RELIABILITY OF CORRODED STIFFENED PLATE SUBJECTED TO UNIAXIAL COMPRESSIVE LOADING

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SUMMARY

The work is focused on the reliability of corroded stiffened plates subjected to compressive uniaxial load based on the progressive collapse approach as stipulated by the Common Structural Rules for Bulk Carriers and Oil Tankers, employing the limit state design. Two different cases have been investigated. In the first model, the corrosion degradation led to uniform thickness loss, whereas the mechanical properties were unchanged, as given in the Rules. In the second model, the plate thickness degradation was followed by mechanical properties reduction. The uncertainties related to the mechanical properties, thicknesses, and initial imperfections of the corroded stiffened plate were taken into account. Several initial design solutions of stiffened plates, as well as different severity levels of corrosion degradation were investigated. The results show that structural reliability significantly decreases with corrosion development, especially when in addition to the initial imperfections and corrosion plate thickness reduction, corroded plate surface roughness and the changes in the mechanical properties were considered. The uncertainties, their origins and confidence levels are discussed. It was found that non-linear time-dependent corrosion degradation accounting not only for the thickness reduction due to corrosion wastage but also the subsequent decrease of mechanical properties lead to a significant reduction in the reliability index. Additionally, it was defined that the reliability estimate is very sensitive to the uncertainties related to the initial thickness and the spread of corrosion degradation as a function of the time. Incorporating the probability of corrosion detection into the original reliability model introduces additional information about the validity of structural degradation that may lead to a higher beta reliability index estimate compared to the original model.

NOMENCLATURE

A_{b_e}	Net sectional area of stiffener with a plating of a width b_e (m^2)
b_e	Width of the attached plating (m)
CoV	Coefficient of Variation
CSR	Common Structural Rules
d	Corrosion depth (m)
DnV	Det Norske Veritas
DoD	Degree of degradation (%)
d_{th}	Corrosion depth threshold value (m)
d_∞	Long-term corrosion depth (m)
E	Young modulus of the material (Pa)
FE	Finite Element
$FORM$	First-order reliability method
g	Limit state function
h	Height of the stiffener (m)
I_{b_e}	Moment of inertia of stiffener with a plating of width b_e (m^4)
I_T	Saint Venant's moment of inertia of the stiffener (m^4)
I_p	Polar moment of inertia of the stiffener (m^4)
I_ω	Sectional moment of inertia of the stiffener (m^6)
NDT	Non-destructive testing
P_f	Probability of failure (-)
PND	Probability of non-detection (-)
POD	Probability of detection (-)
POI	Probability of inspection (-)
Re	Yield stress of the material (Pa)
$StDev$	Standard deviation
t	Thickness (m)
t_0	Initial plate thickness (m)
$\widetilde{X_I}$	Uncertainty factor related to the initial imperfections (-)
$\widetilde{X_R}$	Uncertainty factor related to the welding residual stresses (-)
σ_{CR1}	Beam-column buckling ultimate stress (Pa)
σ_{CR2}	Torsional buckling ultimate stress (Pa)
σ_{CR3}	Web local buckling ultimate stress (Pa)
σ_{E1}	Elastic Euler column buckling stress (Pa)
σ_{E2}	Elastic Euler torsional buckling stress (Pa)
σ_{E3}	Elastic Euler stiffener buckling stress (Pa)
σ_L	Acting stress level (Pa)
σ_U	Ultimate stress (Pa)
τ_c	Coating life (years)

1. INTRODUCTION

Recently, more attention has been paid to the influence of degradation phenomena on structural behaviour of ship and offshore structures. One can distinguish different ageing mechanisms, such as cracking, corrosion, and local denting. In the domain of ageing mechanisms, corrosion seems to be the most common.

The corrosion influence on the load-carrying capacity of different structural elements was studied, both in the experimental and numerical domain considering different structural components, i.e., steel box girders in (Saad-Eldeen, *et al.*, 2012, 2013), stiffened panels (Jurišić and Parunov, 2015; Shi, *et al.*, 2018), stiffened plates (Garbatov, *et al.*, 2017; Jurišić, *et al.*, 2017; Woloszyk, *et al.*, 2018; Woloszyk and Garbatov, 2019b), plates (Paik, *et al.*, 2003; Jiang and Guedes Soares, 2012; Silva, *et al.*, 2013; Zhang, *et al.*, 2016) and beams (Wang, *et al.*, 2020). Additionally, it was observed that the thickness reduction causes capacity loss, but in its action mechanical properties may also be significantly reduced (Garbatov, *et al.*, 2014; Wang, *et al.*, 2017). The combination of these two factors can be critical. In the study of Woloszyk, *et al.*, 2018, several FE models of corroded stiffened plates considering subsequent thickness and mechanical properties reduction were presented and validated by experimental results positively.

Nowadays, reliability analysis is widely incorporated in ship and offshore structures. The first applications in ship structural design related to the safety of hulls subjected to a vertical bending moment were presented in (Mansour, 1972) and (Mansour and Faulkner D., 1972). Additionally, more advanced methods to assess reliability of the ship hull girder were presented recently in (Parunov, *et al.*, 2007; Gaspar and Guedes Soares, 2013; Chen, 2016). The reliability assessment considering the corrosion influence was also performed with regard to single structural elements such as plates (Guedes Soares and Garbatov, 1999a; Silva, *et al.*, 2014) or web frames (Huang, *et al.*, 2014) as well as ship hulls (Wirsching, *et al.*, 1997; Guedes Soares and Garbatov, 1999b; Jiang and Melchers, 2005; Zayed, *et al.*, 2013; Zhu and Frangopol, 2013).

