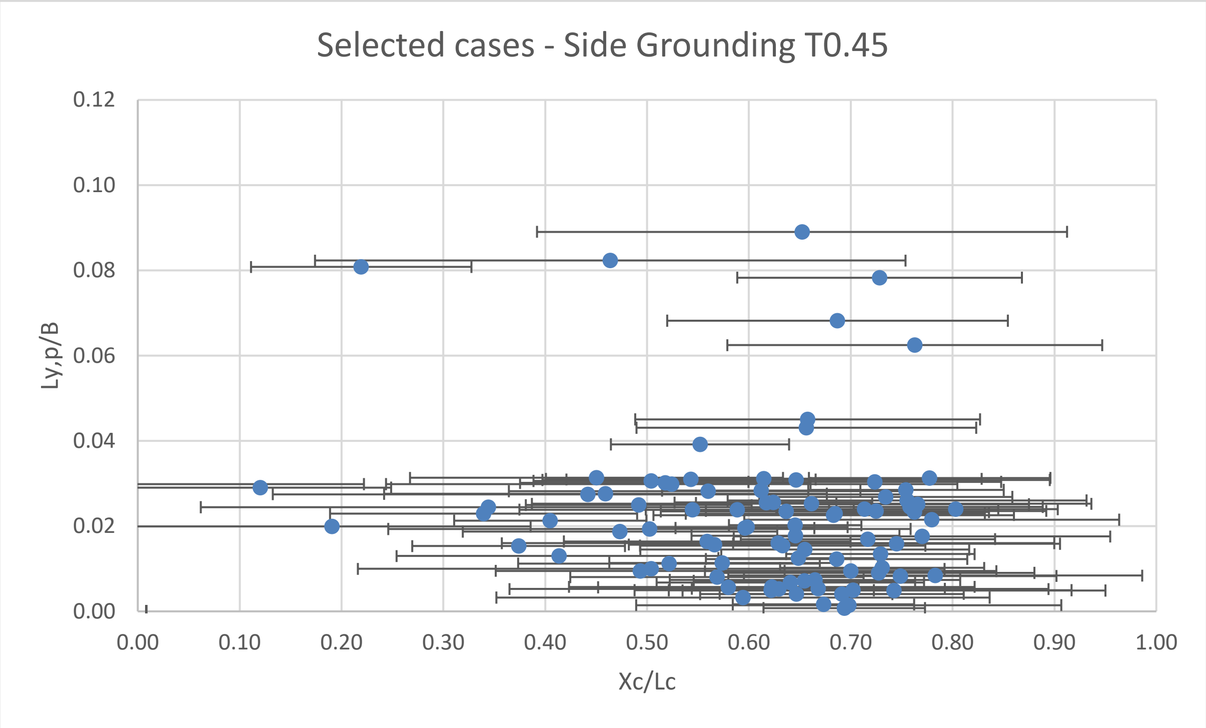


Figure 5 Selected side grounding breaches T0.45 – Ship #10

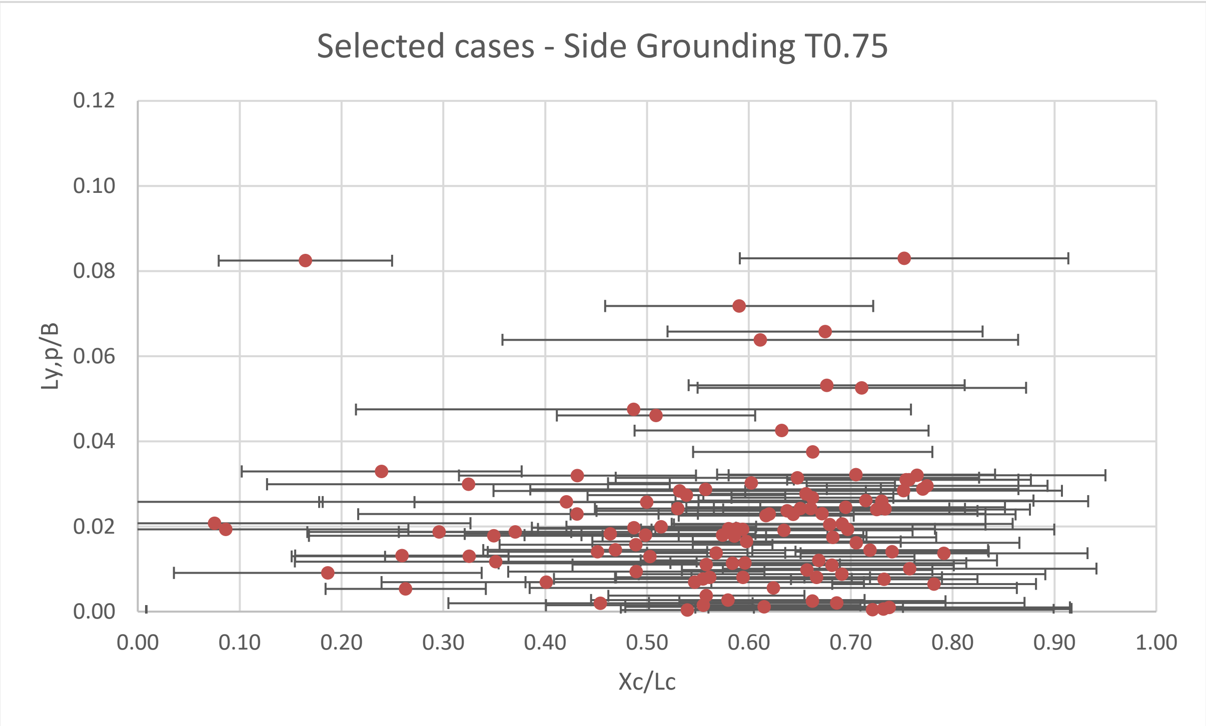


Figure 6 Selected side grounding breaches T0.75 – Ship #10

For the bottom grounding there is just one filtered breach, due to the fact the ship does not capsize when only the double bottom is affected by flooding. Furthermore, the arrangement of the bulkhead deck, and in particular the limited number of vertical penetrations through the bulkhead deck, ensure that flood water entering the vessel because of bottom grounding is prevented from spreading beyond the initial damage extent. Hence only those case with a vertical penetration higher than the double bottom height, significant length and with a high value *freq*pfac*(1-sfac)* are selected.

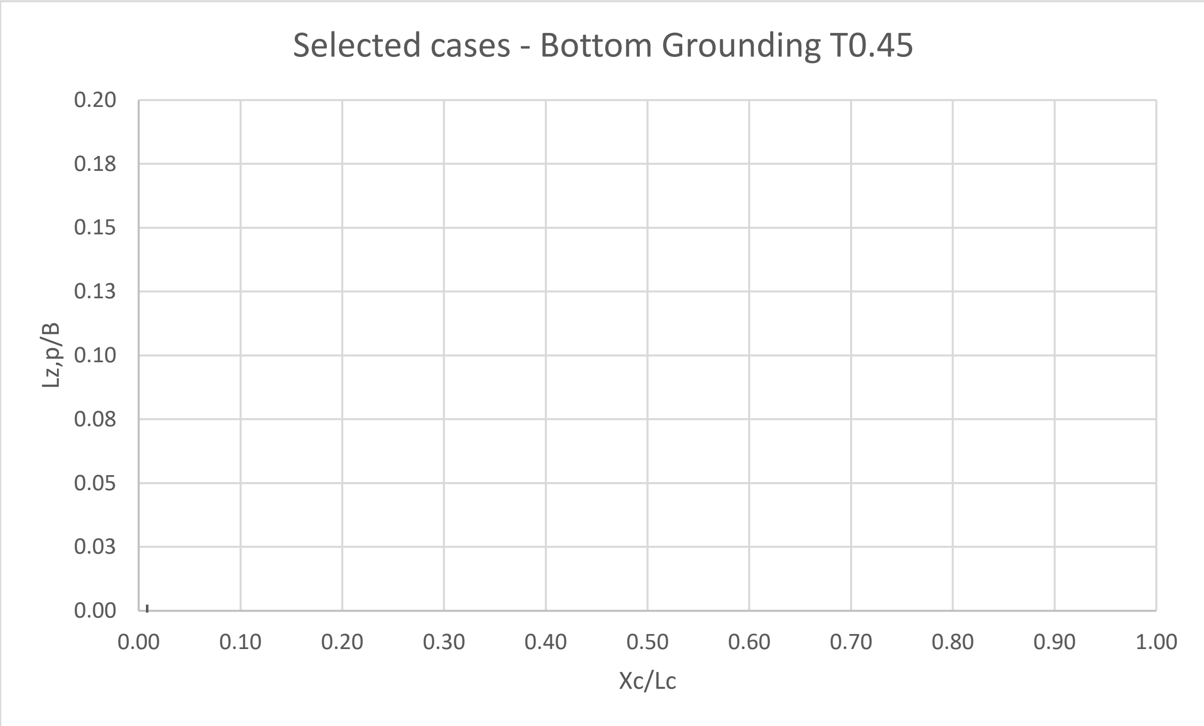


Figure 7 Selected bottom grounding breaches T0.45 – Ship #10

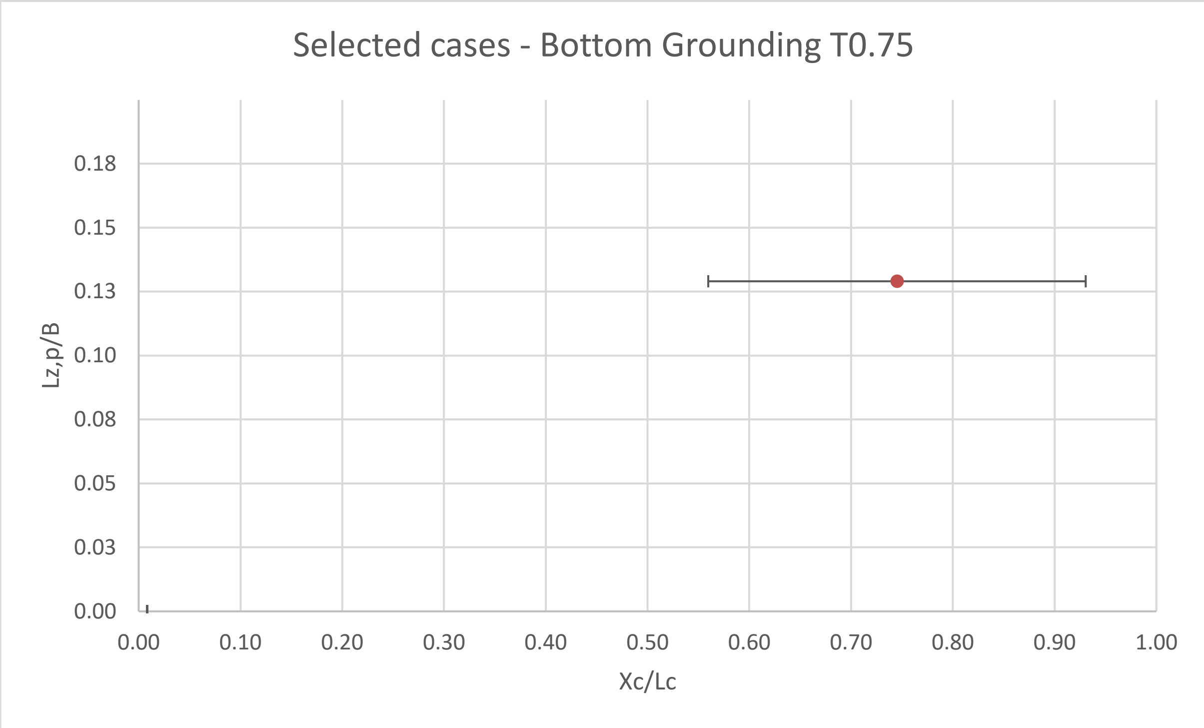


Figure 8 Selected bottom grounding breaches T0.75 – Ship #10

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with Sfac=0 and failure modes for cases with 0<Sfac<1, are showed in the following tables.

Table 8 Breakdown of failure mode for Sfac=0 cases – Ship #10

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	68	140	36	53	0	0	297
Heeling Angle (>15 deg)	8	6	51	51	0	0	116
Smom=0	6	7	0	0	0	1	14
Opening immersion	0	0	0	0	0	0	0
Sfac=0 - Total cases	**82**	**153**	**87**	**104**	**0**	**1**	**427**

Table 9 Breakdown of failure mode for 0<Sfac<1 cases – Ship #10

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	0	0	0	0	0	0	0
Insufficient Range	0	0	0	0	0	0	0
Heeling Angle (>7 deg)	0	0	0	0	0	0	0
Insufficient Restoration (GZmax) + Range	21	30	4	4	0	0	59
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	0
Insufficient Range + Excessive Heel	0	0	1	0	0	0	1
Insufficient Restoration (GZmax) + Range + Excessive Heel	3	10	0	0	0	0	13
0<Sfac<1 - Total cases	**24**	**40**	**5**	**4**	**0**	**0**	**73**

The majority of cases resulted in Sfac=0 (427 cases over 500). About 70% of these had a failure mode corresponding to no equilibrium, with the remaining 30% failing due to a heeling angle greater than 15 deg.

