Corrosion wastage of oil tankers – a case study of an aged ship

J. Parunov & K. Žiha
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Department of Naval Architecture and Ocean Engineering, Ivana Lucica 5, 10002 Zagreb, Croatia.

P. Mage
Center of Technology Transfer, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lucica 5, 10002 Zagreb, Croatia.

ABSTRACT: The paper on the first place examines the corrosion wastage of a single-hull oil tanker after 25 years of service. Next it relates the corrosion wastage statistics for both cargo and ballast tanks of the case study to the proposal of „rule“corrosion deduction thickness in new Common Structural Rules (CSR). Finally, it assesses the effect of measured corrosion of ship scantlings on the ultimate bending capacity of the hull girder and compares the two methods for ultimate strength calculation proposed in CSR – the HULS-1 single step procedure and the progressive collapse analysis (PCA). In addition to the global strength analysis of the ship hull girder with respect to yielding and buckling the paper also investigates the impact of corrosion wastage on ultimate lateral pressure due to local bending of plating. The conclusion reveals the long-term non-linear theoretical model of corrosion wastage that is fitted to measured corrosion on the ship. The findings are hopefully useful in prediction of corrosion propagation after conversion of oil tanker to FPSO.

1 INTRODUCTION

Classification societies most seriously take into consideration the corrosion wastage as one of the very important degradation factors for ship structural strength. Therefore they introduce the “net” thickness approach incorporated in the new Common Structural Rules (CSR) for Double-Hull Oil Tankers by ABS & al. (2006). This approach relies on the requirement that the structural capacity for different failure modes is to be calculated for predicted reduction of hull scantlings due to corrosion effects. The CSR proposal implies the “rule” corrosion deduction thickness for different structural elements and different levels of calculation. In the final consequence the design scantlings of structural elements are corrected for the “rule” corrosion deduction thickness in order to attain the required “net“ thickness. About 600000 systematic thickness measurements on ships in service were taken as the source for the CSR corrosion allowances. The corrosion depth in the CSR is statistically presented by the cumulative probability of 95% for 25 years by Nieuwenhuijs at al. (2006).

Each individual oil tanker, particularly if it is an aged one of single-hull type, represents potential huge threat to the environment. Therefore, it is of interest to examine how the statistically averaged “rule” values of corrosion wastage agree to an individual example of measured corrosion wastage of an aged ship in real life. In order to trace the uncertainty of corrosion effects the paper considers the corrosion wastage of an existing single-hull oil tanker after 25 years of service. The corrosion diminution data for plates and longitudinals are collected and statistically treated first with respect to deck and bottom areas of cargo and ballast tanks. Next, the corrosion diminutions of scantlings effectively contributing to the longitudinal strength are considered. Finally, the theoretical distributions are fitted to the corrosion measurements while maximum measured corrosion is compared to the corrosion deduction thickness proposed in CSR.

Furthermore, the paper investigates the effect of the corrosion on the ultimate bending capacity of the hull girder. The ultimate strength criterion was incorporated first in the Rules of Bureau Veritas (2000). However, the ultimate bending capacity requirement is introduced in the CSR recently relying on two methods for ultimate strength calculation. The paper applies both the single-step procedure (HULS-1) and the progressive collapse analysis (PCA) on the ultimate strength analysis for the ship hull “as-built”, ship corroded according to CSR corrosion allowances and ship with measured corrosion after 25 years of service.

The cargo tank main deck plating corrosion measurement data are used for calibration of parameters of the long-term non-linear corrosion propagation model resulting in prediction of deck plating ultimate lateral pressure degradation under local plate bending in time. The long-term prediction model of corrosion wastage could have several practical applications, as the rational assessment of aged ships condition as well as for long-term prediction of corrosion wastage in case of oil tanker conversion in FPSO.

