Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

APPLICATION OF QUANTITATIVE RISK ASSESSMENT TO SHIPS IN EMERGENCY CONDITIONS

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Abstract

The paper is devoted to safety of ships in emergency conditions The currently valid prescriptive method of safety assessment of ships in damage conditions is included in the SOLAS 2009 Part B-2 Ch.II-1 regulations. It is devoted to the design stage and difficult to apply in operation. A possible alternative described in this paper is a method based on assessment of performance of ships and risk assessment. Type of risk evaluation is the quantitative risk assessment. The matrix type risk model has been applied for estimation the risk and the measure of safety of ships level is based on the risk acceptance criteria from the risk matrix. After the risk assessment the method may be used for the safety management purposes using the risk control options.

INTRODUCTION

The paper presents a few problems regarding a method of safety assessment of ships in emergency conditions. The research is correlated with development of a performance-oriented risk-based method for assessment of safety of ships in emergency conditions, Gerigk (2010).

The proposed method is based on assessment of ship performance and risk assessment. Assessment of ship performance in emergency conditions should enable to obtain a set of ship characteristics then to be used during the risk estimation. For the risk estimation the matrix type risk model has been applied. The preparation of the risk model was with holistic approach in mind. It means that the goal was for it to enable to estimate the risk values for almost all the possible emergency scenarios development. The above mentioned scenarios consist of combinations of hazards, intermediate events, additional events and consequences. Such the risk model enables to take into account the uncertainties connected with the possible scenarios of an accident. After obtaining the risk values or the risk level the risk acceptance criteria can be applied. After the risk assessment the safety management can be used applying the risk control options. Such the procedure enables safety of ships to be evaluated and adequate decisions on ship safety to be made.

The current methods of assessment of safety of ships in damaged conditions are based on the regulations included in the SOLAS convention (Part B-2 Chapter II-1), (IMO 2005a, IMO 2005b, IMO 2008). These methods are directed towards solving the design problems. Those methods are prescriptive in their character and based on the attempt to apply adequate measures for countering hazards by implementing probability of them happening to the equations. . The structure of these methods is such that they only take into account certain sets of scenarios of accidents leading to what is perceived as emergency condition. In these methods emergency condtion means in damage conditions and it concerns flooding of single compartments, or groups consisting of two or more adjacent watertight compartments caused by collision with another ship or grounding.. The other property associated with application of these methods regards the problem that using those methods in case of certain types of ships e.g. car-carriers, ro-ro vessels or passenger ships may lead to insufficient or inappropriately high level of safety or in addition provide unnecessary design or operational restrictions,(University of Strathclyde - 1998).

The basic criteria of the prescriptive method as included in e.g. SOLAS 2009 Part B-2 Ch.II-1 regulations is the following condition, (IMO 2005a, IMO 2005b, IMO 2008):

$$A > R \tag{1}$$

where:

A = attained subdivision index calculated for the draughts d_s, d_p and d_l defined in regulation 2, according to the formula, IMO (2005):

$$A = \sum p_i s_i \tag{2}$$

where:

p_i = accounts for probability that only the compartment or group of compartments under consideration may be flooded, as defined in regulation 7-1; s_i = accounts for probability of survival after flooding the compartment or group of compartments under consideration, as defined in regulation 7-2; R = required subdivision index.

The p_i and s_i are calculated according to the formulae accepted by IMO, (IMO 2005a, IMO 2005b, IMO 2007). The typical process of assessment of safety of ships in damaged conditions at the design stage or when the survivability of existing ships is considered is directed to satisfy the criterion (1).

PRESENTATION OF SELECTED METHODS OF SAFETY ASSESSMENT OF SHIPS IN EMERGENCY CONDITIONS

The concepts of the following methods developed for assessing the safety of ships in emergency conditions remain within the conditions stipulated by criterion (1) and formula (2).