Woloszyk and Garbatov (2019a) conducted reliability analysis of a corroded tanker ship hull, based on both FE and experimental results. In both cases, estimation of the ultimate structural capacity accounting for the existing uncertainties was a time-consuming process affected by the function of the size of structural components. This analysis requires fast and practical tools to be developed for design purposes. In the present study, the method based on analytical equations adopted in Common Structural Rules (International Association of Classification Societies, 2018), is employed to investigate reliability of corroded stiffened plates. The analysed plate is 1.06 m long, 0.4 m wide with a flat bar stiffener of height 0.1 m. The thickness ranges from 5 mm to 8 mm for both plate and stiffener.

2. ULTIMATE STRENGTH

The method used to estimate the ultimate structural capacity is presented in detail in (International Association of Classification Societies, 2018). Three different failure modes of a stiffened plate element, i.e. a typical part of ship cross-section, can be distinguished: beam-column buckling (CR1), torsional buckling (CR2), and web local buckling of the stiffener (CR3). The ultimate structural capacity is the minimum value according to the three modes:

$$\sigma_U = \min(\sigma_{CR1}, \sigma_{CR2}, \sigma_{CR3}) \tag{1}$$

The beam-column buckling failure mode is estimated as:

$$\sigma_{CR1} = \begin{cases} \sigma_{E1}; & \sigma_{E1} \leq \dfrac{Re}{2} \\ Re\left(1 - \dfrac{Re}{4\,\sigma_{E1}}\right); & \sigma_{E1} > \dfrac{Re}{2} \end{cases} \tag{2}$$

where σ_{E1} is the elastic Euler column buckling stress defined as:

$$\sigma_{E1} = \frac{\pi^2 E I_{b_{e1}}}{A_{b_e}} \tag{3}$$

where $I_{b_{e_1}}$ is the moment of inertia of the stiffener with a plating of a width of b_{e1} and A_{b_e} is the net sectional area of the stiffener with a plating of a width b_e. Both widths b_e and b_{e1} dependent on the plate slenderness ratio.

The torsional buckling failure mode is given as follows:

$$\sigma_{CR2} = \begin{cases} \sigma_{E2}; & \sigma_{E2} \leq \dfrac{Re}{2} \\ Re\left(1 - \dfrac{Re}{4\,\sigma_{E2}}\right); & \sigma_{E2} > \dfrac{Re}{2} \end{cases} \tag{4}$$

where σ_{E2} is the elastic Euler torsional buckling stress defined by:

$$\sigma_{E2} = \frac{E}{I_p}\left(\frac{\pi^2 I_\omega}{l^2} + 0.385 I_T\right) \tag{5}$$

where I_p and I_ω are the polar and sectional moments of the inertia of the stiffener about the point that the stiffener is welded to the plate, respectively, and I_T is the Saint Venant's moment of inertia of the stiffener.

The web local buckling mode is estimated as follows:

$$\sigma_{CR3} = \begin{cases} \sigma_{E3}; & \sigma_{E3} \leq \dfrac{Re}{2} \\ Re\left(1 - \dfrac{Re}{4\,\sigma_{E3}}\right); & \sigma_{E3} > \dfrac{Re}{2} \end{cases} \tag{6}$$

where σ_{E3} is the elastic Euler buckling stress of the stiffener, defined by:

$$\sigma_{E3} = 160000\left(\frac{t}{h}\right)^2 \tag{7}$$

where t and h are the thickness and height of the stiffener, respectively.

All three critical stresses are defined as a function of geometrical dimensions of the stiffened plate and mechanical properties of steel. In the case of main dimensions, thickness is the only random parameter considered, whereas length, breadth, and height of the stiffener are deterministic. In the case of mechanical properties, both yield stress and Young's modulus are random. As a result, ultimate load-carrying capacity is a random variable too.

3. RELIABILITY ANALYSIS

3.1 LIMIT STATE FUNCTION

Initial imperfections may cause reduction of the ultimate capacity (Dow and Smith, 1984). In the model, introduced in the previous section, one cannot control the initial imperfection, where the mean level of the initial imperfections is assumed. However, it was shown in (Woloszyk and Garbatov, 2019b), that variations of initial imperfections cause significant variations in the ultimate capacity as well. For that reason, the proposed reliability model considers initial imperfections as an important governing factor.

Uncertainty of the initial imperfections is introduced as a Gaussian random variable ($\widetilde{X_I}$), where the mean value and standard deviation are assumed to be equal to 1 and 0.05, respectively.

In addition to the initial imperfections, welding-induced residual stresses cause reduction in the ultimate capacity. However, the level of reduction depends on the size of the stiffened plate and the level of residual stresses. Some studies related to this topic may be found in (Gannon, *et al.*, 2013; Tekgoz, *et al.*, 2013), where the influence of the residual stresses on the strength of a flat-bar stiffened plates is addressed. The capacity reduction varied between 5 and 16.5 %. As proposed in (Gordo and Guedes Soares, 1993), the maximum capacity reduction of the stiffened plates caused by the welding-induced residual stresses is about 10 %. In the presented study, the uncertainty level related to welding-induced residual stresses is introduced by a normal random variable ($\widetilde{X_R}$). The mean value is assumed 0.95 and standard deviation is equal 0.05.

