Development of Probability Based Quasi-Static Damage Stability Criteria for Naval Ships

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ABSTRACT

This paper provides an overview of the development of a formulation that computes the survival probability of a damaged frigate in a seaway only using static stability calculations. For this purpose, the survival probabilities of 23 damage cases were determined by means of time domain simulations and compared with the corresponding static stability parameters. The formulation was derived by regression analyses through the capsize wave heights, that were obtained from the simulations.

Keywords: *Simulations, Regression, Progressive flooding, Damage stability*

1. INTRODUCTION

Since the 1960s, western navies have used stability standards that are based on the Sargin and Goldberg paper to assess the damage stability of their combatants (Surko, 1994). A number of limitations and disadvantages of these criteria were identified over the past decades. One important disadvantage is the unknown safety level or survival probability that is obtained when the vessel complies with these criteria. Besides, the beneficial effects of additional protective measures that will limit the damage extent are not taken into account as the assumed damage length is proportional to the ship's length.

These shortcomings lead to the requirement of a probabilistic approach. Besides, such an approach allows for a direct integration of damage stability into an overall vulnerability assessment. The outlines of this probabilistic approach is very similar to the probabilistic approach of the IMO, but will have a number of discrepancies as both the threats and the vessels have different characteristics compared to civil ships that face only collisions and groundings. The threats for naval ships may also comprise military weapons like Anti Ship Missiles (ASM) and mines. These weapons can be operated in relatively high sea states (ASM up to sea state 6 or 7) compared to the statistics of collision sea states (max sea state 5). Besides, compared to civil ships, modern combatants generally have a much higher degree of subdivision, a hull form that is more suited for damage stability and training of its personnel. This will lead to a different behaviour in waves and higher acceptable roll angles before capsizing. Therefore, capsize boundaries for civil vessels, that were investigated for the HARDER project (Tagg, 2002), may not be applicable for naval purposes.

This paper presents a study in which the survival probability was computed by a simulation program for 23 damage cases. These capsize probabilities have been correlated with righting arm curve characteristics, similar to the analysis that was performed for the HARDER project. This has resulted in a formulation that predicts the capsize wave height, based on the area under the righting arm curve.

2. COMPUTATION OF THE SURVIVAL PROBABILITY

2.1 The Definition of a Capsize

In this study, only the limiting roll angle that would endanger the survival of the platform and personnel is to be considered. This boundary is always a point for discussion (e.g. Palazzi 2003). From operational experience it is known that incidental roll angles of 50 degrees are not considered to be very dangerous. At much larger roll angles (80 degrees), all kinds of equipment may shift from its position, thus creating an additional heeling lever. For this study a roll angle of 60 degrees was chosen as capsize angle.

When computing an exceedence probability in the time domain, also the duration must be considered. For damage cases, this may be much shorter than for intact cases, which may be comprise a period of a year or even a life span. For damaged ships it should cover the time until first repairs have been done, or aiding ships that can tow the damaged ship have arrived. This period is set at 24 hours.

2.2 Environmental Conditions

The survival probability of a single damage case is the summation of all survival probabilities for all possible ship headings and speeds and all environmental conditions. To limit the number of those combinations it is assumed that the propulsion fails after the damaging incident. At zero speed, most ships drift to beam sea condition, so the number of heading – speed combinations is reduced to two.

The survival probability was computed for the North Atlantic wave scatter diagram as this covers a wide range of wave heights and periods. However, when dealing with actual threats, these ranges may be limited as the operations with naval weapons are limited by weather conditions. Therefore, in later stages, some post processing may be required to convert the results to wave scatter diagrams that are adjusted to specific threats.

2.3 From Simulations to the Survival Probability

Ideally, the capsize probability p_c can be computed by:

$$p_C = \frac{N_C}{N_S} \tag{1}$$

where N_C is the number of capsizes and N_S the total number of simulations. However, this requires a large number of simulations for sufficient accuracy, as was shown by Mac Taggart (2000). The cumulative distribution function (F) of maximum roll angles (ϕ) can be computed in a similar manner:

$$F(\phi_i) = \frac{i}{N_S + 1} \tag{2}$$

where i is the rank of sample ϕ_i. A suitable distribution function was found in the Generalized Extreme Value (GEV) distribution:

$$F(\phi) = \exp\left[-\left(1 + c\,\frac{\phi - b}{a}\right)^{-1/c} \right] \tag{3}$$

where a, b and c are respectively the scale, location and shape parameter and can be determined with a Power Weighted Moments method as is explained by Palutikof (2000). This distribution is well suited for its purpose as it can describe the fat tail that is often found at these damage cases (see the example of Figure 1).

