A METHODOLOGY FOR DESIGN EVALUATION OF DAMAGE STABILITY

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Abstract

In this paper a methodology for determining the probability of the consequence "capsize after a collision" will be presented and applied to the design of a RoPAX ferry. This methodology was developed within the EU-funded research project NEREUS.

This methodology is based on a rational and scientific approach, identifying necessary tools for a rational assessment of the survivability of a damaged RoPAX ferry. Based on this generic identification, existing tools were selected and linked together in the framework of a Monte Carlo simulation. The outcome of the application of the methodology is the probability of survival within a predetermined confidence interval and a predetermined level of significance. This means, that the quality of the result is quantified. The methodology is applied to a RoPAX ferry and the results are given in the paper.

1 Introduction

The stability analysis of ships is mainly determined by empirical stability criteria that are based on the experience from operated ships. The approval itself follows prescribed methodologies with design specificae or physical properties to be met. Consequently, no absolute safety-levels are known that have to be achieved.

Therefore it is not yet possible to evaluate an unconvential or conventional design with respect to intact and damage stability using first principle methods for approval purposes. Opposed to this, applying such methods in the early design stage leads to a better understanding of the physical phenomena and helps to design safer ships.

There is a need for a new methodology, which takes into account risk performance based criteria that can be quantified and judged in line with established performance criteria like resistance, noise level, or pressure pulses.

All the approaches for safety evaluation mentioned above represent different stages of knowledge, available methodologies, and different levels of risk perception in the society. As already discussed in Tellkamp, Cramer, and Krüger (2001), safety of technical systems like ships is achieved using one of the above mentioned strategies or a combination of them.

Today in the shipbuilding industry, two approaches for the evaluation of safety are used in rules and regulations. They are based on either

- prescribing design specificae, e.g. the main engine room has to have A60 walls, or the exact position of the collision bulkhead.

  or

- directly or indirectly prescribtion of physical properties, e.g. the leverarm curve of an intact vessel has to meet certain criteria, or some stresses shall not be exceeded.

Missing is an approach explicitly quantifying risks:
- prescribing acceptable risk levels, e.g. the frequency of a certain hazard shall be lower than a certain rate.

The common aim of all these strategies is to ensure a minimum safety standard. But what is safety? Safety can be defined as the abscence of risk, which itself has three major elements:

1. consequence,
2. frequency,

   and
3. exposure

as shown in figure 1.

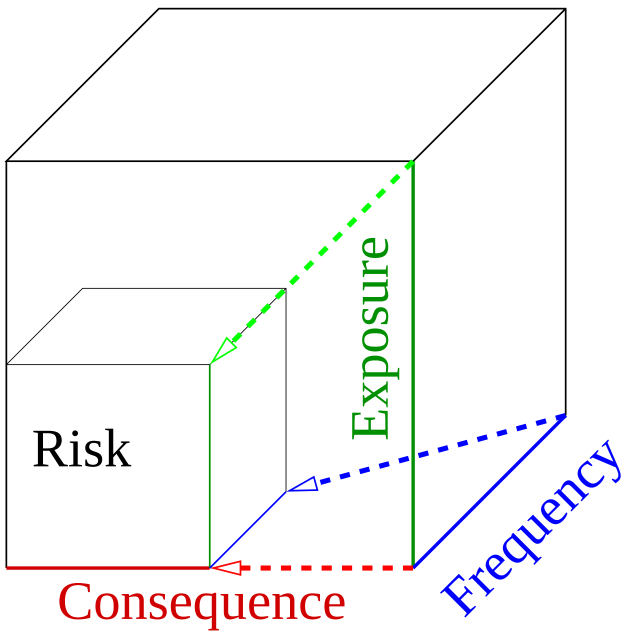


Figure 1: Elements of Risk

Some elements of risk on the example of the hazards 'parametric rolling' and 'collision' are

hazard: parametric rolling

risk: intact capsize

1. **consequence:** intact capsize due to parametric rolling
2. **frequency:** number of wavepackets per time unit causing parametric rolling leading to capsize
3. **exposure:** time sailing off–shore

hazard: collision

risk: capsize

1. **consequence:** capsize after a collision
2. **frequency:** number of collisions per time unit causing capsize
3. **exposure:** time sailing in areas where collisions can occur

The probability of a consequence C, which is frequently used instead of frequency and exposure, is determined to

$$P(C) = \lambda \cdot t \tag{1}$$

and the risk R is defined as

$$R = P(C) \cdot C, \tag{2}$$

The scope of the work presented here is to calculate this probability for the consequence **capsize** of the hazard **collision**, see figure 3.