Based on these assumptions, the limit state function is defined in the form:

$$g = \widetilde{X_R}\widetilde{X_I}\widetilde{\sigma_u} - \widetilde{\sigma_L} \quad (8)$$

where the acting stress ($\widetilde{\sigma_L}$) is assumed a Gaussian random variable whose coefficient of variation (CoV) equals 10%. The ultimate capacity is a log-normal random variable, reflecting uncertainties related to the thickness, yield stress, and Young's modulus:

$$\widetilde{\sigma_U} = f\left(\tilde{t}, \widetilde{Re}, \tilde{E}\right) \quad (9)$$

Uncertainty analysis incorporating these random variables was presented in (Woloszyk and Garbatov, 2019b), based on the experimental results presented in (Garbatov, *et al.*, 2014). Mechanical properties and thicknesses at various levels of corrosion degradation are summarised in Table 1.

The limit state function and the procedure for estimating the ultimate strength were adopted in the STRUREL software (RCP Consult GmbH, 2018), the FORM method (Hasofer and Lind, 1974) is employed to estimate the Beta reliability index.

Table 1. Random variable descriptors.

DoD [%]	Thickness t [mm]		Yield Stress Re [MPa]		Young modulus E [MPa]	
	Mean value	St. dev.	Mean value	St. dev.	Mean value	St. dev.
5 mm plate						
0	5	0.0685	235.0	7.11	196.0	23.1
10	4.5	0.0771	238.3	7.11	185.7	23.1
25	3.75	0.0897	234.6	7.11	170.1	23.1
6 mm plate						
0	6	0.0822	235.0	7.11	196.0	23.1
10	5.4	0.0925	238.3	7.11	185.7	23.1
25	4.5	0.1077	234.6	7.11	170.1	23.1
8 mm plate						
0	8	0.1096	235.0	7.11	196.0	23.1
10	7.2	0.1233	238.3	7.11	185.7	23.1
25	6	0.1435	234.6	7.11	170.1	23.1

Two different models are analysed by means of corroded degradation severity measured by the Degree of Degradation between 0 and 25 %. The first model (A) considers thickness reduction only, as already adopted by the International Association of Classification Societies, 2018. The ultimate capacity check is performed for the net section without half of the corrosion additions. In this model, mechanical properties are independent of DoD, identical to the ones as intact conditions. In the second model (B), thickness reduction is followed by subsequent reduction of mechanical properties (see Figure 1).

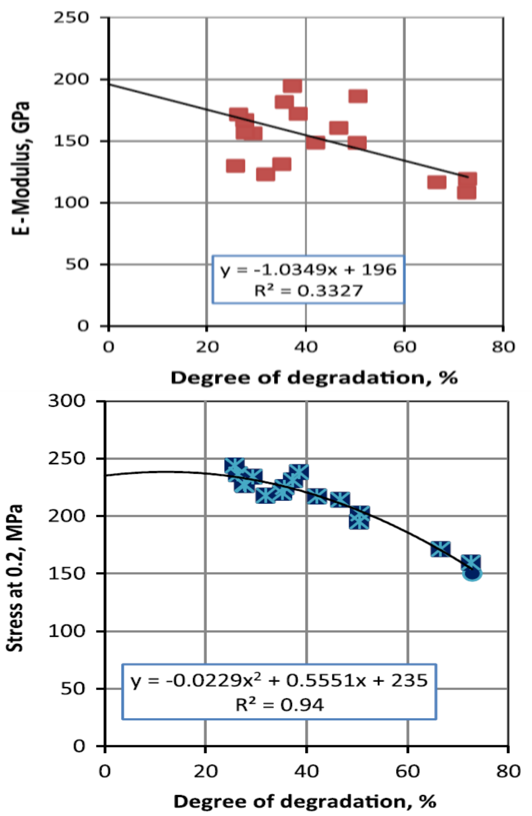

Figure 1. Young's modulus and yield stress as a function of the degree of degradation (Garbatov, *et al.*, 2014)

Table 2. Acting stresses for different thickness levels.

Thickness t [mm]	Acting stresses, σ_L [MPa]		Target reliability index [-]
	Mean value	Standard deviation	
5	95.64	9.56	3.71
6	105.3	10.53	3.71
8	120.9	12.09	3.71

Usually, the loads acting on stiffened plate elements, that are decisive to assess the ship hull cross-section are coming from still water and wave-induced bending moments. However, in the presented study, only one stiffened plate element is analysed. Thus, the acting stress is found to satisfy the initial acceptable level of the Beta reliability index. According to DnV, 1992, the target reliability level for a designed structure, assuming severe consequence of failure should be equal to 3.71. The loading that satisfies the target reliability index for the intact conditions is presented in Table 2 for various plate thicknesses.

Figure 2 presents the results of reliability analysis, where the Beta reliability index is a function of DoD for both models, with different plate thicknesses.