The first method is based on the so-called holistic risk model. The risk should be calculated by a formula, (Jasionowski et al. 2006, Skjong et al. 2006):

$$R = Pc \times Pc/f \times Pc/f/ns \times Pc/f/ns/tts \times C \tag{3}$$

Where: P_c = probability of collision (hazard); $P_{c/f}$ = probability of flooding having the ship hit from given direction at data position with given extent conditional on collision; $P_{c/f/ns}$ = probability of not surviving conditional on having flooding when the ship is hit from given direction at data position with given extent conditional on collision; $P_{c/f/ns/tts}$ = probability of given time to sink conditional on not surviving the conditional on having flooding when the ship is hit from given direction at data

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position with given extent conditional on collision; C = consequences regarding the fatalities, property (cargo, ship) and/or environment.

In this method The $P_{c/f/ns}$ and $P_{c/f/ns/tts}$ remain defined as per the currently used p_i and s_i definitions.

Another method that has been recently published is based on the casualty threshold, time to capsize and return to port concepts, where the basic ship safety objectives have been divided into three categories, Vassalos (2007):

- Category I - vessel remains upright and afloat and is able to return to port under own power (RTP – Return To Port);
- Category II - vessel remains upright and afloat but unable to return to port under own power and is waiting for assistance (WFA – Waiting For Assistance);
- Category III - vessel likely to capsize/sink and abandonment of the ship may be necessary (AS – Abandonment of the Ship).

The safety assessment of the ships in damage conditions is then based on estimation of the probability of ship capsizing which is again calculated according to the formulae used to obtain the p_i and s_i.

From the above mentioned it follows that it seems to be very difficult to submit a new method for the safety assessment using as a basis the requirements and formulae included in the SOLAS 2009 regulations. Three major difficulties in developing a kind of risk-based method using the SOLAS 2009 regulations were identified. The first problem is the structure of those regulations.
They are prescriptive and hence may only take into account fixed number of hazards/coefficients. The second is that that hazards have been prepared/weighted to address ship-ship collision scenarios only. Therefore the risk model is not a holistic one. The third problem is associated with the risk definition. It follows from the fact that within the risk model defined there is no weight factor difference between the probability of the hazard occurrence and conditional probabilities calculated using still the same formula (s_i). The above problems do not let to submit a common measure of safety of ships in damage conditions.

THE SSAMADC METHOD OF SAFETY ASSESSMENT OF SHIPS IN ABNORMAL/ DAMAGE CONDITIONS

For the purpose of defining the method an “abnormal/damage” description has been added. This is to distinguish the emergency conditions and damage conditions from all the other conditions that do not appear in normal ship operation, but are not necessarily caused by damage or emergency situation.

In this Chapter the basic information on the SSAMADC Ship Safety Assessment Method in Abnormal/Damage Conditions will be introduced. The methodology where the risk-based design and a formalized design methodology were integrated together the first time was introduced by Vassalos and the others, (Skjong et al. 2006, SSRC 2009, Vassalos 2006).

The SSAMADC method is a performance-oriented risk-based method which enables to assess the safety of ships in abnormal/damage conditions at the design stage, in operation and during the ship salvage using the same procedure, Gerigk (2010). Within the SSAMADC method the holistic approach to safety assessment is applied. The method is based on implementation of the system integrated approach to safety. The method takes into account an influence of many design and operational factors on safety and safety management related factors.

For the ship performance evaluation the investigations using the physical models and numerical simulation techniques can be applied. The ship performance evaluation enables to determine the intermediate events, additional events (releases) and consequences and risk of each accident scenario.

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However, it is difficult to determine and investigate all such as the above scenarios and determine the response from a ship. Instead of trying to predict all the possible events it is proposed to determine ships ability to mitigate the risks which, among others, involve loss of stability and/or floatability.

The risk assessment is based on application of a risk model which is to allow consideration of all the possible scenarios and the consequences of events during an accident, but from a designed object perspective.

As an example of such approach a simple Monte Carlo simulation has been made. The floating objects of given geometries, but random sizes and weights; both within a predetermined by empirical formulas ranges have been generated and their stability parameters such as range of positive stability and maximum value of GZ have been calculated. The overall number of ships generated exceeded (20000) twenty thousand and allowed for a most vulnerable parameters to stay within a statistical confidence level of 0,95 or more.