To obtain reliable fittings, sufficient samples are required, typically more than 15. Despite the simplifications, 15 simulations of

24 hours per sea condition requires more CPU than that is practical, thus additional reductions were looked for. The first reduction was obtained by reducing the duration of a single simulation. This is a standard procedure for such analysis and means that the capsize probability is predicted for a shorter time span. Besides, in only a very narrow band of wave heights, the time to a capsize is longer than 2 hours as was discussed by Van ‘t Veer (2002) and verified for this study. Therefore, the maximum duration of a simulation was set to 2 hours.

A second reduction was obtained by taking the maximum of every 15 minutes (*r-largest values* approach). Now every 2 hour run results in 8 samples. As the loading condition changes over the time due to inflow and outflow of damage water, this approach is not entirely correct as the samples are not completely statistically independent. However, calculations show that the obtained accuracy is sufficient as the changes in the loading condition occur in the extreme cases where the predicted survival probability is close to 0, independent of the calculation procedure that is used.

Now equation 3 provides the capsize probability for a 15 minute period (D). The following equation can be used to extrapolate this value to the survival probability (P_S) of a 24 hour period (T):

$$P_S = \left[1 - p_C\right]^{\frac{T}{D}} \tag{4}$$

Using this procedure, a maximum of 8 FREDYN simulations per wave condition are required for sufficient accuracy. An example of a fitted distribution is given in Figure 1, where 3 runs resulted in a capsize (these are the 3 points at 60 degree roll angle).

3. THE EQUAVALENT STATIC STABILITY

In principle, the computation of the righting

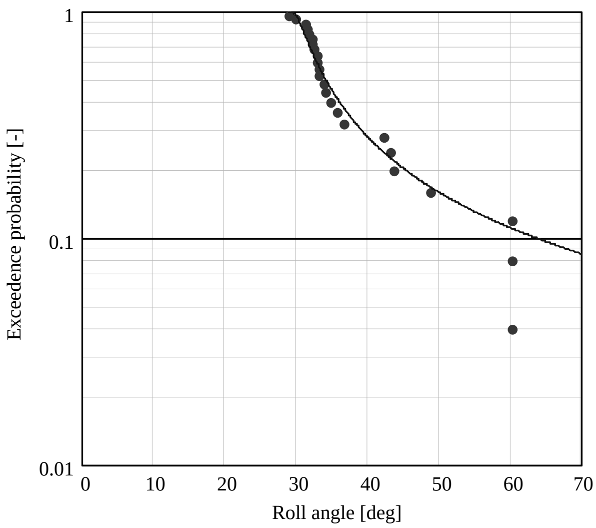

Figure 1 Example GEV fitting

arm curve is relatively straightforward. For static damage stability calculations, the normal procedure is to designate certain compartments as damaged. For dynamic calculations, the damage was defined by means of openings. These openings could be part of the ship design (doors, stair cases, non-watertight openings) or caused by damage (collision, blast, fragments). Water flowing through these openings would expose the adjacent compartments to flooding. In order to use the same damage description for both dynamic and static calculations, a similar procedure was used for the static stability calculations. For each heel angle, the program determined iterative whether the water level inside and outside the ship, reached the openings and thus flooded the adjacent compartments.

This approach may result in a righting arm curve that is suddenly cut short, as the floor of (initially dry) compartments may be below the static waterline before the opening enters the water. Thus this compartment is designated damaged only at larger heel angles.