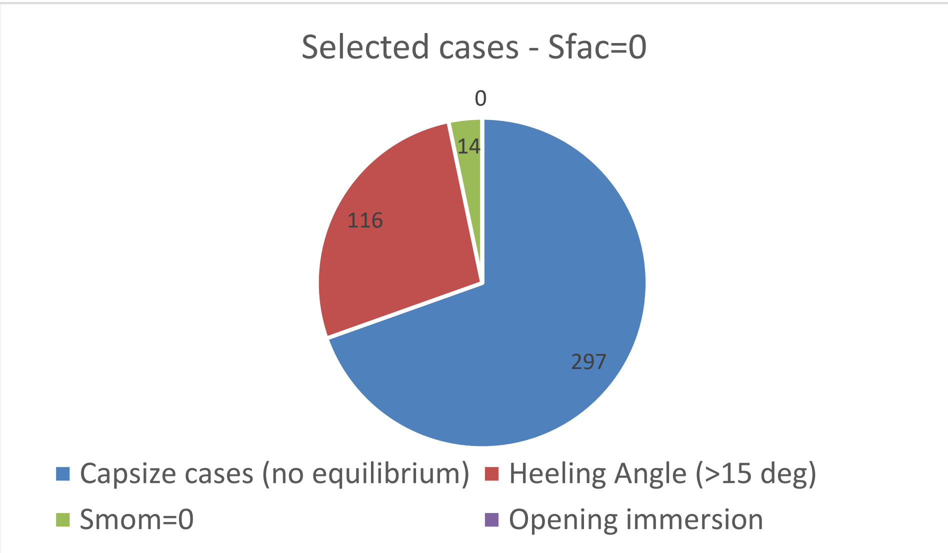


Figure 9 Diagram of failure mode for Sfac=0 cases – Ship #10

In the majority of the cases where equilibrium was not achieved the failure (i.e. no equilibrium) was found at the first stage of flooding when the cross-flooding is not started yet. That stage is not used to calculate the survivability factor s but it is requested by the explanatory notes of SOLAS Ch.II-1 that a positive GZ is achieved at that stage in order to calculate the cross-flooding time. It will be very important to assess those cases by dynamic simulations so that the real physics of the phenomenon will be investigated.

A limited number of damage cases with 0<Sfac<1 (73 cases over 500) have been selected. All of these cases have 0<Sfac<1 due to insufficient GZmax, insufficient Range, and excessive heeling angle or a combination of these factors. Zero cases are due to immersion of openings, due to the arrangement of the bulkhead deck, and in particular the limited number of vertical penetrations through the bulkhead deck.

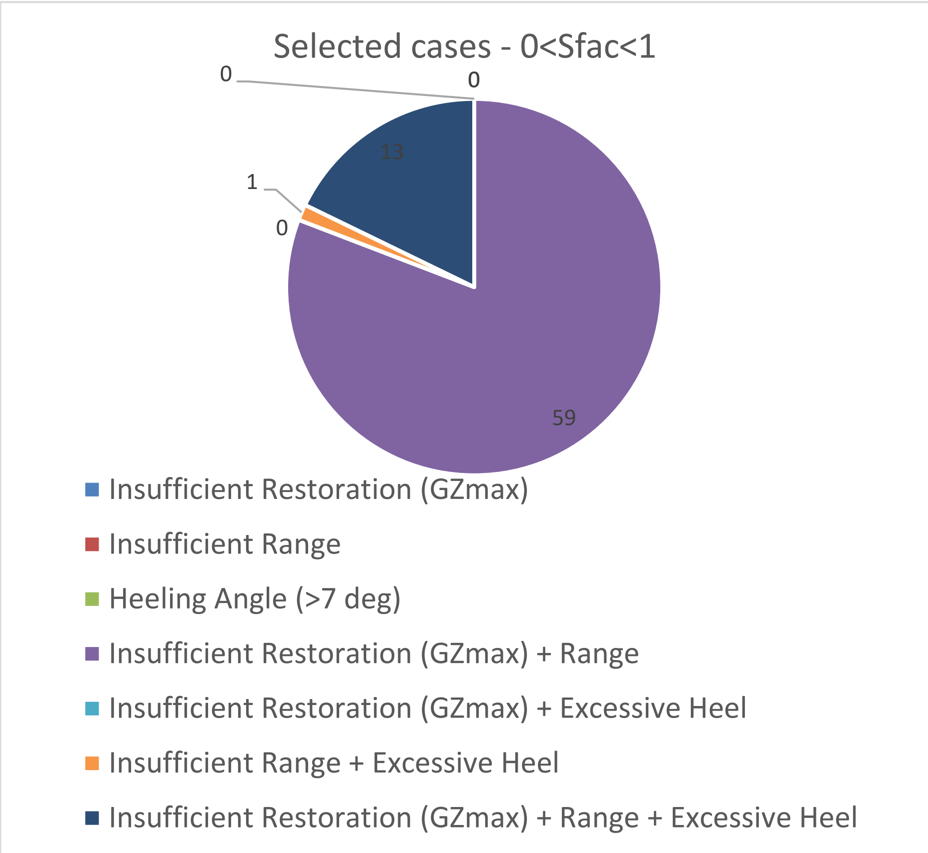


Figure 10 Diagram of failure mode for 0<Sfac<1 cases – Ship #10

2 DYNAMIC ASSESSMENT

2.1 Preparation of the PROTEUS model

The dynamic analysis has been carried out by use of the software *PROTEUS* ([12]. In particular, for the preparation of the model the tool Proteus Manager has been used.

To generate in the Proteus Manager the loading conditions defined in NAPA and corresponding to the two calculation draughts at 45% and 75%, the following lightship values have been generated:

$T_1 = 6.209$ m → LIG_1 [Δ=18725.5 t ; CG (90.52, 0.00 , 12.89) m]

$T_2 = 6.477$ m → LIG_2 [Δ=19889.1 t ; CG (90.27, 0.00 , 12.87) m]

Then, with the aim to show all the defined rooms and corresponding openings, the setup drawings were taken at five different deck slices:

DB = 1.39 m; D1 = 2.5 m; D2 = 5.91 m; D3 = 9.41 m; D4 = 12.11 m; D5 = 14.91 m; D6 = 17.89 m

For this ship a total of 234 openings have been defined. Horizontal openings have been defined on the higher deck of the model to capture the down-flooding through engine casings, vent trunks, vertical escape and lifts.

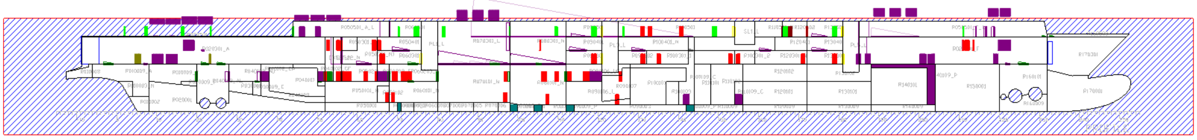


Figure 11 – Openings imported in Proteus Project (longitudinal section)– Ship #10

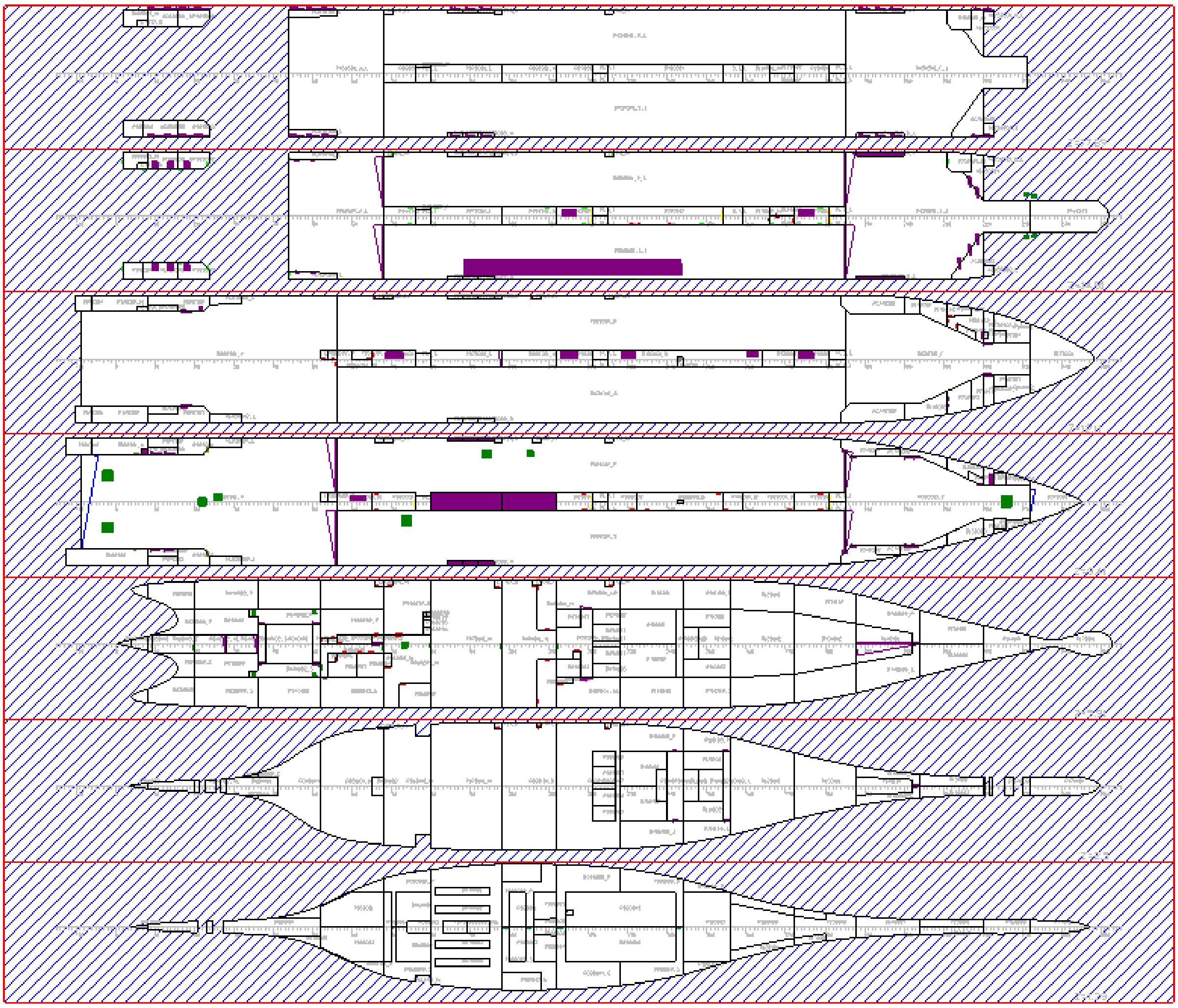


Figure 12 Openings imported in Proteus Project (horizontal section)– Ship #10

Table 10 Opening Types in Proteus Manager

TYPE	Leak Area Ratio 1 to 2	Leak Area Ratio 2 to 1	Collapse Pressure 1 to 2 [meters]	Collapse Pressure 2 to 1 [meters]	Leak Height [meters]	Gap Height [meters]	Effective Height HEff Switch	Open At Time [seconds]	Close At Time [seconds]
Sliding Watertight Door	0.00000	0.00000	15.00	15.00	0.000	0.000	False	0	999999
Hinged Watertight Door	0.00000	0.00000	15.00	15.00	0.000	0.000	False	0	999999
Watertight Hatch	0.00000	0.00000	15.00	15.00	0.000	0.000	False	0	999999
Sliding Light-Watertight Door	0.00000	0.00000	8.00	8.00	0.000	0.000	False	0	999999
Hinged Light-Watertight Door	0.00000	0.00000	8.00	8.00	0.000	0.000	False	0	999999
Sliding Semi-Watertight Door	0.02500	0.02500	8.00	8.00	2.500	0.000	False	0	999999
Hinged Semi-Watertight Door	0.02500	0.02500	8.00	8.00	2.500	0.000	False	0	999999
Hole	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
Hinged Fire Door	0.02000	0.03000	2.50	1.00	0.010	0.006	True	0	999999
Hinged Double Fire Door	0.02500	0.02500	2.00	1.00	0.010	0.006	False	0	999999
Sliding Fire Door	0.02500	0.02500	1.00	1.00	0.010	0.006	False	0	999999
Shell Door	0.00000	0.00000	999.00	999.00	999.000	0.000	False	0	999999
Sliding Lift Door	0.03500	0.03500	1.00	1.00	0.010	0.000	False	0	999999
Hinged Cold Room Door	0.01000	0.01000	3.50	1.00	0.010	0.000	True	0	999999
Sliding Cold Room Door	0.01000	0.01000	3.50	3.50	0.010	0.000	True	0	999999
Hinged Provisions Room Door	0.01000	0.01000	3.50	1.00	0.010	0.000	True	0	999999
Sliding Provisions Room Door	0.01000	0.01000	3.50	3.50	0.010	0.000	True	0	999999
Hinged Weathertight Door	0.02000	0.03000	2.50	1.00	0.010	0.000	True	0	999999
Sliding Weathertight Door	0.02500	0.02500	1.00	1.00	0.010	0.000	False	0	999999
Hinged Non-Watertight Door	0.00000	0.00000	1.50	1.50	0.000	0.000	True	0	999999
Hinged Escape Door	0.02000	0.03000	2.50	1.00	0.010	0.006	True	0	999999
Escape Hatch	0.02000	0.03000	2.50	1.00	0.010	0.000	True	0	999999
Cross-Flooding Pipe	0.00000	0.00000	0.00	0.00	0.000	0.000	False	0	999999
Cross-Flooding Hatch	0.00000	0.00000	1.20	1.20	0.000	0.000	False	0	999999

Since in Proteus the discharge coefficient for the holes is set to 0.6 and it may be not changed, the area of the cross-flooding openings has been reduced in order to take into account the lower discharge coefficient calculated for the structural cross flooding ducts as prescribed by the *Resolution MSC.362(92)*.

