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On the computation of the survivability of navy vessels during the early design stage

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ABSTRACT
A method is presented to determine the probability of survival of naval vessels in different scenarios of threat. The method is applicable especially during the early design phase in order to quickly assess the probability of survival of novel navy ship designs. It also makes it possible to identify and eliminate weaknesses in the design. This development follows the logic of threat-based naval ship design. The method is based on the regulations DMS 1030-1, DMS 1040-1, and DMS 0280 and demonstrates how these regulations can be used as ideal design tools in the early design phase. The method is implemented as a Monte Carlo simulation method within the E4 ship design system, and the methodological principles and their application to a sample design are explained in this article.

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Introduction

Naval vessels are exposed to particular hazards during military operations. In addition, naval vessels participate in civil maritime traffic and are therefore also exposed to the hazards prevalent there. A key objective of the design of the ship, its structure, and its systems is to ensure that the ship survives potential hazards as far as possible and, ideally, remains operational. Determining the probability of survival of a naval vessel is therefore of particular importance. Now the problem exists that most navy design and constructional rules are deterministic regulations, and it is thus challenging to compute probabilities. Boulgouris and Papanikolaou (2004, 2013) have suggested using a probabilistic, Monte Carlo-based damage stability approach where damage probabilities are derived from common defense analysis models (Przemieniecki 1994). They also used that kind of approach for the risk based design of a naval combatant (2013). Other groups of authors (e.g. Harmsen and Krikke 2000; Liwang 2012) follow comparable principles for the probabilistic damage stability of Navy Ships. But it is the aim of the authors of the present study to go one step further: Survivability is regarded in a kind of holistic sense as the combination of three abilities the ship must have after damage: She must remain safely afloat, the structural integrity must be guaranteed, and the relevant systems still need to work. Furthermore, the principles of computing the survivability of a navy ship shall be fully in line with the relevant safety standards, since the Navy ship, of course, needs to comply with these standards. For ships designed and built for the German Navy, the relevant standards are DMS 1030-1 (stability), DMS 1040-1 (structural integrity) and DMS 0280 (functionality of systems). This paper covers the first two issues, while the treatments of functional chains are presently under development.

Background

In principle, the probability of survival of a naval vessel P_S can be calculated as follows:

$$P_S = 1 - P_{SE}(1 - P_{SS}) \tag{1}$$

Here, P_{SE} is the probability that a specific damaging event will occur at all. P_{SS} is the probability that the ship will survive this damage. A direct calculation of the overall probability P_S makes it possible to determine whether the ship is fundamentally suitable for its intended purpose. However, this approach is not effective for the design of the ship, its structure, and its systems. This is because P_S is a purely probability-based variable. However, in safety engineering, it is unacceptable for a technical system to have a statistically high level of safety, but for an extremely minor, albeit unlikely, damage event to immediately lead to the loss of the ship (minor damage – major loss problem). It would, therefore, obviously be inadmissible to dispense with all damage stability measures on a naval vessel if sufficient defensive measures against missiles and similar devices were installed. In

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this way, it would be theoretically possible to achieve a very high value of P_S, but the design of such a ship would certainly not be acceptable. This shows that it is expedient for the platform designer to consider only the probability P_{SS}, because this evaluates the survivability of the platform design regardless of P_{SE}. A sufficiently small value of P_{SE} is then obtained by the reduction of the ship's signatures as well as by the installation of suitable effectors. The operator, on the other hand, wants to consider both. They want a robust design that can safely survive certain damage (sufficient P_{SS}), and at the same time, they want the damage to be survived not to occur in the first place (sufficiently small P_{SE}). Furthermore, the operator of the naval vessel is likely to be the only entity with knowledge of the probability P_{SE}, and therefore only they can calculate the total survivability probability of a naval vessel. Therefore, only the probability of survival P_{SS} for the platform in the event of damage will be considered in the following and calculated as follows:

$$P_{SS} = \frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{\infty} P_{ij} S_{ij} \tag{2}$$

Here, P_{ij} denotes the probability that damage of a certain type and size will occur at a certain location on the ship. S_{ik} denotes the probability that this damage will be survived. The index j denotes the individual damage, the index i the respective type of damage resulting from the assumed type of hazard. Hazards may come from civilian as well as from military scenarios, but we will restrict ourselves to some military hazards here. Because for civilian threats like grounding or collision, suitable methods are available; e.g., SOLAS 2020 (Rusas 2003; IMO 2002; Papanikolau et. al. 2012). The following types of military hazards for a naval vessel will be dealt with in the following:

1. Drone attacks
2. Missile hits
3. Contact mine detonations

Because the ship reacts differently to all these hazards, and because these individual hazards have different probabilities of occurrence, it makes sense to break down Equation (2) according to the hazard in question and then calculate the individual sub-indices. This gives the determination equation for the sub-probabilities for each type of hazard:

$$P_{SS,i} = \sum_{j=1}^{\infty} P_{ij}\, S_{ij} \tag{3}$$

In the following, the probability designations are used in much the same way as they are used in the context of the SOLAS 2020 regulations. The $P_{SS,I}$ is equivalent to the a_i values according to SOLAS. The partial probability P_{ij} is composed as follows (Rusas 2003):

$$P_{ij} = p_{ij}(x_1, x_2)\; r_{ij}(y_1, y_2)\; v_{ij}(z_1, z_2) \tag{4}$$

The individual partial probabilities p, r, v mean that the damage lies in the corresponding intervals in x, y, and z. The probability of survival in the event of an assumed damage event can be calculated as follows:

$$S_{ij} = s_{ij,1030}\; s_{ij,1040}\; s_{ij,0280} \tag{5}$$

$s_{ij,1030}$ is the probability that the ship is still sufficiently buoyant and has sufficient residual stability. This is addressed by the regulation DMS 1030-1, so that the probability calculation for $s_{ij,1030}$ should be based on this rule set. $s_{ij,1040}$ is the probability that the ship's structure will survive the assumed damage, still having sufficient residual strength. This is ensured by DMS 1040-1 in conjunction with DMS 0280. Therefore, this probability calculation should be based on that respective DMS. $s_{ij,0280}$ represents the probability that the ship will still have vital systems such as propulsion or power generation after the damage has occurred, which is regulated by DMS 0280.

