A RISK-BASED METHOD FOR SHIP SAFETY ASSESSMENT AT THE PRELIMINARY DESIGN STAGE

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Abstract

The paper presents the results of research regarding a method for ships safety assessment in critical conditions which has been conducted at the Chair of Ship Hydromechanics, Faculty of Ocean Engineering and Ship Technology, Technical University of Gdansk since 2000. The main objective of research is to work out a risk-based direct method to assess a ship safety in critical conditions at the preliminary stage of design. The method should enable to perform the multi-objective and multi-parametric-variation investigations to achieve the required and optimal levels of ship safety in critical conditions. Such investigations can be done for either the conventional or novel arrangement of internal spaces of a ship. During the design analysis an influence of parameters associated with the hull form, arrangement of internal spaces, loading conditions, position and extent of damage, cargo shift and weather impacts on the ship safety in critical conditions can be taken into account. The method is a kind of risk-based parametric related method using modern solutions combining the design and ship hydromechanics procedures with the formal approach to safety. The main modules of the method are connected with the following problems: design requirements, design criteria, design constraints, risk acceptance criteria, safety objectives, ship and environment definition, design analysis including the hazard and risk assessment regarding the ship hydromechanics characteristics, modification of design (mitigation measures), risk-based ship safety assessment and decisions on safety. The results of investigations are introduced. A new direct risk-based procedure to evaluate the probability of survival is incorporated within the method. The structure of computational model is presented. Some results connected with the computer simulation of safety assessment in critical conditions for a few ships are shown. The practical remarks regarding the method, computational model and ships design for safety are attached.

1. INTRODUCTION

The research problem concerns development of a method for the ships safety estimation in critical conditions at the preliminary stage of design. The major application area for the method should be the ”design for safety” using the risk assessment approach. The objectives followed from the design for efficiency should be taken into account, too. The method is integrated as the influence of many factors on the ships safety may be investigated.

The ships safety estimation is connected with the risk assessment regarding the stability, damage stability, stability in critical conditions and survivability.

The risk assessment may concern as follows:

- estimation of the probability of a ship survival when flooding any group of compartments;
- estimation of the probability of oil out-flow according to the arrangement of internal spaces of a ship;
- estimation of the probability of a ship survival in particular cases (direct method preferred).

The critical conditions have been defined as the ingress of external water into any group of watertight compartments of a ship associated with the following impacts:

- internal, connected with cargo and/or ballast shift;
- external, connected with waves and wind activity.

The knowledge base for the research is as follows:

- naval architecture;
- ship hydromechanics;
- system approach to safety;
- safety case / formal safety assessment (FSA) methodology;
- IMO and SOLAS regulations regarding safety.

2. RESEARCH REGARDING SHIP DESIGN FOR SAFETY IN CRITICAL CONDITIONS

The problems studied according to the ”Safety of Passenger/RoRo Vessels” project established by the Nordic countries were as follows [1]:

- damage stability modelling methods;
- watertight integrity;
- collision damage extent;
- dynamic effects in waves.
-

The results of the project contained three important new elements: minor damage concept, probability of survival, major damages.

There was the SAFER-EURORO programme directed by the Ship Stability Research Centre at the Strathclyde University in the United Kingdom [2]. It was a multi-disciplinary research programme for developing an integrated approach to designing safe passenger/ro-ro ferries and to implement this approach to actual design examples. The programme was structured as a cluster of individual projects, each addressing a special area in ship design and operation. The ”Project 2” of the programme called the ”Design for Survivability (DESURV)” consisted of seven tasks. The majority of them have been solved as expected.

In Poland there has been a set of research projects concerning the ships safety problems. A few of them have been done at the Ship Design and Research Centre (SDRC) in Gdansk. The background of the projects may be found in documents by Pawlowski [3] and

Pawlowski and Laskowski [4]. Some SDRC developments regarding the computer simulations on safety of ships in critical conditions were introduced during the 1st Summer School "Safety at Sea" in 2001 [5].
There was a research project No. 9 T12C 026 16 founded by the Scientific Research Council KBN which concerned a new method and model for the ships safety estimation in critical conditions. This project was under development at the Chair of Ship Hydromechanics, Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology and was terminated by the end of 2000. Some results of the project were presented by Gerigk [6][7].

The tasks associated with the project were as follows:

- damage stability modelling methods;
- large scale flooding;
- dynamic effects due to internal (ballast and/or cargo shift) and external (waves, wind) impacts;
- development of survival criteria for the ships in damaged condition;
- series of investigations including the safety assessment and example preliminary designs.

The main objectives of the research were:

- development of a method for the ships safety estimation when surviving;
- development of the theoretical and computational models for calculation the hydromechanics characteristics of a ship when surviving;
- development of the models (theoretical and computational) for estimating the risk when surviving;
- series of investigations regarding the ships safety when surviving.

The other objectives were:

- development of both the theory of ships and ship hydromechanics;
- supporting the education;
- developing the tools for the preliminary design;
- publications.