With the above input two generation set have been created and the comparison of the geometric and hydrostatic data between Napa and Proteus showed that the differences are negligible in general (from Figure 13 to Figure 19).

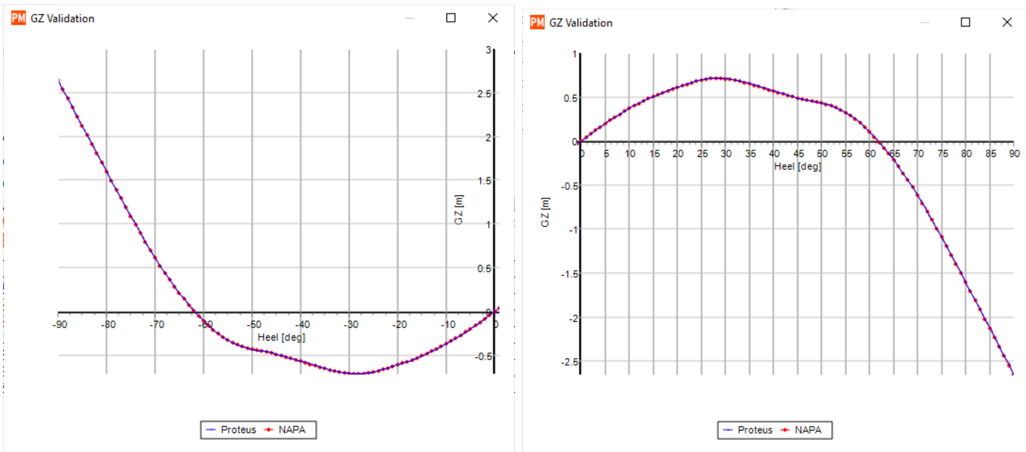


Figure 13 GZ comparison between Napa and Proteus – Ship #10

Table 11 Floating Position comparison between Napa and Proteus – Ship #10

Loadcase Validation

GZ Curve | Floating Position | Volume and CGs | Section Areas

Floating Position

Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Draught [m]	6.209	6.210	-0.001	-0.016
TA [m]	6.209	6.209	0.000	0.000
TF [m]	6.209	6.211	-0.002	-0.032
Trim [deg]	0.000	0.002	-0.002	0.000
Heel [deg]	0.000	0.005	-0.005	0.000
KM [m]	15.201	15.244	-0.043	-0.283
KG [m]	12.888	12.890	-0.002	-0.016
GM0 [m]	2.313	2.356	-0.043	-1.859
GMCorr [m]	0.000	0.000	0.000	0.000
GM [m]	2.313	2.356	-0.043	-1.859

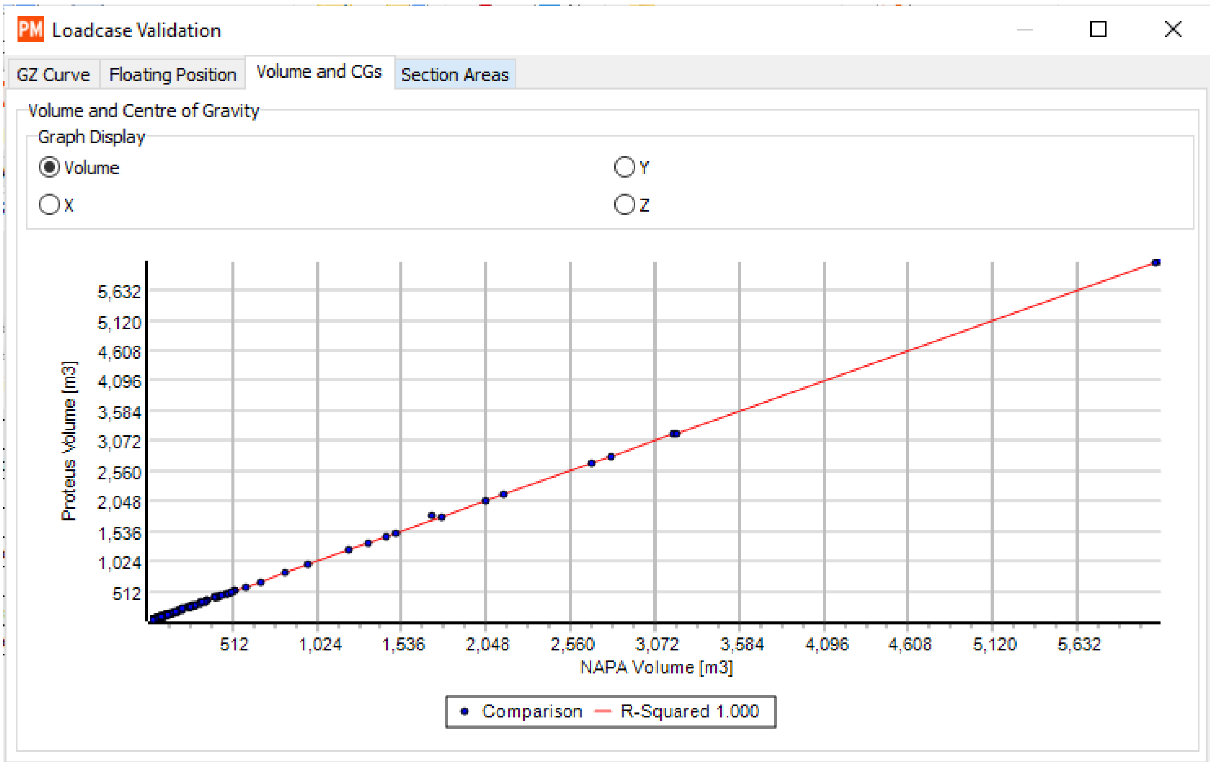


Figure 14 Compartment volume comparison between Napa and Proteus – Ship #10

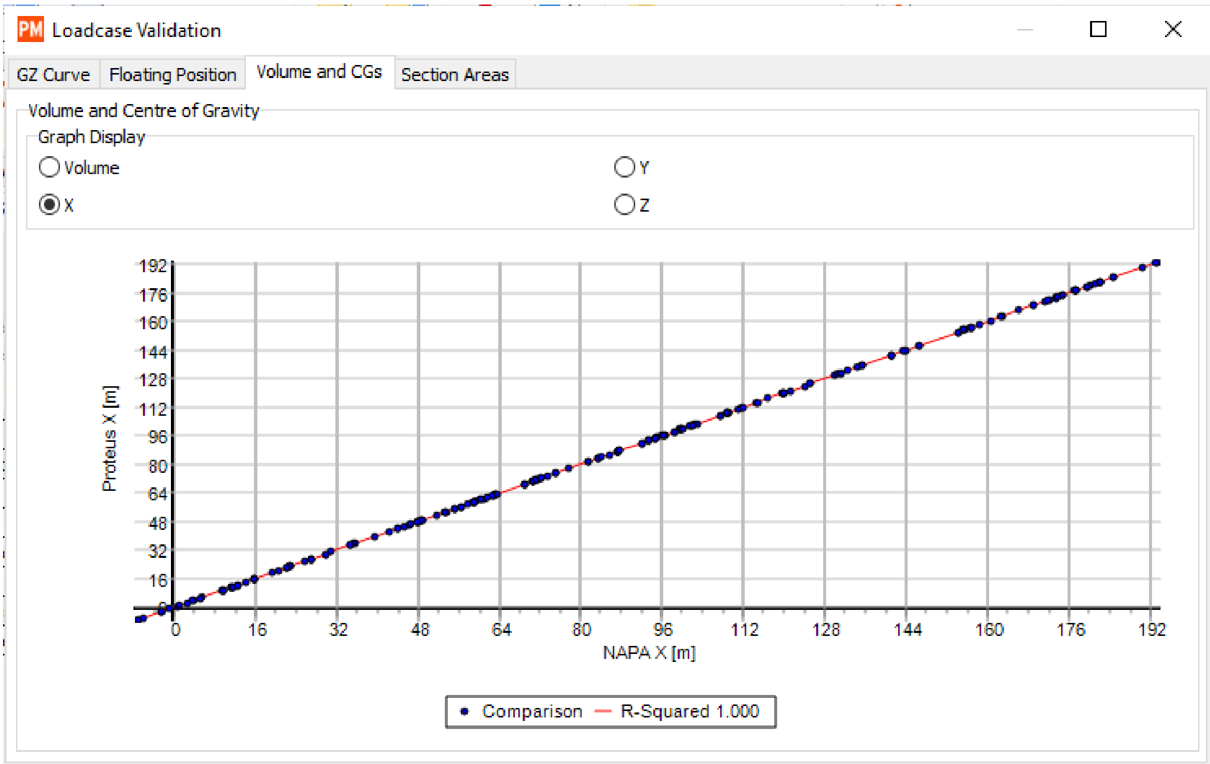


Figure 15 Compartment Long. Centre of Volume comparison between Napa and Proteus – Ship #10

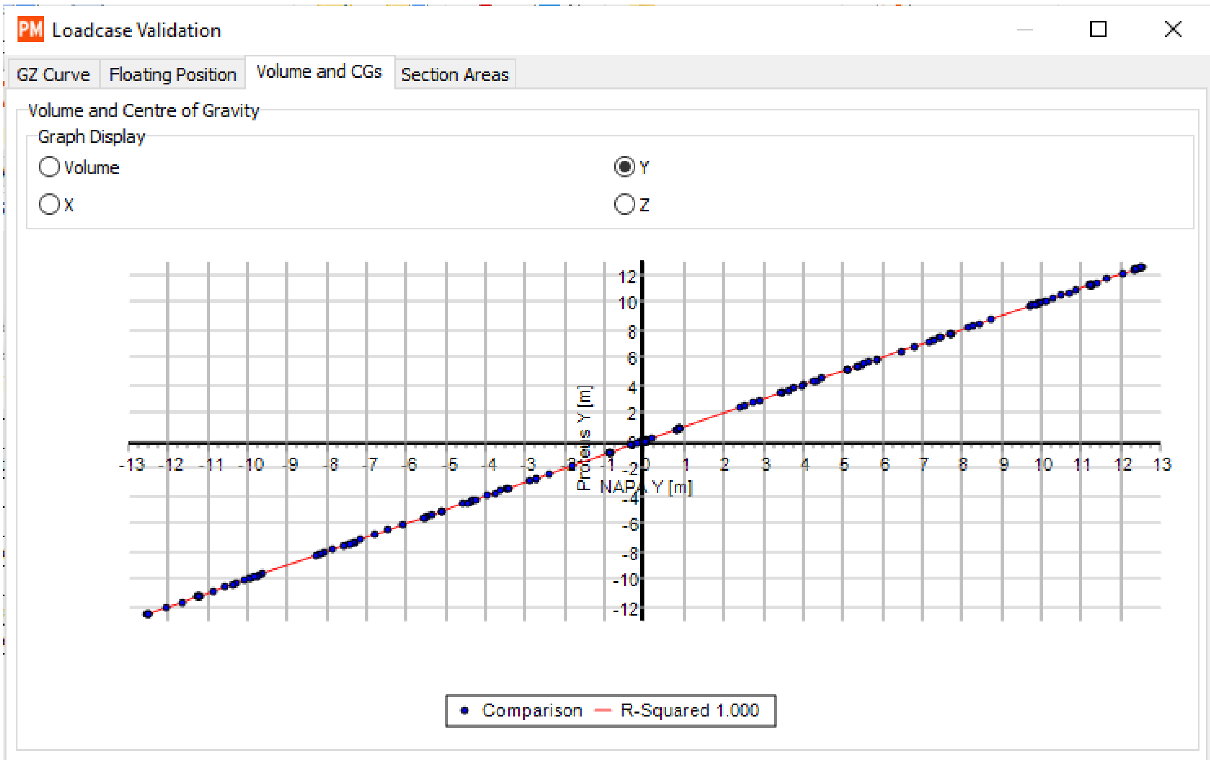


Figure 16 Compartment Trans. Centre of Volume comparison between Napa and Proteus – Ship #10