There is a certain hierarchy between these probabilities: If the ship is no longer buoyant, i.e. if $s_{ij,1030} = 0$, then it is irrelevant whether the structure is still intact or whether systems are still functioning. If the structure fails on a ship that is fundamentally buoyant, then it is irrelevant whether systems are still functioning. Therefore, the first step is to consider 'buoyancy' and 'structural integrity.' Once the effects of assumed damage on these aspects are known, downstream procedures for the calculation of the individual $s_{ij,0280}$ can be applied (Philipson and Krüger 2026).

Damage probabilities

Other than SOLAS, there are no commonly used regulations that represent the statistical distributions of military hazards. They are therefore discussed below, with DMS 1040-1 and DMS 0280 providing valuable input information. DMS 1040-1 provides valuable basics for calculating the extent of damage, but only for manual use. However, it is necessary to calculate a large number of scenarios in a short time; therefore, an automatable procedure must be found with the help of the two DMS, which is described below.

Drone attacks

First of all, drome attacks are considered, where the term 'drone attacks' refers here to attacks by floating vehicles operating on the water surface. Consequently, damage to the ship occurs in the vicinity of the waterline. The drone pilot will most probably attempt to hit a prominent point x_M on the ship, e.g. the bridge.

This point can be specified in advance. Since it is to be expected that the drone pilot will miss this point with a certain degree of uncertainty σ, it makes sense to model the longitudinal distribution of the drone impact with a Gaussian distribution around x_M with a spread σ. This Gaussian distribution can be numerically integrated to model the probability distribution p_{ij} (x).

Figure 1 shows the cumulative density function (CDF) and the probability density function (PDF) of a drone hit in the longitudinal direction for an x_M of 0.71 and a spread value σ of 0.15. If the x-position of the drone hit is fixed, the z-position (which must correspond to the local draft) and, from this, the y-position are immediately determined. This means that the position of the drone hit is then known. The damage radius model of the DMS 1040-1 can be used as a basis for the extent of the damage. According to this, the damage radius R_D is initially.

$$R_D = \sqrt[3]{W_{eq}} \tag{6}$$

This means that all structures within this damage radius are for sure destroyed; see Figure 2.

W_{eq} is the TNT equivalent of the effective explosive quantity in kg. W_{eq} can also be regarded as a random variable that varies randomly between an assumed minimum explosive quantity and an assumed maximum explosive quantity. If nothing else is known, a uniform distribution can be assumed here. Other distributions may need to be requested from ammunition experts. Values of the range of TNT equivalents for different weapon systems can for example be taken from the DMS 0280-1. Now, according to DMS 1040-1, the damage radius R_D must be adjusted with various correction factors, namely:

- Ship type correction factor k that converts from frigates to other ship types. This factor increases the damage radius if the ship is not a frigate, as k = 1 for a frigate. k values for other ship types like corvettes or patrol boats are suggested in the range of 1.2–1.6 by the DMS 1040-1.
- Structural component factors k1: This factor increases the damage radius if the structural component is not a splinter bulkhead or box girder. For these structural elements, the factor k1 is assumed to be 1.0. For other structural components like decks, double bottoms, or ordinary bulkheads, the value of k1 is suggested as 1.3-1.5.
- Shadow factor k2: The damage radius decreases behind destroyed structures, and default values of k2 are suggested in the DMS 1040-1 for different structural members like decks or box girders. Typical values for k2 are 0.4-0.8.

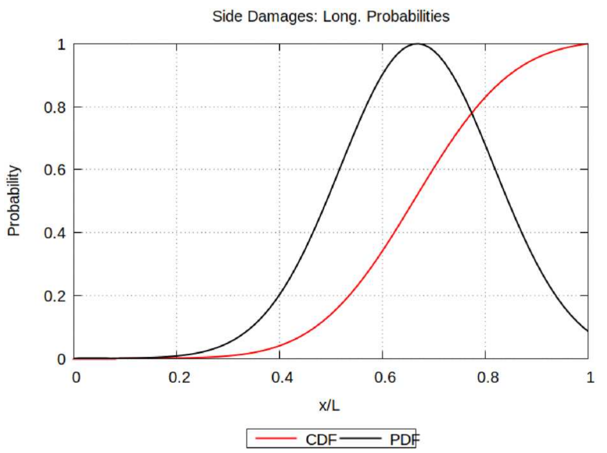

Figure 1. CDF and PDF for a drone hit with x_M = 0.71 and σ = 0.15.