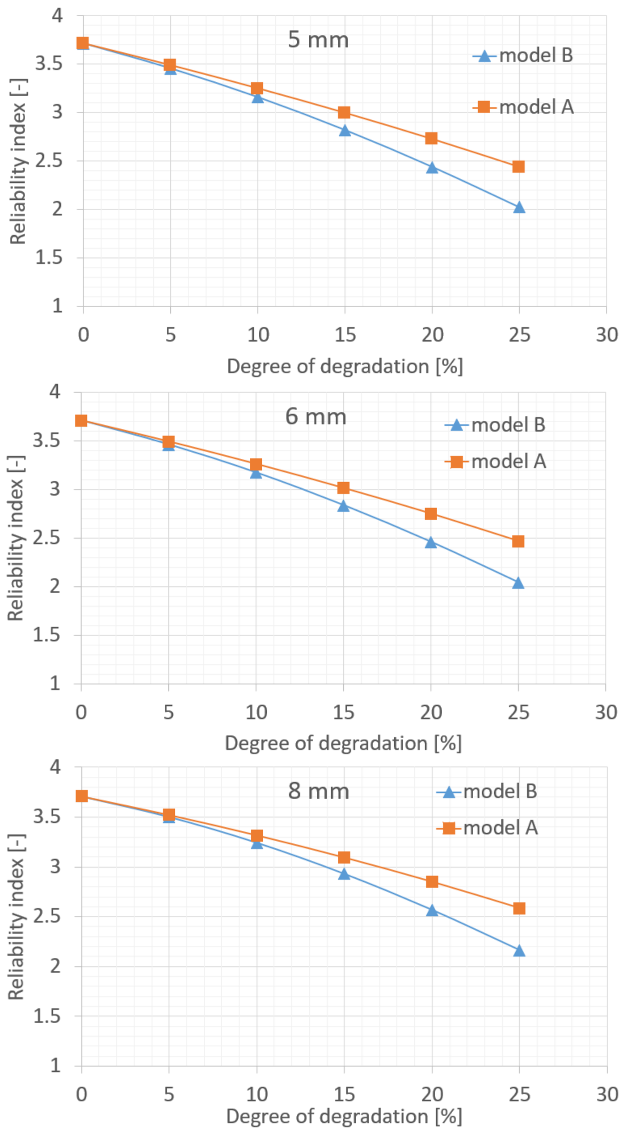

Figure 2. Reliability index as a function of DoD, t=5 mm (top), t=6 mm (mid) and t=8 mm (bottom).

Regarding all thickness variants, the DoD is inversely proportional to the reliability level. Additionally, considering higher values of DoD, the difference between model A and model B becomes more significant. In this case, when considering variations of mechanical properties acting on corrosion development, the Beta reliability index is significantly lower compared to the stiffened plate when reduced thickness is considered only. The differences between model A and model B are quite similar in each case of the stiffened plate: nevertheless, in the case of an 8 mm plate, the reliability index is higher for the same DoD level compared to thinner plates.

3.2 IMPACT OF CORROSION MEASUREMENT DATA

The results of reliability analysis presented in section 3.1 are based on the thickness measurements related to small-scale specimens corroded in laboratory conditions. Hence, the thickness standard deviation is relatively low. Additionally, in this case, the standard deviation is related to a particular Degree of Degradation. In normal ship operating conditions, direct measurements of this kind are impossible. The corrosion measurements are reported during inspections, following specific time frames. In practice, the time-dependent corrosion degradation models are commonly used. This type of model may also be calibrated by real measurement data (Hifi and Barltrop, 2014).

To estimate the corrosion degradation, the non-linear time-dependent model presented in (Guedes Soares and Garbatov, 1998) is applied. The corrosion depth as a time function is estimated as follows:

$$d(t) = \begin{cases} d_\infty \left[1 - \exp\left(-\frac{t-\tau_c}{\tau_t}\right)\right], & t > \tau_c \\ 0, & t \le \tau_c \end{cases} \quad (10)$$

where d_∞ is the long-term corrosion depth, τ_c is the coating life and τ_t is the transition time.

Equation 10 represents the mean value of corrosion depth as a function of time. In the presented study, the parameters are calibrated to reach the maximum corrosion depth after 25 years without considering the coating life (τ_c = 0). The estimated long-term corrosion depth is 3.55 mm, the transition time is 17.5 years. Accordingly, for any specific DoD, the time-dependent corrosion depth is found.

The standard deviation of corrosion depth depends on the corrosion measurement technique. In the common inspection practice, the corroded plate thickness is measured by NDT (non-destructive testing), especially with the use of ultrasonic equipment. Additionally, the results are affected by factors as lighting, cleanliness, inspector experience, and the type of inspected area (Zayed, *et al.*, 2008). Hence, the in situ measurements are subjected to higher scatter compared to laboratory conditions. According to (Garbatov, *et al.*, 2006), the standard deviation value of corrosion depth will be time-dependent and can be determined as (coating life is assumed 0 years in the model):

$$StDev(t) = 0.384\, Ln(t + 10.54) - 0.71 \quad (11)$$

It can be noticed, that time increment makes the standard deviation increase as well. The following equation is based on the real thickness measurements during tanker ship inspections. The standard deviations of corrosion depths of the analysed plates are shown in Table 3. It can be noticed that the variations are significantly higher compared to those presented in Table 1.

Table 3. Standard deviations of corrosion depth.

DoD [%]	Initial thickness t_0 [mm]	Corrosion depth d [mm]	
		Mean value	Standard deviation
0	5	0	0.19
10	5	0.5	0.28
25	5	1.25	0.40
0	6	0	0.19
10	6	0.6	0.30
25	6	1.5	0.45
0	8	0	0.19
10	8	0.8	0.33
25	8	2.0	0.53

The corrosion depth is assumed log-normal (Guedes Soares and Garbatov, 1998). Accordingly, the reliability limit state function is updated. The random variable of the plate thickness takes the form:

$$\tilde{t} = t_0 - \tilde{d} \quad (12)$$

where t_0 is the initial plate thickness.

Reliability analysis is carried out, regarding model B, standard deviation of thickness measurements based on the experimental investigations and in situ measurements are presented in Table 4.

Table 4. Reliability index as a function of thickness uncertainties.

