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A simplified method to assess the impact of ship-to-ship collision on the risk of tanker ship hull girder breaking accounting for the effect of ageing

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ABSTRACT: One of the most critical structural failures is the exceedance of the ship hull girder's ultimate strength, which may result in hull breaking, and subsequent severe consequences, including loss of life and property as well as environmental damage in case of an oil spill. A cause for such loss of structural continuity can be triggered by a collision with another vessel. In addition, the ageing mechanisms of the hull structure could increase this risk. However, the majority of models for damage risk dedicated to collision and grounding accidents do not sufficiently account for the ageing effect. Furthermore, current risk models usually only consider oil spills due to perforation of the ship side, neglecting the ensuing risks of hull girder breaking. Therefore, in the presented work, we propose a simplified method to assess the probability of exceedance of the hull girder's ultimate strength of a tanker ship, accounting both for the impact of corrosion degradation and the loss of the part of the midship cross-section due to collision with another vessel. A case study of a VLCC tanker ship is analysed to demonstrate the proposed methodology. Further ensuing consequences related to a hull girder failure are briefly discussed. Finally, key conclusions are given, and future research directions are outlined.

1 INTRODUCTION

Ships operating in marine waters are subjected to various hazards. While the frequency of ship-ship collisions has reduced significantly over the last decades (Eliopoulou et al. 2023), the potential for severe consequences of these accidents remains. It is well-documented that collisions can lead to significant loss of life, lead to high financial damages, and have significant ecological impacts (Ventikos & Sotiropoulos 2014). To reduce the risk of ship-ship collision accidents, several frameworks and risk analyses have been proposed. These concern risk mitigation measures for reducing the probability of accident occurrence and/or for reducing the consequences should an accident occur (Puisa et al. 2021).

Significant work has been dedicated to developing real-time approaches to estimate collision risks in ongoing operations, aimed at reducing the occurrence of accidents through improved decision-making for ship officers or Vessel Traffic Service (VTS) operators, see e.g. (Gil et al. 2020, Ozturk & Cicek 2019) for reviews. Closely related work has been dedicated to proposing methods for analysing collision risks in sea and waterway areas, aimed at area-based management of marine spaces, see e.g. (Chen et al. 2019, Du et al. 2020) for reviews. Finally, other risk analyses to reduce the probability of ship collision accident occurrence are targeted towards improvements in ship design (Sotiralis et al. 2016, Montewka et al. 2017) or towards managerial decision-making for reducing human and organisational errors in collision avoidance processes (Valdez Banda et al. 2016, Martins & Maturana 2013).

Much work has also been dedicated to developing models to estimate the consequences of ship-ship collisions, see e.g. Liu et al. (2018) for a comprehensive review. Very recently, some new methodologies to analyse the structural behaviour of ships subjected to collision and grounding were proposed (Kuznecovs et al. 2021, Liu et al. 2021) employing advanced FE simulations. These consequence models have been subsequently used in risk-based ship design frameworks and models to optimise the hull design to better withstand impact scenarios, see e.g. Klanac & Varsta (2011) and Tan et al. (2019). Depending on the ship type, ship damage consequence models have also been coupled with further consequence models, for instance, flooding and stability for passenger vessels (Zhang et al. 2021) and oil spill models for cargo vessels and oil tankers (Tavakoli et al. 2012, Goerlandt & Montewka 2014).

While consequence models for ship collision have accounted for several phenomena, including the deformability of the impacting bow (Haris & Amdahl 2013), the structural configuration of the impacted hull (Hogström & Ringsberg 2013), configuration between striking and struck ship (Ringsberg et al. 2023), the influence of sloshing and hydrodynamic loads on collision energy dissipation (Tabri et al. 2009), but there has been very limited focus on the influence of ageing mechanisms on the local hull damage due to the collision impact. Similarly, there is no systematic understanding of the significance of ageing effects on the ensuing risk of hull girder failure. Notably, one of the most important ageing effects is corrosion degradation, with a recent growing interest in dedicated modelling of this phenomenon, with applications e.g. in grounding accident problems (Liu et al. 2018).

