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DEVELOPMENT OF A NEW METHOD FOR ASSESSMENT OF SAFETY OF SHIPS IN DAMAGED CONDITIONS WITH USE OF THE MATHEMATICAL RISK CALCULATION MODEL.

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Abstract

There is a need for developing improved methods of evaluating the safety of cargo ships that would quantify and assess the ship safety more comprehensively than current methods and further allow for a more direct comparison of ship designs safety-wise so that safety could become one of the goals of design process. This newly developed method will not only have to allow for effective determination of ship safety, but also should meet expectations from various industries. This paper presents an alternative approach to safety of ships in damaged conditions, which when further verified and evaluated, could serve as a useful tool for designers and ship operators alike. It was shown that a computationally efficient quasi-dynamic method that addresses the main drawbacks of current regulations can be formulated for evaluating the exact risk levels at any stage of vessel's life.

1. INTRODUCTION

In the history of shipbuilding numerous efforts have been made to assure that transportation by sea is safe to an acceptable level. With the knowledge and experience of designers increasing in time and digitalization of the design process with harmonization of navigational rules and requirements, formulation of advanced methods of design for safety seems more possible today.

Certain systems onboard are responsible for the safe operation of vessels. When the ship environment equilibrium is somehow impaired by, e.g. collision, cargo explosion, or system malfunction, the risk is greatly increased. In the case of cargo ships, the calculation of risks can be greatly simplified when compared with, for example, passenger ships. One of the main disadvantages of current regulations is that they treat the risk to cargo ships selectively and address it separately for each system instead of comprehensively describing the combination of systems of the ship as the one system for whom risks are not simply a sum of the risks to each individual system (Figure 1).

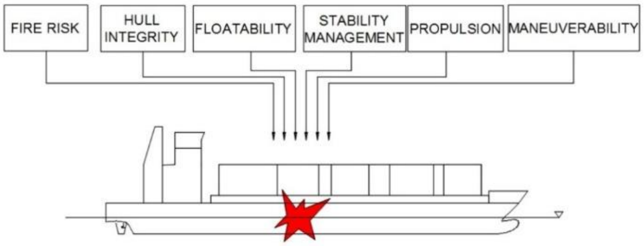


Figure 1. Risks after hazard occurrence during cargo ship system exploitation.(not caring dangerous goods)

Risks to ship safety, at the design stage can be understood in many ways and evaluated using different methods and techniques, hence a selection of a method has to be carefully planned and accurately engineered with mitigation of subjectivity of the process. Accordingly, the purpose of this work is to utilize the gathered experience over the years of shipbuilding and couple it with tools and techniques the modern technology provides. In addition, it is of uttermost importance that the developed method is easy to apply at any stage of the life of ships. Ideally, the method can be further developed to give the crew onboard a ship the green light (safe) or the red light (unsafe) when making their decisions in emergency situations.

The industry standard for measuring stability of the vessels is to measure their geometrical and mass parameters in both intact and damage conditions. There have been attempts to introduce other properties of ships as governing stability [Cichowicz, Kendrick, Papanikolau], but they have not found their way to common application as yet. However, with digitalization of the design process it can now be seen that, with limited number of simplifications, a direct calculation of vessels dynamical righting moment is not much more complicated than the calculation of the static righting arm on its own. With introduction of the dynamical calculations a large error related to confrontation of a changeable with vessel's size and parameters relationship between the heeling moments acting on a ship and righting moments can be greatly reduced.

2. SAFETY – WHAT IS IT?

2.1 DEFINITION OF SAFETY

In the last several years, numerous attempts have been made to formulate a method of assessing safety for ships in damaged conditions [Jasionowski, Brown, Kluwe, Wortley, Gerigk etc.].

When assessing the safety of a design or a ship in operation it is an imperative that general definition of safety is agreed on. In general it may seem evident that the application of the risk calculation method is the methodology the scientists have agreed on. However, there are still differences of opinion with regard to the final shape of the method.

It may well seem possible that one of the reasons there are differences of opinion is the lack of a clear definition of safety. Also, the way we understand safety of ships may change in the future. Some scientists define Safety in relation to Risk as follows :

> "*Safety is the state of acceptable risk*"
> - Vassalos, Jasionowski

"Property that reflects acceptable risk in relation to people, property and environment"
- Gerigk

However, the proposed in this work definition is the one from Merriam-Webster Dictionary and is:

"Safety is freedom from harm or danger: the state of being safe"
[Merriam-Webster Dictionary]

On the basis of the Merriam-Webster Dictionary definition a conclusion has been drawn that no subjectivity should be applied to the definition "freedom from (…)". Judging from this definition it is evident that safety cannot be numerically calculated and is inherently related to time and environment in which the object operates (life, natural environment, property). The probability of an error in observations and/or understanding of hazards related to the operation of the analyzed object is very high. This error introduces risk to safety (as per definition) and therefore we will not know for sure if it is safe to operate the object until we stop operating it.