This approach identified a shortcoming of the static stability methodology. Bulkheads may contain small openings that are above the waterline of the equilibrium condition. These openings may be part of the ship design or for example caused by individual fragments from a

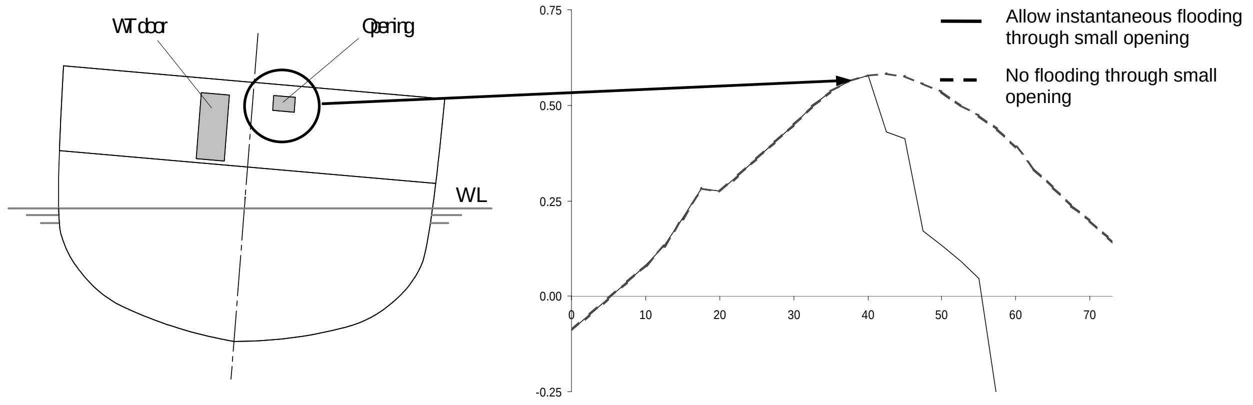

Figure 2 Effect of openings on righting arm

missile warhead. These openings may come below the waterline due to roll or water motions in the damaged compartments, allowing water to flow from one compartment to another for a short period of time. Due to the limited duration of flooding and limited size of the opening only a relatively small amount of water flows to the adjacent compartment leaving the equivalent. As the ship rolls back to its equilibrium, the condition is almost the same as before. So as time passes, the ship condition gradually changes from one condition to another.

For these studies, two righting arm curves are computed, both with and without taking into account these small openings above the still waterline (see Figure 2).

4. CALCULATION SETUP

4.1 Numerical Simulation Model

The simulation tool that was used for this study is the simulation model FREDYN. This program is capable of predicting large amplitude motions, both for intact and damage condition. The damage part is well validated for frigates as described by De Kat (2002) and Palazzi (2003).

The flow between compartments is based on the Bernoulli equations that are applied to each opening. The water inside the ship is considered as a free particle with a time-varying mass. The water level is assumed to be horizontal at each time instant.

4.2 Simulated Ships

Five different modern frigate designs, with displacements varying from 3,000 to 10,000 tons, have been chosen for this study. These frigate designs complied with the traditional naval damage stability requirements.

The modelling of the frigates included detailed compartmentation, doors, hatches, staircases and other non-watertight openings. The automatic generation of the damage openings (collision or explosion), panels were defined at the compartment boundaries representing the bulkheads, decks and hull plating. Structural properties, such as plate thickness and collapse pressure, were assigned to each panel.

4.3 Damage Description

The 23 damage cases contained both damages caused by collisions and Anti Ship missiles. The collision damage was defined by a longitudinal position and a collision length and depth, resulting in a wedge-shaped damage volume. All parts of the compartment boundary panels within this volume are considered open.

The ASM causes a damage due to blast effects and fragments. The location of the burst is defined by the longitudinal and vertical position of the ship. The warhead is fitted with a delay fuse, thus the explosion will be inside the ship. The blast causes the collapse of panels within the so-called *blast damage radius* (ANEP 43, 2003). The extent of this radius depends on the explosive charge and scantlings of the panel. The casing of the missile warhead brakes into different sized fragments, causing a high number of openings in the ship construction. The penetration of the panels was determined by means of the THOR equations (ANEP 43, 2003). The total number of openings due to fragments can exceed 5,000. As this high number has a negative effect on the required CPU, a group of fragments in a specific panel was replaced by a single overlaying opening with adjusted flow coefficients, so that the water flow through this opening would be equivalent to the smaller openings.