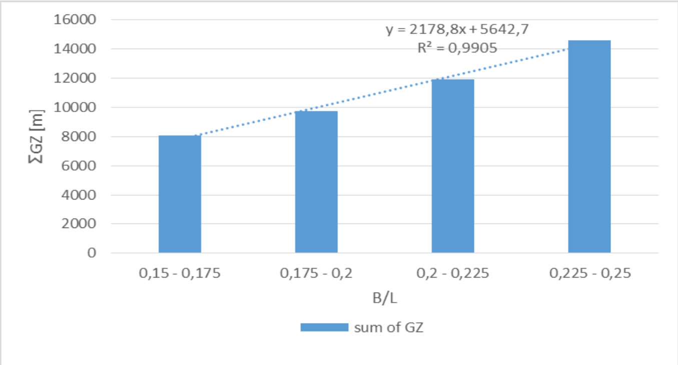

Figure 1. An example of the result from Monte-Carlo analysis for fixed shapes of a floating body and impact of B/L ratio on the statistical Maximum GZ value.

The natural conclusion from the above presented (Fig.1) calculation is that the risk of a vessel with lower Breadth to Length ratio (B/L) having lower GZ can be quantified with use of a linear function of first degree. This result, if correctly applied, can be used to evaluate the risk.

The aim of a performance based risk assessment method is to achieve an adequate level of risk by reducing the risk if necessary. Providing a sufficient level of safety based on the risk assessment is the main objective. It is either the design, operational or organizational objective. Then, safety is not a limitation existing in the regulations. It is just the design objective parallel to other objectives. The measure of safety of a ship in abnormal/damaged conditions is the risk or level of risk.

The structure of a method must remain such to allow the results from the calculation to be used at any ship's life circle, including safety assessment of a ship during a catastrophe. Some elements of the method can be used for this purpose. The application of this safety assessment to different means and systems of maritime transportation can also be made. In the future the method can be useful in elaboration of a new methodology of safety assessment of ships in abnormal/damage conditions using the risk assessment.

The SSAMADC method is based on the following main steps:

- Setting the requirements, criteria, limitations, safety objectives;
- Defining the ship and environment;
- Identifying the hazards;
- Identifying the sequences of accident (scenarios development);
- Assessing the ship performance in abnormal/damage conditions;
- Evaluating the risk;
- Assessing the risk according to the risk acceptance criteria and safety objectives;

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- Managing the risk according to the risk control options;
- Selecting the design (or operational procedure) that meets the requirements, criteria, limitations, safety objectives;
- Optimizing the design (or operational procedure);
- Making the decisions on safety, (Abramowicz-Gerigk 2006, Abramowicz-Gerigk 2008, Abramowicz-Gerigk & Burciu 2013, Arangio 2012, Burciu & Grabski 2011, Gerigk 2004, Gerigk 2005, Gerigk 2006, Gerigk 2008, Gerigk 2010, Gerigk 2012, Nowakowski & Werbińka 2009).

The structure of the SSAMADC method is presented in Figure 2, Gerigk (2010).

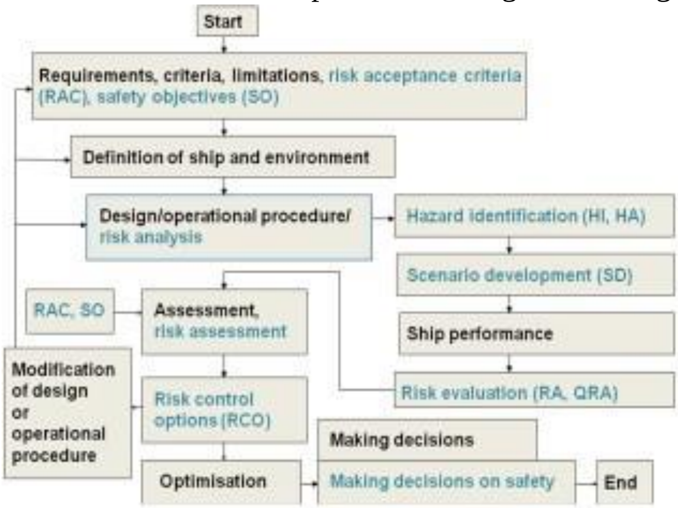

Figure 2. Structure of the method of risk and safety assessment of ships in damaged conditions.