The DMS 1040-1 offers two possibilities for the determination of the individual k-factors: For the most important structural components, reasonable default values are suggested which might be used during the initial design phase of the ship. On the other hand, detailed k-factors can be individually determined for each structure if the details of the plates and stiffeners are known. In our calculation model, we have foreseen that each subdivision element of the ship's compartmentation can have individual k-factors, regardless whether they are default values or from detailed calculations, and these factors are used during the calculation. This approach allows us to cover both the

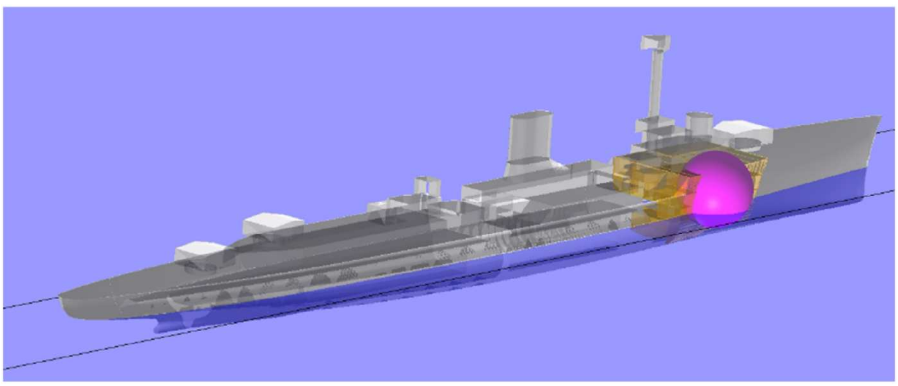

Figure 2. Damage radius concept of a drone hit.

very early design stage as well as the detailed design phase of the ship.

The damage extent of drone attacks is now calculated as follows: First, the outer skin must be destroyed by the detonation effect. This means that all structures in the ship are in the destruction shadow of the shell. No k_2 factor is specified for the shell in DMS 1040-1, so we initially set this to 0.5, which appears to be a conservative value, as it is larger compared to the value suggested for a deck. This means that the penetration depth at the point (x_M, y_M,T) is initially $0.5R_D$. Next, we check the local ship's breadth at this point. If the penetration depth is greater than the local ship breadth, then the opposite shell is also in the destruction shadow and is therefore destroyed immediately. This means that we have a quasi through shot through the structure, and this can happen near the forward terminal of the ship where the local breadth of the structure is quite narrow. This event is not covered by the existing DMS 1040-1, because in this code, structural damages are assumed to be close to the middle of the ship only. Therefore, we must consider a possible extension of this code. In the case of such a through shot, we assume that the essential pressure energy is dissipated outwards, which leads to a reduction of the vertical extent of the damage. To cover this vertical reduction, a new factor is introduced in the case of a quasi through shot, which we denote as $k_{2,\ penetration}$. The damage radius in the vertical direction during the trough shot is therefore set as $k_{2,\ penetration}$ times the damage radius R_D. A reasonable and, at the same time, probably conservative value for this could be suggested as 0.5, but it needs to be validated in the future. If there is no shot through, then a check is made to see which compartments would be damaged if the damage radius in the y-direction is $0.5R_D$ and in the x - and z-directions is $1.0R_D$. From these damaged compartments, it is determined how many decks are located within the damage radius above and below the point of impact. Then, for each deck, the k_1 and k_2 factors are taken from each deck, and the damage radii in the z-direction are determined individually, whereby no resulting damage radius may be smaller than the original R_D. In the x-direction, the full damage radius is used because the destruction of the outer skin would also destroy an adjacent transverse bulkhead if it lies within the damage radius, which will lead to the flooding of the adjacent compartment. These assumptions ensure that reasonable damage distributions are computed for any drone hit scenario in accordance with DMS 1040-1.

Missile hits

Missiles usually target the surface ship and attempt to hit a specific point on the surface ship using their sensors. Various sensors have been implemented for this purpose: Radar sensors target the lateral centre of gravity, infrared sensors may target heat sources and optical sensors may target the maximum lateral surface change. The first two sensors can again be described with a distinctive point x_M and a Gaussian distribution, whereby a spread σ can also be specified here. The lateral surface change can be determined such that the lateral surface A_{lat} is a function.

$$A_{lat}(x) = \int_0^x a(x)dx \; or A_{lat}(z) = \int_T^z a(z)dz \qquad (7)$$

from which the corresponding probability for longitudinal and altitude position can then be obtained by appropriate normalization. It is assumed that the missile can only strike above the waterline, so the possible point of impact in the altitude direction lies in the z interval $[T,Z_{Max}]$. Any number of sensors in any combination can be taken into account. The individual partial probabilities are simply added proportionally and the result is normalized accordingly. Figure 3 shows the probabilities for the longitudinal (top) and vertical (bottom) positions of a missile with all three sensors.

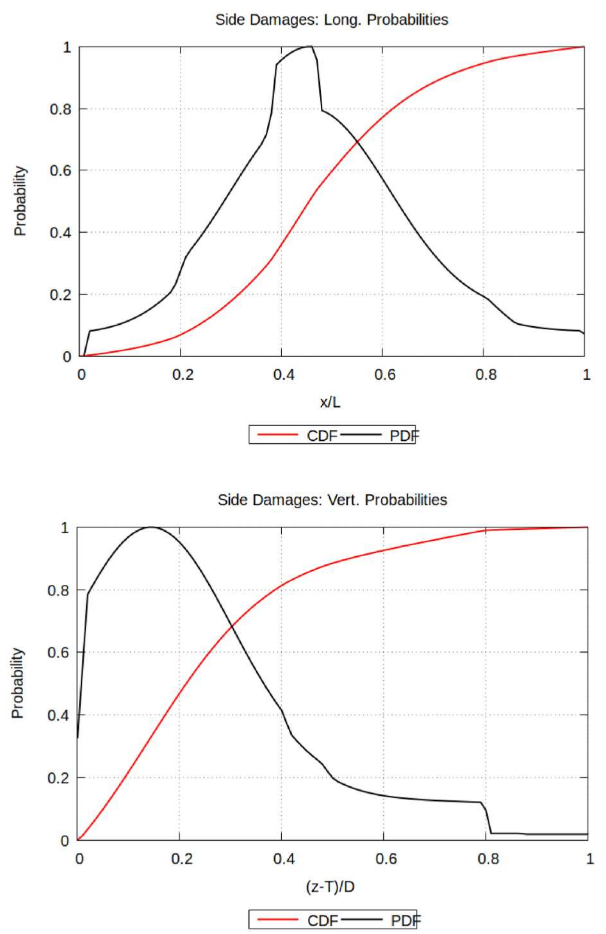

Figure 3. CDF and PDF in the longitudinal and vertical directions for a missile with the three sensors mentioned above.