The aim of the presented work is to estimate, using a proposed simplified method, the ultimate strength of the tanker ship hull girder when subjected to both corrosion degradation and collision-induced damage due to impact by another ship. The main research question is what the impact of corrosion degradation is when non-uniform thinning of the structural elements on a local scale is considered as an ageing mechanism. Notably, such an approach for corrosion degradation modelling was not analysed before regarding the ship's ultimate strength. This is done by introducing a correction factor to the progressive collapse modelling approach, as described in detail in the next Section. Such a type of simplified modelling is suitable for further use in risk frameworks, as it provides a sufficient compromise between attainable accuracy and modelling effort for the given purpose. Further, the probability of failure of the hull girder breaking is estimated using a reliability analysis approach, and a discussion about the possible ensuing consequences of hull girder breaking is given.

2 ULTIMATE STRENGTH OF SHIP HULL GIRDER

In the present work, the commonly used Smith (1977) approach, which is adopted in Common Structural Rules (IACS 2022), is used for the calculation of the ultimate strength of a ship's hull girder. The algorithm itself can be found in the reference and will not be introduced in detail herein for reasons of brevity. To outline the approach, the vessel's cross-section is divided into plate and stiffened plate elements, and the stress-strain relationship in each of them is determined. Further, the sum of forces acting in those elements should equal 0 for each curvature, which is incrementally enlarged. Finally, the moment-curvature relationship for the entire ship hull girder is determined.

However, in contrast to this classical approach, the method proposed in the current article applies a different corrosion degradation modelling approach. The algorithm for calculating the ultimate strength is implemented using Python programming language.

2.1 *Corrosion degradation modelling*

In the current CSR approach (IACS 2022), the ultimate strength computations are performed considering a 50% reduction of the corrosion additions. The design thickness consists of a net thickness (based on the structural calculations) and corrosion addition. Thus, the thickness considered for the ultimate strength computations is net thickness plus 50% of corrosion addition. Such an approach is adopted since corrosion additions are determined so that 90% of ships should have lower values of thickness reductions in particular structural elements during their lifetime. Thus, there is a low probability that in the entire cross-section, the corrosion additions will be fully used. In fact, such an approach is adopted in most structural calculations, including Finite Element analysis, except buckling, which is performed on the local structural level (thus, it considers single elements), and the net thickness approach is adopted.

Significantly, two key assumptions are considered in such corrosion modelling:

- the corrosion causes uniform thinning of the structural elements;
- mechanical properties of steel are considered to be unchanged.

In view of recent research, both of these assumptions are questionable. First, it was found that the mechanical properties of steel are, in fact, deteriorated due to corrosion degradation (Woloszyk et al. 2022). Second, the occurrence of corrosion degradation can cause not only a uniform reduction of plate thickness, but some level of irregularity can be observed as well (Woloszyk et al. 2021). In fact, when both of these factors are considered, the ultimate strength of corroded stiffened plate elements can be more accurately captured than using a net thickness reduction approach, as is commonly done. This is shown by a

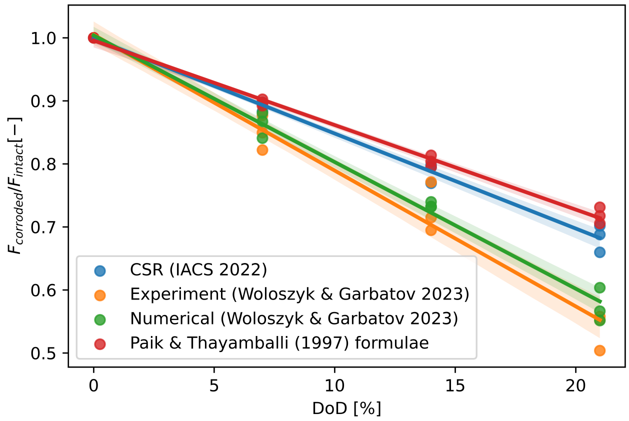

Figure 1: Comparison between ultimate strength prediction models: relative loss of ultimate strength in relation to the extent of corrosion development

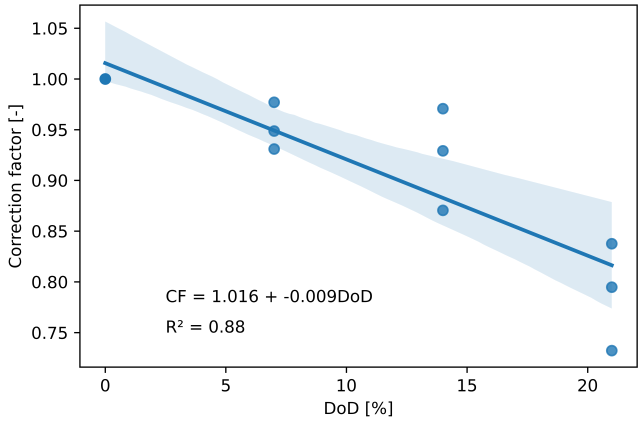

Figure 2: Correction factor to account for the effect of non-uniform corrosion degradation on the loss of ultimate strength, compared to the uniform thinning approach

comparison of experiments and numerical modelling (Woloszyk & Garbatov 2023).