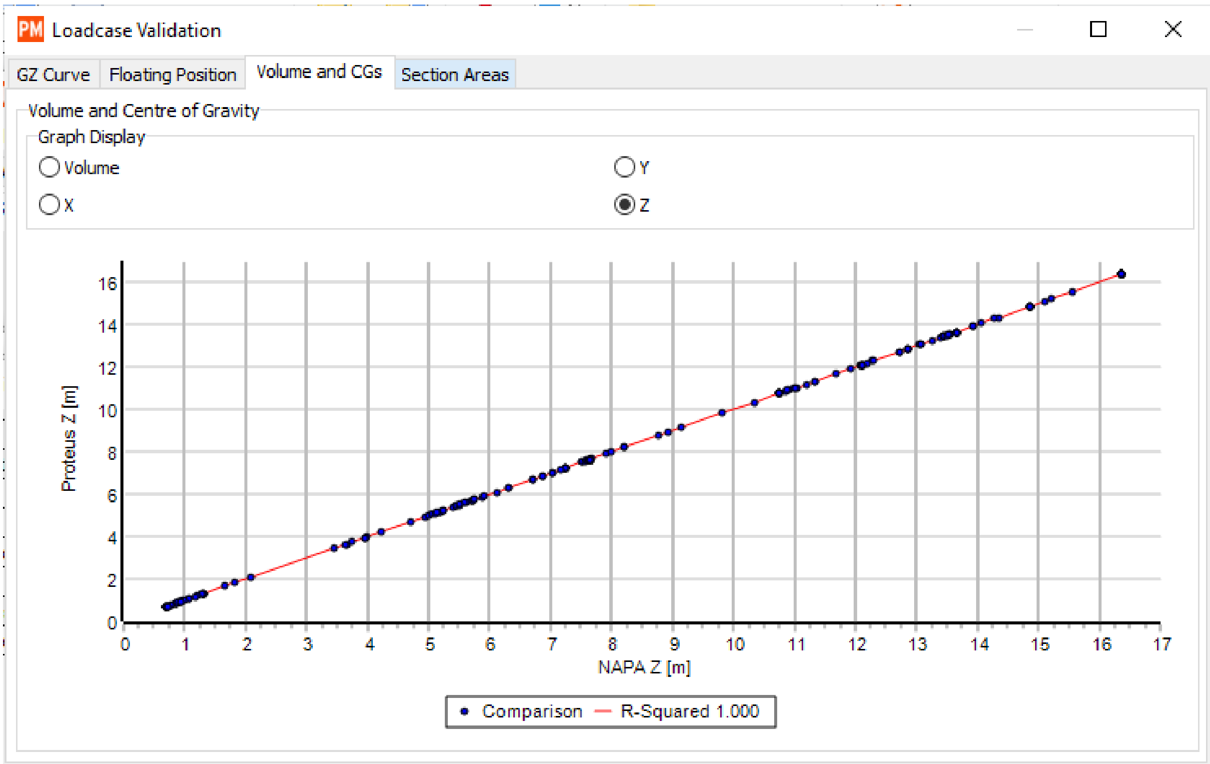
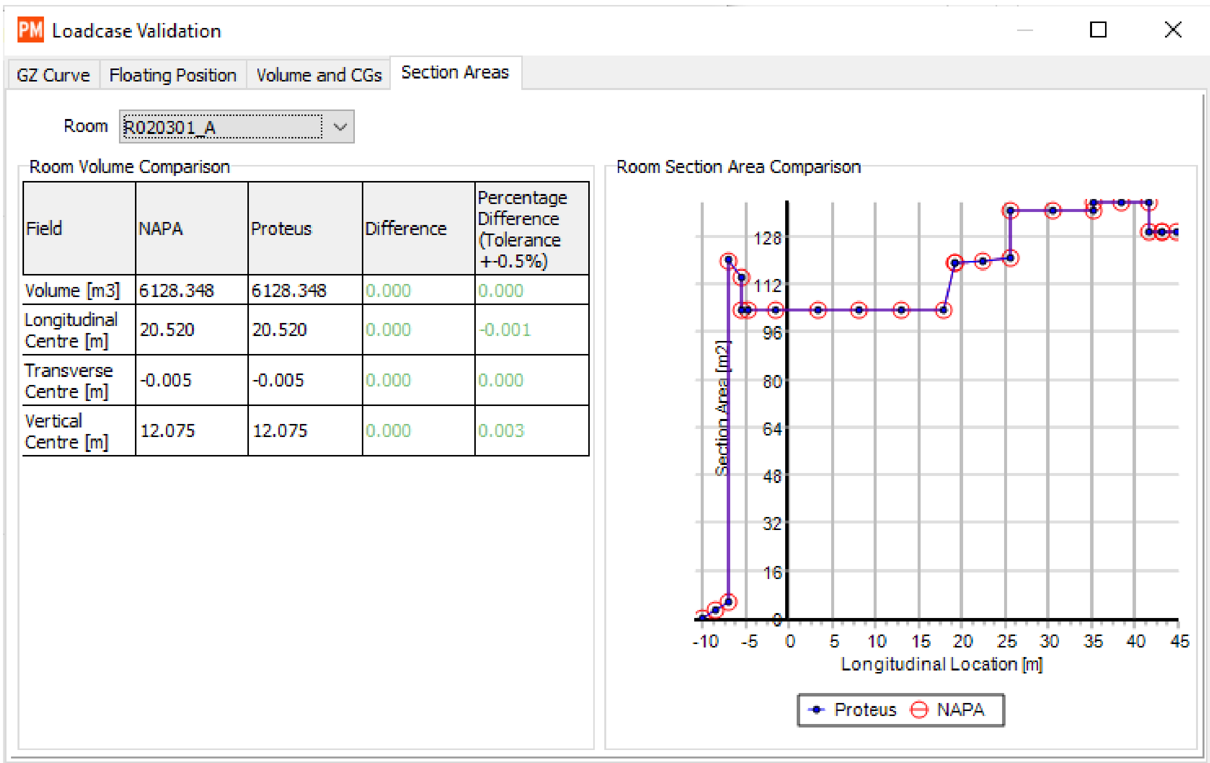
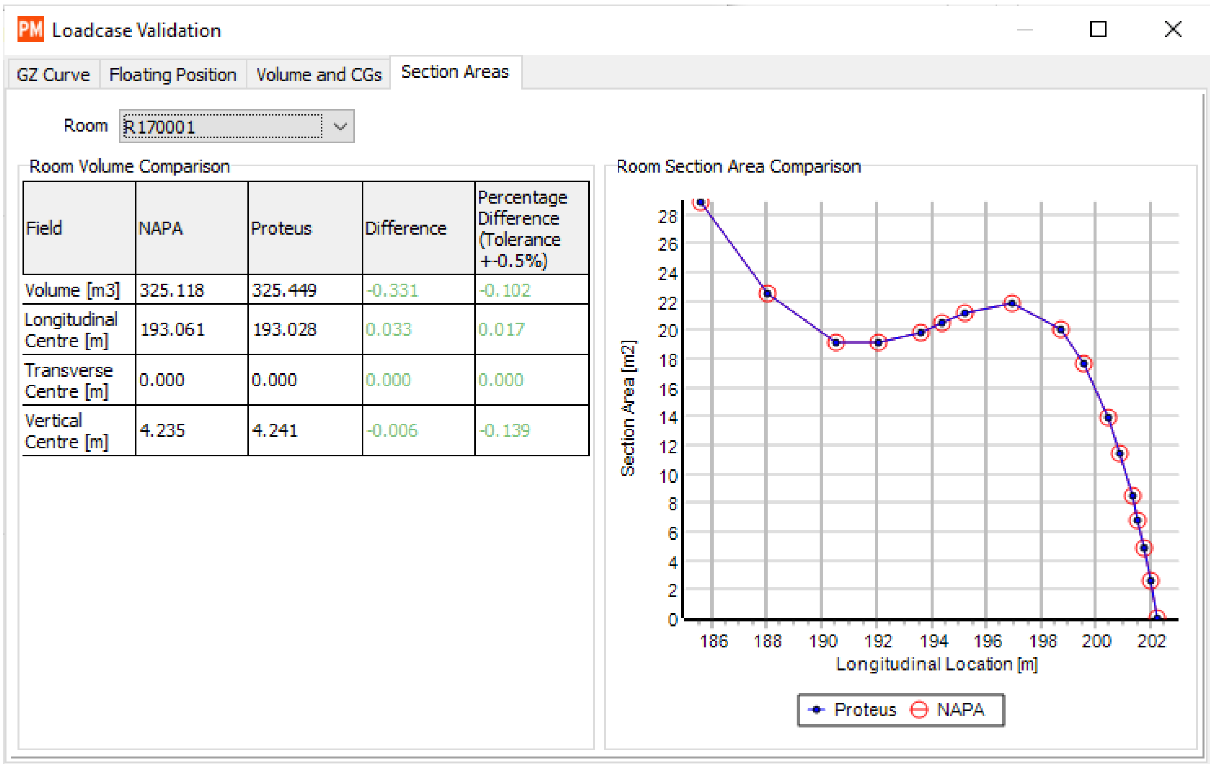


Figure 17 Compartment Vert. Centre of Volume comparison between Napa and Proteus – Ship #10



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	6128.348	6128.348	0.000	0.000
Longitudinal Centre [m]	20.520	20.520	0.000	-0.001
Transverse Centre [m]	-0.005	-0.005	0.000	0.000
Vertical Centre [m]	12.075	12.075	0.000	0.003

Figure 18 Aft Car Deck comparison between Napa and Proteus – Ship #10



Field	NAPA	Proteus	Difference	Percentage Difference (Tolerance +-0.5%)
Volume [m3]	325.118	325.449	-0.331	-0.102
Longitudinal Centre [m]	193.061	193.028	0.033	0.017
Transverse Centre [m]	0.000	0.000	0.000	0.000
Vertical Centre [m]	4.235	4.241	-0.006	-0.139

Figure 19 Forepeak comparison between Napa and Proteus – Ship #10

2.2 Results of dynamic simulations

In the first round of simulations all the 500 breaches have been simulated up to 30 minutes, then for 35 breaches a second simulation round has been executed up to 60 minutes, as these were found with progressive flooding still occurring at the end of first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1=capsize 0=not capsize) and TTC for cases where a capsize was found. In the following graphs the results for each hazard and the global results of simulations are presented.

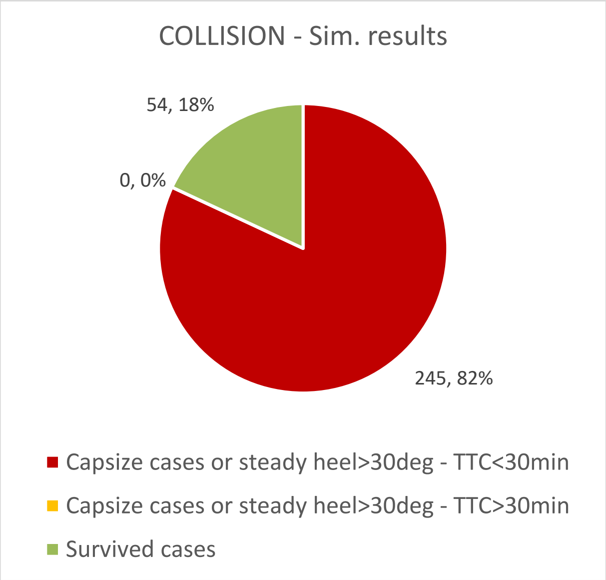


Figure 20 Simulation results for collision – Ship #10

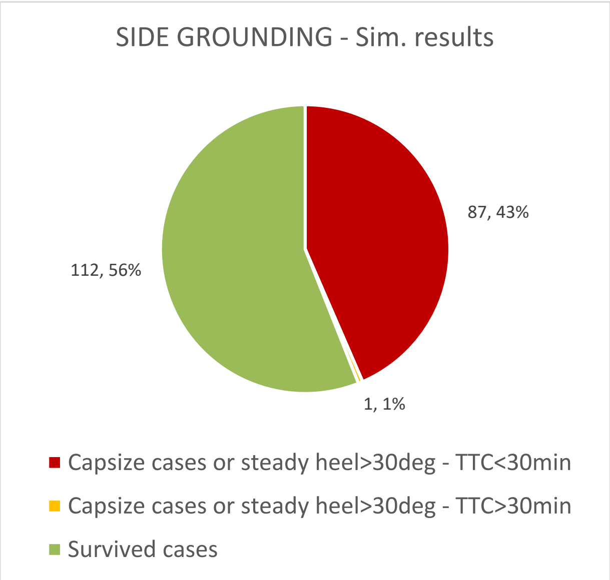


Figure 21 Simulation results for side grounding – Ship #10

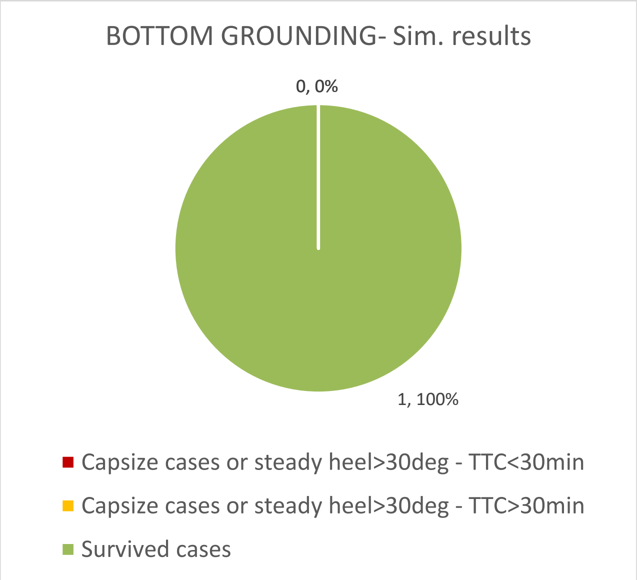


Figure 22 Simulation results for bottom grounding – Ship #10

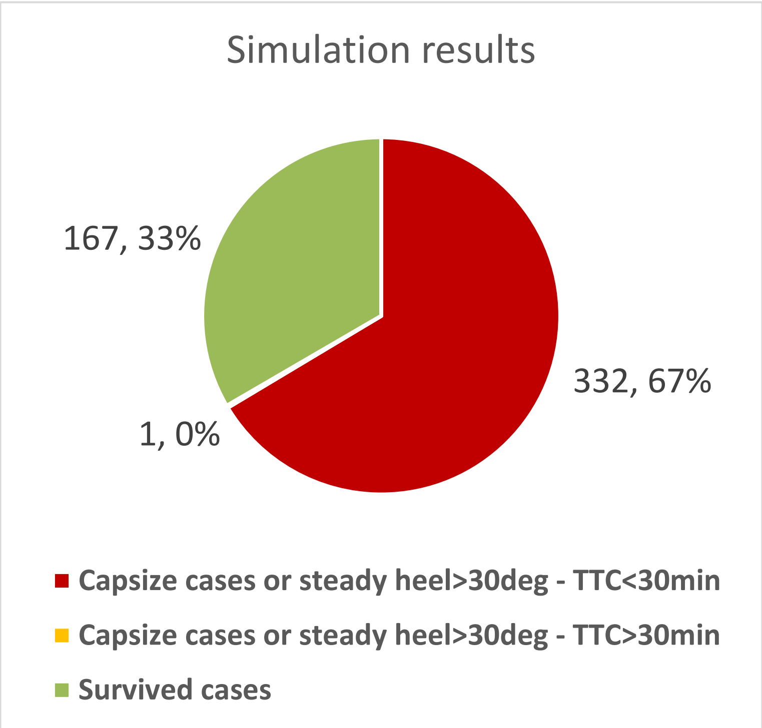


Figure 23 Global simulation results for the 500 filtered breaches – Ship #10

These results show that, while the majority of cases (67%) result in rapid capsize or steady heel greater than 30 degrees, the remaining cases (33%) survive. This indicates that the static results are conservative as almost all of those case had a sfac=0 in the static analysis.