DoD [%]	Initial thickness t_0 [mm]	Reliability index [-]		Difference [%]
		Exp.	Real measurements	
0	5	3.71	3.72	0.2
10	5	3.16	3.09	2.0
25	5	2.02	1.88	6.9
0	6	3.71	3.72	0.2
10	6	3.17	3.14	1.2
25	6	2.04	1.92	6.0
0	8	3.71	3.72	0.2
10	8	3.24	3.23	0.3
25	8	2.16	2.07	4.2

It can be observed that in the case of non-corroded plates, the thickness standard deviation does not affect the Beta reliability index. However, with corrosion development, the differences are growing. In the case of severely corroded plates (DoD = 25 %), the probability of failure significantly increases for plates whose thickness is measured with higher uncertainties. Nevertheless, it may be observed that the differences are smaller in the case of higher initial thickness of the plate.

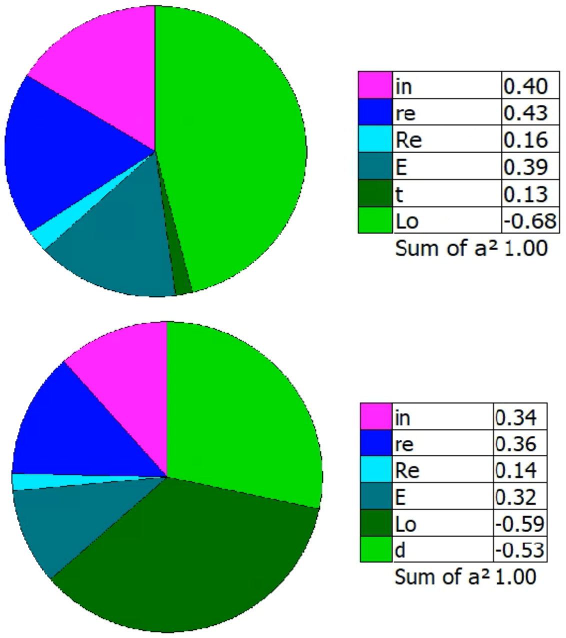

Figure 3. Sensitivity factors of reliability analysis, laboratory (top), and in situ (bottom) measurements.

The influence of standard deviation of plate thickness on reliability estimates is analysed. The sensitivity factors for any specific analysis are presented in Figure 3, where the sensitivity factors (derivatives of reliability indices with respect to random variables defining the limit state function) for a 5 mm plate of DoD of 25 % are plotted in both cases. Figure 3 (top) shows the initial model where the sensitivity factor concerning the thickness is 0.13, relatively low compared to other factors. Figure 3 (bottom) shows the model with a corrosion depth based on real measurements and the sensitivity factor concerning the corrosion depth (*d*) is -0.53. The increase of the thickness standard deviation makes the thickness random variable more critical in the reliability analysis.

It can be noticed that the reliability analyses are strongly affected by the origin of the data and the level of uncertainties.

3.3 PROBABILITY OF DETECTION INFLUENCE

In both models, as presented in sections 3.1 and 3.2, the outcome, i.e. reliability index was based on the assumption that neither inspections nor replacements were carried out. However, in normal conditions, if significant corrosion degradation occurs, exceeding the allowable level, the relevant structural component is replaced. This is a failure mode of the structural components omitted during an inspection only.

To quantify the probability of corrosion degradation detection, the mathematical models presented in (Zayed, *et al.*, 2008) are applied. The conditional probability of detection consists of two terms. The first one is the probability of inspection (POI), related to the probability that some structural components will be inspected. Typically, during the inspection, only selected areas are checked, which are chosen as places of the highest risk to severe corrosion and thickness diminutions. Nevertheless, some severely corroded locations may be omitted. The second term is the unconditional probability of detection (POD), related to the inspection only. Corrosion degradation may be detected when it exceeds a given threshold level d_{th}, which is related to testing equipment accuracy and environmental factors. The POD is given by:

$$POD(t) = P(d(t) \geq d_{th}) = 1 - F_{d(t)}(d_{th}) \qquad (13)$$

When corrosion depth is log-normal, the probability expressed in Eqn 13 reads:

$$POD(t) = 0.5 - 0.5\,\mathrm{erf}\left(\frac{\ln(d_{th}) - \lambda_{d(t)}}{\varepsilon_{d(t)}\sqrt{2}}\right) \qquad (14)$$

where $\lambda_{d(t)}$ and $\varepsilon_{d(t)}$ are defined as:

$$\lambda_{d(t)} = \ln\left(\frac{\bar{d}(t)}{\left(1 + \frac{\sigma^2_{d(t)}}{\bar{d}(t)^2}\right)^{0.5}}\right) \qquad (15)$$

$$\varepsilon_{d(t)} = \sqrt{\ln\left(1 + \frac{\sigma^2_{d(t)}}{\bar{d}(t)^2}\right)} \qquad (16)$$

where $\bar{d}(t)$ and $\sigma_d\ (t)$ are the mean value and standard deviation of the corrosion depth in a particular time, respectively.

Thus, the conditional probability of detection is the result of the product of *POI* and *POD*(*t*) as:

$$POD_c(t) = POD(t) \cdot POI \qquad (17)$$

The structural members that can be omitted during the inspection are those that cannot be detected. The conditional probability of non-detection is:

$$PND_c(t) = 1 - POD_c(t) \qquad (18)$$

The probability of failure of a structural component considering the non-detected severely corroded plates only is defined as:

$$P_{fND}(t) = P_f(t) \cdot PND_c(t) \qquad (19)$$

where $P_f(t)$ is the probability of failure as calculated in reliability analysis.