There is a project No. 5 T12C 004 22 founded by the Scientific Research Council KBN associated with developing a model for direct risk assessment when ship in critical conditions. This project is currently under development at the Chair of Ship Hydromechanics, Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology.

There is the HARDER research programme financed by the European Union to revise the SOLAS Chapter II-1 Parts A, B and B-1 and it is connected with solving the following problems [8]:

- reviewing model tests and methodology including the development of A.265 methodology and development of a methodology for Ro-Ro ships in the 1990's;
- HARDER project prediction of survival in waves including:
    a. observed mechanisms of capsize;
    b. survival estimation for high freeboard cases;
    c. survival estimation for low freeboard RoRo ships;
    d. survival estimation for low freeboard conventional ships;
    e. conventional methodology for non-RoRo ships;
- probability of sea state occurrence at the time of a casualty;
- development of survival factor "s".

The research presented in the paper is connected with developing the method and model for the ships safety estimation when surviving.

3. MODERN APPROACH TO SHIP SAFETY IN CRITICAL CONDITIONS

The factors affecting the safety may follow from different sources: design, operation and management.

There are a few levels of factors affecting the safety and they exist in the method as the following levels:

first level: human factor, control systems/technical means, legislative actions;
second level:

- ship including hull, propeller and rudder particulars;
- cargo including arrangement of internal spaces, cargo and ballast distribution and loading condition;
- environment including wind, waves and current;
- operational connected mainly with the integrated ship management system if available;
- human including both the psychological and physical predispositions, character, morale, integrity, knowledge, experience and training degree;

third level: interrelated parameters and characteristics following from the safety domains: stability, damage stability, survivability.

The major source of information on hazards and risks involved in shipping are both the statistics and investigations into serious casualties, documented by Gerigk [9]. Studying these data it becomes clear that the safety of life at sea and the pollution of the environment are a function of the ship's design, operation and management. Therefore, the method should be a procedure incorporating the above mentioned.

Modern approach to ships safety is connected with combining: system approach and formal safety assessment (FSA) methodology.

Formal Safety Assessment major elements are: hazard identification, risk assessment and risk reduction. Taking into account these elements the method has gradually been developed to include the following components:

- design requirements, criteria and constraints;
- risk acceptance criteria;
- safety objectives;
- ship and environment definition;
- design analysis:
    - hazard identification;
    - hazard assessment;
    - scenario development;
    - hydromechanics-based design analysis (intact stability, damage stability, dynamical stability in damaged condition);
- risk assessment;
- risk reduction (mitigation measures);
- modification of design;
- ship safety assessment;
- decisions on ships safety.

4. A METHOD FOR SHIP DESIGN FOR SAFETY IN CRITICAL CONDITIONS

A method for ship safety estimation when surviving has been worked out and it is associated with solving a few problems regarding the naval architecture, ship hydromechanics and ships safety and it is novel to some extent.

The method consists of two sub-methods [10]:

- parametric method - when stability and damage stability characteristics are calculated;
- semi-probabilistic or probabilistic-based method - for the survivability and risk assessment related problems.

From the theoretical point of view the method uses:

- global approach;
- technical approach.

Practically, the method is a kind of a database.
The global approach regards the method framework as follows:

- method philosophy development including reviewing literature, estimating safety of existing vessels, reviewing regulations, etc.;
- ship and environment definition;
- hazard identification and hazard assessment;
- scenario development;
- risk assessment;
- risk mitigation measures;
- hazard resolving and risk reduction;
- decisions made on ships safety (selection of optimal design, operational and mitigation measures).

The technical approach has been connected with developing the following:

- logical structure of design system;
- design requirements, criteria and constraints;
- logical structure of computational model;
- both analytical and numerical methods;
- application methods regarding the intact stability, damage stability, dynamical stability in critical and damaged condition.

Between the well known approaches to risk management:

- bottom-up approach and
- top-down approach

the top-down risk management methodology has been applied for the method which is suitable to be applied for design for safety at the preliminary design stage.

This approach should work in the environment of performance-based standards and help designing the ships against the hazards they will encounter during their operational life.

5. COMPUTATIONAL MODEL FOR SHIP DESIGN FOR SAFETY IN CRITICAL CONDITIONS

The structure of the design system and computational model combine the global approach and technical approach and it is presented in Figure 1.
The most important features of the system/computational model are as follows:

- system/model is open;
- system/model structure is hybrid-modular;
- system/model has a common library of analytical and numerical methods;
- system/model has a common library of application methods (direct geometry-based methods are preferable);
- system/model should enable the analysis to be done at a few project stages.

From the practical point of view the computational model is based on the DYNAMICAL DATABASE (DDB) concept and it is original. The structure of DDB database is modular and it relates to the logical structure of the computational model. The DDB data base enables to provide the safety estimation when a ship hydromechanics characteristics are estimated using either the numerical calculations (direct methods), model tests results, results from the full scale trials, empirical and hydro-numerical calculations (semi direct methods) or empirical calculations (indirect methods).

The ship and environment are defined as hydromechanics objects described by a set of parameters. The safety domains included in the "Hydromechanics Analysis" module are called the design methods using both the functions and procedures associated with solving particular ship hydromechanics problems. The

"Risk Assessment" module includes the methods that combine both the "hydromechanics" and "risk assessment" functions and procedures.