2 Risk Based Design Methodology

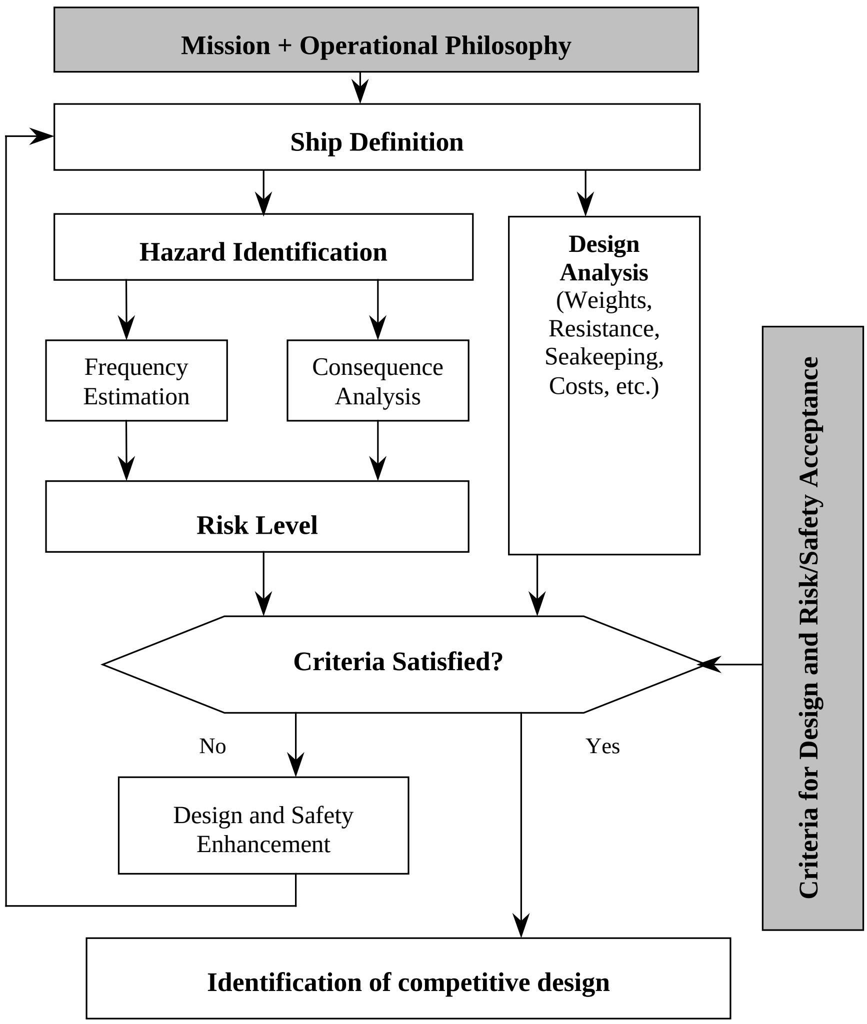


Figure 2: Risk–Based Design Procedure

The aim of the methodology shown in figure 2 is to integrate performance based risk criteria into the design process. Thus the designer is enabled to handle safety like any other performance based design criterion, e.g. resistance, costs, etc. Within the NEREUS–project, this methodology was developed and proven on the example of the hazard **collision** with the consequence **capsize**, which is shown in figure 3. The basic concept of this methodology is given in Oestvik (2001).