Furthermore, the capsize case majority is driven by the collision breaches, while for bottom and side grounding the majority of cases survive.

Finally, it is clear that, when capsize occurs, it will happen quickly (less than 30 minutes) leaving insufficient time for evacuation.

2.3 Calculation of PLL level 2.1

The results of the flooding simulations permit to get the TTC too, therefore the fatality rate may be estimated for the cases with TTC>30min according to the procedure for calculation of Risk (Level 2.1).

In the Table 12 the details of the results obtained are reported and it can be noted that the PLL has been reduced from 0.5372 (Level 1) to 0.4677 (Level 2.1).

Table 12 PLL level 2.1 – Ship #10

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	6.209	6.477	6.209	6.477	6.209	6.477	
PLL L1 (1/ship year) (static assessment)	**1.32E-01**	**2.09E-01**	**7.32E-02**	**8.71E-02**	**1.62E-02**	**1.95E-02**	**0.5372**
	0.3412		**0.1603**		**0.0357**		
Number of filtered damage cases	106	193	92	108	0	1	500
Capsize cases or steady heel>30deg - TTC<30min	84	161	33	54	0	0	332
Capsize cases or steady heel>30deg - TTC>30min	0	0	0	1	0	0	1
Survived cases	22	32	59	53	0	1	167
PLL L2.1 (1/ship year) (dynamic assessment)	**1.28E-01**	**2.00E-01**	**4.42E-02**	**5.99E-02**	**1.62E-02**	**1.90E-02**	**0.4677**
	0.3284		**0.1041**		**0.0352**		
PLL L2.1 vs L1 (variation percentage)	**-3.7%**		**-35.0%**		**-1.3%**		**-12.9%**

In the following figures the diagrams of the breaches which lead to capsize after dynamic simulations are reported.