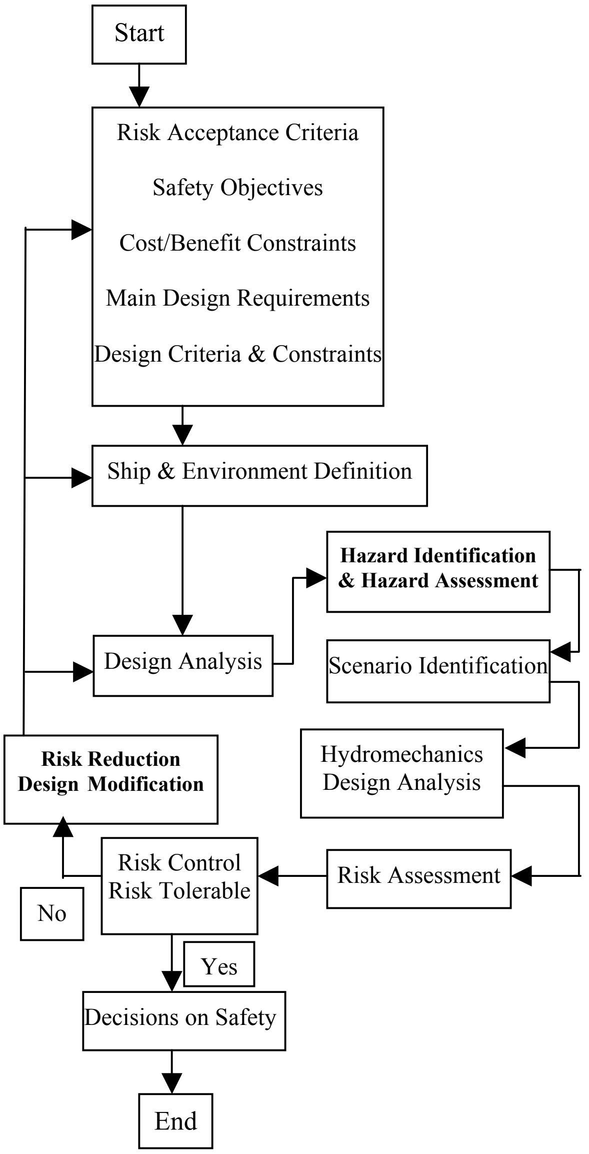


Figure. 1. Structure of the design system and model combining the global approach and technical approach.

The "Main Requirements" module may consist of the following:

- general requirements,
- IMO regulations,
- requirements of classification societies and
- requirements of conventions.

The current set of requirements used by the DDB database includes the IMO regulations. The DDB database should include both the risk acceptance criteria, safety objectives, main requirements and design criteria and constraints. These are the very important components of the computational model.

The method and model have been worked out towards their application at the preliminary stage of design.

Two separate design processes can be initiated:

- iterative approach;
- parametric-related investigations.

Current design options of the computational model are as follows:

- calculation of the "Attained Subdivision Index A";
- calculation of the "Local Subdivision Indices ΔA_j";
- calculation of the "Probability of Oil Outflow";
- calculation of the "Probability of Capsizing in Critical Conditions", when the IMO regulations are not used (direct risk assessment method).

6. RISK ASSESSMENT: CALCULATION OF THE PROBABILITY OF FLOODING ANY GROUP OF COMPARTMENTS.

At the design stage the estimation of the probability of survival of flooding any group of compartments is connected with calculation of the "Attained Subdivision Index A". The risk assessment is associated with satisfying the criteria:

$$A >= R \quad (1)$$

where:

A - attained subdivision index and generally
$A = \sum p_i s_i$;
p_i – probability of flooding the group of compartments under consideration;
s_i - probability of survival after flooding the group of compartments under consideration;
R - required subdivision index.

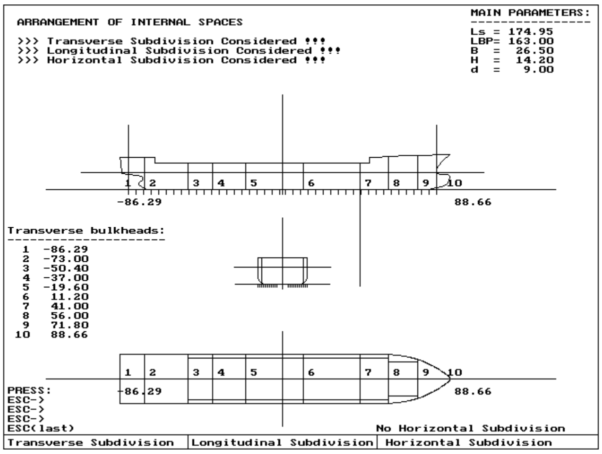
Both the indices are calculated according to the well known formula accepted by IMO. For the following example we may use the formula included in the Resolution MSC 19/58 – Subdivision and damage stability of cargo ships over 100 m.