Figure 4. CDF and PDF of the longitudinal position of a contact mine hit with a slightly trimmed floating position.

In the *y*-direction of the ship, we assume that the detonation point is evenly distributed in the interval $[y_{stb}, y_{bb}]$, where the two *y* values represent the breadth coordinates of the ship approximately at the *x* and *z* positions of the impact. With regard to the extent of the damage, we proceed in the same way as when modelling the drone impact: Since the missile hit is an internal detonation, no energy is required to destroy the outer skin first. Therefore, the first step is to check whether the damage radius is large enough to destroy both sides of the outer skin almost simultaneously. If this is the case, the approaches described above for a penetration apply. Then we check which structures are located in the damage area, and the damage ellipse can then be determined using the k-factors specified in DMS 1040-1.

Contact mine detonation

Contact mine detonation is an external detonation and is treated in a similar way to a drone attack. The longitudinal distribution must correspond approximately to the shape of the current waterline. This means that a hit behind the widest frame is extremely unlikely. However, it is possible that a contact at the stern could still occur if the ship is trimmed down by stern, which is why a trim component is added to the waterline. Figure 4 shows the longitudinal distribution of such a contact mine detonation.

For the height detonation position, a uniform distribution in the interval *[0,T]* is assumed. The *y* – position of the hit is then determined from the local ship breadth at the point *[x,z]*. The extent of damage is calculated in exactly the same way as for a drone attack.

Survival probabilities

The DMS 1030-1 specifies the following basic requirements to survive damage; see Figure 5 (Russell 2024; BAAINBw 2022):

- Including free fluid shifting moments and 40 kN beam wind, the equilibrium φKrä must not exceed 25 degrees.
- Under these conditions, the maximum residual righting lever GZR must be a minimum of 0.05 m.
- The range r until a weather-tight opening is submerged or until the vessel capsizes must be larger than 15 degrees.
- The residual freeboard FB until a weather-tight opening is submerged must be at least 0.5 m, and the residual freeboard to any non-weathertight

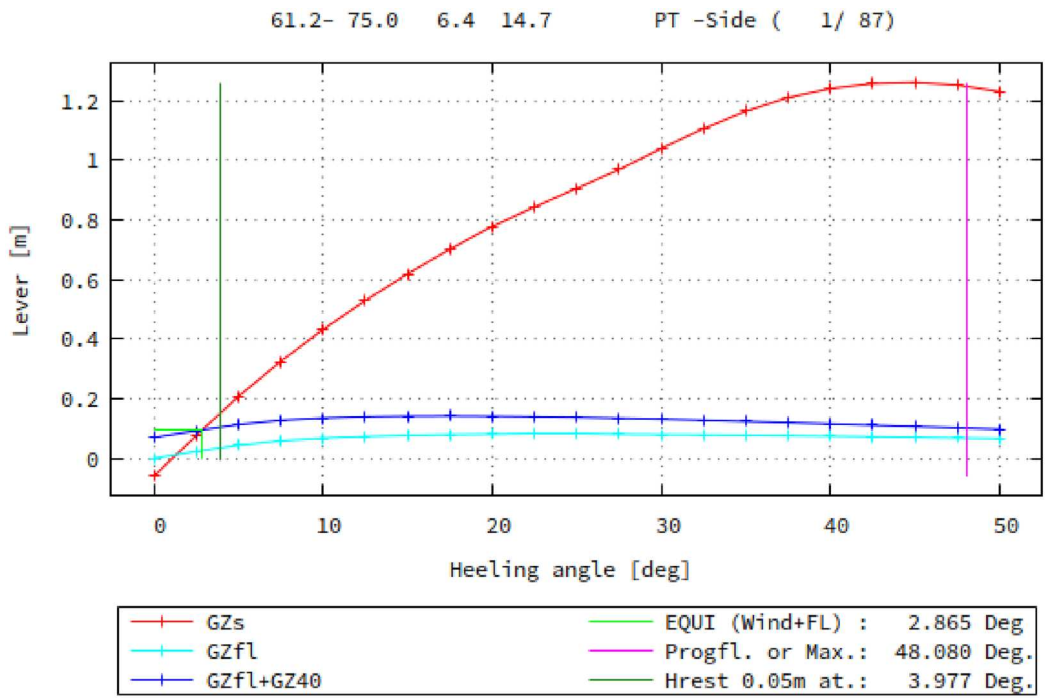

Figure 5. DMS 1030-1 damage stability evaluation of one single damage case of the sample ship.

opening must be at least half of the design wave height for the ship, which is L/(10 + 0.05L)