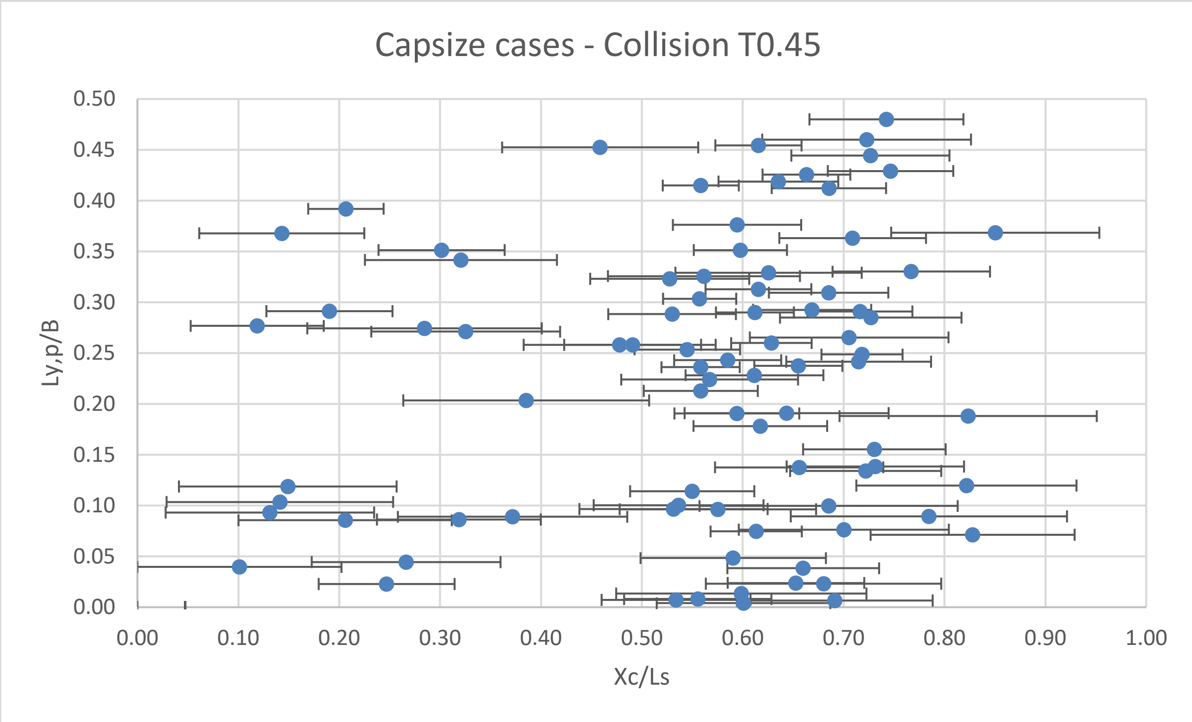


Figure 24 Collision leading to capsize T0.45 – Ship #10

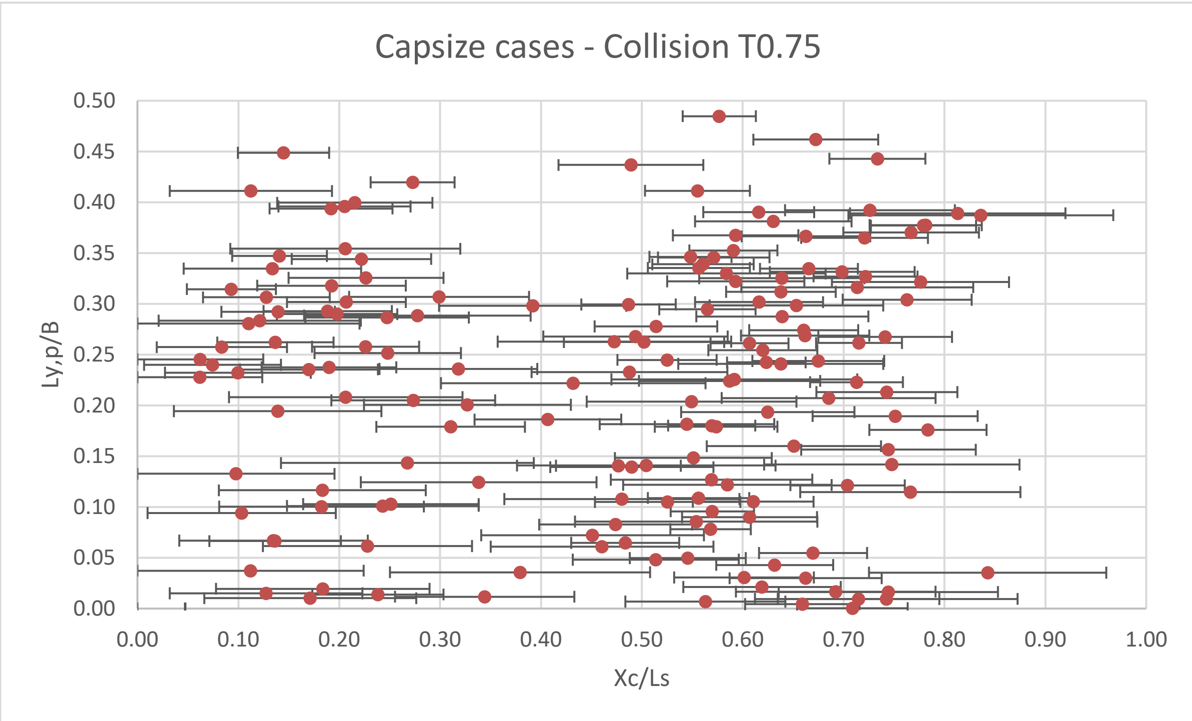


Figure 25 Collision leading to capsize T0.75 – Ship #10

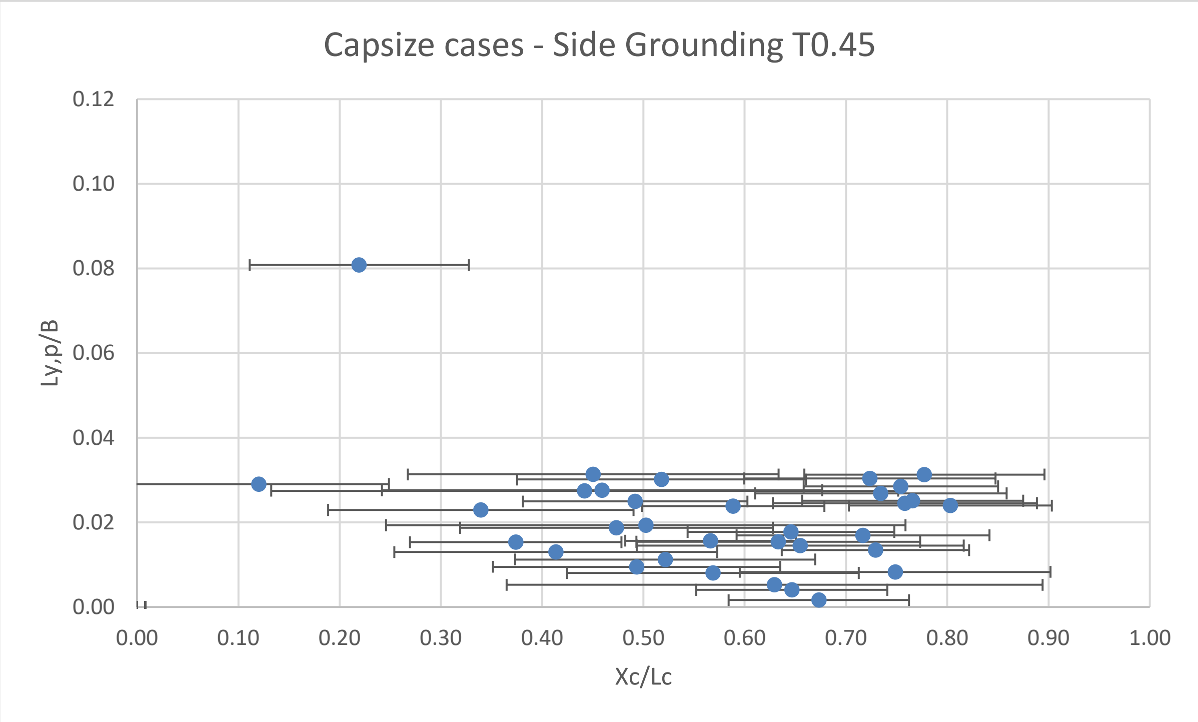


Figure 26 Side grounding breaches leading to capsize T0.45 – Ship #10

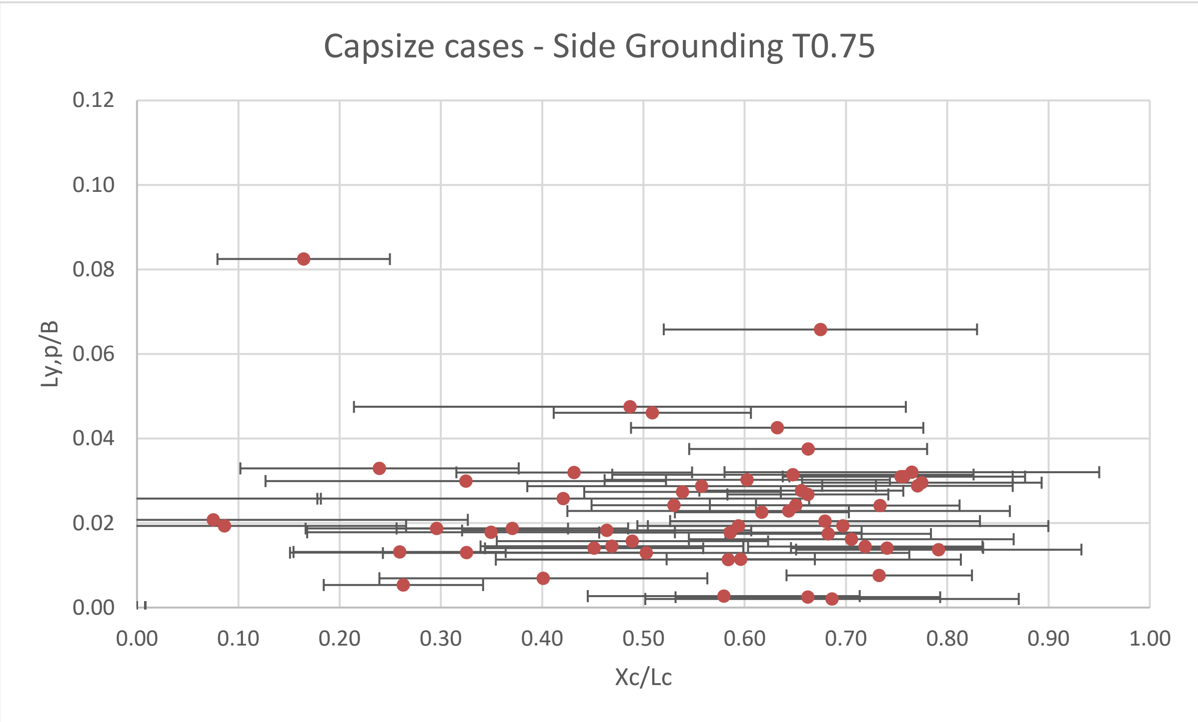


Figure 27 Side grounding breaches leading to capsize T0.75 – Ship #10

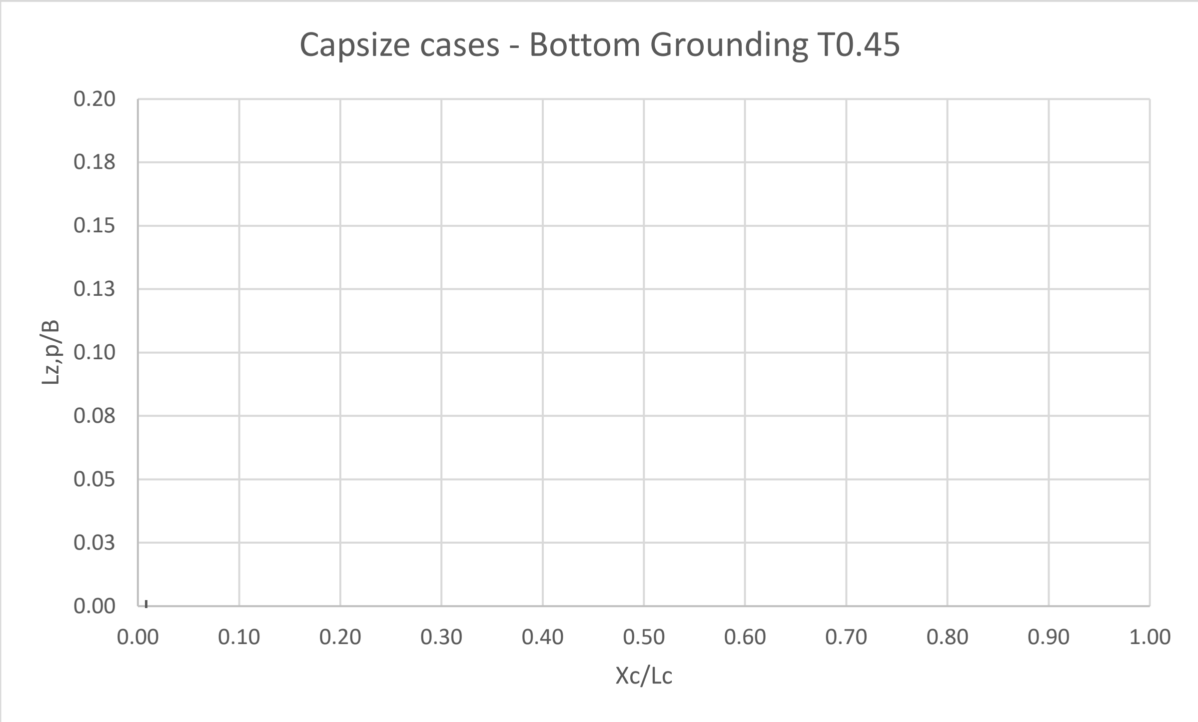


Figure 28 Bottom grounding breaches leading to capsize T0.45 – Ship #10

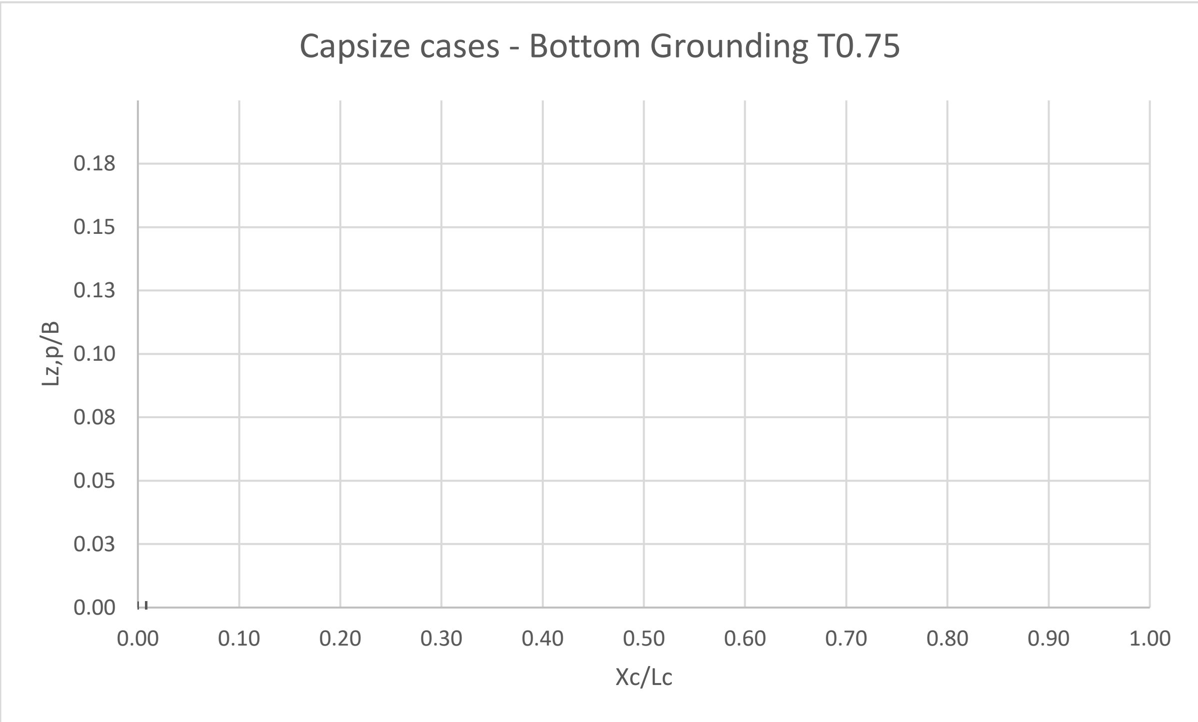


Figure 29 Bottom grounding breaches leading to capsize T0.75 – Ship #10

The identified capsizal cases showed in Figure 24 to Figure 29 may be investigated in WP7.2 when Risk Control Options are to be implemented.

2.4 Sensitivity analysis of the fatality rate

From the simulation results it has been observed that just 1 case resulted into a TTC greater than 30 minutes but lower than 60 minutes. For this case linear Interpolation between 0% and 80% has been used for the estimation of the fatality rate. Given that this case survived for almost the full 60 minutes, with a TTC of 3615 seconds, the resulting fatality rate is approximately zero. Furthermore, there are further 6 cases where progressive flooding is still occurring after 60min and for these cases no fatalities have been assumed (Figure 30).

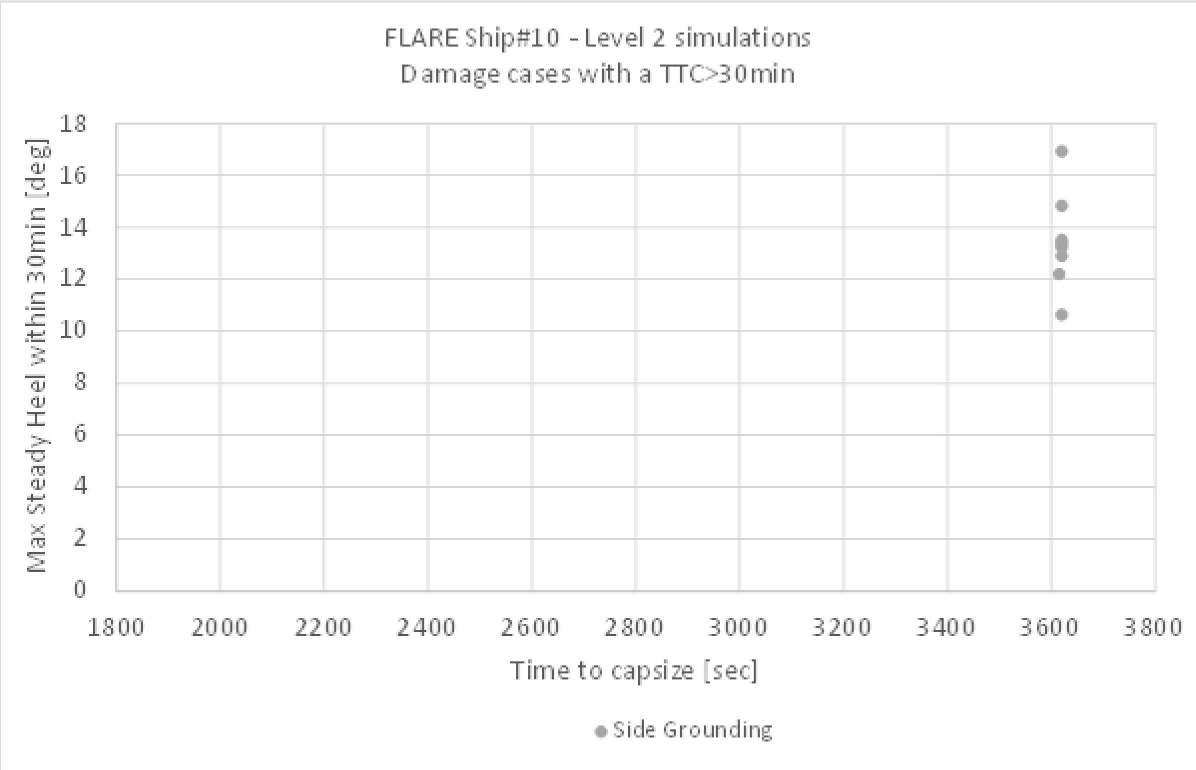


Figure 30 Cases with TTC>30min or progressive flooding still occurring after 60min – Ship #10

Given these results, the PLL should not be sensitive to changes in fatality rate. In order to verify the potential impact of the fatality rate deviation on the PLL, a sensitivity analysis has been carried out on the total 7 cases (with TTC>30min or progressive flooding still occurring after 60min). For this, the impact on the PLL has been evaluated by use of the simplified formula (main report equation 5) but assuming a variation of the fatality rate by ± 30% of the POB.

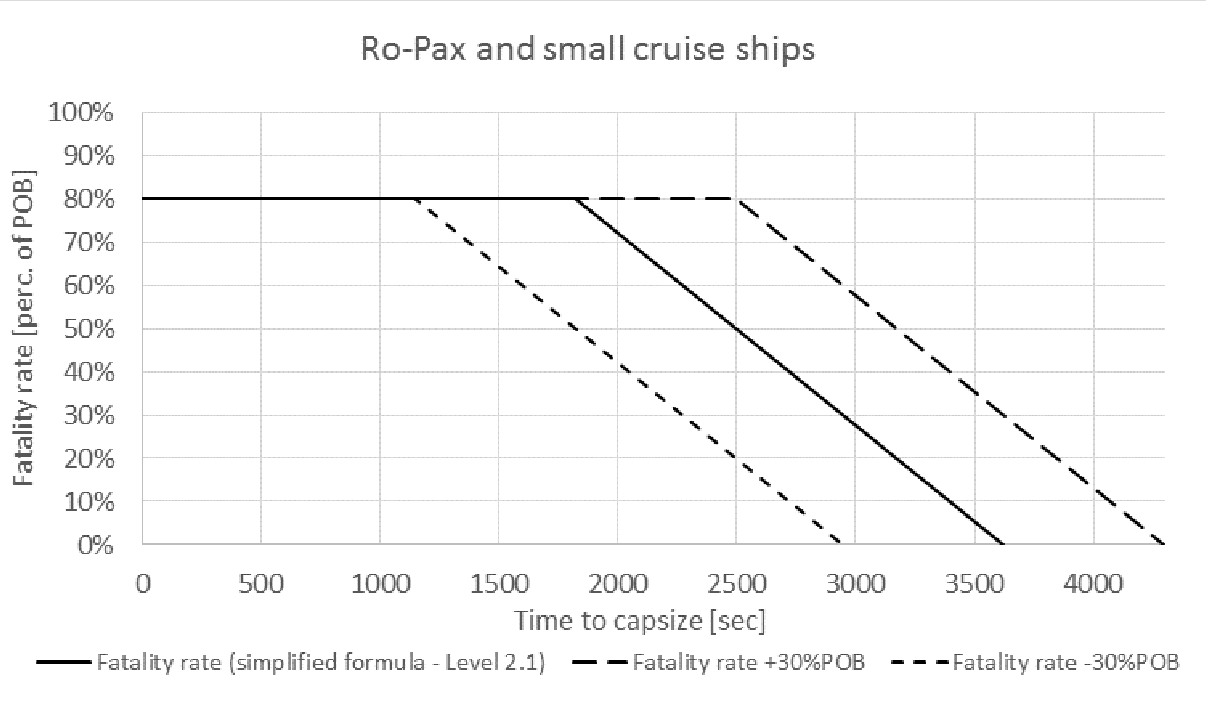


Figure 31 Sensitivity analysis of simplified formula for fatality rate calculation – Ship #10

The calculation with +30% in the fatality rate resulted into a PLL of 0.4690 (+0.26% compared to the reference PLL) while the calculation with -30% for the fatality rate resulted into a PLL of 0.4677 (no reduction compared to the reference PLL). These values demonstrated that for this ship the simplified formula to derive the fatality rate used in the calculation of risk (Level 2.1) is insensitive with respect to PLL because PLL is mainly based, for this ship, by the scenarios leading to fast capsize.