A typical set of data and results of the risk assessment for the given ship may be as follows:

Main parameters:

L_{OA} = 175.00 m
L_{BP} = 163.00 m
Ls = 174.98 m
B = 26.50 m
H = 14.20 m
d_{max} = 10.50 m
d = 9.00 m

Documentary: stability data, hull form, arrangement of internal spaces presented in Figure 2.



```
ARRANGEMENT OF INTERNAL SPACES

>>> Transverse Subdivision Considered !!!
>>> Longitudinal Subdivision Considered !!!
>>> Horizontal Subdivision Considered !!!

MAIN PARAMETERS:
----------------
Ls = 174.95
LBP= 163.00
B  =  26.50
H  =  14.20
d  =   9.00

Transverse bulkheads:
---------------------
  1  -86.29
  2  -73.00
  3  -50.40
  4  -37.00
  5  -19.60
  6   11.20
  7   41.00
  8   56.00
  9   71.80
 10   88.66

PRESS:
ESC->
ESC->
ESC->
ESC(last)
No Horizontal Subdivision
Transverse Subdivision | Longitudinal Subdivision | Horizontal Subdivision
```

Figure. 2. Arrangement of internal spaces for the ship considered as an example design.

Loading data: centre of gravity

light ship:
P=8220.00 [t]
LCG=66.28 [m]
VCG(KG)=10.87 [m]

Loading condition: loading data

d_l=10.5 [m]
$d_p=d_{ls}+0.6(d_l–d_{ls})=3.56+0.6(10.5–3.58)=$ 7.73[m]

Set of permeabilities:

0.85 – occupied by machinery;
0.60 – appropriated to stores;
0.95 – occupied by accommodation;
0.00 or 0.95 – intended for liquids;
0.7 – for dry cargo spaces.

The results connected with the Attained Subdivision Index "A" calculation for the considered ship are presented in Table 1.

Table. 1. Results regarding the Subdivision Index "A" estimation.

Comp.	p_i	p_{ir}	Load. cond.	s_l	s_p	ΔA_j
1	0.07719	-	F	1		0.03816
		-	P		1	0.03807
2	0.03565	-	F	1		0.01783
		-	P		1	0.01779
3	0.02631	-	F	0.931		0.01228
		-	P		1	0.01311
3A	0.00247	-	F	1		0.00120
		-	P		1	0.00120
4	0.09270	0.02714	F	1		0.00786
		-	P		1	0.04632
5	0.10212	-	F	0		0
		-	P		1	0.05108
6	0.02062	-	F	0.542		0.00567
	0.02762	-	P		1	0.01376
7	0.01730	-	F	0.873		0.00753
		-	P		1	0.00867
8	0.03564	-	F	0		0
		-	P		1	0.01778
9	0.02129	-	F	0		0
		-	P		1	0.01059
1+2	0.06280	-	F	1		0.03136
		-	P		1	0.03139

2+3	0.04715	- -	F P	1	1	0.01368 0.02355
3+3A	0.01374	- -	F P	0.991	1	0.00398 0.00689
3A+4	0.02194	0.00574 -	F P	1	1	0.00167 0.01099
4+5	0.08921	- 0.02182	F P	0	1	0 0.01088
5+6	0.06362 0.05525	- -	F P	0	1	0 0.02769
6+7	0.03381	0.00870 -	F P	0	1	0 0.01684
7+8	0.03358	- -	F P	0	1	0 0.01679
8+9	0.03129	- -	F P	0	1	0 0.01563
1+2+3	0.02052	- -	P		1	0.01027
2+3+3A	0.00868	- -	P		1	0.00434
3+3A+4	0.05023	- -	P		1	0.01386
1+2+3+3A	0.00156	- -	P		1	0.00077

The Attained Subdivision Index “A”value is as follows:

$A = \sum \Delta A_j = 0.5501$

The Required Subdivision Index is:

$R=(0.002+0.0009*L_S)^{1/3}=$
$(0.002+0.0009*174.98)^{1/3}=0.54230$

where:

L_S – subdivision length;
L_S=174.98 [m] (for the B-191 container ship)

The final result is as follows:

A>R
0.5501>0.5423

From a designer point of view a question can be given if the ship is safe indeed. We know that according to the HARDER research programme and other research running across Europe and in many institutions all over the world the new formula for the “s_i” factor calculation should be submitted and it may include the components following from the fact that there are four stages during the flooding process [8]:

- creation of damage (stage 1);
- transient heel and intermediate flooding (stage 2);
- progressive flooding (stage 3);
- final stage (stage 4).

Of course during the above mentioned stages the internal and external forces may appear according to the following:

- wind heeling moment;
- action of waves;
- ballast/cargo shift;
- crowding of people;
- launching life saving appliances;
- etc.

The conditional probability to survive a damage may be a product of the elementary probabilities associated with surviving each stage:

$$s_i = s_1 * s_2 * s_3 * s_4 \qquad (2)$$

where:

s_i - probability of survival after flooding the group of compartments under consideration;
s_1, s_2, s_3, s_4 - elementary probabilities associated with surviving each stage.