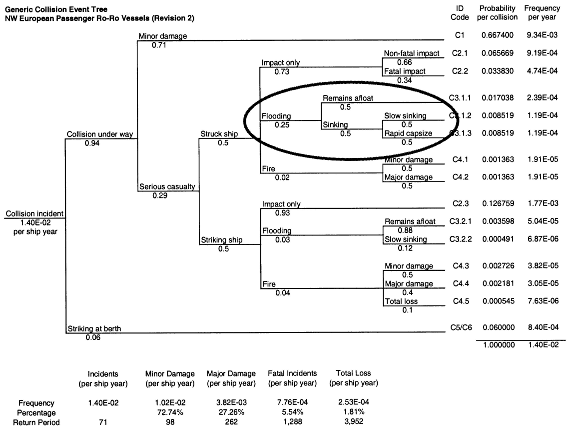


Figure 3: Event–Tree for collision incidents and their consequences

A risk based design methodology has to meet several criteria:

- the methodology should be inline with or similar to current practise,
- it should be based on the use of first principle tools,
- it should be generic and comprehensive,
- the results should be digits,

  and
- the quality of the results should be quantifiable.

The methodology which is presented here and which fulfills these requirements was developed in the NEREUS–project. Within this RBD[1]–methodology a Monte–Carlo–Simulation is utilized to calculate the probability of remaining afloat after a vessel encountered a collision (encircled area in figure 3).

In this document an applicable Monte–Carlo–Simulation will be presented as an useful tool within the RBD–procedure. The Monte–Carlo–Simulation is used within the procedure for the estimation of the probability of capsizing provided a collision has occured.

[1]Risk Based Design

To apply this methodology on the calculation of the probability of survival after a collision, a set of tools was identified. These tools were named F1–tool, C1–tool, C2–tool, and R1–tool, respectively. They are shown in figure 4. The F1–tool has the output 'collision impact and environmental conditions' in terms of damage extend and significant waveheight. From this the C1–tool determines the set of damaged compartments which together with the significant waveheight is input for the C2–tool. Here the ships' response is calculated, in terms of surviving these conditions or not. Finally, the R1–tool quantifies the risk of not surviving damaged conditions by means of giving the probability of survival.

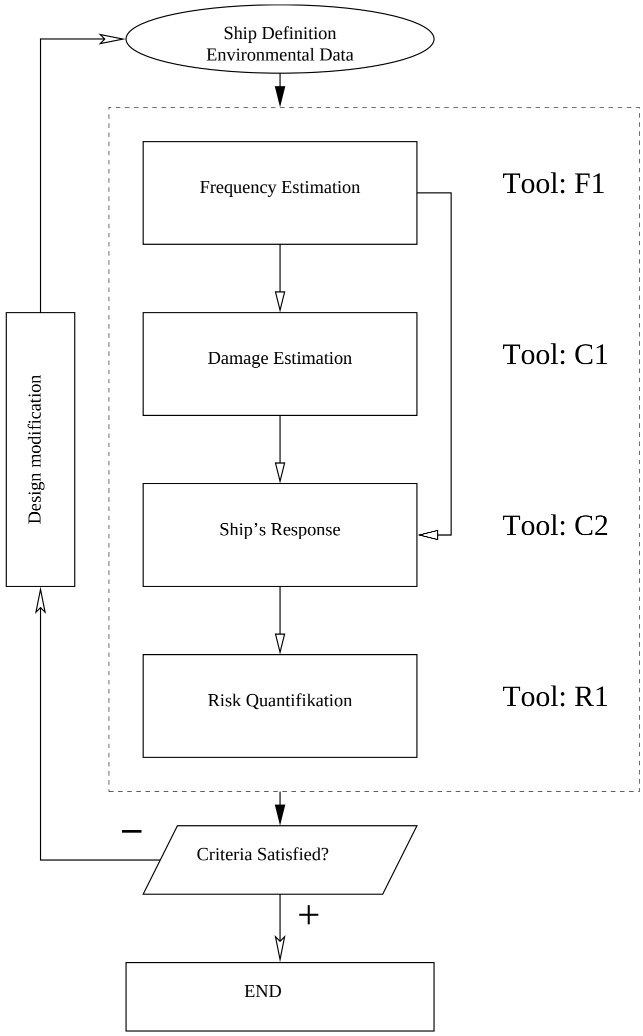


Figure 4: Flow diagram for the safety evaluation for collision incidents

3 Monte–Carlo–Simulation in Damage Stability Calculations

The set of generic tools, which were defined in section 2, was taken and existing tools were identified for being used:

Monte–Carlo–Simulation as a framework

F1 HARDER and SOLAS damage statistics, Seastate statistics, Söding (2001),

C1 Ship Design System E4,

C2 SEM,

R1 Outcome of the Monte–Carlo–Simulation.