This gives $s_{ij,1030} = 1$ under the condition that $\varphi_{Krä} < 25$ degrees and $r > 15$ degrees and $GZ_R > 0.05$ m and $F_B > 0.5$ m. If any of these values is beyond the limits, $s_{ij,1030}$ is exactly 0 according to DMS 1030-1. With the probabilistic approaches presented here, it makes sense not only to distinguish between 0 and 1, but also to create a smooth transition between 0 and 1. Analogous to SOLAS 2020, $s_{ij,1030}$ can be defined as follows:

$$s_{ij,1030} = c\sqrt[3]{\left(\frac{gz_R}{0.05}\right)\left(\frac{r}{15}\right)\left(\frac{F_B}{0.5}\right)} \tag{8}$$

No values greater than 0.05, 15, and 0.5 must be used for GZ_R, r, and F_B. The coefficient c is also set in accordance with SOLAS 2020 and is defined as follows:

$$c = \sqrt{\frac{30 - \varphi_{Kr\"a}}{30 - 25}}\ if\ 25^\circ < \varphi_{Kr\"a} < 30^\circ \tag{9}$$

At the same time, c = 1 if $\varphi_{Krä}$ is less than 25 degrees and 0 if $\varphi_{Krä}$ is greater than 25 degrees. Thus, $s_{ij,1030}$ is fully defined in accordance with DMS 1030-1 and is also based on known procedures from SOLAS.

When calculating $s_{ij,1040}$, the procedure is first to base the calculation on the longitudinal strength assumptions of the IACS (S 11 IACS Longitudinal Strength Standard, IACS 2020). Then the connection to DMS 1040 is established. The ship model contains several frames on which the steel structure of the ship is explicitly described (so-called read-out points). Any damage case consisting of a given combination of breached compartments, with the damage occurring in a zone in the interval $[x_{z,min}, x_{z,max}]$. For each individual detonation in the damage case, a check is now performed to determine which detonation leads to the greatest extent of damage. This detonation is used for further structural investigations, see Figure 6.

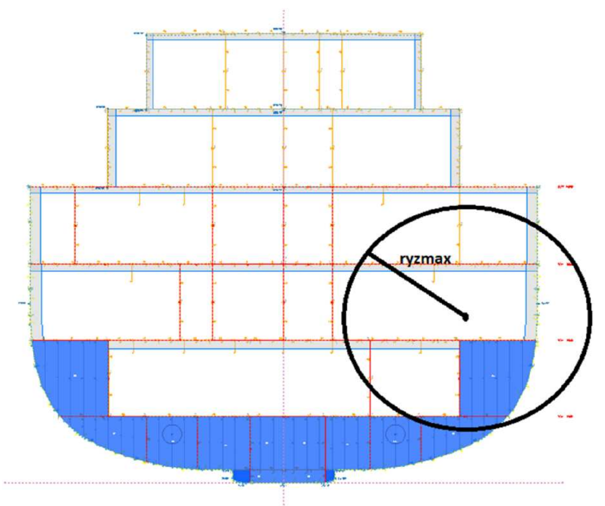

Figure 6. Readout – cross section and initial damage radius.

During the calculation of damage stability according to DMS 1030-1, the longitudinal strength of the ship is now also considered, namely the shear forces and the bending moments. Now, for each individual structural frame, it is checked whether it is located within this largest damage radius (or ellipse). If this is the case, all longitudinal structural members located within this damage radius (or ellipse) are disregarded and the section values are then calculated without these components, i.e. assuming these are completely destroyed. As the cross-section is highly asymmetrical after the damage, nonsymmetrical bending must be taken into account. This means that the moments of inertia I_{YY} (vertical bending), I_{zz} (horizontal bending), and the deviation moment I_{YZ} are required to be calculated. The rotation angle of the neutral axes φ_H is then calculated as follows:

$$\varphi_H = arc\tan\left(\frac{2I_{yz}}{I_{yy} - I_{zz}}\right) \tag{10}$$

The section modulus w is calculated as follows:

$$W = \frac{I_{yy}I_{zz} - I_{yz}^2}{I_{yz}y + I_{zz}z} \tag{11}$$

To obtain the section modulus for bottom or deck, the corresponding y and z coordinates for the bottom or the deck must be used, where $y = y_{NF} + z\ sin\ (\varphi_H)$. Here, y_{NF} is the y position of the neutral axis. The permissible harbour bending moment can be immediately derived from section modulus by multiplying the smaller of these two moduli by the permissible stress. This permissible stress (in N/mm^2) is obtained either from 175/k, where k is the material factor, or from the permissible buckling stress in the deck or bottom, depending on whether the cross-section is loaded by hogging or sagging. The linear buckling stresses can be easily calculated according to the rules of IACS S11 S11.5.2. However, for marine vessels, it is recommended by the authors that all structures to be included in the buoyancy body shall be designed so that the critical buckling stress is greater than 175/k, which is easily achieved by selecting suitable stiffener spacings and plate thicknesses.

The permissible harbour bending moment determined in this way is now subtracted from the existing stillwater bending moment in the damage case under consideration, taking into account hogging and sagging. This gives the residual wave bending moment $M_{BS,Rest}$, which is still available to withstand wave loads after the damage to the cross-section. This is now compared with the standard wave bending moment according to IACS $M_{BS,IACS}$ (S11, S11.2.2.). This has the advantage that it is immediately apparent what the ship can still withstand after damage: If the ratio of $M_{BS,Rest}$ to $M_{BS,IACS}$ is 1 or more, then the ship could still be able to sail the North Atlantic without restriction (in terms of longitudinal strength). Thus, the probability of survival for the hull bending $s_{ij,1040,MB}$ can basically be defined from the ratio of $M_{BS,Rest}$ to $M_{BS,IACS}$ as follows:

$$s_{ij,1040,MB} = \frac{M_{BS,Rest}}{k_B M_{BS,IACS}} \tag{12}$$

The factor k_B can then be determined at a suitable time so that it relates the permissible bending moment required by DMS 1040-1 to the IACS bending moment $M_{BS,IACS}$. The same procedure can then be applied to the shear forces to calculate the survival probability $s_{ij,1040,SF}$. In order for the structural strength to be given the same weighting as the buoyancy, the following must then apply:

$$s_{ij,1040} = \sqrt{s_{ij,1040,MB}\ s_{ij,1040,SF}} \tag{13}$$

This means that all the necessary fundamentals have now been presented to calculate the ship's probability of survival in terms of buoyancy and structural strength. The implemented calculation method is based on the Monte Carlo simulation principle, see Kehren and Krüger (2007), Krüger and Dankowski (2009).