The case study in the paper briefly presents the principal characteristics of the single-hull aged oil tanker. After that, results of corrosion measurements on the case study ship are presented in tabular and graphical form and compared to the CSR corrosion allowances. In the following sections, the results of the ultimate strength calculations using the two procedures proposed by CSR and applied to three hull conditions are presented as well as the application of the long-term non-linear corrosion propagation model of the main deck. The brief discussion and the conclusions support the usefulness of the investigation of the rule based corrosion effect and measurements in practice.

2 DESCRIPTION OF THE CASE STUDY SHIP

The case study in the paper is an existing aged single-hull oil tanker which is considered for conversion to FPSO, Table 1. The whole cargo area, Fig. 1, is made of MS shipbuilding steel with guaranteed yield strength of σ_y=235 N/mm^2.

Table 1. Main characteristics of single-hull tanker

Length between perpendiculars	*Lpp*	217	m
Moulded breadth	*B*	32.2	m
Moulded depth	*D*	19.6	m
Scantling draught	*T*	12.75	m
Deadweight	*DWT*	63150	dwt

Central tanks along cargo hold area are cargo oil tanks, while wing tanks serve as ballast tanks, Fig. 1.

3 THICKNESS MEASUREMENTS ON THE CASE STUDY

The paper takes the detailed thickness measurements on the case study oil tanker cargo hold area after 25 years of service as it is required according to the rules of classification societies. The statistical analysis of the results of thickness measurements provides mean values and standard deviations of corrosion depth for plating and stiffeners effectively contributing to the hull girder longitudinal strength.

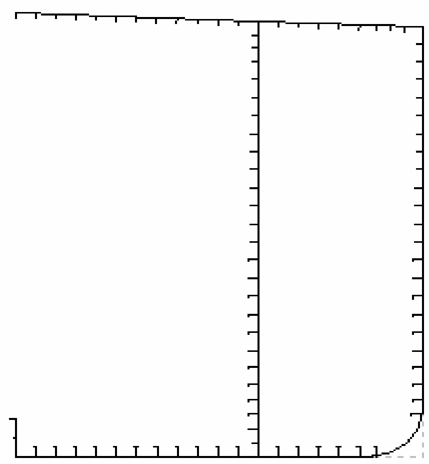

Figure 1. Midship section of single-hull oil tanker in cargo area

The maximum measured corrosion depth and CSR corrosion wastage in addition to means and standard deviations of measured values are given for cargo tanks and for ballast spaces as well as for deck and bottom areas, Table 2.

Table 2. Statistical properties of corrosion degradation of thickness and the CSR „rule“ corrosion allowances in millimeters

Structural element	Area	Mean	Standard deviation	Maximum measured	CSR
Deck plates	Cargo	2,11	0,88	4,2	4,5
	Ballast	0,25	0,37	2,5	4
Deck longitudinals	Cargo	2,35	1,08	6,1	4,5
	Ballast	0,60	0,14	1,7	4
Bottom plates	Cargo	0,22	0,18	1,4	3
	Ballast	0,38	0,41	1,8	3
Bottom longitudinals	Cargo	0,14	0,09	0,5	3,5
	Ballast	0,10	0,12	0,3	3

Maximum values of corrosion diminution of the deck structure in cargo tanks exceeds in some cases the values proposed by CSR, Table 2. However, these exceedances occur very seldom. Mechanism of corrosion progression in deck area of cargo oil tanks is explained in details in ISSC report by Paik & al. (2006).

4 FITTING THEORETICAL DISTRIBUTIONS TO CORROSION WASTAGE DEPTH

The paper investigates in the sequel how to fit theoretical probability density functions of the corrosion wastage depth to the empirical data. It was found that Weibull 2-parameter distribution among many others provides closest fit to the measured corrosion. The best agreement between theoretical distribution and empirical data is achieved for the most important data sets, i.e. those in cargo tank deck areas, Figures 2-9 by Mage (2006).