The likelihood (probability) of any hazard occurrence (on the basis of physics, or/and our experience and knowledge) may be lower in certain conditions or at a certain time and higher in others. Safety, however, is an absolute.

Another obstacle in quantification of consequences is related to their severity. It may seem sufficient to use a numerical, probability based, model for decision making process when the possible consequences are negligible (for example, if one bets a dollar by tossing a coin). Generally, the risk of applying the above mentioned model to the gambling process is acceptable. However, it may be wrong (or at least inadequate) when the stakes are high. One may easily assume that most people would not bet their lives even when the chance of failing was much smaller (e.g. 0.167).

Safety-wise, it is clear that potential consequences of losing any large ship (cargo or passengers) are disastrous, and the risk level we are willing to accept for them is very low.

Consequently, the risks we are facing during the operation of a vessel must be constantly kept in mind. The qualitative risk model allows for a better control of the acceptable risks level. The risk analysis allows us to understand how unsafe the task is that we are going to be involved in, and how much human effort is really needed to lower it. After all, we will not know for sure that the ship is safe until we have successfully completed its scheduled decommission, and we will not know that the ship is unsafe until it sinks.

In other words, the cargo ship is safe if she does not cause any harm to life, environment or property during her entire life cycle. Accordingly, the ship safety is not a function of risks the vessel faces, but rather depends on her characteristics and properties that allow her to withstand any of the risk encountered in her operation.

To summarize the above and on the basis of the definition of the word 'safety' from Merriam-Webster Dictionary, the safety cannot be evaluated in terms of probability or subjectivity and therefore, cannot be holistically assessed by the quantitative risk calculation alone, which by definition, depends on probability of hazards. Safety is an absolute. No ship can be regarded safe until proven otherwise during her time in/of operation. Therefore, commonly used opinions such as "higher levels of safety" are misleading and relate to semantics. Safety is an absolute freedom from hazards which in real life cannot be fully ensured during operation, and we must accept certain levels of risk involved in the operation of vessels.

2.2 HOW IS SAFETY GOVERNED IN THE CURRENTLY VALID REGULATIONS

The currently valid regulation for calculation of probability of a vessel surviving a damage “s” factor (as described in SOLAS 2009) has been to a large extent based on the formulas included in the ICLL 66/88 and further evaluated by independent studies [e.g. Cichowicz]. The studies that lead to preparation of the SOLAS 2009 formula for the factor “s” were based on statistical analysis of the sea condition during accidents and the stability parameters of the vessels at that time [Cichowicz]. This also has large impact on the disadvantage of the evaluated approach. Because the method formulation did not take into the account the actual righting ability of vessels represented by the righting moment acting against the external heeling moments, but basic righting arm properties instead, it does not provide designers and/or crew with information about survival ability of the vessel in practical emergency situation.

Therefore, it would seem rational to seek parameters and formulas that would provide more information and be a good compromise between user-friendliness and accuracy. An attempt to present a direct method of evaluation of safety of ships that provides measurable levels of safety of a floating object for any user and at any life stage of this ship is presented in the subsequent parts of this work.

3. CALCULATION METHOD

3.1 RISK - R

Risk analysis may provide useful information about the environment, design and operation of ships that may cause a ship to become dangerous to life, environment or property during her life. After all, it must be the physical properties of the environment, design and operation of ships that provide ground for decision making process.

Risk may be defined as follows:

> “Possibility of loss or injury”
> - Merriam-Webster

> “A chance of loss”
> - Jasionowski, Vassalos

The risk can be calculated in terms of probabilities related to the object and not to (its) safety. Therefore, we can make a decision whether the vessel is capable of withstanding all the identified through risk analysis hazards and dangers and not cause harm to people, environment and/or property in certain conditions, and effectively determine the conditions in which the operation of a vessel is safe or not. It is to be stressed that measuring a risk is not the same as the measuring of safety, and it cannot be directly related to it.

The techniques of evaluating risks vary, but are all defined by mathematical formula for risk calculations. In general, the differences between the risk models are mainly related to:

- Weight factors applied to statics for probability of hazard occurrence calculation
- Vulnerability calculation methodology
- Consequences categorization

The formula presented by Gerigk is the following

$$\mathrm{R} = \mathrm{P_c} * \mathrm{P_{c/f}} * \mathrm{P_{c/f/ns}} * \mathrm{P_{c/f/ns/tts}} * \mathrm{C} \qquad (1)$$

where:
P_c – Probability of collision
$P_{c/f}$ – Conditional probability of flooding
$P_{c/f/ns}$ – Conditional probability of not surviving the flooding
$P_{c/f/ns/tts}$ – Conditional probability of not surviving the flooding at a given time.
C – Consequences