Application

The method is now applied to a generic design of a navy ship with a length of about 140 m, a beam of about 20 m, a draft of about 7 m, and a displacement of about 9500t. Figure 7 shows the mass and buoyancy distribution, as well as shear forces and bending moments for the undamaged sample ship.

From a simple strip method calculation, the wave moments according to DMS 1040-1 can be determined for various x – positions to obtain the factor(s) k_B. Figure 8 shows the RAOs of the vertical bending moment over the wave period and the encounter angle for the x – Position L/2. From this calculation, k_B can be determined as abt. 0.32. If now the difference between the permissible harbour moment and the existing still water bending moment (after flooding) is larger than or equal to 0.32 times the IACS wave bending moment, then the structural survivability equals 1 according to the assumptions of DMS 1040-1.

Figure 9 shows the results of the survivability evaluation of a simulated drone attack on the sample vessel. The minimum equivalent of TNT was set to 300 kg, the maximum 500 kg. The drone is assumed to attack the ship from the port side. As the ship was designed according to the DMS 1030-1 (Krüger 2024), all probabilities s_{1030} equal 1.0. As the drone attacks the ship close to its neutral axis, there remains sufficient section modulus even in nonsymmetric bending so that all probabilities s_{1040} also equal 1. The sample ship remains afloat and still has sufficient structural integrity. In total, this results in 87 individual damage cases.

Figure 10 shows the results of the survivability evaluation of a simulated missile attack on the sample vessel. The minimum equivalent of TNT was set to 100 kg, the maximum 200 kg. The missile is assumed to attack the ship from the port side. In total, 3005 damage cases were found. As the ship was designed according to the DMS 1030-1 (Krüger 2024), all probabilities s_{1030} equal 1.0. The total probability of survival does not equal 1; some cases in the very front end of the ship do not have the required structural

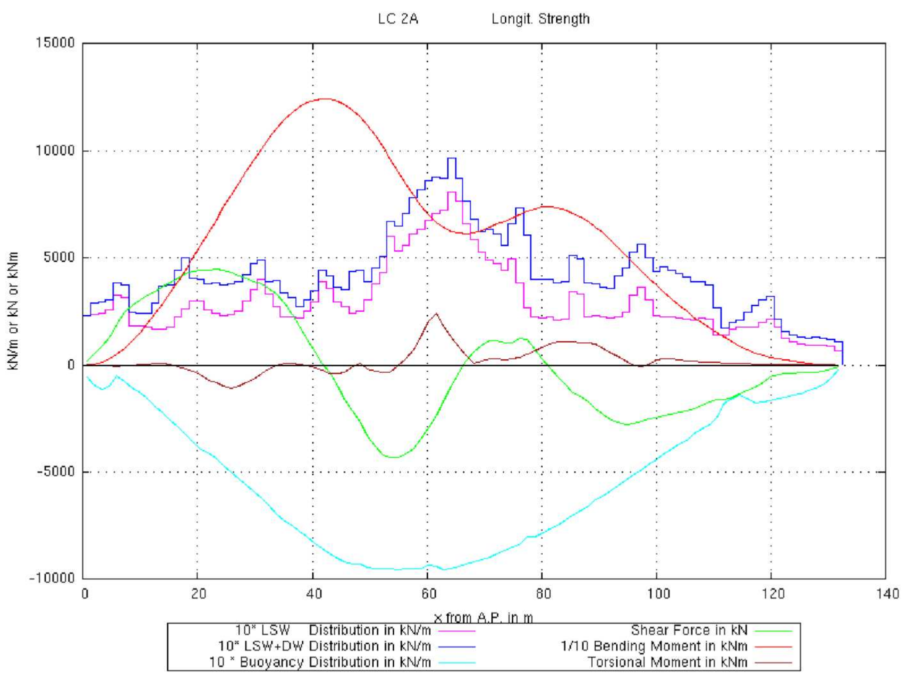

Figure 7. Longitudinal strength evaluation of the sample ship.