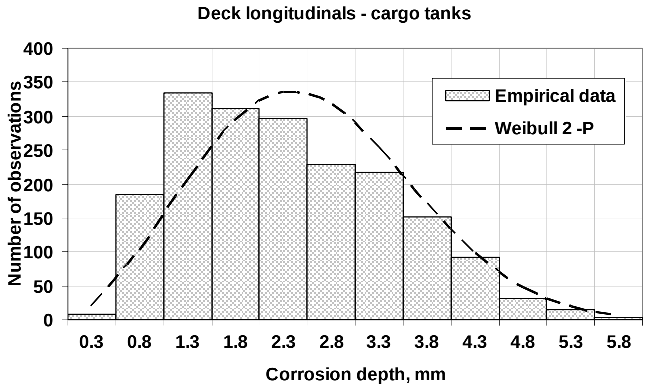

Figure 2. Weibull 2-P probability density function of the corrosion wastage of deck longitudinals in cargo tanks

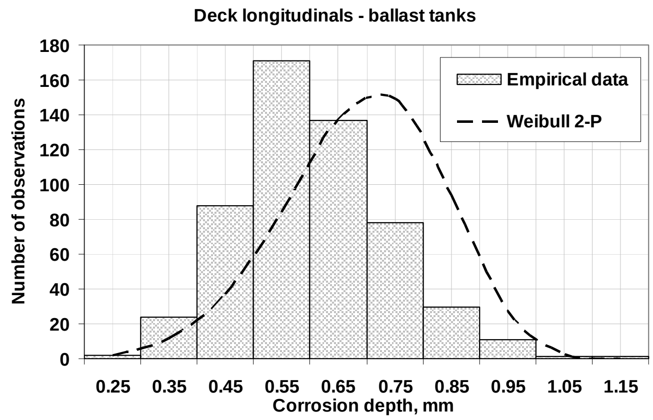

Figure 3. Weibull 2-P probability density function of the corrosion wastage of deck longitudinals in ballast tanks

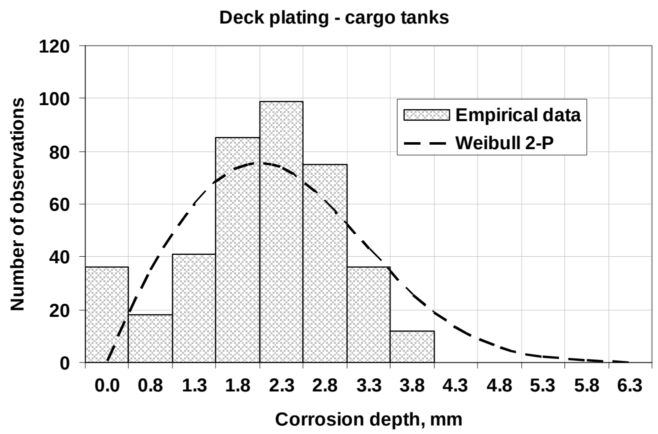

Figure 4. Weibull 2-P probability density function of the corrosion wastage of deck plating in cargo tanks

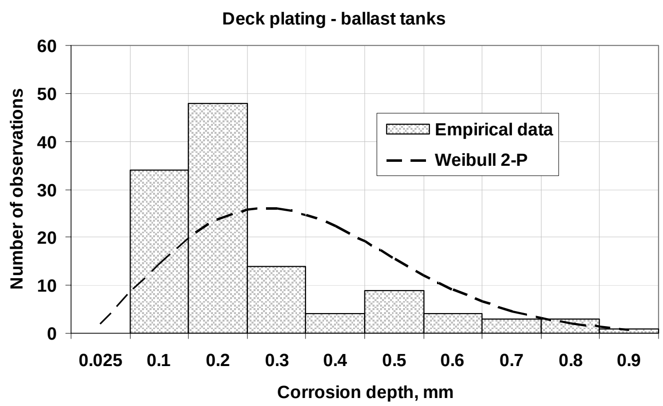

Figure 5. Weibull 2-P probability density function of the corrosion wastage of deck plating in ballast tanks