The formula presented by Jasionowski is:

$$\mathrm{f_T(t)} = \sum_{\mathrm{i}}^{3} \sum_{\mathrm{j}}^{\mathrm{n_{flood}}} \sum_{\mathrm{k}}^{\mathrm{n_H}} \mathrm{w_i} * \mathrm{p_j} * \mathrm{e_k} * \mathrm{c_{i,j,k}(t)} \ (2)$$

where:
$f_T(t)$ – Unconditional probability that an event of time to capsize t occurs (corresponding to Risk of ship sinking in time t). Commonly named as “ship vulnerability to flooding”.
w_i – Probability mass function of the 3 specific loading conditions.
p_j – Probability mass function of the damage extents and the n_{flood} number of flooding extents calculated according to the harmonized probabilistic rules for ship subdivision [39].
e_k – Probability mass function derived from the statistics of sea states recorded at the instant of collision where n_H is the number of sea states considered.
$c_{i,j,k}(t)$ – Probability mass function of the event of capsizing in the set time.

After careful verification of the above cited models (and others [Cichowicz, Papanikolau, et al]), the proposed risk model and formula for risk well known to the shipping and engineering societies is presented in the following form for any damage/emergency scenario:

$$\mathbf{R} = \mathbf{P} * \boldsymbol{V}^{\boldsymbol{T}} * \mathbf{C} = \begin{bmatrix} p_1 \\ \cdots \\ p_n \end{bmatrix} * \begin{bmatrix} v_1 & \cdots & v_m \end{bmatrix} * \begin{bmatrix} c_1 \\ \cdots \\ c_m \end{bmatrix} = \begin{bmatrix} p_1 v_1 c_1 + \ldots + p_1 v_m c_m \\ \cdots \\ p_n v_1 c_1 + \ldots + p_n v_m c_m \end{bmatrix} \qquad (3)$$

where:
- **P** - Probability of hazard occurrence - given weather conditions (probability mass function – distribution) <l;…;r>
- $\mathbf{V}^{\mathbf{T}}$ - Vulnerability of the object in the given condition to the hazard in different terms: <k;…;m>
- **C** - Consequences, in terms of loss of life, harm to environment and cargo or ship loss for given vulnerability object properties <k;…;m>

The main difference between the models above and the proposed model is that the probabilities <1…r> and <k…m> are not dependent on each other and/or do not force the end user (e.g. Master, Approval Engineer, Designer) to use advanced mathematics for verification This means that they are calculated separately and that they are governed by equations with predetermined factors releasing the end user from need for evaluating the cause and effect scenario and as a consequence, allowing for a final black and white result for each and any hazard. This approach allows for better risk control and increases the possibilities for risk mitigation for selected environmental conditions (in the selected case: weather at sea). Furthermore, it allows for easy transformation of mathematical equations describing risk.

As mentioned in the previous part of this work the difficulties arising from the use of any risk model are related to the accurate quantification of probabilities and consequences and to the acceptance criteria. One may argue that they are subjective, but following the general definition of safety from the Webster-Miriam dictionary quoted above, it has been chosen to select a descriptive form for modelling consequences (qualitative). Consequently, a chance of losing a ship or/and dangerous cargo or a loss of life onboard is modelled as a separate cell in the risk matrix that allows control over the evaluated risk levels.

The vulnerability of the object may be calculated on the basis of the ship speed, stability, structural integrity and fire/chemical risk mitigation abilities and operation properties (including location). In recent years a lot of research has been done to move away from statistical approach in describing hazards [Papanikolau]. The method proposed in this paper utilizes some of the currently available research results [Gerigk, Papanikolau].

The calculation methodology details are presented in Chapter 4.

3.2 GOAL TO ATTAIN

The goal is to present a tool/method that can be used at any stage of the life of the ship and will be easy to use and most of all, will be accurate enough to become an industry standard for black-and-white decision making processes.

In recent years, and for selected types of ships, the goal based design standards have been realized by the industry in the form of regulations [Cichowicz, Guerdes Soares, Weintrit, Jiang, Ray etc.]. These rules focus on efficiency and structural integrity. Ship resistance to hazards remains a limitation there.

The ship design methodology that focuses on safety and efficiency may be implemented if prescriptive nature of regulations governing safety is changed. Example of such methodology for cargo ships is shown in the flow chart. (Figure 2).