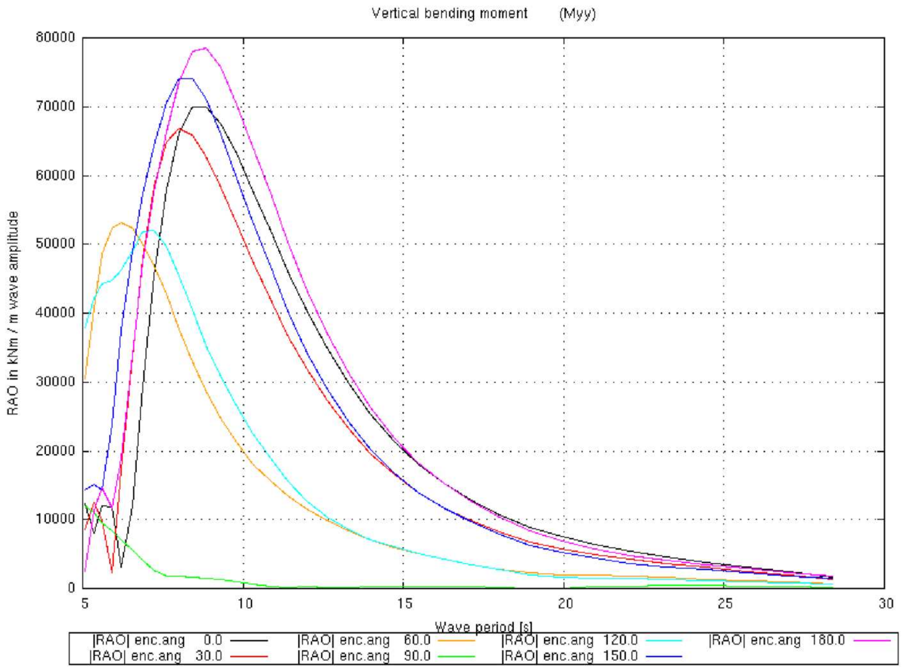

Figure 8. RAOs of the vertical bending moment at L/2 for different encounter angles over wave period.

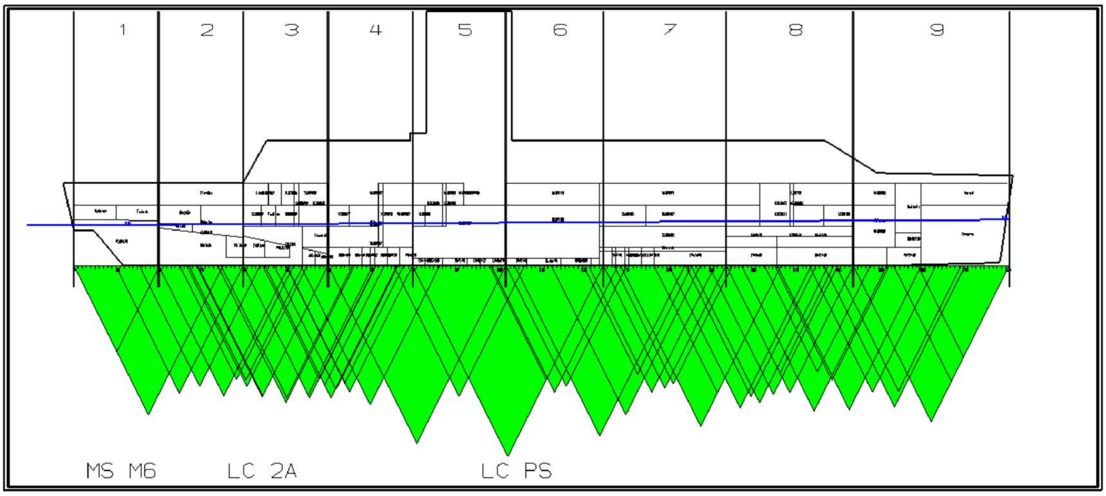

Figure 9. Results of the survivability evaluation of a drone attack with 300–500 kg TNT equivalent.

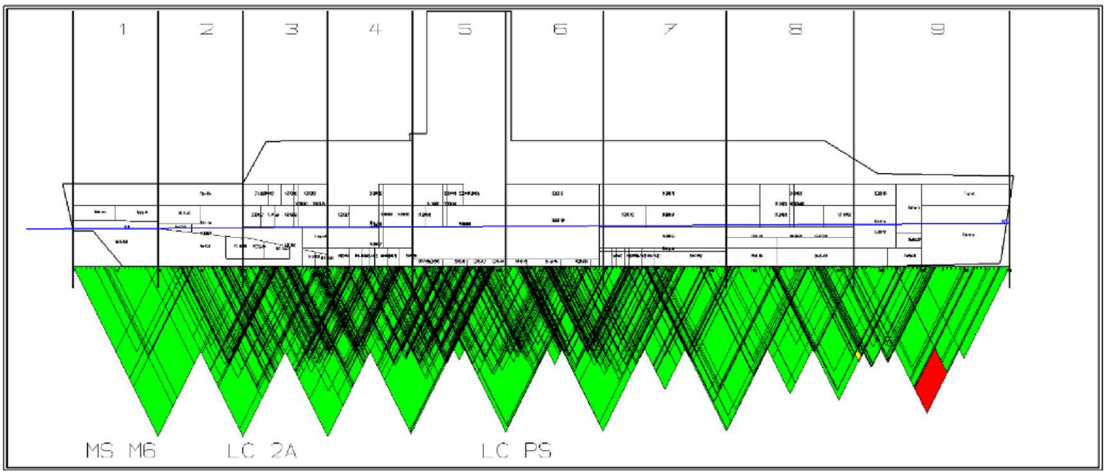

Figure 10. Results of the survivability evaluation of a missile attack with 100–200 kg TNT equivalent.