Based on the probability of failure given by Eqn 13, the conditional Beta index can be estimated. To investigate the impact of probability of detection on the final reliability index, the model discussed in section 3.2 is employed. In this case, it is considered that the probability of inspection value is 0.3, and the corrosion depth threshold value is 0.8 mm.

The values of $POD_c(t)$ are shown in Figure 4 for three different plate thicknesses. Since the curves are shown in the DoD domain, the time values are estimated using Eqn 10 based on the assumptions of the corrosion degradation process as presented in section 3.2.

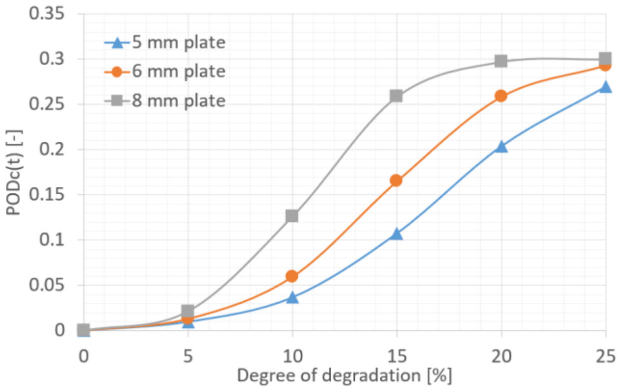

Figure 4. Conditional probability of detection.

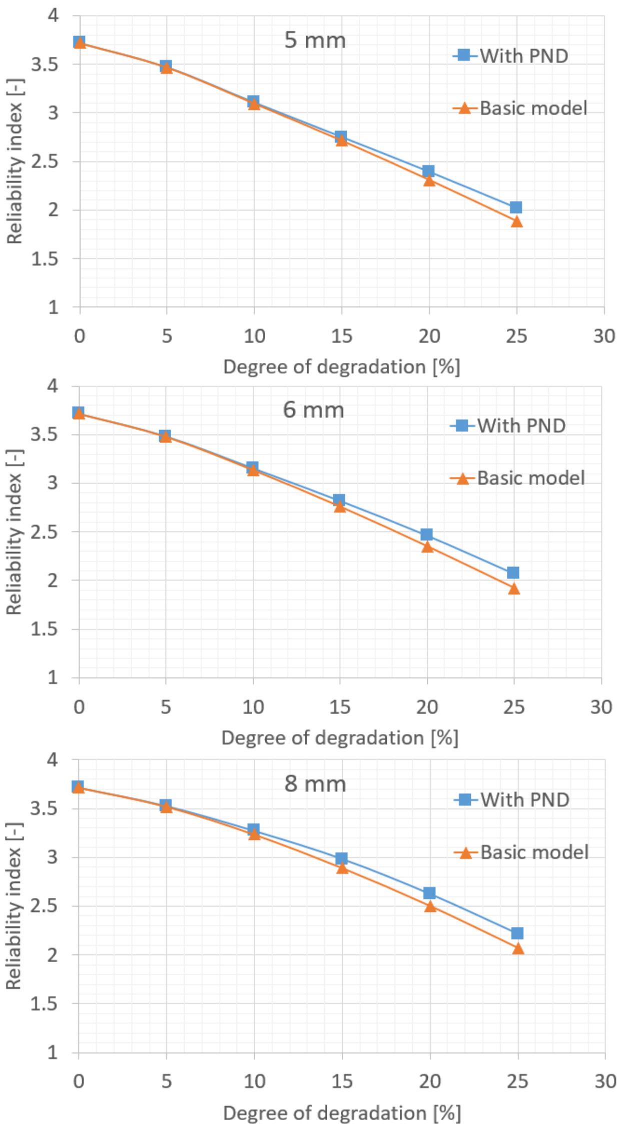

Figure 5. Reliability of corroded plates with and without consideration of corrosion detection.

It is observed that higher plate thickness leads to a higher probability of detection, also related to the corrosion detection threshold level. In the case of a 5 mm plate, the 25 % degradation results in a 1.25 mm mean corrosion depth, whereas in the case of an 8 mm plate the same degradation level leads to a 2 mm corrosion depth. In the first case, the relation between the corrosion depth and threshold level is significantly less compared to the second one. The influence of the probability of detection to the resulting Beta index is presented in Figure 5.

In all cases, reliability increase is higher for higher DoD levels. This is related to the probability of detection, which increases as the DoD grows higher, as presented in Figure 4. Additionally, the highest increase of the reliability index is observed in the case of 8 mm plate.

4. VALIDATION OF DEVELOPED APPROACH

In order to verify the proposed CSR formulation presented in Section 2, a non-linear FE method is conducted. The FE model has been addressed in (Woloszyk, *et al.*, 2018), showing good agreement with the experimental results. The average initial imperfections have been incorporated in the model as presented in (Woloszyk and Garbatov, 2019b). The bilinear material model has been applied, mechanical properties were taken into account as mean values, as presented in Table 1.

The comparison of normalised ultimate strength (the ultimate stress divided by the yield stress) between the CSR formulation and FE analysis is presented in Table 5.

Table 5. Ultimate strength values of FE analysis and CSR approach.