THE MATRIX TYPE RISK MODEL

The safety case concerns the ships in abnormal/damage conditions when the ship skin is damaged due to the following hazards: collision, grounding, stranding or other reasons, Gerigk (2010).

The risk assessment starts from the modeling of the risk contribution tree. For each recognized hazard a separate standard event tree is modeled using the Event Tree Analysis ETA, Gerigk (2010).

The holistic approach to ship safety has been applied. According to this approach two major assumptions have been done. First that the system failures can be either the hardware, software, organizational or human failures. The second assumption was that the risk model for assessment of safety of ships in abnormal/damage conditions should be the holistic risk model. The holistic risk model should enable to take into account all the possible scenarios development, Gerigk (2010).

From the mathematical point of view the relations between the events within an event tree (ETA) are represented by the conditional probabilities which are the components of the risk formula for each sequence of events (accident scenario), Gerigk (2010).

The basic formula for the risk evaluation associated with the different hazards and scenario development is according to the well known general formulae, Gerigk (2010):

$$R_i = P_i \times C_i \qquad (6)$$

where: P_i = probability of occurrence of a given hazard; C_i = consequences following the occurrence of the data hazard and scenario development, in terms of fatalities, property losses and damage to the environment.

Of course in this model, the major problem is how to adequately quantify the consequences: In order to mitigate the risk of assigning inadequate weights to consequences the

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risk model (6) was divided into four different kinds of losses regarding the human fatalities (HF), cargo and ship losses (CS), environment pollution (E) and financial losses ($) and for a given ship can be presented as follows:

$$R=P_c\ P_{c/f}\ PoC_{dam} \times C \tag{7}$$

where P_c = probability of hazard occurrence; $P_{c/f}$ = probability of extent of damage conditional on hazard occurrence; PoC_{dam} = probability of capsizing or loosing floatability subject to the P_c and $P_{c/f;}$ and which allows for adding the transformation function between the environment, object and consequences and C = consequences regarding the fatalities, property (cargo, ship), environment and finance ($C = C_{HF/C}, C_{CS/C}, C_{E/C}, C_{\$/C}$). The PoC_{dam} probability of capsizing in damaged conditions in given time can be calculated according to the following formulae, Gerigk (2010):

$$PoCdam = Pc/f/ns\ Pc/f/ns/tts \tag{8}$$

where $P_{c/f/ns}$ = probability of not surviving after hazard occurred; $P_{c/f/ns/tts}$ = probability of given time to sink conditional on not surviving after hazard occurred.

The PoC_{dam} probability can be estimated during the accident at sea using the following methods, Gerigk (2010):

- Binary method;
- Method based on definition of the probability of surviving a collision;
- Method based on definition of the damage stability;
- Method based on definition of the ship performance during the accident.

In the case of the last method the roll function in time domain has been anticipated as a major characteristics/function enabling the risk assessment, Gerigk (2010).

The risk analysis requires to calculate the conditional probabilities regarding the initial events ZI_i, major events (hazards) ZG_j, intermediate events ZP_k and final events ZK_l which can be treated as consequences. The basic mathematical formula are as follows, Gerigk (2010). First of all the row matrix of initial events is evaluated:

$$P(ZI) = P(ZI_i) \qquad \text{for i=1 to n} \tag{9}$$

Then the matrix of major events is calculated:

$$MP_{ZG} = P(ZG_j / ZI_i) \qquad \text{for j=1 to m} \tag{10}$$

After that the matrix of intermediate events is calculated:

$$MP_{ZP} = P(ZP_k / ZG_j) \qquad \text{for k=1 to m1} \tag{11}$$

Then the matrix of final events is calculated:

$$MP_{ZK} = P(ZK_l / ZP_k)\ \text{dla l=1 do m2} \tag{12}$$

Finally, the row matrix of final events may be estimated as follows:

$$P(ZK) = P(ZI)\ MP_{ZG}\ MP_{ZP}\ MP_{ZK} \tag{13}$$

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The above mathematical model is representing the entire risk model called as the matrix type risk model. This model enables to consider almost all the possible scenarios of an accident using event trees. In the case when additional events occur the PoC(C_i) probability of occurring the C_i given consequences can be calculated according to the formula presented by Gerigk, Gerigk (2010). The typical additional events may concern e.g. water on deck, air cushions, cargo leakage passenger behavior or terrorist attack.

APPLICATION OF THE SSAMADC METHOD

The ship accidents at sea may lead to the loss of life, loss of properties (ship and cargo) and pollution of environment. The modern approach to safety of maritime transportation requires to apply the so-called life-circle approach by integrating the design for safety, safe operation and safe salvage methods. Most of the salvage activities have been associated with using the rules of thumb without a support based on the safety assessment process. The effective and safe ship salvage requires to develop the methods, models and tools for the assessment of risk and safety of ships in damaged conditions.

The SSAMADC method approach to ship safety assessment in abnormal/damage conditions is focused on predicting any further deterioration of a damage condition. In any case the further flooding of compartments and ship listing increase may be expected. This assessment also regards predicting how long it would take a ship to capsize or sink. If a ship survives flooding (a ship remains upright (or heeled) and afloat) and is unable to return to port under own power it is necessary to solve the problems associated with towing when waiting for an assistance. The number of towing points and towing speed in the calm and rough weather conditions should then be evaluated. (Perera & Soares Guedes 2011, Skjong & Vanem & Rusas & Olufsen 2006, Soares Guedes & Teixeira 2001).

The structure of the entire procedure for the assessment of safety of ships in abnormal/damage conditions during the accident at sea and for salvage purposes is presented in Figure 2, Gerigk (2010).

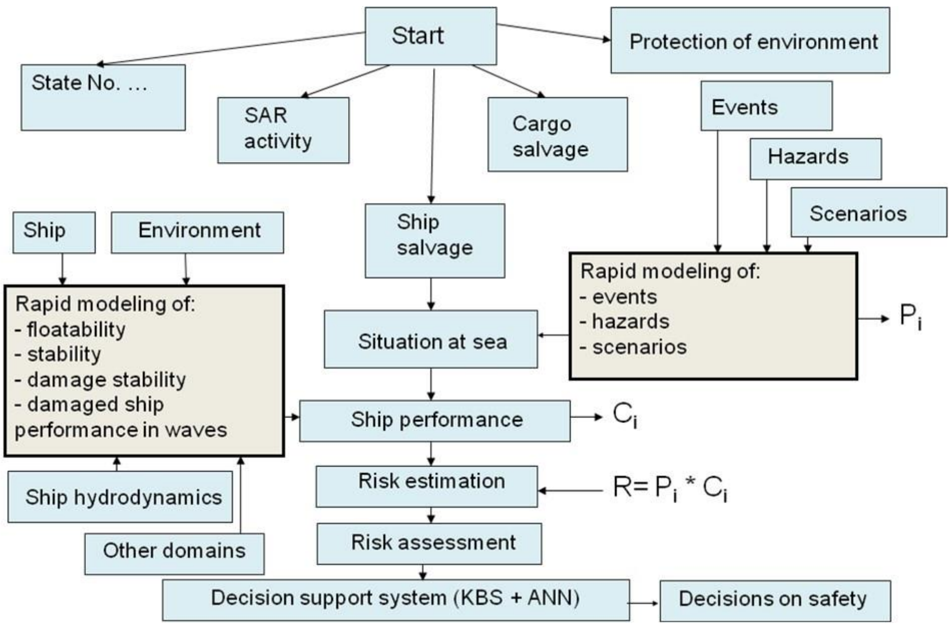

Figure 3. An example of the roll function in time domain and risk evaluation criteria applied for the assessment of safety of a ship in damaged conditions.