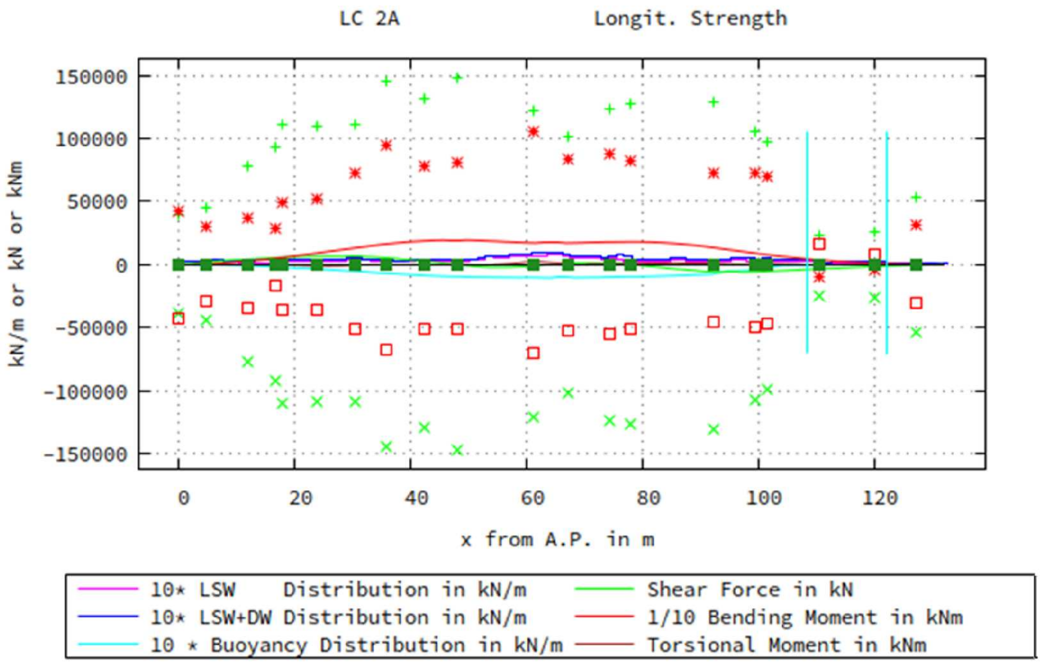

Figure 11. Results of the longitudinal strength analysis of one critical damage case.

integrity. The minimum s_{1040} is computed as about 0.25, which does not necessarily mean that the ship will be lost, as the section can still absorb some bending moment; see Figure 11. There, the damage radius is indicated by the vertical blue lines.

In Figure 11, the markers (by colour) represent the permissible values at the readout points for bending moments and shear forces in comparison to the still-water bending moments and shear forces of that damage case. In the damage zone, the permissible bending moment is drastically reduced, as the section is extremely thin there. Therefore, not much section modulus is left when there is a shot through the structure close to the deck of the ship. These few cases may be analysed in a more detailed structural analysis before structural alterations may be decided upon.

Figure 12 shows the results of the survivability evaluation of a simulated contact mine attack on the sample vessel. The minimum equivalent of TNT was set to 150 kg, the maximum 900 kg. In total, 383 damage cases were found. All probabilities s_{1030} equal 1.0 again. The total probability of survival does not equal 1, as some cases in the very front end of the ship do not have the required structural integrity. The minimum s_{1040} is computed as about 0.4. This is larger compared to the missile attack, and it is a consequence of the fact that due to the large depth, the deck structure remains intact. However, the probability of survival is slightly smaller compared to the missile attack due to the fact that forward damage is more probable for a contact mine compared to a missile.

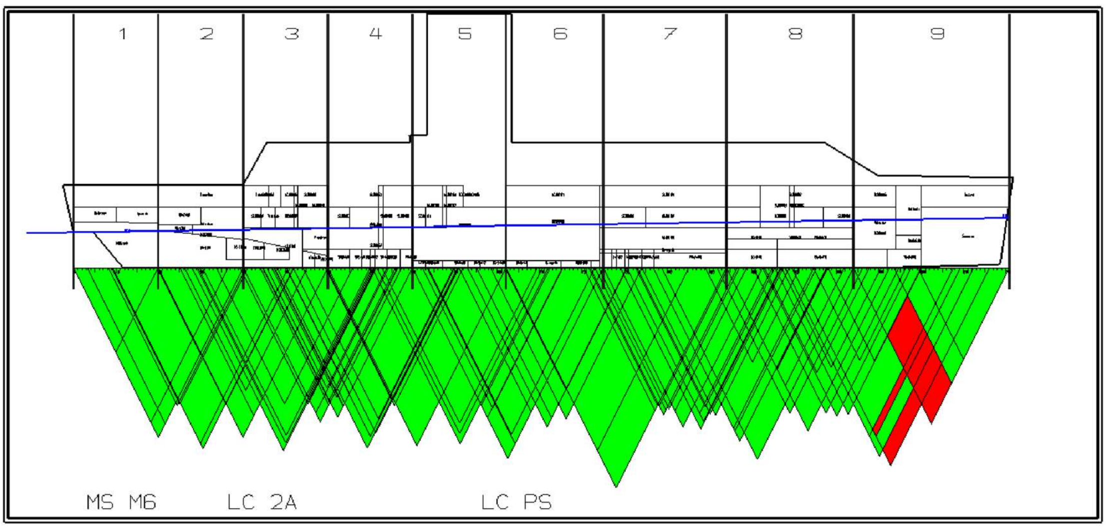

Figure 12. Results of the survivability evaluation of a contact mine with 150–900 kg TNT equivalent.

Summary and conclusion

A method was presented which allows the determination of the survivability of a Navy Ship during the initial design stage. The method is based on a Monte Carlo simulation principle and requires damage probabilities for different military threats and probabilities of survival. Damage probabilities have been provided for drone attacks, missiles and contact mines. The probabilities of survival have been developed with respect to floatability and structural integrity, taking into account the relevant regulations for German Navy ships. The application of the method to a sample design of a Navy Ship has shown reasonable results. An important future development will be that, in addition, the probabilities of survival for the intactness of relevant functional chains should be included (Philipson and Krüger 2026). The inclusion of functional chains is already under development. Further, the actual progressive flooding event in the time-domain may be considered.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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