Thickness [mm]	DoD [%]	Normalized ultimate strength [-]		Difference [%]
		FE	CSR	
5	0	0.618	0.684	10.5
	10	0.527	0.567	7.6
	25	0.382	0.404	5.7
6	0	0.669	0.751	12.3
	10	0.577	0.627	8.7
	25	0.428	0.463	8.1
8	0	0.820	0.857	4.6
	10	0.659	0.724	9.8
	25	0.489	0.540	10.3

The ultimate strength estimated by the FE method is lower compared to the CSR approach by approximately 9 %. In both cases of 5 mm and 6 mm plates, the difference is decreasing with the corrosion development, the opposite case concerns the 8 mm stiffened plate. Thus, the CSR results are non-conservative. A possible way to incorporate it into reliability analysis is to introduce the modelling uncertainty factor, in the form of a Gaussian random variable with a mean value equal to the ratio between ultimate strength values of FE analysis and CSR approach. The standard deviation of modelling uncertainty will be equal to the deviation of that ratio, respectively. Nevertheless, the introduction of such modelling uncertainty results in lower acting stress σ_L, whereas the dependency between the reliability index and degree of degradation (Figures 2 and 5) will be rather similar. This issue can be considered a possible future work.

5. CONCLUSIONS

The presented study developed a simplified approach to assess the ultimate strength and reliability of corroded stiffened plates with progressive uncertainties due to the nature of corrosion degradation. The approach presented here, is fast and practical, compared to the advanced non-linear FE analysis. When both thickness reduction due to corrosion degradation is taken into account and the subsequent decrease of mechanical properties are considered, the reliability index is significantly lower. In the second case, for severely corroded plates, the reliability index may even be 50% smaller than the intact plates: however, the reliability index reduction may be smaller for thicker plates.

Nevertheless, the outcome of the reliability assessment is highly sensitive to the initially defined random variables regarding their uncertainties. Two different uncertainty levels of plate thickness were investigated based on the laboratory measurements and results of ship inspections. Different standard deviations of the corroded plate thickness led to quite different reliability estimates. In many cases, the initial uncertainty level is assumed, so further studies concerning the uncertainty qualification and the level of confidence are required.

Finally, when the probability of detection of corroded components, during their inspection is taken into account, the reliability index is slightly higher than the reference model.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. CHEN, N.-Z. (2016) '*Hull girder reliability assessment for FPSOs*', Engineering Structures, 114, pp. 135–147.
2. DNV (1992) '*Structural Reliability Analysis of Marine Structures.*', Classification notes No 30.6.
3. DOW, R. S., and SMITH, C. S. (1984) '*Effects of localised imperfections on compressive strength of long rectangular plates*', Journal of Constructional Steel Research. Elsevier, 4(1), pp. 51–76.
4. GANNON, L., LIU, Y., PEGG, N. and SMITH, M. J. (2013) '*Effect of three-dimensional welding-induced residual stress and distortion fields on strength and behaviour of flat-bar stiffened panels*', Ships and Offshore Structures, 8(5), pp. 565–578.
5. GARBATOV, Y., GUEDES SOARES, C., PARUNOV, J. and KODVANJ, J. (2014) '*Tensile strength assessment of corroded small scale specimens*', Corrosion Science, 85, pp. 296–303.
6. GARBATOV, Y., GUEDES SOARES, C. and WANG, G. (2006) '*Nonlinear Time-Dependent Corrosion Wastage of Deck Plates of Ballast and Cargo Tanks of Tankers*', Journal of Offshore Mechanics and Arctic Engineering, 129(1), pp. 48–55.
7. GARBATOV, Y., TEKGOZ, M. and GUEDES SOARES, C. (2017) '*Experimental and numerical strength assessment of stiffened plates subjected to severe non-uniform corrosion degradation and compressive load*', Ships and Offshore Structures, 12(4), pp. 461–473.
8. GASPAR, B., and GUEDES SOARES, C. (2013) '*Hull girder reliability using a Monte Carlo based simulation method*', Probabilistic Engineering Mechanics, 31, pp. 65–75.
9. GORDO, J. M. and GUEDES SOARES, C. (1993) '*Approximate Load Shortening Curves for Stiffened Plates Under Uniaxial Compression*', Proc. Integrity of Offshore Structures - 5, pp. 189–211.
10. GUEDES SOARES, C. and GARBATOV, Y. (1998) '*Non-linear time-dependent model of corrosion for the reliability assessment of maintained structural components*', A. A. Balkema, Safety and Reliability, 2, pp. 929–936.
11. GUEDES SOARES, C. and GARBATOV, Y. (1999a) '*Reliability of maintained, corrosion protected plates subjected to non-linear corrosion and compressive loads*', Marine Structures, 12(6), pp. 425–445.
12. GUEDES SOARES, C. and GARBATOV, Y. (1999b) '*Reliability of maintained ship hulls subjected to corrosion and fatigue under combined loading*', Journal of Constructional Steel Research, 52(1), pp. 93–115.
13. HASOFER, A. M. and LIND, N. C. (1974) '*Exact and Invariant Second-Moment Code Format*', Journal of the Engineering Mechanics Division. ASCE, 100(1), pp. 111–121.
14. HIFI, N. and BARLTROP, N. (2014) '*Correction of Prediction Model Output--Application to General Corrosion Model*', The

International Journal of Maritime Engineering, 156(a4), pp. 363–374.