How to solve the problems associated with calculating the elementary probabilities will be briefly discussed during the Workshop according to a given matrix of events presented in Table 2.:

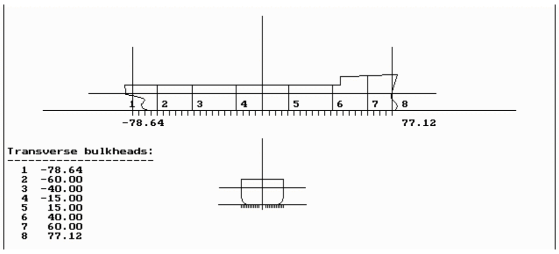
Table. 2. An example matrix of events during a flooding.

	Stage 1 creation of damage	Stage 2 transient heel and intermed. Flooding	Stage 3 progressive flooding	Stage 4 final stage of flooding
wind heeling moment	X	X	X	X
action of waves	X	X	X	X
ballast/ cargo shift			X	X
crowding of people		X	X	X
launching life saving aids		X	X	
air-flow bags action			X	X

7. RISK ASSESSMENT: OPTIMISATION OF THE “ATTAINED SUBDIVISION INDEX A”

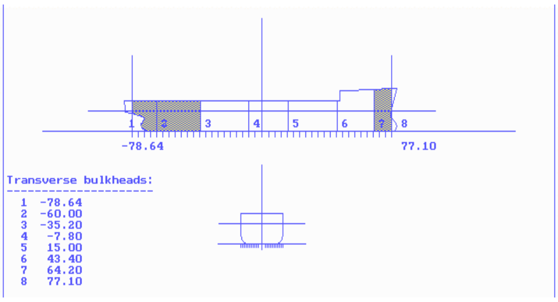
For more advanced procedures for design for safety for a ship in damaged condition the following approach has been applied. In Figure 3, the arrangement of internal spaces for a cargo ship is presented. Three design versions regarding the number and positions of transverse bulkheads are taken into account during the computer simulation of the risk assessment in critical conditions. The Table 3 presents the results of the Attained Subdivision Index A optimisation for all the mentioned design versions introduced in Figure 3. The preliminary and final positions of each bulkhead for all the design versions are presented in Table 4. The system of co-ordinates is placed at the midship.

Design version ”A”:



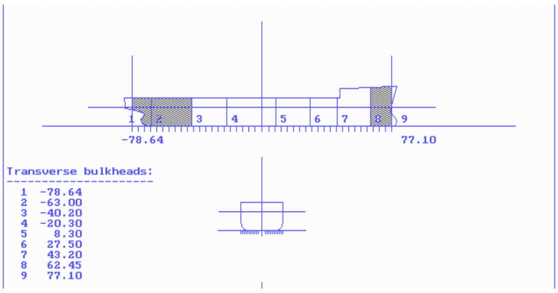
```
Transverse bulkheads:
---------------------
  1  -78.64
  2  -60.00
  3  -40.00
  4  -15.00
  5   15.00
  6   40.00
  7   60.00
  8   77.12
```

Design version ”B”:



```
Transverse bulkheads:
---------------------
  1  -78.64
  2  -60.00
  3  -35.20
  4   -7.80
  5   15.00
  6   43.40
  7   64.20
  8   77.10
```

Design version ”C”:



```
Transverse bulkheads:
---------------------
  1  -78.64
  2  -63.00
  3  -40.20
  4  -20.30
  5    8.30
  6   27.50
  7   43.20
  8   62.45
  9   77.10
```

Figure. 3. Arrangement of internal spaces for a cargo ship.

Table. 3. Results of the Attained Subdivision Index “A” optimisation.

Ship type: general cargo Design criteria: optimisation of the Attained Subdivision Index A		
Design version “A”	No. of iteration	Index A value [-]
	I	0.6560
	II	0.7181
	III	0.8162
	IV	0.8171
	V	0.8174
	VI	0.8177
Design version “B”	No. of iteration	Index A value [-]
	I	0.6050
	II	0.7261
	III	0.7951
	IV	0.7974
	V	0.7976
Design version “C”	No. of iteration	Index A value [-]
	I	0.6690
	II	0.8210
	III	0.8225
	IV	0.8278
	V	0.8233

Table. 4. Positions of bulkheads during the design process
(positions of bulkheads for intermediate iterations are not presented).

Design version “A”

No.of bulkhead	Bulkhead Preliminary Position [m]	Bulkhead Final Position [m]
1	-78.64	-78.64
2	-60.00	-60.00
3	-40.00	-40.00
4	-15.00	-16.69
5	15.00	15.00
6	40.00	38.40
7	60.00	60.00
8	77.10	77.10

Design version “B”

No.of bulkhead	Bulkhead Preliminary Position [m]	Bulkhead Final Position [m]
1	-78.64	-78.64
2	-60.00	-60.00
3	-35.20	-35.20
4	-7.80	-9.63
5	15.00	15.00
6	43.40	41.29
7	64.20	64.20
8	77.10	77.10

Design version “C”

No.of bulkhead	Bulkhead Preliminary Position [m]	Bulkhead Final Position [m]
1	-78.64	-78.64
2	-63.00	-63.00
3	-40.20	-40.20
4	-20.30	-20.99
5	8.30	8.30
6	27.50	27.50
7	43.20	43.20
8	62.45	62.45
9	77.10	77.10

The optimisation methodology was based on maximization of the objective function value represented by the Subdivision Index “A”. The aim concerned to obtain the possible maximum values of the p_i*s_i factors for each group of watertight compartments. Between the constraints used in the optimisation was the condition that the s_i value should never be equal to null. The major starting design conditions were as follows:

- number of bulkheads;
- positions of bulkheads.