The actual formulation of the Static Equivalent Method, SEM, is described in IMO (2002b).

As damage stability calculations use several deterministic and random data and a functional correlation between input data and result is not known, the Monte–Carlo–Simulation is well suited to determine the contribution $P(remain\ afloat)$ to the survivability of ships in the case a damage has occured.

The basic idea is to generate a random sample for the result of a random experiment, see figure 5. From this sample, using statistical tools, statements on the random result can be made. Details on Monte–Carlo–Simulations are given in Knuth (1997) and Flannery et al. (1995).

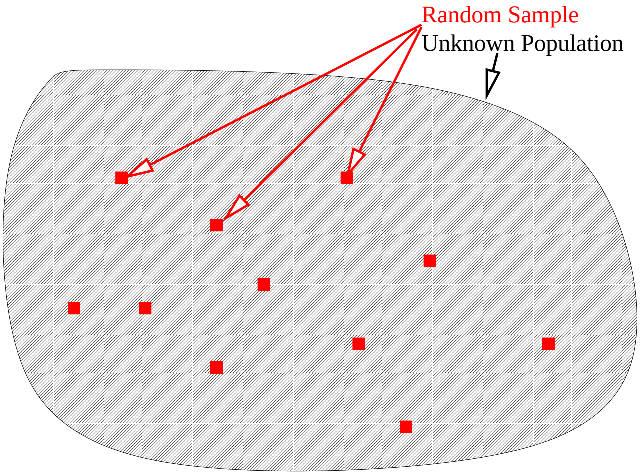


Figure 5: Random Sample as result of a Monte–Carlo–Simulation

3.1 Input data

The data used for damage stability calculations can be subdivided into deterministic data and random data:

1. deterministic data
   (a) Hullform
   (b) Compartmentation
   (c) loading condition and intact floating condition
      - mass and draught
      - vertical center of gravity
      - longitudinal center of gravity
      - transversal center of gravity
      - tank filling, permeability of the car–deck
2. random data
   (a) damage center on the hull
   (b) longitudinal damage extend
   (c) transversal damage extend
   (d) vertical damage extend
   (e) sea state

Item 1c should be treated deterministic, as in the stability booklet several loading conditions are specified and well known with all their properties, and typically a vessel is restricted to sail at this loading conditions. This approach also ensures compatibility between intact and damage stability. If loadcases are not known, statistics could be applied.

3.2 Probability distributions

As the damage location and extend are taken as probabilistic data, appropriate distributions must be used. The distributions used here were proposed to IMO as a result of the HARDER–project, see IMO (2002a):

$$F(dx) = \begin{cases} 0 & , dx < 0 \\ dx \cdot (-30 \cdot dx + 10.5) & , dx \le \frac{1}{6} \\ 0.75dx \cdot (-dx + 1) + 0.7916 & , dx \le 0.5 \\ 1 & , 0.5 < dx \end{cases} \tag{3}$$

$$F(x0) = \begin{cases} 0 & , x0 < 0 \\ x0 & , x0 \le 1 \\ 1 & , x0 > 1 \end{cases} \tag{4}$$

$$F(dy) = \begin{cases} 0 & , dy < 0 \\ dy \cdot (-\frac{12}{5} \cdot dy + \frac{16}{5}) & , dy \le 0.5 \\ 1 & , 0.5 < dy \end{cases} \tag{5}$$

$$y0 = y(x0) - \frac{1}{2} \cdot dy \tag{6}$$

$$F(dz) = \begin{cases} 0 & , dz < 0 \\ dz & , dz \le 1 \\ 1 & , dz > 1 \end{cases} \tag{7}$$