15. HUANG, W., GARBATOV, Y. and GUEDES SOARES, C. (2014) '*Fatigue reliability of a web frame subjected to random non-uniform corrosion wastage*', Structural Safety, 48, pp. 51–62.
16. International Association of Classification Societies (2018) Common Structural Rules (BC & OT).
17. JIANG, X. and GUEDES SOARES, C. (2012) '*Ultimate capacity of rectangular plates with partial depth pits under uniaxial loads*', Marine Structures, 26(1), pp. 27–41.
18. JIANG, X. and MELCHERS, R. E. (2005) '*Reliability Analysis of Maintained Ships Under Correlated Fatigue and Corrosion*', The International Journal of Maritime Engineering, 147(a3), p. 15, pp. 9-18.
19. JURIŠIĆ, P. and PARUNOV, J. (2015) '*Influence of corrosion-related degradation of mechanical properties of shipbuilding steel on collapse strength of plates and stiffened panels*', in Towards Green Marine Technology and Transport. CRC Press, pp. 427–432.
20. JURIŠIĆ, P., PARUNOV, J. and GARBATOV, Y. (2017) '*Aging effects on ship structural integrity*', Brodogradnja, 68(2), pp. 15–28.
21. MANSOUR, A. (1972) '*Methods of computing the probability of failure under extreme values of bending moment*', Journal of Ship Research, pp. 113-123.
22. MANSOUR, A. E. (1972) '*Probabilistic design concepts in ship structural safety and reliability*', Transactions of the SNAME, 80, pp. 64–97.
23. MANSOUR, A. E. and FAULKNER D. (1972) '*On applying the statistical approach to extreme sea loads and ship hull strength*', Transactions of the RINA, 114, pp. 273–314.
24. PAIK, J. K., LEE, J. M. and KO, M. J. (2003) '*Ultimate compressive strength of plate elements with pit corrosion wastage*', Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment. SAGE PublicationsSage UK: London, England, 217(4), pp. 185–200.
25. PARUNOV, J., SENJANOVIĆ, I. and GUEDES SOARES, C. (2007) '*Hull-girder reliability of new generation oil tankers*', Marine Structures, 20(1–2), pp. 49–70.
26. RCP Consult GmbH (2018) 'STRUREL User Manual'.
27. SAAD-ELDEEN, S., GARBATOV, Y. and GUEDES SOARES, C. (2012) '*Effect of corrosion degradation on ultimate strength of steel box girders*', Corrosion Engineering, Science and Technology. Taylor & Francis, 47(4), pp. 272–283.
28. SAAD-ELDEEN, S., GARBATOV, Y. and GUEDES SOARES, C. (2013) '*Ultimate strength assessment of corroded box girders*', Ocean Engineering, 58, pp. 35–47.
29. SHI, X. H., ZHANG, J. and GUEDES SOARES, C. (2018) '*Numerical assessment of experiments on the ultimate strength of stiffened panels with pitting corrosion under compression*', Thin-Walled Structures, 133, pp. 52–70.
30. SILVA, J. E., GARBATOV, Y. and GUEDES SOARES, C. (2013) '*Ultimate strength assessment of rectangular steel plates subjected to a random localised corrosion degradation*', Engineering Structures, 52, pp. 295–305.
31. SILVA, J. E., GARBATOV, Y. and GUEDES SOARES, C. (2014) '*Reliability assessment of a steel plate subjected to distributed and localised corrosion wastage*', Engineering Structures, 59, pp. 13–20.
32. TEKGOZ, M., GARBATOV, Y. and GUEDES SOARES, C. (2013) '*Finite element modeling of the ultimate strength of stiffened plates with residual stresses*', in Analysis and Design of Marine Structures. CRC Press, pp. 309–317.
33. WANG, Y., XU, S. and LI, A. (2020) '*Flexural performance evaluation of corroded steel beams based on 3D corrosion morphology*', Structure and Infrastructure Engineering, pp. 1–16.
34. WANG, Y., XU, S., WANG, H. and LI, A. (2017) '*Predicting the residual strength and deformability of corroded steel plate based on the corrosion morphology*', Construction and Building Materials, 152, pp. 777–793.
35. WIRSCHING, P. H., FERENSIC, J. and THAYAMBALLI, A. (1997) '*Reliability with Respect to Ultimate Strength of a Corroding Ship Hull*', Marine Structures, 10, pp. 501–518.
36. WOLOSZYK, K. and GARBATOV, Y. (2019a) '*Structural Reliability Assessment of Corroded Tanker Ship Based on Experimentally Estimated Ultimate Strength*', Polish Maritime Research, 26(2), pp. 47–54.
37. WOLOSZYK, K. and GARBATOV, Y. (2019b) '*Uncertainty assessment of ultimate strength of corroded stiffened plates subjected to maintenance*', in Georgiev, P. and Soares, C. G. (eds) Sustainable Development and Innovations in Marine Technologies. CRC Press, pp. 429–436.
38. WOLOSZYK, K., KAHSIN, M. and GARBATOV, Y. (2018) '*Numerical assessment of ultimate strength of severe corroded stiffened plates*', Engineering Structures, 168, pp. 346–354.
39. ZAYED, A., GARBATOV, Y. and GUEDES SOARES, C. (2008) '*Nondestructive Corrosion Inspection Modeling of Tanker Structures*', in Volume 2: Structures, Safety, and Reliability. ASMEDC, pp. 465–476.
40. ZAYED, A., GARBATOV, Y. and GUEDES SOARES, C. (2013) '*Reliability of ship hulls*

subjected to corrosion and maintenance', Structural Safety, 43, pp. 1–11.

41. ZHANG, Y., HUANG, Y., ZHANG, Q. and LIU, G. (2016) '*Ultimate strength of hull structural plate with pitting corrosion damnification under combined loading*', Ocean Engineering, 116, pp. 273–285.
42. ZHU, B. and FRANGOPOL, D. M. (2013) '*Reliability assessment of ship structures using Bayesian updating*', Engineering Structures, 56, pp. 1836–1847.