5. SIMULATION RESULTS

5.1 General Characteristics

The following general characteristics have been observed:

1. The survival probability in a wave system coming from leeward with respect to the damage, is lower or similar to waves coming from the windward side. According to Tagg (2002), this is similar to findings in the HARDER project for high freeboard ships. This is caused by the smaller righting arm levers at the damage side and the higher wave and wind loads in leeward direction. It was decided to limit all further analyses to the situation where the damage was located at the leeward side, covering the worst possible position of the ship in a wave system.
2. In all but a few cases, the transition from a survival probability of one to zero (with increasing wave height) is very steep, within 1 metre significant wave height, see also Figure 3. This phenomenon makes it possible to define a *capsize wave height*, which is a function of the wave period, that describes the safety boundary. A possible definition of this capsize wave height is the significant wave height at which the capsize probability is 0.5.
3. A trend is noticed where the capsize wave height increases with the increase of the wave period. The steepness of this trend increases with the reduction of the capsize probability. This is shown in the two examples in Figure 3. Here the scatter diagram at the right hand side is a case with a higher survival probability.
4. In 10 out of 23 damage cases, there was a significant effect of progressive flooding effects on the righting arm curve (see section 3).

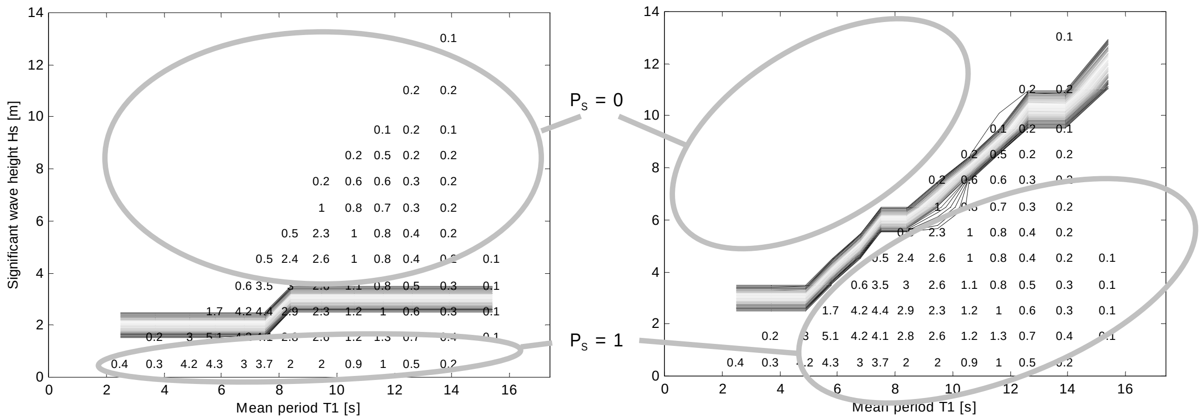

Figure 3 Example capsize boundaries

5. The range of the righting arm curve for damaged frigates is generally relatively large. A damage case with reduced stability leads to a lower maximum righting arm lever and lower GM, while the reduction in range is limited.

5.2 Regression Analyses

The survival probability was compared with various righting arm curve parameters. best correlation was obtained for the area under the righting arm curve, which is shown in Figure 4. For the 10 damage cases with a significant progressive flooding effect, the areas of the two different righting arm curves (with and without progressive flooding) are shown as error bars. For these damage cases it was found that the best correlation can be obtained using a point between the two extremes with ratio of 1:4 (see also Figure 4).

A direct fitting can be applied to the data of Figure 4, which would provide a formulation to compute the survival probability in the North Atlantic for a damaged ship given the area under the righting arm curve. However, this way the probability distribution of the damage occurrence with respect to the sea states is not included. For example, most ASMs can be operated to a maximum sea state of 6 or 7, which would exclude the top of the scatterdiagram of the North Atlantic. Therefore, a formulation that computes the capsize wave height (H_{crit}) with the variables mean wave period (T_1) and righting arm area (A) would be much more suitable as these wave heights can be applied to any wave scatter diagram to compute the survival probability.

The data points in Figure 5 represent the capsize wave heights that were obtained from the simulations. From these point two different phenomena were identified. The first is the increase of the capsize wave height with increasing area under the righting arm curve independent of the wave period. This increase is pronounced for small areas, but reduces as the area is larger than approximately 5 mdeg. The second phenomenon, regarding the wave period dependency, is already explained in the previous paragraph (point 3).