$$F(z0) = \begin{cases} 0 & , z0 < 0 \\ z0 & , z0 \le 1 \\ 1 & , z0 > 1 \end{cases} \tag{8}$$

$$\tag{9}$$

with the nondimensial figures

$$x0 = \frac{X_0}{L_{oa}} \tag{10}$$

$$dx = \frac{dX}{L_{oa}} \tag{11}$$

$$y = \frac{Y(X0)}{B} \tag{12}$$

$$dy = \frac{dY}{B} \tag{13}$$

$$z0 = \frac{Z_0}{H_{max}} \tag{14}$$

$$dz = \frac{dZ}{H_{max}} \tag{15}$$

where $Y(X0)$ is measured at the actual draft and H_{max} is the maximum damage height according to IMO (1993) and IMO (2002a), respectively.

3.3 Calculation of survivability using Monte–Carlo–Simulation

The output of a damage stability calculation using a Monte–Carlo–Simulation should be a figure, that allows to assess the survivability of a specific vessel under consideration on a scientific base. To do so, the probability of survival under the condition a damage, specified as a penetration of the outer shell, has occured should be calculated.

The application of Monte–Carlo–Simulation to damage stability problems could easily be outlined using pseudocode:

- set $c = 0$ and do n times...
  1. Generate seastate and damage cuboid ....
  2. Generate list of damaged compartments from damage cuboid.
  3. Generate buoyancy body taking into account loading condition.
  4. Calculate if seastate will be survived.
  5. If yes, increase c by 1.
- take
  $$\frac{c}{n} = \hat{p} \tag{16}$$
  as estimation for the probability p of surviving a damage on this loading condition

In the context of figure (4), the F1–tool – generation of damage cuboid and seastate – can be identified as step 1. The C1–tool – consequence from damage cuboid – is equivalent to steps 2 and 3, and 4 forms the C2–tool – consequence from buoyancy body in the seastate. Equation (16) as an estimation for the survivability, whith the quality of the estimation quantified by equation (20), then is the R1–tool.

3.4 Level of confidence and magnitude of n

The type of the distribution of c is the binomial distribution. A binomial distribution is characterized by one parameter p. p gives the probability that the result of an experiment is *successful*, in our example *the ship survives a damage*, and $B(p, c, n)$ gives the probability that in n damage cases the ship survives c times:

$$P(C = c) = B(p, c, n) = \binom{n}{c} p^c (1-p)^{(n-c)} \tag{17}$$

with the mean

$$\mu_C = np \tag{18}$$

and the variance

$$\sigma_C^2 = np(1-p) \tag{19}$$

gives the probability that in n experiments c are successful.

In section 3.3 a fraction $\frac{c}{n}$ is calculated. This fraction is taken as an estimation $\hat{p}$ for the probability p of surviving a damage, which is the unknown parameter of the binomial distribution. As this figure is the result of the generation of a random sample, it is a random value itself. The quality of this estimation is quantified by

$$P\Big(p \in \big[\hat{p} \pm \frac{\Delta_p}{2}\big]\Big) = 1 - \alpha. \tag{20}$$

On the level of significance $1 - \alpha$ for a binomial distribution the confidence interval Δ_p is calculated to

$$\Delta_p \leq \frac{2}{\sqrt{n}} \sqrt{\hat{p}(1-\hat{p})} z_{1-\frac{\alpha}{2}} \tag{21}$$

with $z_{1-\frac{\alpha}{2}}$ as the $(1 - \frac{\alpha}{2})$–quantile of the standard normal distribution. So n becomes

$$n \geq 4\hat{p}(1-\hat{p}) \Big(\frac{z_{1-\frac{\alpha}{2}}}{\Delta_p}\Big)^2. \tag{22}$$

For a $B(p, c, n)$–distributed population

$$\hat{\sigma}^2 = \hat{p}(1-\hat{p}) \leq \frac{1}{4} \tag{23}$$

surely is true and without a–priori information about p the size of the random sample has to be determined to

$$n \geq \Big(\frac{z_{1-\frac{\alpha}{2}}}{\Delta_p}\Big)^2. \tag{24}$$

Using the equations (17) to (24) it is possible to quantify the accuracy of the RBD–Methodology. This is an important aspect, as numbers are calculated which are used to determine wether a vessel is safe or not. Additionally, if used in conjunction with methodologies which assess other hazards like intact capsize as discussed in Cramer and Tellkamp (2002) (this workshop), this is the only way to ensure comparable results.