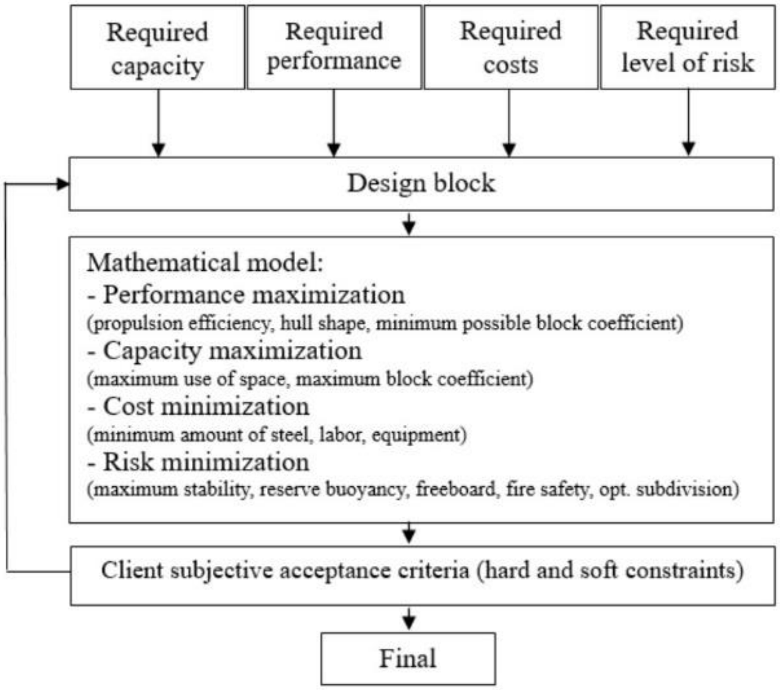


Figure 2. Application of the proposed method to a sample design flow chart

4. RISK MODEL STRUCTURE

4.1 PROBABILITY OF HAZARD OCCURENCE

Probability of hazard occurrence can be expressed in different terms. Up to date, it has been a common practice to investigate statistical data of ship-ship collisions, their size and location. The main drawback of the current approach is that the different than that hazards have not been taken into account and so accurate addressing of such other threats has been disallowed. The other drawback is that statistical data have to be filtered. Even after the introduction of a sheet for reporting collision damages for the GOALDS [Cihowicz] program, the data filtering was still a major task to overcome [Cichowicz, Vassalos, Pawlowski]. In practice, apart from the increased probability of a damage to the most forward area of the ship which seems to be adequately addressed by the ICLL requirement for installation of a collision bulkhead, there is no physical proof that any part of the ship is at a greater risk to be damaged than other parts thereof. [Pawlowski] (Figure 4). On the basis of this approach, the proposed here method implements sample data of collisions at a different stage and for the risk control associated with an object. For the purpose of calculations of level of risk it has been decided to apply a constant factor of significance to any compartment/combination of compartments. Having a constant factor of significance of any damage will provide a statistically unbiased result of risk from flooding a compartment to the vessel, which then may be further evaluated with the help of statistics stipulated in Risk Control Criteria or ALARP methodology [Gerigk]. Similarly to the above damage, the risk of caring a dangerous cargo (in terms of pollution, high value, or fire) may also be considered in control options.

Bad weather that is unrelated directly to the object is a hazard taken into account at this stage. Current methods do not provide any visible assessment of bad weather impact on the safety of ships in serious accident situations. Up to date, masters on-board ships have not had any tool to help them estimate the stability of a ship in emergency conditions. Naval Architects know that a vessel subjected to a collision and flooding may be evaluated for safety with the use of s-factor present in the SOLAS 2009; however, in an emergency situation, such assessment becomes almost impossible to perform because it involves going through detailed calculations which often consist of hundreds of pages and as the s-factor was developed on the basis of statistical data, it cannot (ad hoc) provide an answer with sufficient amount of confidence.

As sea going vessels may freely change routes, operators and owners, and may be therefore engaged in worldwide trade in any location almost regardless of ship characteristics; probability of bad weather hazard occurrence may be calculated on the basis of available worldwide statics for ocean states and for a long period of time. In order to meet the sought after in this paper goal, it is important to emphasize that this statistical derivation must not be directly used for decision making process, but the final result must show the response of the vessel to different visible weather characteristics. This can be achieved through a matrix model of the probability P (3).

This measurement of weather conditions that usually takes place in practice determines the significant wave height and the apparent wind force in Beaufort scale. It is important to note that most trained mariners are familiar with and proficient in recalculating the apparent wind force to the true wind force. In line with the set up goal for this method, vessels characteristics must be confronted with measured by seafarers values.

There is no proven correlation between weather conditions and probability of hazard occurrence, hence for the purpose of this method long term weather statistics for the worldwide sea waters was used. The statistics used in this paper were the statistics first presented and tabularized in previous publications. [Cramer] (Figure 3).

The above approach to environmental conditions is based on the assumption that serious accidents happen regardless of the weather and the vulnerability of the object to this accident must be evaluated. As mentioned previously, the likelihood (probability) of accident happening may then be introduced into the method at the risk control options [Gerigk] (e.g. RCC – Risk Control Criteria) stage.