2.5 Additional Simulations

As discussed in Ch. 1.5, 500 cases were selected for dynamic simulations, however as shown above, the resulting simulations did not provide suitable scenarios to allow meaningful evacuation analyses to be performed. To allow the selection of meaningful cases for the demonstration of the evacuation analysis, an additional 1384 simulations have been selected, giving a total of 1854 dynamic simulations. These 1854 cases represent the entire set of filtered damage scenarios from which the 500 cases were selected.

In the following table a summary of the 1854 simulated reaches is reported.

Table 13 Filtering results for dynamic simulation – Ship #10

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught	6.209m	6.477m	6.209m	6.477m	6.209m	6.477m	
Number of filtered damage cases	438	598	279	319	96	124	1854
$\sum pfac$ (for the filtered damage cases)	0.0908	0.1548	0.0520	0.0689	0.0103	0.0130	0.0708
$\sum pfac \cdot (1 - sfac)$ (for the filtered damage cases)	0.0716	0.1144	0.0494	0.0585	0.0103	0.0130	0.0571
Potential PLL (if the ships would not capsize for all selected cases)	1.62E-02	2.50E-02	5.92E-03	7.37E-03	4.05E-03	4.11E-03	0.0627
	0.0412		0.0133		0.0082		
Potential PLL reduction (if the ships would not capsize for all selected cases)	87.9%		91.7%		77.1%		88.3%

While, when considering only 500 cases, the PLL would be reduced by about 51% if all the simulated cases did not capsize, when 1854 cases are considered, the PLL would be reduced by about 88% if all the simulated cases did not capsize.

With the aim to differentiate the failure modes captured by the filtering criteria the methodology presented in deliverable D5.7 has been used. The breakdown of failure modes, for cases with Sfac=0 and failure modes for cases with 0<Sfac<1, are showed in the following tables.

Table 14 Breakdown of failure mode for Sfac=0 cases – Ship #10

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Capsize cases (no equilibrium)	333	479	139	172	0	0	1123
Heeling Angle (>15 deg)	48	37	132	131	0	1	349
Smom=0	20	21	0	1	94	121	257
Opening immersion	0	0	3	2	1	1	7
Sfac=0 - Total cases	**401**	**537**	**274**	**306**	**95**	**123**	**1736**

Table 15 Breakdown of failure mode for 0<Sfac<1 cases – Ship #10

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Insufficient Restoration (GZmax)	0	0	0	0	0	0	0
Insufficient Range	0	1	0	0	0	0	1
Heeling Angle (>7 deg)	1	0	0	3	0	0	4
Insufficient Restoration (GZmax) + Range	33	48	4	9	1	1	96
Insufficient Restoration (GZmax) + Excessive Heel	0	0	0	0	0	0	0
Insufficient Range + Excessive Heel	0	2	1	1	0	0	4
Insufficient Restoration (GZmax) + Range + Excessive Heel	3	10	0	0	0	0	13
0<Sfac<1 - Total cases	**37**	**61**	**5**	**13**	**1**	**1**	**118**

As before, the majority of cases resulted in Sfac=0 (1736 cases over 1854) with a similar distribution of failure modes.

In the first round of simulations all the 1854 breaches have been simulated up to 30 minutes, then for 159 breaches a second simulation round has been executed up to 60 minutes, as these were found with progressive flooding still occurring at the end of first simulation round.

After the completion of the second round, the results have been collected in terms of capsize probability (1=capsize 0=not capsize) and TTC for cases where a capsize was found.

Table 16 PLL level 2.1 – Ship #10

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	6.209	6.477	6.209	6.477	6.209	6.477	
PLL L1 (1/ship year) (static assessment)	**1.32E-01**	**2.09E-01**	**7.32E-02**	**8.71E-02**	**1.62E-02**	**1.95E-02**	**0.5372**
	0.3412		**0.1603**		**0.0357**		
Number of filtered damage cases	428	598	279	319	96	124	1854
Capsize cases or steady heel>30deg - TTC<30min	365	501	141	175	1	2	1185
Capsize cases or steady heel>30deg - TTC>30min	3	4	1	4	1	3	16
Survived cases	70	93	137	140	94	119	653
PLL L2.1 (1/ship year) (dynamic assessment)	**1.21E-01**	**2.01E-01**	**3.35E-02**	**4.76E-02**	**4.22E-03**	**4.50E-03**	**0.4122**
	0.3224		**0.0811**		**0.0087**		
PLL L2.1 vs L1 (variation percentage)	**-5.5%**		**-49.4%**		**-75.6%**		**-23.3%**

From the extended set of simulation results it has been observed that 16 cases resulted in a TTC greater than 30 minutes but lower than 60 minutes. An evacuation analysis has been performed on a selection of these cases as described below.

3 EVACUATION ANALYSIS

3.1 Selection of flooding scenarios for the evacuation analysis

The sensitivity analysis carried out in Ch. 2.4 for this ship demonstrated that the calculation of level 2.1 for PLL is robust enough and the evacuation analysis (level 2.2) would be not needed as it has a low impact on the PLL. However, for this ship some cases have been selected from the extended 1854 damage cases in order to demonstrate the procedure for the evacuation analysis and to check if the simplified formula used to estimate the fatality rate for the PLL (level 2.1) is conservative.

Since one objective of this analysis is to demonstrate the conservativeness of the simplified formula for the fatality rate (PLL level 2.1), the choice of the cases to be simulated has been driven by the spread of the TTC greater than 30min and by the need to select cases with a high steady heel (within 30min). This approach is based on the fact that in the evacuation simulations, the speed of the agents is reduced when large heeling angles occur.

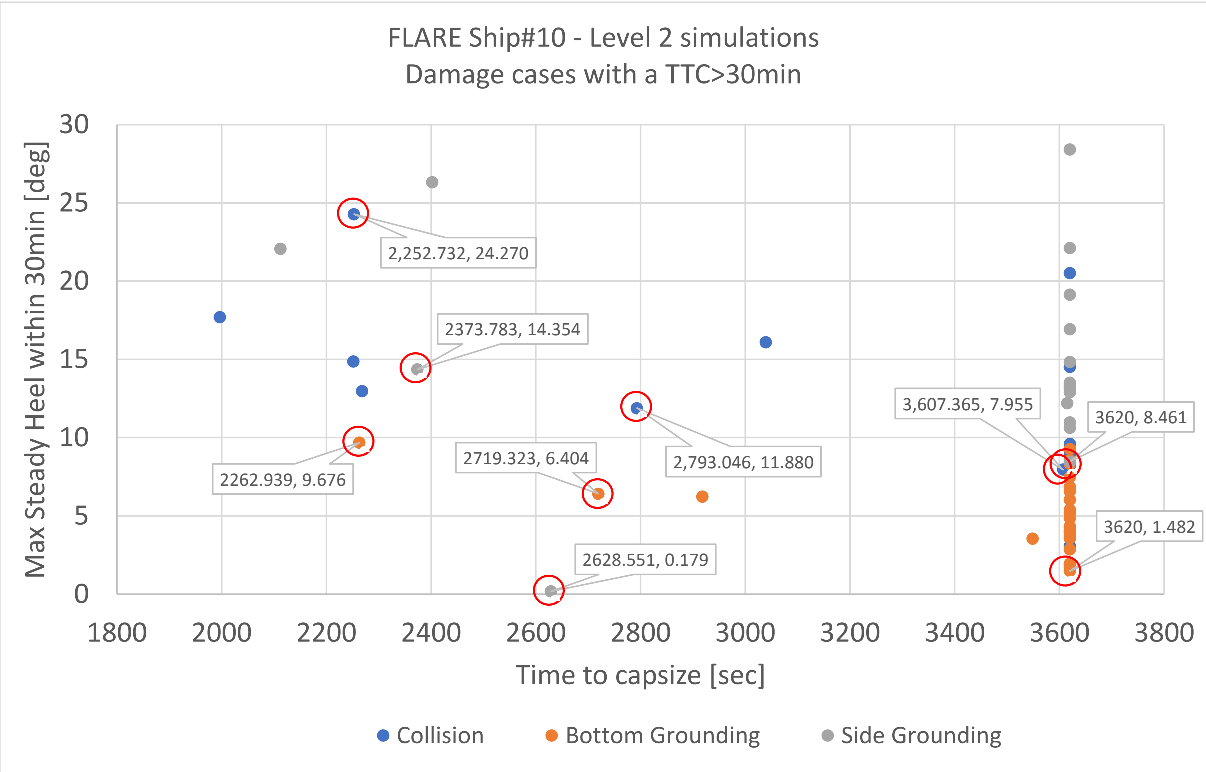


Figure 32 Cases selected for the evacuation analysis – Ship #10

Figure 32 shows the 9 capsize scenarios (3 each from collision, side and bottom grounding) selected for the evacuation analysis for this ship.

3.2 Preparation of the EVI model

The latest EVI version 4.3.3, has been used for the evacuation analysis. An Eve model has been created according to the General Arrangement of the FLARE RoPax ship#10, see Figure 33, which consists of 10 decks and 6 muster stations. 5 muster stations were located at deck 7 and 1 muster station was located at deck 8, see Figure 34

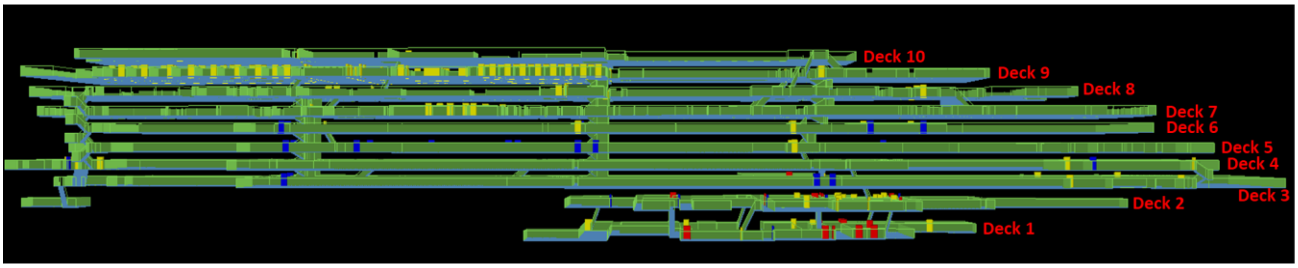


Figure 33 Side view of the EVI model displaying different decks – Ship #10

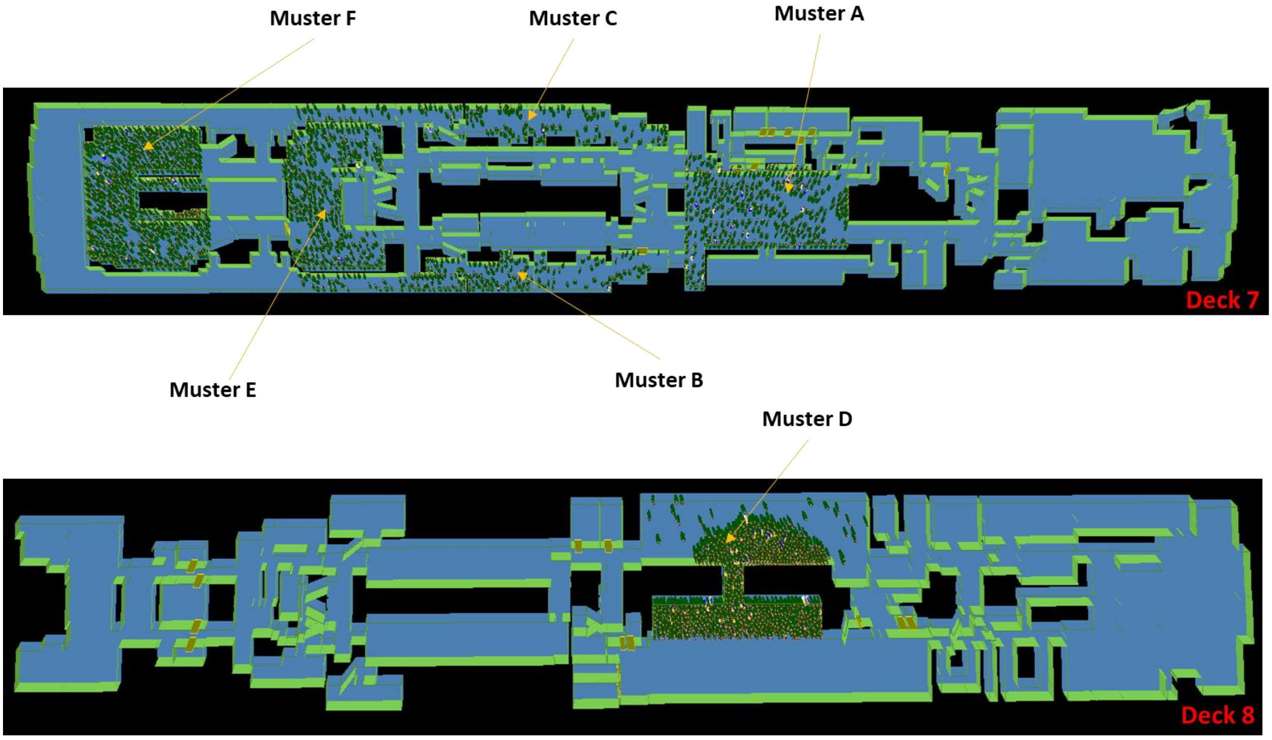


Figure 34 Top view of deck 7 (top) and 8 (bottom) showing locations of muster stations – Ship #10

The evacuation software (EVI) has been interfaced with the software for flooding simulation (PROTEUS) in order to simulate the evacuation with each specific flooding scenario as per the selected cases.