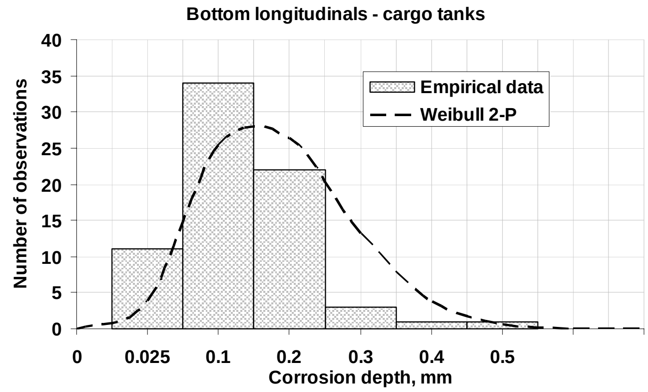

Figure 6. Weibull 2-P probability density function of the corrosion wastage of bottom longitudinals in cargo tanks

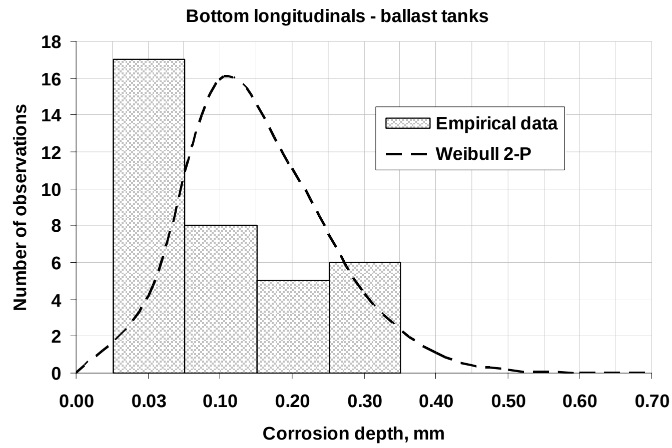

Figure 7. Weibull 2-P probability density function of the corrosion wastage of bottom longitudinals in ballast tanks

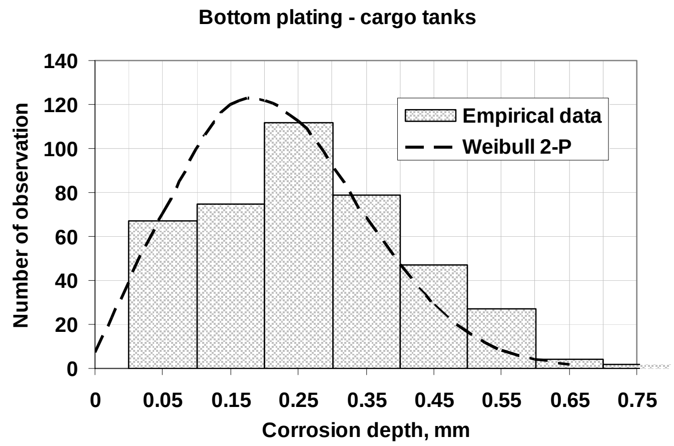

Figure 8. Weibull 2-P probability density function of the corrosion wastage of bottom plating in cargo tanks

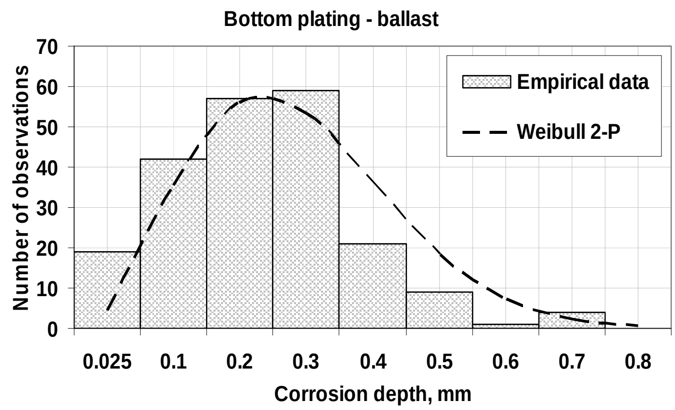

Figure 9. Weibull 2-P probability density function of the corrosion wastage of bottom plating in ballast tanks