The investigations showed that a larger number of bulkheads not necessary guarantee much higher values of the Index ”A”. Between the conclusions there are many very important for design. For example, applying one bulkhead more the p_i values are getting greater for the groups including two or more single compartments but in the same time the conditional probabilities s_i are decreasing. The values of p_i and s_i factors are interrelated but in irregular manner.

In general, one bulkhead more or less slightly affects the Subdivision Index "A" value. The small changes regarding the positions of bulkheads do not give much different values of the Subdivision Index "A" but the local safety indices presented in the Chapter 8 may change very much.

8. RISK ASSESSMENT: CALCULATION OF THE LOCAL SAFETY INDICES

The calculation of the local safety indices is a kind of an optimisation procedure which may provide the same level of safety for each watertight compartment considered. The local safety indices should be calculated according to the following formula [11]:

$$\Delta A_j = (\Sigma\ p_i\ s_i) / (\Sigma\ p_i) \qquad (3)$$

The optimisation process of the ΔA_j indices is connected with the iteratively moving the bulkheads against each another so far as the ΔA_j values become more or less equal and as maximum as possible for each compartment. In Table 5 the ΔA_j local safety indices are presented according to four iterations performed. The calculations have been done for the design version "A" presented in Figure 3.

In the case when a tanker is damaged it is possible to calculate the P_o probability of avoiding the pollution of the environment by cargo using the following formula [11]:

$$P_o = \Sigma\ p_{bi} \qquad (4)$$

where:

P_o – called as the probability of zero outflow;

p_{bi} – probability p_i of flooding a compartment group containing no oil.

Table. 5. Optimisation of the local safety indices ΔA_j for "Design version "A""

Comp. no. 1	Comp. no. 2	Comp. no. 3	Comp. no. 4	Comp. no. 5	Comp. no. 6	Comp. no. 7
-78.60	-60.00	-40.00	-15.00	15.00	40.00	60.00
-60.00	-40.00	-15.00	15.00	40.00	60.00	77.10
0.8363	**0.4953**	**0.3522**	**0.4311**	**0.3521**	**0.6080**	**0.9140**
-78.60	-60.00	-40.00	-15.00	15.00	38.40	60.00
-60.00	-40.00	-15.00	15.00	38.40	60.00	77.10
0.8363	**0.4953**	**0.3539**	**0.6239**	**0.5478**	**0.6270**	**0.9286**
-78.60	-60.00	-40.00	-16.69	15.00	38.40	60.00
-60.00	-40.00	-16.69	15.00	38.40	60.00	77.10
0.8979	**0.8137**	**0.6104**	**0.7457**	**0.6724**	**0.6453**	**0.9286**
-78.60	-60.00	-40.00	-17.14	15.00	38.40	60.00
-60.00	-40.00	-17.14	15.00	38.40	60.00	77.10
0.8979	**0.9096**	**0.6228**	**0.7415**	**0.6726**	**0.6453**	**0.9286**

The P_j local probability of zero outflow (from a given part of the ship) can be calculated as:

$$P_j = (\Sigma\ p_{bi}) / (\Sigma\ p_i) \qquad (5)$$

The average oil outflow O_m (global or overall mean outflow) may be estimated as follows:

$$O_m = \Sigma\ p_i\ v_i \qquad (6)$$

where:

v_i – volume of oil contained in the compartment group under consideration.

The above mentioned formula can be relatively useful when a ship is damaged in the calm sea condition. To estimate the risk of pollution for the rough sea is much more complicated. The accident of "Prestige" has confirmed that knowing the extension of damage and the ship data is to little to predict the quantity of oil outflow. We can not predict the consequences properly. Some conclusions regarding the risk assessment in such a case will be delivered during the workshop. The problem are as follows. Can we do the Quantitative Risk Assessment (QRA) for predicting the range of pollution. Can we predict the time of sinking.

9. RISK ASSESSMENT USING A DIRECT METHOD

There is a problem how to assess the risk in the case of unconventional ships like high speed craft (HSC), navy ships, etc. . The question is why we do not have the probabilistic risk-based measures to predict the behaviour of such the ships in critical conditions. One between the answers is that the mentioned ships differ from each another and there is a lack of modern performance predicting and risk-based analysis methods for such the ships+.

Some elements of an alternative method for estimating the risk in critical conditions have been worked out. As an example it is possible to estimate the probability of capsizing a ship in critical conditions using the direct risk assessment method for stability and damage stability estimation. The simplest version of the method is briefly presented below.