To capture the effect of corrosion degradation on ultimate strength in a simplified manner, the ultimate strength of stiffened plate elements analysed in Woloszyk & Garbatov (2023) is compared with the current formulation in CSR and the formulation proposed by Paik & Thayamballi (1997). Figure 1 depicts the relative loss of ultimate strength in the function of the degree of degradation (DoD). The former is defined as the ultimate capacity in aged conditions divided by the ultimate capacity for the non-corroded stiffened plates. Whereas DoD stands for the percentage of the mass loss, which relates to the mean thickness reduction. It can be noted that both models considering a uniform thickness loss (CSR and Paik & Thayamballi (1997)) significantly overestimate the ultimate strength compared to experimental data (Woloszyk & Garbatov 2023).

Therefore, the approach presented here assumes a 50% reduction of corrosion additions. However, the ultimate force that particular elements composing the cross-section of the ship hull can sustain is reduced in relation to their mean level of degradation (DoD). To this end, a correction factor (CF) is introduced, based on a comparison between the CSR approach ($F_{CSR}(DoD)$) and the experimental curve ($F_{experiment}(DoD)$), as shown in Figure 1. The correction factor is equal to:

$$CF(DoD) = \frac{F_{experiment}(DoD)}{F_{CSR}(DoD)} \tag{1}$$

When both of those values are divided for each extent of corrosion development (i.e., the respective values for each DoD combination), a regression curve is fitted using linear regression, as presented in Figure 2. Thus, the ultimate capacity of particular elements is calculated as stipulated by CSR and then multiplied by a correction factor. It can be observed that for a DoD of 20%, the ultimate strength can be reduced by approx. 20% compared to the case where only uniform thinning of the structural members is considered. For the considered case study (see Section 2.3), the design thickness reduced by 50% of corrosion additions yields DoD in the range of 6% to 13%. Nevertheless, due to limited experiments and numerical modelling work, the correction factor is also associated with a notable uncertainty band of 5-10% depending on the DoD, as depicted in Figure 2.

In the proposed approach, the ultimate strength of each structural member in the cross-section is multiplied by the correction factor, as obtained from Figure 2. Thus, for each member, the DoD is calculated as the percentage of the cross-section loss when both thicknesses of plating and stiffener are reduced, considering 50% of corrosion additions deduction.

Although the presented approach captures the corrosion impact only indirectly through an estimated correction factor, this can be justified from an engineering and risk analysis point of view. Notably, it provides a more accurate estimate of the hull girder's ultimate strength capacity compared to current practice.

2.2 *Damage extent scenario*

In the CSR (IACS 2022), two Accidental Limit States are considered. The first one relates to grounding, and the second one to a collision impact by another ship. In the presented study, the second case is considered. The simplified damage extent scenario considered to illustrate the approach presented in this work is shown in Figure 3. One needs to note that the damage extent will be different in an as-built state compared to a corroded hull (Kuznecovs et al. 2021). However, according to Technical Background for CSR related to Residual Strength (IACS 2014), the considered damage case is considered a conservative one and rather larger than the "most probable damage size at failure" regardless of the ship's age. Thus, it implicitly considers the corrosion effects. Nevertheless, in future studies, the impact of corrosion on the damage

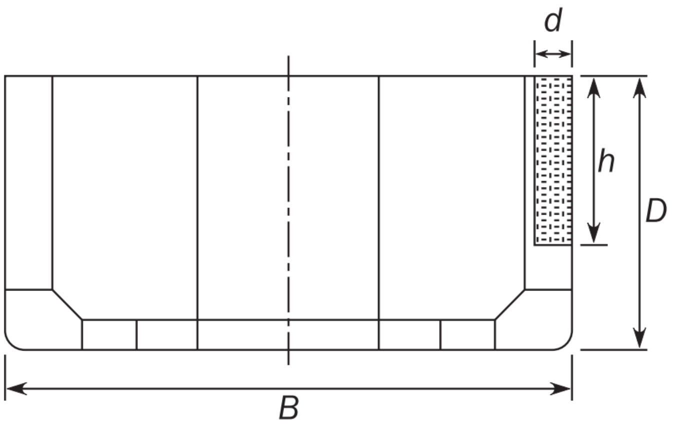

Figure 3: Damage extent scenario for collision (IACS 2022)