4 Design Exercise

4.1 Reference Design

A reference design was developed using the 'conventional' approach, applying the SOLAS solely. The principal layout of this vessel is given in figure 6 below with the maindimensions in table 1

L_{OA}	Length over all	201.54	m
L_{PP}	Length between perpendiculars	189.1	m
L_{CWL}	Length of CWL	192.7	m
B_{TD}	Moulded Breadth at T=6.5m	28.93	m
$B_(max)$	Maximum Breadth	31.7	m
DEP	Depth to Freeboard Deck	9.3	m
DEP_2	Depth scantling	17.1	m
T_D	Draft design	6.5	m
T_{CWL}	Draft scantling	6.7	m
T_G	Draft summer Freeboard	6.7	m
Δ	Deplacement design draft	20544	t
V_{Trial}	Trial speed	25	kn

Table 1: Maindimensions of reference design

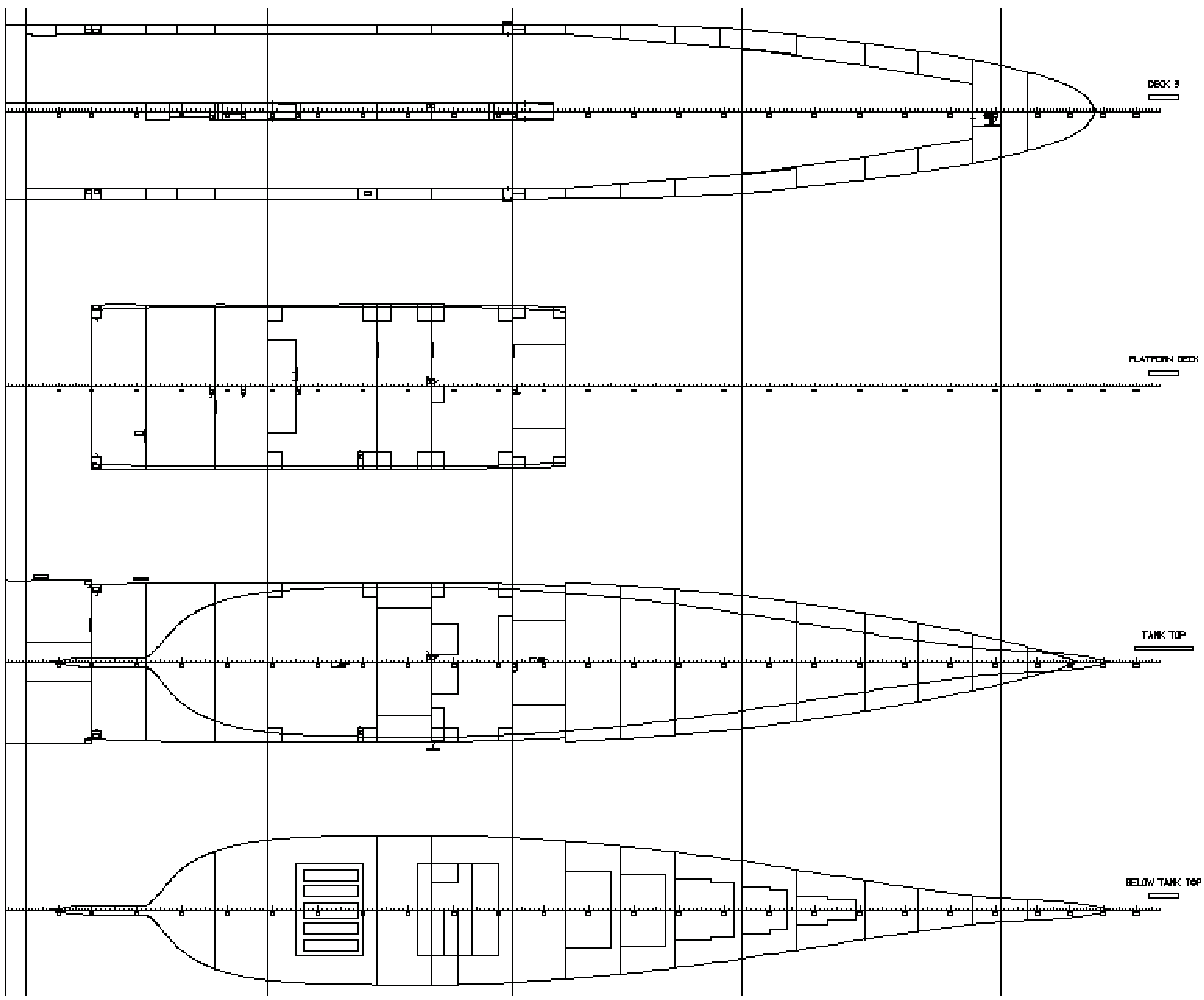


Figure 6: Reference Design, watertight compartmentation

4.2 Design Alternatives

4.2.1 RoRo-Deck Arrangement

Based on the reference design, a set of design alternatives were defined and evaluated:

A reference design, short center casing and long side casings,

B short center casing, no side casings,

C long side casings, no center casing,

D short center casing and partly side casing each side,

E long center casing, no side casings.

The survivability was calculated using the Monte–Carlo–Simulation on a level of significance of 95% with a confidence interval of ±2%. Given are the overall probabilities of survival and the survivabilities under the condition that the RoRo–Compartment is damaged. The changes in survivability are significant if they exceed 2%. From table 2 it can be seen, that it was not possible to improve the survivability of the reference design on the given level of significance and confidence interval.