The probabilities of capsizing for both the intact and damage stability have been defined as follows:

$$P_{CI} = 1 – P_{SI} \qquad (7)$$
$$P_{CD} = 1 – P_{SD} \qquad (8)$$

where:

P_{CI} , P_{SI} - probabilities of capsizing and stability for intact stability conditions;
P_{CD} , P_{SD} - probabilities of capsizing and survivability for damage stability conditions.

The probability of stability for both the intact and damage stability conditions can be determined as follows [12][13]:

$$P_{SI}=P(((HA_{IP}<=k_1RA_{MAX})\cup(A_1>=k_2A_2))) \qquad (9)$$
$$P_{SD} = P(((\phi_c<=20^o)\cup(A_1>=k_2A_2))) \qquad (10)$$

where:

HA_{IP} – heeling arm at the intersection point;
RA_{MAX} – maximum of the righting arms;
A_1 – “righting energy”;
A_2 –“heeling energy”;
ϕ_c – static heel angle;

k_1, k_2 – coefficients estimated working on the research project No. 5 T12C 004 22 founded by the Scientific Research Council KBN.

It follows from the above relations that the performance function may be as $A_1<k_2A_2$ for example and the capsizing becomes when $A_1–k_2A_2<0$.

Then, the P_C probability of capsizing can be given as the integration of the joint probability density function of

$$Z_{RV} = g(X_1, X_2, ..., X_n) \qquad (11)$$

random variables:

$$P_C = p(A_1<k_2A_2)=\int_{-\infty}^{+\infty} f_{A1}(x)f_A(x)dx \qquad (12)$$

where:

$A_1–k_2A_2<0.1$;
$f_{A1}(x)$ - cumulative distribution function of A_1;
$f_A(x)$ - probability density function of k_2A_2.

The reliability methods use the mean and variance (first and second moments) of basic random variables in calculating a reliability measure according to a specified performance function. Below, different reliability methods are briefly presented according to the manner with which they deal with the probabilistic characteristics of the basic design parameters.

According to the first-order second–moment method an approximate mean and an approximate variance of the performance function (11) are determined using the Taylor’s series expansion of g about the mean value of the X’s truncating the series at the linear term.

The expressions for the approximate mean and variance are as follows:

$Z_{RV}^{mean} = g(X_1^{mean}, X_2^{mean},\ldots,X_n^{mean})$ (13)
and
$\sigma^2_Z=[\Sigma_{i=1}^{m}\Sigma_{j=1}^{n}(\delta g/\delta X_i)(\delta g/\delta X_j)\mathrm{cov}(X_i,X_j)]$ (14)

where:

Z_{RV}^{mean} – is the mean value of Z;
σ_Z – is the standard deviation of Z.

The reliability measure is the reliability index:

$RI = Z_{RV}^{mean} / \sigma_Z$ (15)

where:

RI – is the reciprocal of the cov (coefficient of variation) of Z.

If the Z function is normally distributed the probability of capsizing P_C is as follows:

$P_C = 1 - \varphi\,(RI)$ (16)

where:

φ – is the cumulative distribution function of the standard normal variant.

The advantage of the method is that it produces the exact value of probability when Z is linearly and normally distributed. For the log-normally distributed random variables the logarithmic transformation can be applied to obtain the exact solution.

There is the advanced second-moment method enables to deal with a non-linear performance function and with non-normal random variables. Then, the performance function can be defined in terms of the following reduced variables:

$u_i = (X_i - X_i^{mean}) / \sigma_{Xi}$ (17)

where:

u_i – is the reduced variable for X_i.

The limit state g' in the reduced space is given by:

$g' = 0$ (18)

The RI safety index is defined as the minimum distance from the origin of the reduced coordinates of the basic random variables to the limit state as shown in Figure 4 for two variables X_1 and X_2.

The RI safety index is determined by iteratively solving the following set of equations:

$\alpha_i = [(\delta g/\delta X_i)\,\sigma_{Xi}\,] / [\Sigma_{j=1}^{n}\,(\delta g/\delta X_i)^2\,\sigma^2_{Xi}\,]^{½}$ (19)
$X_i^* = X_i^{mean} - \alpha_i\,RI\,\sigma_{Xi}$ (20)
$g(X_1^*, X_2^*, ..., X_n^*) = 0$ (21)

where the derivatives $\delta g/\delta X_i$ are evaluated at the design point or the most probable failure point $(X^{*1}, X^{*2}, ..., X^{*3})$ and α_i is the directional cosine of the variable X_i and RI is the reliability index.

The probability of capsizing in this method is the same as given by equation (16). In Figure 4 the X^* point is called the most probable failure point and it corresponds to the shortest distance on the limit state.

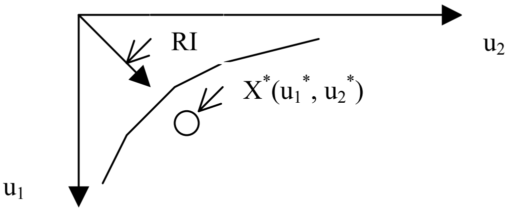


Figure. 4. Limit state in reduced coordinates.