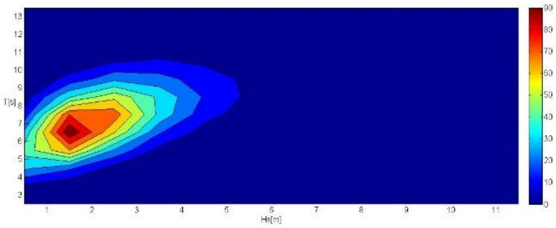


Figure 3) Frequency distribution of sea states in function of wave periods and significant wave height for world-wide trade. (Total number normalized to 1000) [Cramer]

4.2 VULNERABILITY TO HAZARDS

The vulnerability of a ship to hazards described in the above sections is related to many different factors. The response of the vessel to a damage to its original structure is related to the following factors:

- Weight distribution and initial stability of a vessel
- Subdivision and Arrangement:
    1) Position of a damaged compartment (damaged compartments)
    2) Size of a damaged compartment (damaged compartments)
    3) Geometry of a damaged compartment (damaged compartments)
- Initial floating condition of a vessel
- Quantity and type of cargo onboard
- Response of a vessel to damage (in function of damage position)

In order to determine the actual vulnerability of the vessel, all these aspects need to be investigated separately and independent of each other:

4.2.1 WEIGHT DISTRIBUTION AND INITIAL STABILITY OF A VESSEL:

As described above in part 2.2, the current calculation of stability method is based on evaluation of static parameters of ship hull and appendages only: righting arm curve and metacentric height in selected possible damage scenarios being investigated with a weight factor assigned on the basis of statistical evidence of collisions only and a separate deterministic investigation of stability after damage to the bottom of the hull. As a separate requirement for ships over 80 meters in length, a minimum allowable freeboard is governed by the ICLL regulations. It is not a holistic approach that addresses the evidenced serious accidents.

The stability of a ship in sea waters is governed by multiple parameters. Furthermore, it is essential to underline that damage stability and intact stability cannot be easily compared. This is mainly related to the fact that the Maritime Law suggests that any ship that is involved in a collision should remain in its location [Dannish Maritime Authority]. Consequently, after a collision the movement parameters change, and the forward speed of the vessel is minimized.

The impact of forward speed and the risk of oscillations have been very well described in the literature [Ibrahim, Kornev et al]. The difficulty of assessing safety of the vessel in terms of damage stability may originate because of two aspects of the vessel situation:

- Initial stability and floatability after the collision with another ship or object, or after the introduction of emergency condition for other reasons (such as hull integrity failure, cargo shifting, ballast system malfunction etc.).
- Stability and floatability of the ship after Master’s reaction to the emergency that may include some alteration of the course and speed in order to decrease the roll movement of the ship [Gerigk].

After a collision, the initial condition is assessed by officers onboard. If excessive roll angles are observed, a decision is made to change the course so that the vessel goes to head waves or wind and at a low or dead-slow speed. Additional tool that officers onboard a ship may use is to add or remove ballast water in order to change the weight distribution and/or position of center of gravity of a ship. This will have a significant impact on behavior of ships in waves too, but requires plenty of time prior to the effect of it to take place. There is no requirement for the time in which Master must make a decision to change course and the decision is based on Master’s judgment only. It is difficult, therefore, to assess the time in which the captain orders a change of the course and in which the course is changed. This would then have to be assumed and for the purpose of this work the author assumes a 100 second- period in which the vessel’s unsteady behavior in waves can be addressed.

As the available research clearly shows the risk of oscillations changes with the change of initial conditions, these being:

- Change of natural period of roll of the ship due to flooding
- Change of speed of the vessel

If in the new condition after damage the oscillations appear to be dangerous to safety (and if the situation allows for this), a Master will make a decision to alter the heading. If for stability and/or floatability reasons a Master decides to improve stability by changing course, the new condition must also be assessed, but the criteria for the new condition must be different and must assure safety outside the time domain.

Consequently, there may be two initial vessel's conditions on which officers onboard must have sufficient information to allow for a decision making process:

- Initial condition with 0 speed and worse heading, but with damage applied to vessel.
- Condition with low speed ahead and the heading in which roll angles are minimized.

With application of the described risk model such calculations may be easily carried out as two separate scenarios.

4.2.2 SUBDIVISION AND ARRANGEMENT

When the number of fatalities during the ship construction and dismantling is confronted with the number of casualties during the operation of ships, it is visible that every average sized cargo ship may pose a much higher risk to life during construction than during the entire operation cycle of it. Because of lack of access to the confidential statistical data on deaths in shipyards, the author may only speculate on a relationship between the weight of steel used for construction of ships and the number of lives they have taken in shipyards. Since this number may be much greater than the number of casualties among seafarers, it is imperative that the recommendations to ship designers, such as the one presented in this paper, should not involve unnecessary increase in the lightweight of designed ships and optimize the subdivision of ship to provide most efficient allocation of steel watertight boundaries.