In general, the settings are based on MSC.1/Circ.1533. Following are the main settings/assumptions for this ship:

- Evacuation Night scenario;

- Passengers and crew demographic: According to MSC.1/Circ. 1533 Annex 3, Appendix 1;
- Response duration: Night Scenario - according to MSC.1/Circ. 1533 Annex 3, Appendix 1, Item 3.2.2 (About 300sec ± 90sec for the crew in service and 600sec ± 180sec for the resting people and);
- Agents located in the rooms affected by flooding have not been evacuated (they are considered lost);
- 10 runs for each breach scenario;
- Speed reduction function based on the heeling angle of the ship (Figure 35);

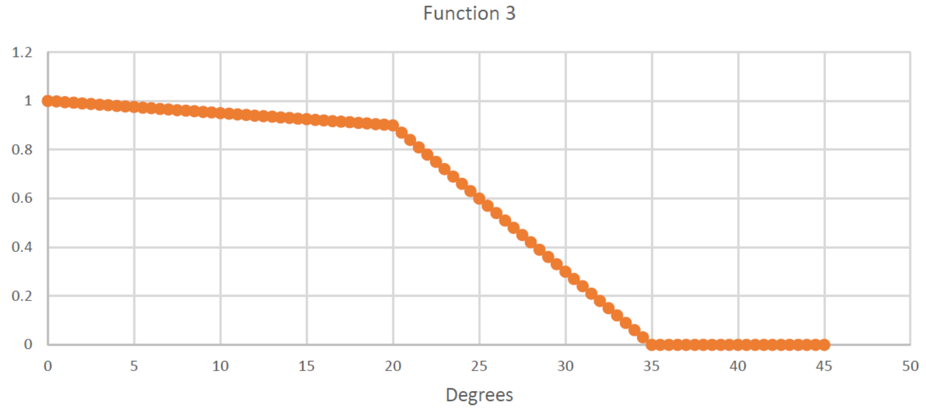


Figure 35 Speed reduction function vs heeling angle of the ship

The night scenario has been selected as it is conservative in terms of TTE (Time to Evacuate) as the response duration for the passenger is higher at night. Furthermore, ten runs (instead of fifty requested by MSC.1/Circ.1533) have been performed to evaluate the 95%ile.

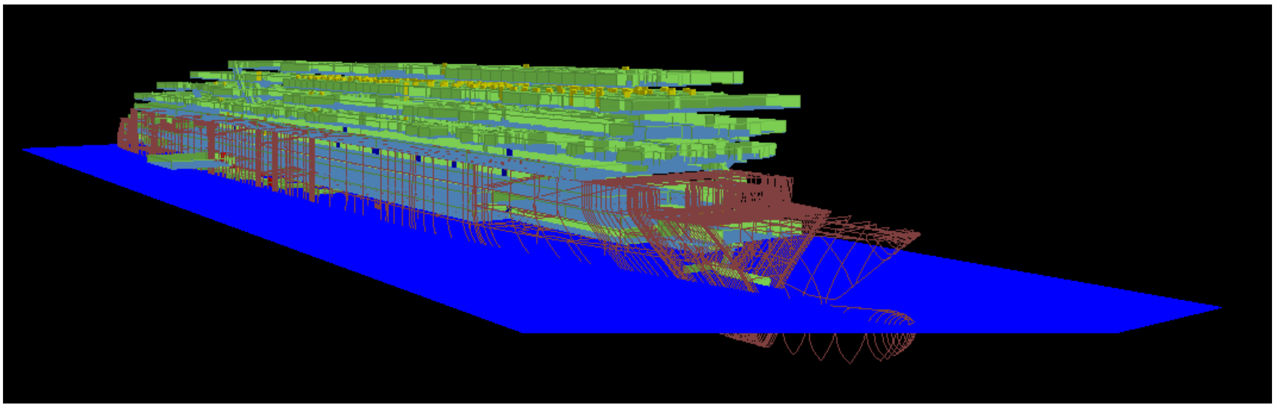


Figure 36 EVI snapshot of simulation, scenario-1 – Ship #10

3.3 Results of the evacuation simulations

The results of the evacuation analysis permitted to generate the diagrams with the numbers of persons evacuated versus the time. Entering within these diagrams with the TTC it is possible to calculate for each case the number of persons evacuated before the ship capsizes. Figure 37 shows an example of calculating the number of people evacuated from various muster stations at a given TTC (in this case, for Scenario-1 TTC = 2252.7 sec).

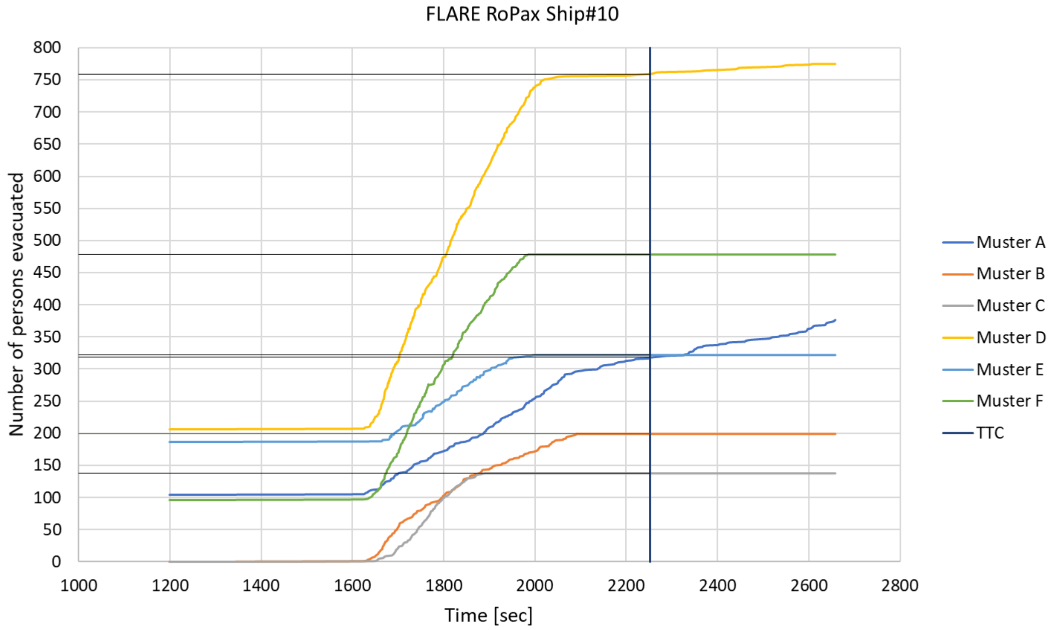


Figure 37 Evacuation of passengers over time from different muster stations, scenario-1 – Ship #10

Figure 38 shows a comparison of the resultant fatality rates of three selected flooding scenarios with the simplified formula (PLL level 2.1).

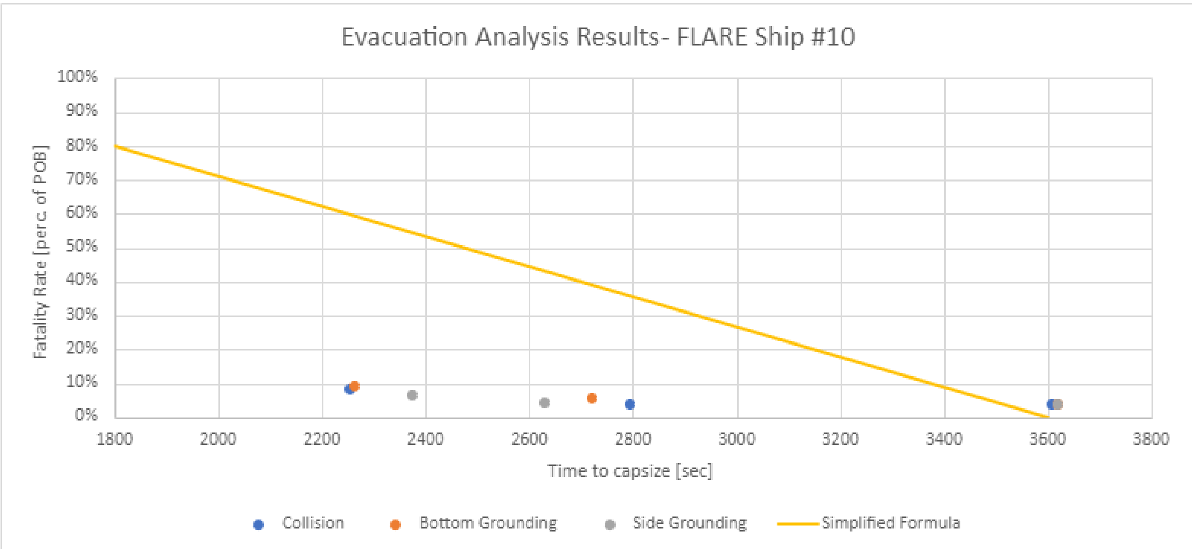


Figure 38 Comparison of evacuation analysis vs simplified formula – Ship #10

For all cases, the fatality rate is lower than the value calculated by the simplified formula (PLL level 2.1), with 30min<TTC<60min. For TTC>60min, fatality rate is marginally higher than simplified formula (3.7%).

Hence it is confirmed that the simplified approach for the fatality rate calculated as a linear function of the TTC (PLL level 2.1) is conservative.

3.4 Calculation of PLL level 2.2

Using the fatality rate that has been obtained from the evacuation analysis, the PLL level 2.2 has been calculated. Table 17, shows the overview of the results obtained at different PLL levels.

Table 17 PLL level 2.2 – Ship #10

Damage Type	**Collision**		**Side Grounding**		**Bottom Grounding**		**TOTAL**
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	6.209	6.477	6.209	6.477	6.209	6.477	
PLL L1 (1/ship year) (static assessment)	1.32E-01	2.09E-01	7.32E-02	8.71E-02	1.62E-02	1.95E-02	0.5372
	0.3412		0.1603		0.0357		
PLL L2.1 (1/ship year) (dynamic assessment)	1.21E-01	2.01E-01	3.35E-02	4.76E-02	4.22E-03	4.50E-03	0.4122
	0.3224		0.0811		0.0087		
PLL L2.1 vs L1 (variation percentage)	-5.5%		-49.4%		-75.6%		-23.3%
PLL L2.2 (1/ship year) (evacuation analysis)	**0.3222**		**0.0810**		**0.0086**		**0.4118**
PLL L2.2 vs L2.1 (variation percentage)	**-0.05%**		**-0.18%**		**-1.40%**		**-0.11%**

4 CONCLUSIONS

The complete procedure for calculation of Risk has been applied on Ship#10 and the results obtained demonstrated that the procedure is coherent with the multi-level approach. In fact the PLL has been reduced from 0.5372 (level 1) to 0.4122 (level 2.1).

The PLL Level 1 is conservative, but it seems more robust than PLL calculated by EMSA3 Risk Model as the fast/slow sinking node has not been used in the FLARE procedure.

The dynamic analysis in level 2 leaded to a reduction of the PLL by about 13% with the simulation of 500 breaches and 23% with the simulation of 1854 breaches. Such reduction of the PLL is essentially based on the fact that about 33% and 35% of cases have been found to survive in the dynamic analysis, for 500 and 1854 breaches, respectively, while they had Sfac=0 when the static analysis has been carried out.

Furthermore, a sensitivity analysis demonstrated that the impact on the PLL level 2.1 by even a large deviation of the fatality rate (calculated with the simplified formula) is negligible (less than 0.3%).

The flooding simulations showed a percentage of 98% of fast capsize cases (TTC<30min) and 2% only for slow capsize cases (TTC>30min). This fast/slow rate is very far from the percentages assumed in the EMSA3 risk model for which only 50% fast capsizing rate was used.

With the aim to check if the simplified formula for the fatality rate (applied for cases with TTC>30min) is conservative, 9 cases have been selected for the evacuation analysis and PLL Level 2.2 has been calculated accordingly. In such a way the PLL obtained after flooding simulation has been reduced marginally by further 0.11%.

The results obtained from the evacuation analysis showed that in general the simplified formula for the fatality rate (PLL level 2.1) is conservative. However, when the updated fatality rates from the evacuation simulations are applied to the PLL calculations, the change is marginal.