A little example can be given taking into account the stability characteristics for the ship as follows:

- displacement Δ=15000 tons;
- heeling moment equal to 9240*cosΦ [m*tons].

The stability characteristics:

Φ [deg]	GZ [m]	Righting Moment M_R [mtons]	Heeling moment M_H [mtons]
-5	-0.139	2079.0	9204.6
0	0	0	9240.0
10	0.277	4158.0	9099.5
20	0.616	9240.0	8682.5
30	0.847	12705.0	8001.8
40	0.924	13860.0	7077.8
50	0.832	12474.0	5939.2
60	0.616	9240.0	4620.0
70	0.323	4851.0	3160.0
80	0	0	1604.7

The uncertainties in both the righting and heeling moments at each angle of inclination result in uncertainties in A_1 and A_2 values.

The coefficient of variation of the estimated capsizing probability is:

$$\mathrm{Cov}(P_{c\,AV})=\left(\sqrt{((1-Pcav)Pcav)/n}\right)/P_{c\,AV} \quad (22)$$

where:

n – total simulation cycles;
n_c – number of simulation cycles for which g<0;
$P_{c\,AV}$ – mean capsizing probability, $P_{c\,AV}=n_c/n$.

The probabilistic characteristics of A_1 and A_2 are as follows:

Random variables	Mean values [mtons]	Coefficient of variation	Distribution Type
A_1	28028.0	0.1	Normal
A_2	19712.0	0.1	Normal

The capsizing probability using different reliability methods:

Method	Results
Deterministic approach	The ship is totally stable and capsizing is unlikely to occur
First-order second-moment method	RI=1.301707 P_C = 0.09650
Advanced second-moment method	RI=1.301707 P_C = 0.09650

The reliability index according to the advanced second-moment method is the same as for the first-order second-moment method because the performance function is linear and the random variables are normal.

The above calculations have shown that the basic random variables regarding the stability need to be probabilistically characterized. Any correlation and dependency among them needs to be assessed. The selection of a reliability method for a ship stability study depends on available information and complexity of the performance function. In general, either the advanced second moment or simulation with variance reduction techniques can be used. It is to early to compare the methods between each other before a larger computer simulation is done.

The further investigations regarding the direct method requires to incorporate the elements of the Formal Safety Assessment FSA. Currently the research concerns the following problems:

- phenomena affecting the stability (internal factors, external factors, flooding);

- ship operating conditions;
- biases between predicted and measured values of the basic random variables;
- development of probabilistic characteristics of basic random variables (mean values, cov, distribution type).

The most recent research is connected with preparing a few risk assessment procedures for the integrated survivability process presented in Figure 5.

7. SUMMARY

An integrated safety estimation method and model for assessing the safety of a ship in critical conditions has been worked out. It is directed towards the ship safety estimation in critical conditions at the preliminary stage of design. Using the method/model the hazard and risk assessment may be done according to the IMO regulations for cargo ships.

In the case when there is no possibility to assess the hazards (for example in the case of special types of ships) an alternative direct procedure to assess the risk should be applied.

So far, the method and model have been used for investigating the new solutions regarding the ship safety from the damage stability and survivability point of view. The method/model can be used for intelligent guiding ship subdivision for safety. A few arrangements of internal spaces for cargo ships including either transverse or combined subdivision have been investigated. The damage stability, survivability and risk assessment were done for each case. The method can use semi-probabilistic and probabilistic safety measure procedures. It can be classified as a combined ”parametric-risk-based assessment method” for the safety estimation of ships in critical conditions, at the preliminary stage of design.

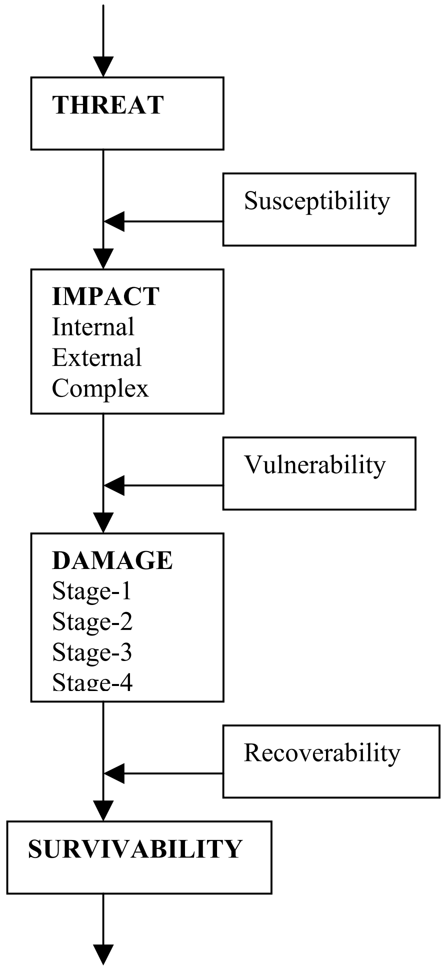


Figure. 5. Structure for the integrated survivability process.

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