5 IMPACT OF CORROSION WASTAGE ON ULTIMATE BENDING MOMENT CAPACITY OF THE SHIP HULL GIRDER

Ultimate bending moment capacity is defined as the maximal bending moment under which the hull-girder collapses. Normally it is between the elastic and the fully plastic moment since it accounts for the load deflection characteristics and post-collapse strength of all longitudinally effective elements.

The ultimate bending moment capacity is calculated herein by two procedures proposed in the CSR:

a) By progressive collapse analysis (PCA) of the ship hull-girder
b) By the single step procedure (HULS-1).

The method of progressive collapse analysis was earlier proposed by Smith and still is the most frequently used method for ultimate strength assessment, Gordo et al. (1996). The Smith's method uses stress-strain relationship for beams-columns that comprise the stiffened panels of the ship hull. Stress-strain relationships used in the present work are those proposed in CSR of ABS & al. (2006). Ultimate bending moment calculation in the paper is the incrementally-iterative procedure implemented in computer program MARS by Bureau Veritas (2006).

The single step method (HULS-1) for calculation of the sagging hull-girder ultimate bending capacity is a simplified method based on reduced hull-girder bending stiffness accounting for buckling of the main deck. The ultimate buckling capacity of main deck plating and framing is calculated using PULS computer program, Steen et al. (2001).

Ultimate bending moment capacity calculations are performed for three states of the hull:

- „as-built“ state, with gross thickness of structural members as they are built-in the new ship;
- „CSR“ state, with net thickness of structural elements by deducing „rule“ corrosion depth;
- „Survey“ state, with measured thickness after 25 years of service.

CSR „rule“ corrosion wastage used in ultimate bending moment calculation is taken as a half of the maximum corrosion wastage, column CSR in Table 2. It should be also noted that the ultimate strength calculation for „survey“ state is performed for only one representative section in the midship area taking the measured thicknesses after 25 years of service. Somewhat different results could be obtained in other hull sections due to the fluctuation of the corrosion wastage along the hull.

Results of the ultimate strength calculations with two programs and for three hull states are recapitulated in Table 3. Note that HULS-1 procedure is applicable only for sagging failure mode.

Table 3. Ultimate bending moments, M_U, for three different states of the ship hull and for two different calculation methods

Hull state		AS BUILT	CSR	SURVEY
		M_U , MNm	M_U, MNm	M_U, MNm
HULS-1(sagging)		4683	4119	4353
PCA	Sagging	5192	4466	4879
	Hogging	5403	4736	5149

It appears that the HULS-1 procedure is more conservative since the ultimate bending moments in sagging obtained by PCA are for about 10% larger, Table 3. This happens because the PCA method accounts for some additional reserve of the bending moment capacity after collapse of the main deck. It also appears that the corrosion margin according to the CSR is more conservative since the results for "survey" state of the hull after 25 years of ship service indicate larger ultimate strength than strength predicted for corrosion according to CSR, Table 3.

Intermediate results necessary for HULS-1 calculation may help to explain the differences between CSR and "survey" states in more details, Table 4.