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An example application of the SSAMADC method has been done and is summarized below.

The original assessment took place for a container ship, but has been generalized to a transversally irregularly subdivided barge of block coefficient equal to a midship coefficient and equipped with main propulsion engine. The example barge parameters are presented below:

- Length: L_{BP}=163,0 m - breadth: B = 26,5 m
- Height to the main deck: H = 14,2 m
- Draught to subdivision waterline: d_1 = 9,0 m
- Draught to summer waterline: d_2 = 10,5 m

The arrangement of internal spaces of the barge is presented in Figure 3.

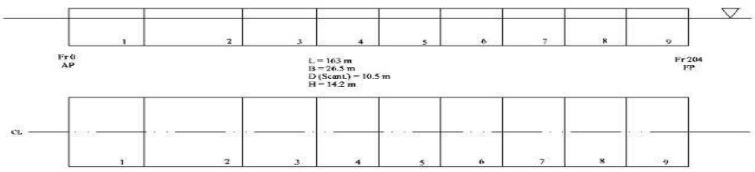

Figure 4. The arrangement of internal spaces for the barge under consideration.

During the safety assessment, for the purpose of stability and floatability, of the barge in abnormal/damage conditions the following damage zones were considered to be flooded:

-zone 1: compartment 1
-zone 2: compartment 2
-zone 3: compartment 3
-zone 4: compartment 4
-zone 5: compartment 5
-zone 6: compartment 6
-zone 7: compartment 7
-zone 8: compartment 8
-zone 9: compartment 9
-zone 10: compartment 1+2
-zone 11: compartment 2+3
-zone 12: compartment 3+4
-zone 13: compartment 4+5
-zone 14: compartment 5+6
-zone 15: compartment 6+7
-zone 16: compartment 7+8
-zone 17: compartment 8+9
-zone 18: compartment 1+2+3
-zone 19: compartment 2+3+4
-zone 20: compartment 3+4+5
-zone 21: compartment 4+5+6
-zone 22: compartment 5+6+7
-zone 23: compartment 6+7+8
-zone 24: compartment 7+8+9

The event tree for a floating object was prepared and published by Gerigk, Gerigk (2010). Other scenarios, though not calculated, were not neglected and were accounted for, but with use of another model that does not calculating response from an object.

Generally, sixteen safety functions have been used for each event tree from the ship safety in damaged conditions point of view. Between them are as follows, Gerigk (2010):

- Function1 (avoiding the hazard),
- Function 2 (water ingress (flooding)),
- Function 3 (position and extent of damage),
- Function 4 (equalization of the ship heel at the preliminary stage of flooding),
- Function 5 (loss of the ship stability at the preliminary stage of flooding),
- Function 6 (loss of the ship stability during the intermediate stages (and phases) of flooding,

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- Function 7 (loss of the ship stability at the final stage of flooding),
- Function 8 (loss of the ship floatability at the final stage of flooding),
- Function 9 (ship is waiting for assistance),
- Function 10 (ship returns to port under own power),
- Function 11 (ship returns to port by tow),
- Function 12 (ship is continuing the mission),
- Function 13 (mustering and abandonment of the ship (evacuation)),
- Function 14 (SAR action),
- Function 15 (fire and/or explosion),
- Function 16 (emergency cargo unloading (pollution of the environment)).

Assessing the performance of the damaged container ship the following impacts were taken into account, (Gerigk 2004, Gerigk 2005, Gerigk 2006, Gerigk 2008, Gerigk 2010, Gerigk 2012):

- Gravitational forces,
- Hydrostatic forces,
- Excitation Froude-Krylov forces,
- Excitation diffraction forces, - accumulated flood water forces, - cargo shift forces.

An example of the damaged container ship performance data as the roll function in time domain is presented in Figure 4.

An example of the risk evaluation criteria for the assessment of safety of the container ship in abnormal/damage conditions is presented in Figure 5.