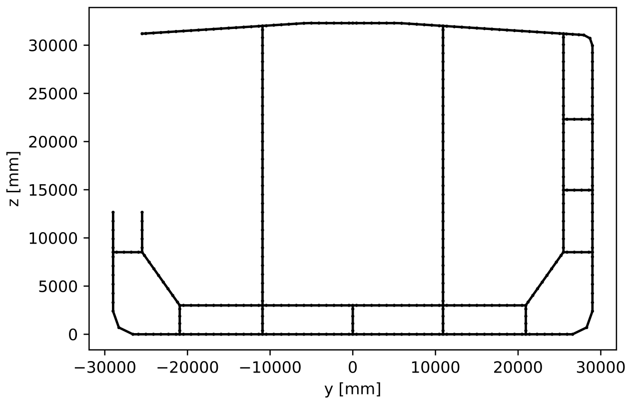

Figure 4: Cross-section of the considered case study with damage extent

extent should also be considered.

The damage extent is defined in relation to the ship's main dimensions, i.e. breadth and height. The damage height is equal to $0.6D$, and the damage depth is equal to $B/16$. The damage extent for the considered case study is presented in Figure 4. It is noted that, in this case, both the outer and inner hull were perforated.

2.3 *Case study*

The considered case study used to illustrate the proposed approach for assessing the impact of corrosion degradation on the risk of hull girder breaking in a ship-ship collision concerns a VLCC tanker ship, with main dimensions and characteristics given in Table 1.

Table 1: Main dimensions and key characteristics of the vessel considered in the presented case study

Dimension	Symbol	Value	Unit
Length over all	L	320	m
Moulded breadth	B	58	m
Moulded depth	D	31	m
Scantling draught	T	22	m
Block coefficient	Cb	0.83	–
Designed speed	v	16.7	kn

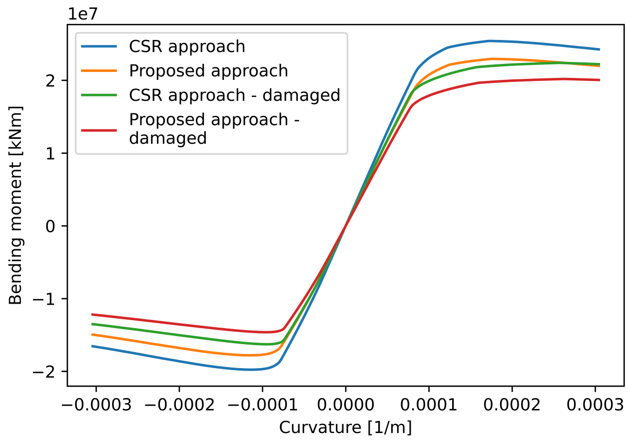

Figure 5: Comparison between initial ultimate capacity for both approaches

2.4 *Ultimate strength values*

In order to gain insight into the difference between the current CSR approach and the newly proposed one in this paper, the ultimate strength for intact cross-section (without consideration of damage extent) is calculated. The results are presented in Figure 5. The positive values of curvature relate to the hogging condition, whereas negative values relate to the sagging condition. It is noted that damaged conditions cause a higher relative reduction in ultimate capacity in the sagging condition compared to the hogging one. This is understandable since, in the sagging condition, the area of the deck is in a compression zone, where the cross-section is significantly reduced. It can be observed that the proposed approach shows lower values of ultimate capacity in both conditions (intact and damaged). Notably, the difference is significant.

3 PROBABILITY OF FAILURE

3.1 *Limit state function*

The probability of failure considering hull girder breaking can be estimated using a reliability analysis approach. The examples of reliability analysis of ship hulls considering also cases of grounding and damage due to collision can be found in literature (Hussein & Guedes Soares 2009, Luís et al. 2009, Prestileo et al. 2013, Bužančić Primorac et al. 2020). The basis for the calculation will be the deterministic limit state function as given in the CSR (IACS 2022):

$$\gamma_{SW} M_{SW} + \gamma_{WV} M_{WV} \leq \frac{M_U}{\gamma_R} \tag{2}$$

where M_{SW} and M_{WV} are the still water and wave bending moments, respectively; M_U is the hull girder ultimate capacity as calculated in the previous Section for both intact and damaged case and $\gamma_{SW}, \gamma_{WV}, \gamma_R$ are partial safety factors.