Table 4. Data for calculation of ultimate hull bending moment capacity by HULS-1 method

	AS BUILT	*CSR*	*SURVEY*
σ_U, N/mm^2	194	191	188
Z_{Red}, m^3	19,9	17,2	18,5
I_{Red} ,m^4	214,6	190,4	202,6
A_{Red} ,m^2	3,45	3,07	3,32

Note the differences for three hull states of the ultimate hull bending capacity of the stiffened deck panel σ_U calculated by program PULS as well as of the reduced sectional modulus, moment of inertia and area of the ship cross section Z_{Red}, I_{Red} and A_{Red} after collapse of the main deck respectively, Table 4. It appears how the ultimate load carrying capacity of the main deck is lower of the capacity obtained for predicted CSR corrosion margins. However, the overall hull sectional properties are better for „survey“ state, providing a larger ultimate bending capacity. The reason for this is in the observation that the measured corrosion depth in all areas except the main deck in cargo tanks is substantially lower of the rule corrosion depth proposed by CSR, Table

1. This observation holds even for calculation of ultimate hull bending moment capacity by taking only the half of „rule“ corrosion as required by CSR.

6 LONG-TERM NON-LINEAR CORROSION WASTAGE PROGRESSION MODEL

When an aged oil tanker is planned for conversion to FPSO it is useful to assess the structural degradation to the end of the life-time by employing theoretical models describing long-term corrosion wastage. Several different non-linear models describing long-term growth of corrosion depth are available, such as Garbatov et al. (2005), Sun & Guedes Soares (2006). These models describe either corrosion depth or corrosion rate in three phases:

- The first phase without corrosion since corrosion protection system is effective
- The transition phase when failure of corrosion protection system is initiated
- The third phase when either corrosion wastage either corrosion rate tends to be a constant value.

The long-term corrosion wastage of deck plates and stiffeners in cargo tanks has no obvious physical limitation to the corrosion progression. Therefore the model assuming constant corrosion rate in the third phase appears more appropriate for the case study.

The model of time variant corrosion rate progression *r(t)* proposed by Sun & Guedes Soares (2006), for example Fig. 10, is as shown:

$$r(t) = r_s\,(1 - e^{-\frac{t-\tau_i}{\tau_t}}) \qquad (1)$$

where r_S is the steady corrosion rate, τ_i is the coating lifetime, while τ_t is the transition time that may be identified also using α as it is shown:

$$\tau_t = \frac{r_s}{tg\alpha} \qquad (2)$$

By integrating equation (1), the corrosion depth in time *d(t)* can be obtained by the following term:

$$d(t) = r_s\left[t - (\tau_i + \tau_t) + \tau_t e^{-\frac{t-\tau_i}{\tau_t}}\right] \qquad (3)$$

The choice of parameters in the above model (1)-(3) depends on many factors, such as coating properties, cargo composition, inert gas properties, temperature of cargo and maintenance practice, Sun & Guedes Soares (2006). Therefore, the choice of these parameters is highly uncertain. For mean values of corrosion wastage of main deck plates in cargo tanks, Table 2, reasonable agreement with measurements is achieved with the following parameters of non-linear long-term corrosion propagation model: r_S = 0.14 mm/year, $\tau_i = \tau_t$ =5 years. The selected parameters define the variation of the corrosion rate with years, Fig. 10, and the progression of corrosion depth with time, Fig. 11.

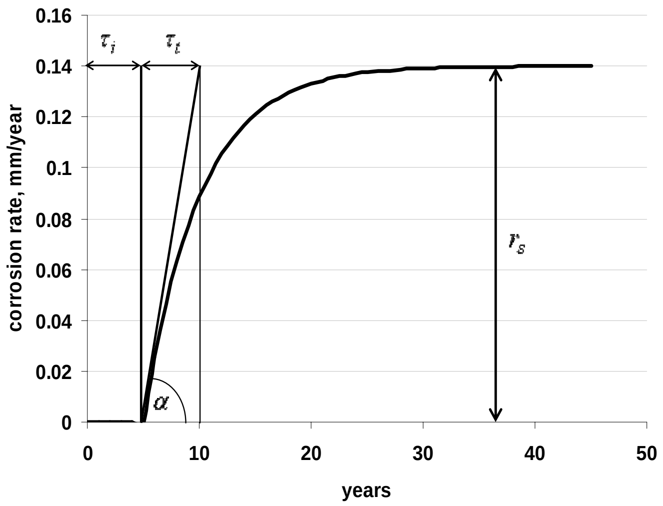

Figure 10. Model of corrosion rate variation with time of the main deck plating in cargo tanks