Ships are designed to maximize their capacity and efficiency and in the Adam Smith's model of economics it would not make much sense to design and build cargo ships for any other reasons. In order to maintain safety standards, rules are imposed on the designers to stay within certain boundaries in their pursuit to maximize cost efficiency regardless of costs to life and environment. In order to address it, one must first introduce a knowledge based regime on the design. First and foremost, the statistical evidence clearly show the frequency of serious accidents at sea and from this data the significance levels for safety can be derived. As there is no rational reason why different ship types are subjected to different levels of risks of colliding or grounding, the population of different types of ships was taken into consideration.

Statistical records show that in the years 1990 – 2012 there were 2271 grounding incidents and 7598 of other different collisions. In that period the total amount of ship-years was 602998 [Papanikolaou]. Assuming an average lifespan of a vessel is 25 years, there is a nearly 10% probability that any given ship will run aground at some point in its life, and a 31.5 % chance it will face a serious accident related to either machinery, collision or hull breach. With the length of the ship divided in ten equal parts and with the assumption that a damage is sustained inside these parts, one may arrive at final figures of probability of flooding in these areas. These probability figures remain relatively high in all areas of the ship. Figure 4 shows that different importance factors towards different area of the ship assigned (as it was made in regulations

A.265 and SOLAS 90) cannot be fully justified in the light of this new statistical data. Furthermore, the increased value of probability assigned to the most-aft and most-forward area considered for flooding (as in the current regulation) cannot be justified either.

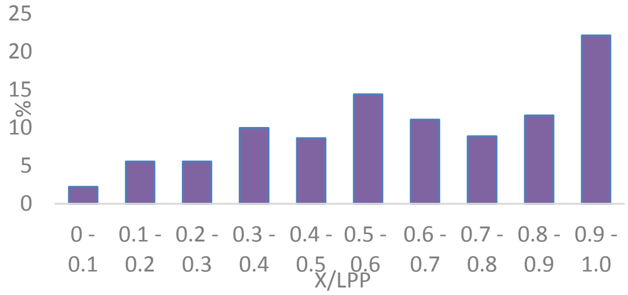


Figure 4. Damage location for collision damages according to GOALDS database

An assessment of energy absorption of a structure subjected to force seems to be an overwhelming task. Numerous attempts have been made to make analysis of a structure response to an impact [Luetzen et al]. All these attempts neglected the fact that the structure of the vessel along with thicknesses of plating varies in different areas of the vessel (e.g. tug area, thicknesses for Ice-Class etc.). Without knowing where the damage was sustained, any investigation of all the possible scenarios of structure response is a very difficult and time consuming task.

Extensive research on the applied size of a damage has been made in the past as well and currently valid regulations utilize a lot of knowledge and data gathered during this research [HARDER etc.]. In reality, the probability of e.g. flooding any tank adjacent to the outer-shell is always bigger than the probability of flooding tanks away from the outer-shell. This was reflected in the current regulations. However, in the current regulations this increased probability is not directly related/linked to risk and possible consequences from flooding of these compartments resulting with a possibility of catastrophic consequences from flooding of even a potentially small tank, for which the flooding probability is relatively low and even if the tank is located close to the outer skin of a ship. Furthermore, by introducing the Required Subdivision Index, the possibility of catastrophic consequences is not eliminated or controlled by current regulations. To address this issue, it is necessary to investigate all the large tanks (e.g. >1% of displaced volume) in terms of their impact on stability regardless of statistically derived probabilities and apply our knowledge about the likelihood of event happening at the risk control stage. Risk calculations must be then carried out for all such scenarios.

The geometry of tanks when flooded has a significant influence on their impact on stability. The current industry standard stipulated by regulations is to assess direct reduction of buoyancy and free surface effect from water inside of the flooded tank(s). In order to account for time - dependent process of flooding and changing geometry of tanks in vertical direction, some regulations also require the intermediate stages of flooding to be assessed [SOLAS], but again from the two mentioned above factors perspective only.

In reality, the mechanism of flooding is far more complex and it impacts stability of a vessel in the following ways:

- Reduction of buoyancy due to flooding

- Free surface effect
- Sloshing inside of tank(s) effect
- Change of floating position

The time dependency of tank flooding process introduces a risk of mistake in evaluation of condition of it. Flooding of a tank will depend on factors which are difficult to assess by crew onboard a ship at a time of incident. Furthermore, mathematical models that govern cushions in tanks and the flow of water through openings at ship position varying with movement would be difficult to apply and use in practice. In the proposed method risk calculations can be performed for any given tank in terms of risk to stability and floatability it induces.

In the presented method the calculation is therefore based on seeking the largest negative impact that flooding of each tank may have on stability and floatability of the vessel. Consequently, for some tanks it is the reduced buoyancy, for other tanks the free surface effect and for yet another group of tanks it may be the combination of the two. The impact of sloshing for majority of tanks and spaces onboard is relatively small, but for relatively large tanks should still be assessed and added to the final result.