4.2.2 Hullform Modifications

After the first design iteration was completed, the vessels lines were improved with respect to seakeeping performance as shown in figures 7 and 8.

The influence of these modifications on the damage stability performance of the vessel are shown in table 2. The modifications do not change the ranking of the configurations A – E, and the changes in survivability taking into account all damage cases are not significant, as they are lower than 2%. But the changes for the survivability under the condition the RoRo–deck is damaged is improved significant for the arrangements A, C, and D.

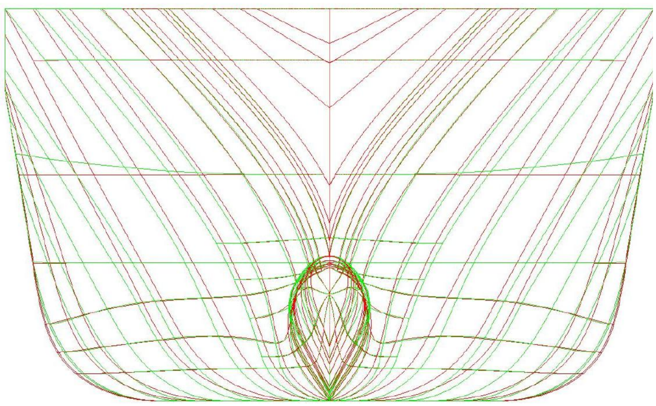


Figure 7: modified Hullform, forebody

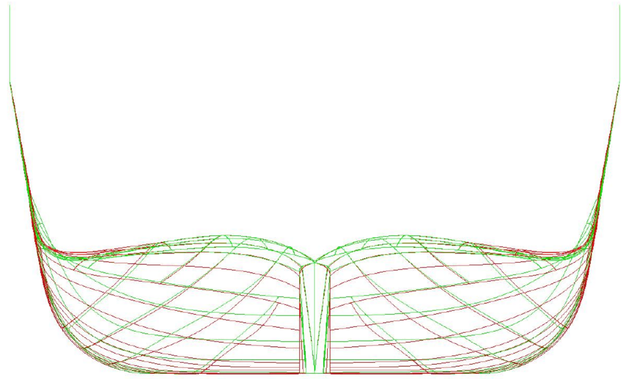


Figure 8: modified Hullform, aftbody

4.2.3 Modification of deck height

Based on the results with the modified hullform, the influence of the deck height was investigated. Moving the deck is relevant to two counteracting phenomena:

1. increasing freeboard
2. decreasing vertical center of gravity

Within the range of the modifications, a significant improvement of survivability was found only for the 'A'– and 'C'–configurations. But other performance criteria like seakeeping were decreasing and the weather criterion could not be fulfilled with the respective vertical center of gravity.