When Equation 2 is transferred into a probabilistic representation, the limit state function can be determined:

$$g = \widetilde{x_U}\widetilde{M_U} - \widetilde{x_{SW}}\widetilde{M_{SW}} - \widetilde{x_W}\widetilde{x_S}\widetilde{M_{WV}} \quad (3)$$

where $\widetilde{M_{SW}}, \widetilde{M_{WV}}, \widetilde{M_U}$ are the still water bending moment, wave bending moment and ultimate capacity, respectively. However, in this case, these are considered as random variables. The mean value of ultimate capacity $\widetilde{M_U}$ is based on the computations as described in the previous Section (see Figure 5), with the Coefficient of Variation being considered equal to 0.08, as suggested by Garbatov et al. (2018) following the log-normal probability distribution. Further, $\widetilde{x_U}$ is the modelling uncertainty related to the ultimate capacity (accounting for the assumptions considered in the modelling (see Section 2)); $\widetilde{x_{SW}}$ is the uncertainty of still water bending moment prediction; $\widetilde{x_W}$ is the uncertainty of wave-induced bending moment predictions, whereas $\widetilde{x_S}$ takes into account nonlinearities in sagging loading condition.

The random variables that are related to uncertainties can be considered from previous studies (Guedes Soares & Teixeira 2000, Garbatov et al. 2018) and follow the normal distribution. The only difference is the mean value of modelling uncertainty $\widetilde{x_U}$, which was considered equal to 1.0 in this study to yield more conservative results:

$$\widetilde{x_U} \sim N\{1, 0.1\} \quad (4)$$

$$\widetilde{x_{SW}} \sim N\{1, 0.1\} \quad (5)$$

$$\widetilde{x_W} \sim N\{1, 0.1\} \quad (6)$$

$$\widetilde{x_S} \sim N\{1, 0.1\} \quad (7)$$

3.2 *Still water and wave loading*

Although formulations for both still water and wave loading are given in the CSR (IACS 2022), these cannot be directly used in the reliability analysis since these are informing about extreme values that are exceeded with a probability of 10^{-8}. On the contrary, a structural reliability analysis needs the entire probability distributions of the considered loads.

The still water bending moment distribution can be considered as a Normal distribution, as suggested in Guedes Soares & Moan (1988), where regression equations for mean value and standard deviation were determined based on the large dataset of 2000 ships of different length and deadweight ratio ($W = DWT/FullLoad$). The mean value and standard deviation are equal to:

$$Mean = \frac{(114.7 - 105.6W - 0.154L)M_{SW,CSR}}{100} \quad (8)$$

$$StDev = \frac{(17.4 - 7W + 0.035L)M_{SW,CSR}}{100} \quad (9)$$

where L is the ship length and $M_{SW,CSR}$ the still water bending moment calculated according to the CSR formulation.

When considering wave loading given in the CSR modelled by Weibull distribution with a probability of exceedance of 10^{-8}, the distribution of extreme values of wave-induced bending moment over a specified time period can be modelled as a Gumbel distribution with the following parameters (Guedes Soares et al. 1996):

$$\mu = q(ln(n))^h \quad (10)$$

$$\sigma = \frac{q}{h}(ln(n))^{\frac{1-h}{h}} \quad (11)$$

where μ and σ are the parameters of the Gumbel distribution, n is the load cycles number over reference time period T_r for a given mean period value of the wave T_w. It is considered that $T_r = 1year$, and $T_w = 8sec$.

Notably, both the wave loads and still water loads are dependent on the loading condition. It is considered that 40% of the time is a full-loading condition and 40% of the time is a ballast condition, whereas 10% of the time is a partial loading condition and the rest 10% is considered a harbour condition. The resulting probability of failure is the sum of probabilities of failure for full-load, partial, ballast and harbour conditions, respectively.

3.3 *Software*

The structural reliability analysis is conducted using STRUREL software (RCP Consult GmbH 2018), applying the Second Order Reliability Method to determine the probability of failure.

3.4 *Calculation results*

The probability of hull girder failure is determined separately for hogging and sagging conditions. The summary of the calculated probabilities of failure for the various cases is presented in Table 2. Since, in harbour conditions, there is no wave loading considered, the resulting probability of failure is very low in comparison to other loading conditions and does not influence the total probability of failure. Thus, it was not included in the table. Additionally, the commonly used reliability index β (Ditlevsen & Madsen 1996) is calculated. The β index is related to the probability of failure as follows:

$$\beta = -\phi^{-1}(P_f) \quad (12)$$

Thus, the higher the reliability index is, the more safe structure is.