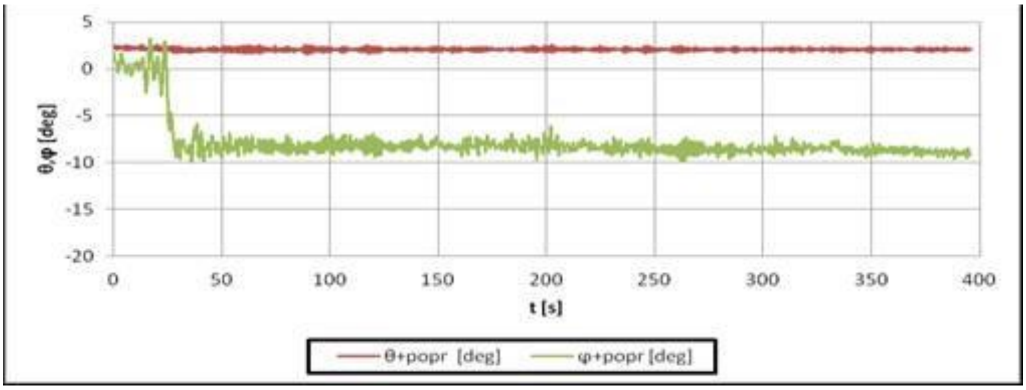

Figure 5. An example of the roll function in time domain.

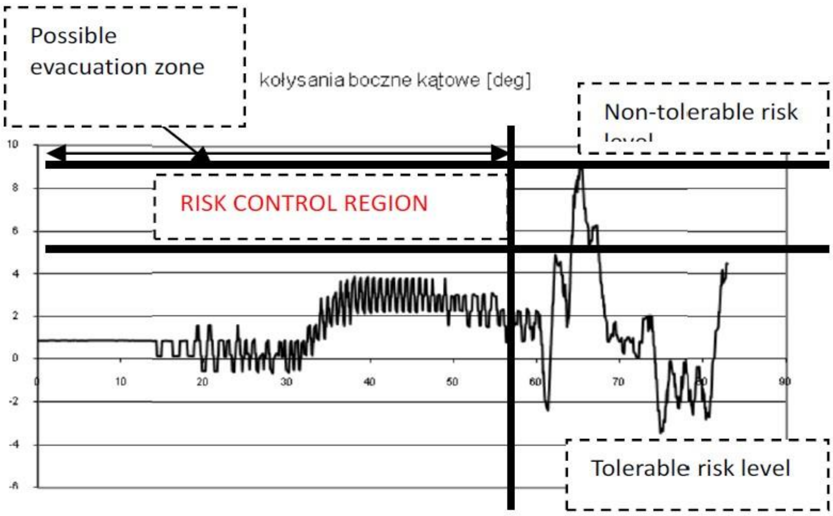

Figure 6. An example of the roll function in time domain and risk evaluation criteria applied for the assessment of safety of the container ship in abnormal/damaged conditions.

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CONCLUSIONS

A few elements of the method of assessment of safety of ships in abnormal/damaged conditions are presented in the paper. The method is based on the assessment of ship performance and risk assessment.

The method has the following features:

1. No disadvantages which exist in SOLAS;
2. Holistic approach to safety (design, operation, catastrophe, salvage);
3. Holistic approach to safety: safety factors (sources of factors: design, operation, management, human factor);
4. Holistic approach regarding the risk model;
5. Assessment of safety for all the possible scenarios.

The key issue to apply the method is to have accurate matrix type holistic risk model. The proposed risk model enables to estimate the risk level for all the possible scenarios of an accident. The proposed risk model is much more complicated than the models published in literature.

The current research is associated with further developing the risk models necessary for the ship performance-oriented and risk-based assessment. From the practical point of view the research should bring a model for the computer simulation of the ship salvage process.

The research has been carried out at the Gdansk University of Technology according to support obtained from the Ministry of Science and Higher Education in Warsaw. The author would like to express his sincere gratitude to the above organisations.

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