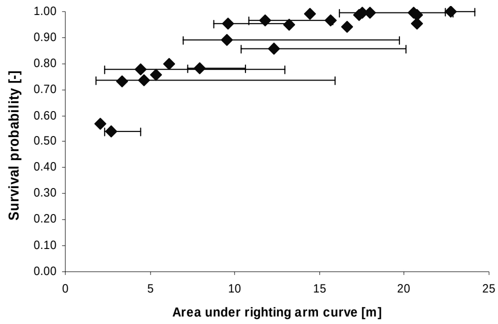

Figure 4 Righting arm curve area – survival probability relation

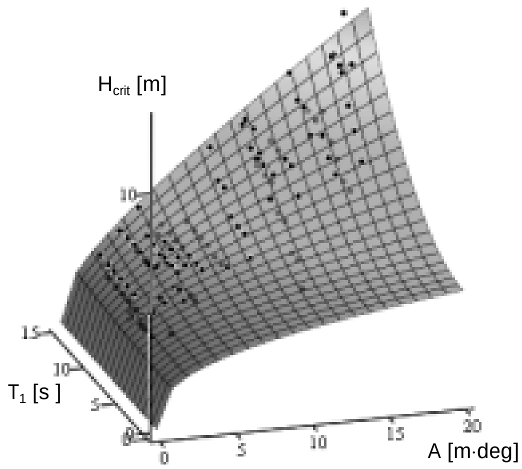

Figure 5 Capsize wave height data points and fitting surface

Using these observations, linear regression analyses resulted in the following formulation for the capsize wave height:

$$H_{crit} = 1.63\sqrt[3]{A} + 0.0016 A T_1^2 \qquad (5)$$

where the area under the righting arm curve A is in m·deg and the mean wave period T_1 in s. This regression surface is also plotted in Figure 5. The Pearson's r correlation coefficient (R^2) for this fitting is 0.89, which is acceptable. Applying this formulation to the North Atlantic scatter diagram results in the fitting of Figure 6. The data points are the same as in Figure 4, but to clarify the graph the error bars have been removed. The correlation coefficient for this fitting is 0.93.

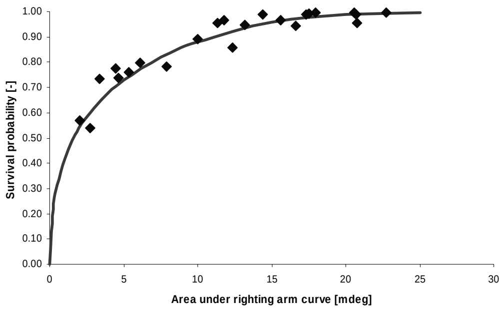

Figure 6 Simulation results and fitting result

With the obtained formulation (5), it is now possible to predict the survival probability of a damaged frigate in a dynamic environment, using only the static righting arm curve.

6. FUTURE DEVELOPMENTS

This methodology can be used to investigate the effects of design changes on the survival probability, where the traditional stability criteria provide give insufficient insight. Ultimately, this should result into a transition of the current deterministic criteria into a probabilistic approach. Such an approach requires the specification of the threats, operational areas and required survival probabilities for the 25 year lifespan of the ship. This will require many additional studies as the specified threats and environment can change dramatically over such a long period.

However, this direction provides the opportunity to include the analyses of other work fields such as the remaining girder strength and fire fighting capabilities, so that the ship design can be balanced to all possible failures.

7. CONCLUSIONS

The survival probability of a damaged ship in a particular sea way can be computed by means of simulations, using a Generalised Extreme Value distribution to obtain the capsize probability.

The effects of progressive flooding through small openings in watertight bulkheads, can have a significant effect on the righting arm curve. Although the results of this study show some trends, additional studies are required on how to deal with these effects in static stability calculations.

The survival probabilities that were found with the simulations, correlate well with the area under the righting arm curve. A formulation was derived, that computes the capsize wave height for a given righting arm area and wave period. In combination with a wave scatterdiagram, this can be used to compute the survival probability for every combination of threat characteristics and wave statistics.

This methodology can provide insight in the effects of design changes on the survival probability for which the traditional naval criteria have no solution.

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