4.2.4 Comparison of Designs

In table 2 the survivabilities of the different designs are shown. The reference design has a survivability of 0.918, based on all damages, and of 0.854, based on those damages, where the RoRo–compartment is being hit. The survivabilities of other configurations do not differ significant from the survivability of this configuration, if they are within the interval 0.981 ± 0.02, see section 3.4. The results are presented in table 2.

Based on the presented results, the 'B'–configuration with a deck height of 10.0m was chosen as the final design. The survivability differs not significant, but the costs are lower.

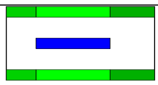
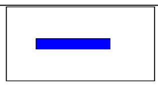
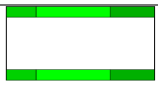
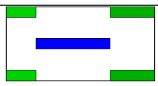
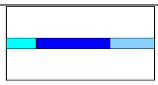
Configuration		Survivability				
		initial Design		modified hull		deck at 10m
		A	B	A	B	B
A		0.854	0.918	0.872	0.931	0.953
B		0.792	0.890	0.794	0.889	0.931
C		0.851	0.922	0.884	0.937	0.963
D		0.819	0.904	0.843	0.912	0.945
E		0.737	0.861	0.732	0.856	0.900

Table 2: Comparison of Results, column 'A' gives the survivability under the condition of a damaged RoRo compartment, column 'B' the survivability taking into account all damage cases

5 Conclusions

A risk based design methodology utilizing first principle tools for assessing the resistance against capsize for damaged RoPAX vessels was presented. The criteria given on page are kept, especially is the quality of the results quantified. This methodology was successfully applied within a design exercise and is promising to be a valuable tool for the assessment of risks of arbitrary ships.

Within the exercises changes in survivability compared to a reference design were quantified. Once performance based criteria for damage stability are available, this methodology will also be usable for design assessment with respect to those criteria.

As the methodology determines whether a change in the results is significant or not, it can clearly be shown that local changes to the compartmentation, do not have a significant impact on the overall survivability, if a commonly used level of significance of 0.95 and a commonly used confidence interval of ± 0.02 are applied. This result is reasonable, as it confirms, that safety is built into a design by hullform and major compartmentation and that details like light recesses do not have an impact on survivability.

This method could be improved by use of a C2–tool, which is able to predict the behaviour of a RoPAX–vessel with a non–damaged RoRo–compartment. Furthermore, statements on the time to sink of a damaged vessel would be a valuable output of an improved C2–Tool. At the moment, damages where the RoRo–compartment is not hit, are considered to survive any seastate. The reason for this is within the concept of the SEM.

6 Acknowledgements

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A Appendix

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A.1 Nomenclature

Symbol	Description
C	random number of survives in damaged condition
c	realization for C
$B(p,c,n)$	binomial–distribution
$f(X)$	probability density function
$F(X)$	probability function
λ	frequency of an event
$\overline{X}$	mean for X
μ_X	expected value for X
n	size of random sample
$N(\mu,\sigma^2)$	normal–distribution
p	probability of surviving a damage
$\hat{p}$	estimation for p as result of a Monte–Carlo–Simulation
Δ_p	confidence interval for p
$P(C=c)$	probability that the realisation for C equals c
π	uniform distributed random number
RBD	Risk Based Design Methodology
RNG	random number generator
S_X^2	standard deviation for X from random sample
σ_X^2	variance for X
t	period of an RNG
t	time of exposure
X	random Variable
x	realization for X
$1-\alpha$	level of significance