4.2.3 INITIAL FLOATING CONDITION OF A VESSEL

Traditionally, the initial floating condition of a vessel is described by the following factors:

- Righting arm curve (restoring moment)
- Initial metacentric height

In more detail, movement of any ship on water is governed by more properties or properties that influence the two mentioned above factors. A prudent designer will consider the following parameters governing stability and floatability of any vessel.

- Position of center of buoyancy of a ship
- Position of center of gravity of a ship
- Mass/Weight distribution of a ship
- Hull and appendages size and geometry.
- Floating position (draught, trim and heel)

Currently, apart from detailed mass distribution around the longitudinal center of gravity axis and the geometry of hull appendages, all these additional parameters are at some stage examined for the purpose of intact stability and damage stability assessments. The hull appendages (if present) missing parameters may be easily taken from the structural drawings of any ship, the distribution of mass around the longitudinal center of gravity axis is very difficult to determine, but luckily it oscillates within a certain narrow range [Krueger, Reid]. In practice, an approximate formula is used to determine this value called Weiss formula (4).

$$T_N = \frac{\sqrt{g*GM}}{2*i}; \qquad i = \sqrt{\frac{I_{xx}}{\Delta}} \cong 0.4B \qquad (4)$$

4.2.4 QUANTITY AND TYPE OF CARGO ONBOARD

Any cargo vessels' vulnerability to flooding depends also on the cargo it carries. Various cargo has a different reaction when in contact with water. Some cargo absorbs water (some grains) some provides additional buoyancy to the vessel (e.g. timber). For example at this very moment guidelines are published how to treat additional timber on deck cargo in terms of stability.

However, these guidelines to be used in conjunction with SOLAS 2009 are seldom followed in practice because of computational difficulties. The impact of cargo does not only have direct impact on stability, but also influences vessels' moment of inertia around the center of gravity longitudinal axes. Currently no rule or regulation obligates designers to check or assess this impact as no rule or regulation requires checking the mass moment of inertia around the longitudinal axis going through the center of gravity of a ship in general.

Additional impact of type and cargo is its potential threat not only to stability and hence hazard to life, environment and property, but also to other safety aspects. Some cargoes are highly toxic, radioactive or highly flammable imposing enormous threat to a ship and even more so the environment and must be assessed to determine risks of carrying them onboard.

This assessment may be made on the basis of the available Codes (Such as CSS [IMO]) which describe levels of risk from carrying different types of cargoes. In addition this may further be confronted with cargo risk mitigation systems (such as fire extinguishing systems) available onboard an assessed ship.

4.2.5 RESPONSE OF A VESSEL TO DAMAGE

Any given vessel will have different responses to identical external hazards. In case of hull breach the governing factor for vulnerability of a vessel is its ability to return to an upright position, minimize the roll angle to a value in which it is still possible to navigate a ship and in which her weather-tight openings are not submerged maintaining sufficient floatability. In different rules and requirements, different approaches to assessing this response were utilized. In the ICLL 66/88 one selected representative condition is assessed; MARPOL 78 requires all approved intact loading conditions to be checked and SOLAS 2009 obligates the designers to check stability of a vessel in 3 loading conditions.

In this developed method, one condition (as in ICLL) for checking may be a valid solution to a problem of complexity in this aspect of the current regulations. This condition similarly to the ICLL 66/88 is equivalent to a vessel at its minimum allowable freeboard and with the initial stability parameters corresponding to the lowest approved intact GM value. However, when using this approach there is a risk of not taking into account some conditions with different trim or different loading configuration. To address the above an additional concept of a theoretical floating condition with maximum allowable trim aft and maximum allowable trim forward was introduced. Such theoretical condition would have a lowest approved intact GM assigned. With these assumptions the risk of omitting an approved condition which may offer less stability/floatability margin than the one selected is greatly reduced and for the met in practice hull shapes adequately addressed.

The response of the ship in the above described condition to a damage will depend on the flooding of compartments.

4.3 CONSEQUENCES OF HAZARD OCCURRENCE:

As presented in multiple studies and supported by statics [Cichowicz, Vassalos etc.], the most common and critical hazards to safety of ships are listed below:

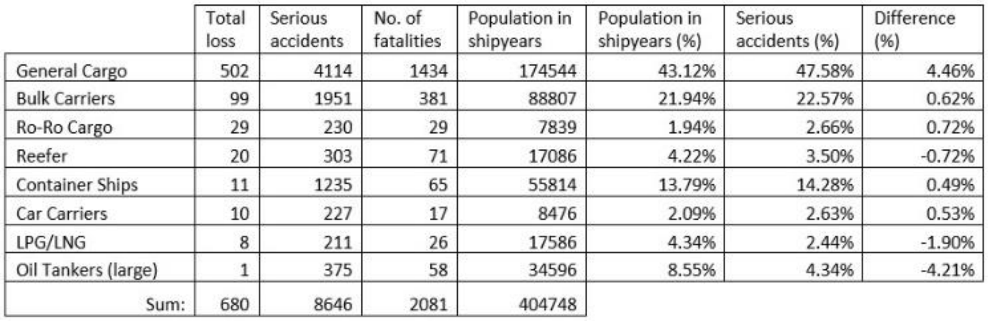
1) Grounding
2) Hull damage
3) Machinery damage

4) Contact/foundering/collision
5) Fire/explosion
6) Pollution

Reasons 1 to 5 constituted 99.3% of all serious accidents between the years 1990 and 2012 (when only the ships built after 1980 are considered) [Cichowicz]. The percentage contribution of each type of hazard is summarized in Table 1.