Table 2: Summary of the calculated probabilities of hull girder failure accounting for newly proposed corrosion degradation modelling

		Probability of hull girder failure [-]				
Damaged case	Loading conditions	Full load	Partial load	Ballast	Sum	Beta index [-]
No	Sagging	$1.82{\cdot}10^{-3}$	$1.35{\cdot}10^{-4}$	$3.01{\cdot}10^{-4}$	$2.26{\cdot}10^{-3}$	2.84
No	Hogging	$1.36{\cdot}10^{-6}$	$4.50{\cdot}10^{-5}$	$4.91{\cdot}10^{-6}$	$5.13{\cdot}10^{-5}$	3.88
Yes	Sagging	$1.43{\cdot}10^{-2}$	$1.16{\cdot}10^{-3}$	$2.59{\cdot}10^{-3}$	$1.80{\cdot}10^{-2}$	2.10
Yes	Hogging	$8.66{\cdot}10^{-6}$	$2.88{\cdot}10^{-4}$	$3.18{\cdot}10^{-5}$	$3.28{\cdot}10^{-4}$	3.41

4 DISCUSSION

According to DNV (1992), the target failure probability level is equal to 10^{-3} for less serious consequences and 10^{-4} for serious consequences of failure. These probability values correspond to reliability indices $\beta = 3.09$ and $\beta = 3.71$, respectively. The breaking of the hull girder should be considered as a failure that has serious consequences. When compared with the results presented in Table 2, it is noted that this condition is not satisfied for each of the cases. It was found that the worst scenario for eventual collision is the sagging, full load condition. The probability of failure, in that case, is equal to $1.43 \cdot 10^{-2}$, which is very high in terms of structural reliability.

Notably, when calculating the reliability index for the non-damaged case in the sagging condition in the currently used CSR approach regarding corrosion degradation modelling, the probability of failure is equal to $5 \cdot 10^{-4}$. Thus, it is approx. twenty times higher than the probability of failure in the proposed approach for the same case, but with the newly proposed approach to cover the non-uniform character of the corrosion degradation.

There are certain limitations of the presented approach relating to the assumptions considered in the analysis. First, a simplified modelling approach for including corrosion degradation in the ultimate strength calculations was adopted by introducing a correction factor. Second, the corrosion degradation was considered uniformly distributed within the cross-section, which likely is not fully realistic in real-world hull structures. Third, the rotation of the neutral axis was not considered in the damaged conditions, which could result in even higher values of ultimate strength (Fujikubo et al. 2012). Fourth, it would be beneficial to validate the presented method, especially considering the specific aspects of the corrosion degradation modelling in realistic ship hulls. In addition, the structural reliability analysis requires proper uncertainty quantification, and while the adopted normal distribution of loading conditions is reasonable, future studies in that direction would improve the results. Finally, in the presented study, only Vertical Bending Moment was considered as an acting load. It is known that Ultimate Limit State could consider both Vertical and Horizontal Bending moments. However, as was shown by Kuznecovs et al. (2021), the most unfavourable loading conditions are in the head and following waves, where only Vertical Bending Moment is acting. Thus, from a safety perspective, considering only Vertical Bending Moment is sufficient.

As a more general direction for future research, there may be merit in developing a more comprehensive risk analysis approach to mitigate the accident-related hull girder failure risk of tankers. Such an approach could then estimate not only the risk associated with hull girder failure but also the risk of local hull damage and the ensuing consequences, such as the associated extent of the oil spill and associated costs. Work by Klanac & Varsta (2011) and Ventikos & Sotiropoulos (2014) can be inspirational in this respect, and linking such an extensive modelling approach to realistic damage extents for different hull configurations could lead to an advanced risk-based ship design methodology. For such a more comprehensive approach, the simple 10^{-4} criterion may need to be reconsidered as well, e.g. using ALARP approaches and cost-effectiveness criteria as described e.g. by Papanikolaou (2009).