Grounding	20.95%
Hull/Machinery Damage	37.12%
Contact/Collision	32.97%
Fire/Explosion	8.26%
sum:	99.30%

Table 1. Percentage breakdown of serious accidents as per the IHS definition



	Total loss	Serious accidents	No. of fatalities	Population in shipyears	Population in shipyears (%)	Serious accidents (%)	Difference (%)
General Cargo	502	4114	1434	174544	43.12%	47.58%	4.46%
Bulk Carriers	99	1951	381	88807	21.94%	22.57%	0.62%
Ro-Ro Cargo	29	230	29	7839	1.94%	2.66%	0.72%
Reefer	20	303	71	17086	4.22%	3.50%	-0.72%
Container Ships	11	1235	65	55814	13.79%	14.28%	0.49%
Car Carriers	10	227	17	8476	2.09%	2.63%	0.53%
LPG/LNG	8	211	26	17586	4.34%	2.44%	-1.90%
Oil Tankers (large)	1	375	58	34596	8.55%	4.34%	-4.21%
Sum:	680	8646	2081	404748			

Table 2. Table showing the apparent relationship between the "ship-years" of each type of ship and number of serious incidents

It is important to differentiate between serious accidents and ship losses. The definition of serious accidents is determined by the IHS:

"A marine casualty to a ship, as defined, which results in: Structural damage, rendering the ship unseaworthy, such as penetration of hull underwater, immobilization of main engines, extensive damage, etc. /breakdown/ actual total loss/ any other undefined situation resulting in damage or financial loss, which is considered to be serious." - [Cichowicz - IHS]

The most recent statistics data reveal a correlation between serious accidents and the number of "ship-years" regardless of ship types. This is opposite to the loss of ships and/or number of fatalities which seem to be governed by more complex relationship (Table 2), but also that the LPG/LNG and Large Oil Tankers (over 60000 DWT) show lower numbers than other types of ships of serious accidents in comparison with the "ship-years" number. One may speculate about the reasons of a lower percentage of serious accidents to "ship-years" ratio for LNG and Oil Tankers. One of the possible reasons is that these ships are governed by different construction regime (e.g. MARPOL) than other types of ships investigated. Regardless of the reason behind this difference, these types of ships were excluded from the statistical evaluation of a database. Consequently, by introducing a mean average for all remaining ship types it was determined that any ship is subjected to a risk of being in a serious accident equal to 2.29% per year. Assuming the average life of any ship of 25 years the chances of any vessel being in a serious accident during its life increase to 57.15%. The serious accidents taken into equation here were listed in Table 1.

From the above assessment of risk and hence consequences, the conclusion is drawn that it is essential to address all the hazards listed in Table 2 and risks of serious accidents that lead to damage to property, environment and loss of life without prioritizing any of them.

4.4 RISK CONTROL

There is limited statistical data on the length of time that a vessel carries certain type cargo. For the sake of uniform and unbiased assessment, constant factors may be applied to all types of vessels designed to carry a cargo that is potentially valuable or dangerous to life or property. Such control, with use of constant coefficients may also be made prior to any voyage. Similarly, a threat of cargo fire emerging can be quantified. For cargo ships, the risk of cargo fire is substantial and must be addressed by design and careful operation. Current requirements and guidelines, when followed, greatly reduce the risks, but are separate from a general notion of safety and/or stability in intact and emergency conditions. Furthermore, a risk of cargo fire must be evaluated in terms of its potential consequences, which are different from the consequences of loss of cargo, or ship damage.

The control of risk may also take place by confrontation with the statistical data of accidents at sea. The method may be based on e.g. Probability Density Function as introduced by Pawlowski and Luetzen and implemented into SOLAS 2009. From the latest statistical data gathered and filtered from the GOALDS and HARDER programs, a minimum requirement for any vessel and a safety goal may be determined.

5. CONCLUSIONS

In this work a general description of the developed method of assessment of safety of ships in abnormal/damaged conditions is presented. 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. Can be applied at any stage of vessel’s life (design, operation, catastrophe, salvage);
3. Holistic approach to safety by introduction of safety factors (sources of factors: design, operation, management, human factor);
4. Possibility of assessment of risk 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 complex 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 result with a model for the computer simulation of the ship emergency situations and salvage process.

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