5 CONCLUSIONS

The main aim of the presented work was to assess the impact of corrosion degradation and collision damage by impact from another ship on the ultimate strength of a hull girder and the hull girder failure probability. It was found that when corrosion degradation is considered a phenomenon causing irregular thickness reduction, the ultimate capacity will be notably lower compared to the approach currently included in the common structural rules. These results indicate that the current approach may be too optimistic, i.e. that the actual risk associated with tankers built under these rules is higher than earlier believed. Hence, future deeper studies need to be conducted that will show if eventual rule revisions may be needed. It is, however, stressed that this is only a preliminary study based on a single tanker under one damage scenario. Further research is required to confirm these findings, e.g. by considering different vessel sizes, damage extents, and corrosion extents. Considering this, apart from presenting a new approach to include the corrosion degradation effect on hull girder failure probability in a more realistic manner, further research directions have been outlined in this article.

REFERENCES

Bužančić Primorac, B., Parunov, J., & Guedes Soares, C. 2020. Structural Reliability Analysis of Ship Hulls Accounting for Collision or Grounding Damage. *Journal of Marine Science and Application* 19(4): 717–733.

Chen, P., Huang, Y., Mou, J., & van Gelder, P. 2019. Probabilistic risk analysis for ship-ship collision: State-of-the-art. *Safety Science* 117: 108–122.

Ditlevsen, O. & Madsen, H. O. 1996. *Structural reliability methods*. Chichester: John Wiley and Sons.

DNV 1992. Structural Reliability Analysis of Marine Structures. *Classification notes No 30.6*.

Du, L., Goerlandt, F., & Kujala, P. 2020. Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from AIS data. *Reliability Engineering & System Safety* 200: 106933.

Eliopoulou, E., Alissafaki, A., & Papanikolaou, A. 2023. Statistical Analysis of Accidents and Review of Safety Level of Passenger Ships. *Journal of Marine Science and Engineering* 11(2): 410.

Fujikubo, M., Zubair Muis Alie, M., Takemura, K., Iijima, K., & Oka, S. 2012. Residual Hull Girder Strength of Asymmetrically Damaged Ships. *Journal of the Japan Society of Naval Architects and Ocean Engineers* 16: 131–140.

Garbatov, Y., Sisci, F., & Ventura, M. 2018. Risk-based framework for ship and structural design accounting for maintenance planning. *Ocean Engineering* 166: 12–25.

Gil, M., Wróbel, K., Montewka, J., & Goerlandt, F. 2020. A bibliometric analysis and systematic review of shipboard Decision Support Systems for accident prevention. *Safety Science* 128: 104717.

Goerlandt, F. & Montewka, J. 2014. A probabilistic model for accidental cargo oil outflow from product tankers in a ship–ship collision. *Marine Pollution Bulletin* 79(1-2): 130–144.

Guedes Soares, C., Dogliani, M., Ostergaard, C., Parmentier, G., & Pedersen, P. T. 1996. Reliability Based Ship Structural Design. *Transactions of the Society of Naval Architects and Marine Engineers (SNAME)* 104: 359–389.

Guedes Soares, C. & Moan, T. 1988. Statistical analysis of still-water load effects in ship structures. *Society of Naval Architects and Marine Engineers-Transactions* 96.

Guedes Soares, C. & Teixeira, A. 2000. Structural reliability of two bulk carrier designs. *Marine Structures* 13(2): 107–128.

Haris, S. & Amdahl, J. 2013. Analysis of ship–ship collision damage accounting for bow and side deformation interaction. *Marine Structures* 32: 18–48.

Hogström, P. & Ringsberg, J. W. 2013. Assessment of the crashworthiness of a selection of innovative ship structures. *Ocean Engineering* 59: 58–72.

Hussein, A. & Guedes Soares, C. 2009. Reliability and residual strength of double hull tankers designed according to the new IACS common structural rules. *Ocean Engineering* 36(17-18): 1446–1459.

IACS 2014. Harmonised CSR TB Report: Hull Girder Longitudinal Strength. Technical report.

IACS 2022. *Common Structural Rules (BC & OT)*.

Klanac, A. & Varsta, P. 2011. Design of marine structures with improved safety for environment. *Reliability Engineering & System Safety* 96(1): 75–90.

Kuznecovs, A., Schreuder, M., & Ringsberg, J. W. 2021. Methodology for the simulation of a ship's damage stability and ultimate strength conditions following a collision. *Marine Structures* 79: 103027.

Liu, B., Garbatov, Y., Zhu, L., & Guedes Soares, C. 2018. Numerical assessment of the structural crashworthiness of corroded ship hulls in stranding. *Ocean Engineering* 170: 276–285.

Liu, B., Pedersen, P. T., Zhu, L., & Zhang, S. 2018. Review of experiments and calculation procedures for ship collision and grounding damage. *Marine Structures* 59: 105–121.

Liu, B., Villavicencio, R., Pedersen, P. T., & Guedes Soares, C. 2021. Analysis of structural crashworthiness of double-hull ships in collision and grounding. *Marine Structures* 76: 102898.

Luís, R., Teixeira, A., & Guedes Soares, C. 2009. Longitudinal strength reliability of a tanker hull accidentally grounded. *Structural Safety* 31(3): 224–233.

Martins, M. R. & Maturana, M. C. 2013. Application of Bayesian Belief networks to the human reliability analysis of an oil tanker operation focusing on collision accidents. *Reliability Engineering & System Safety* 110: 89–109.

Montewka, J., Goerlandt, F., Innes-Jones, G., Owen, D., Hifi, Y., & Puisa, R. 2017. Enhancing human performance in ship operations by modifying global design factors at the design stage. *Reliability Engineering & System Safety* 159: 283–300.

Ozturk, U. & Cicek, K. 2019. Individual collision risk assessment in ship navigation: A systematic literature review. *Ocean Engineering* 180: 130–143.

Paik, J. K. & Thayamballi, A. K. 1997. Empirical formulation for predicting the ultimate compressive strength of stiffened panels. In *Proceedings of the International Offshore and Polar Engineering Conference*.

Papanikolaou, A. 2009. *Risk-Based Ship Design*. Berlin, Heidelberg: Springer Berlin Heidelberg.

Prestileo, A., Rizzuto, E., Teixeira, A. P., & Soares, C. G. 2013. Bottom damage scenarios for the hull girder structural assessment. *Marine Structures*.

Puisa, R., McNay, J., & Montewka, J. 2021. Maritime safety: Prevention versus mitigation? *Safety Science* 136: 105151.

RCP Consult GmbH 2018. STRUREL User Manual.

Ringsberg, J., Kuznecovs, A., & Johnson, E. 2023. Analysis of how the conditions in a collision scenario affect the size of a struck vessel's damage opening and ultimate strength. In J. Ringsberg & C. Guedes Soares (eds), *Advances in the Analysis and Design of Marine Structures*, 639–647. London: CRC Press.

Smith, S. 1977. Influence of Local Compressive Failure on Ultimate Longitudinal Strength of a Ship's Hull. *Proc. Int. Sym. on Practical Design in Shipbuilding*: 73–79.

Sotiralis, P., Ventikos, N., Hamann, R., Golyshev, P., & Teixeira, A. 2016. Incorporation of human factors into ship collision risk models focusing on human centred design aspects. *Reliability Engineering & System Safety* 156: 210–227.

Tabri, K., Matusiak, J., & Varsta, P. 2009. Sloshing interaction in ship collisions—An experimental and numerical study. *Ocean Engineering* 36(17-18): 1366–1376.

Tan, X., Tao, J., & Konovessis, D. 2019. Preliminary design of a tanker ship in the context of collision-induced environmental-risk-based ship design. *Ocean Engineering* 181: 185–197.

Tavakoli, M. T., Amdahl, J., & Leira, B. J. 2012. Analytical and numerical modelling of oil spill from a side tank with collision damage. *Ships and Offshore Structures* 7(1): 73–86.

Valdez Banda, O. A., Goerlandt, F., Kuzmin, V., Kujala, P., & Montewka, J. 2016. Risk management model of winter navigation operations. *Marine Pollution Bulletin* 108(1-2): 242–262.

Ventikos, N. P. & Sotiropoulos, F. S. 2014. Disutility analysis of oil spills: Graphs and trends. *Marine Pollution Bulletin* 81(1): 116–123.

Woloszyk, K. & Garbatov, Y. 2023. Advanced numerical modelling for predicting residual compressive strength of corroded stiffened plates. *Thin-Walled Structures* 183: 110380.

Woloszyk, K., Garbatov, Y., & Kłosowski, P. 2022. Stress–strain model of lower corroded steel plates of normal strength for fitness-for-purpose analyses. *Construction and Building Materials* 323: 126560.

Woloszyk, K., Garbatov, Y., & Kowalski, J. 2021. Indoor accelerated controlled corrosion degradation test of small- and

large-scale specimens. *Ocean Engineering* 241: 110039.
Zhang, M., Conti, F., Le Sourne, H., Vassalos, D., Kujala, P., Lindroth, D., & Hirdaris, S. 2021. A method for the direct assessment of ship collision damage and flooding risk in real conditions. *Ocean Engineering* 237: 109605.