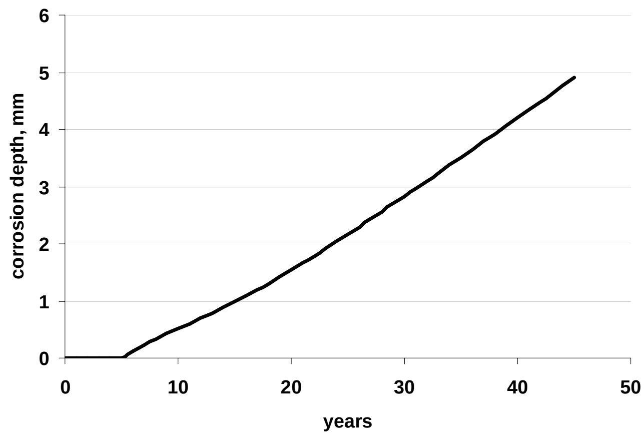

Figure 11. Model of long-term mean corrosion depth variation of the main deck plating in cargo tanks

After 20 years of operation of ship as FPSO, i.e. after 45 years of ship lifetime, mean corrosion wastage of the main deck plates in cargo tanks is estimated to 4.9 mm, Fig 11.

7 IMPACT OF CORROSION WASTAGE ON ULTIMATE LATERAL PRESURE DUE TO LOCAL BENDING OF STIFFENED PANELS

The ultimate bending strength with respect to multimodal plastic failure of plates between stiffeners can be assessed according to DNV (1978) by the interaction formula $\frac{M}{\sigma_y \cdot W_{p,p}} + \frac{1}{\beta}\left(\frac{\sigma_L}{\sigma_y}\right)^2 = \beta$. The acting bending moment due to lateral pressures *p* is $M = k_m \cdot p \cdot s^2$, the in-plane load is σ_L, and the unit plate plastic section modulus $W_{p,p} = t^2/4$. The usage factor β

relates the maximal permissible load to the collapse load. Using the interaction factor $k_{L,p} = \left[\beta - \frac{1}{\beta} \left(\frac{\sigma_L}{\sigma_y} \right)^2 \right]$ to represents the influence of the in-plane stress σ_L and the semi-empirical plate side aspect ratio $k_s = 1 - 0,4 \left(\frac{s}{\ell} \right)^2$ the ultimate lateral pressure on plating is as shown:

$$p_{u,p} = 3 \cdot \left(\frac{t}{s} \right)^2 \cdot \frac{k_{L,p}}{k_s} \cdot \sigma_y \qquad (4)$$

Following the long-term mean corrosion depth for the most exposed main deck plating in cargo tanks, Fig. 11, the diminution of the ultimate lateral pressure (green seas for example) (4) with time can be calculated, Fig. 12.

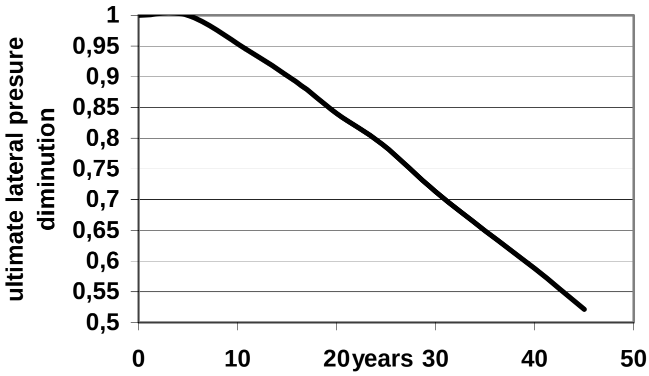

Figure 12. Diminution of the ultimate lateral pressure on the main deck plating in cargo tanks due to local inter-frame bending based on long-term mean corrosion depth variation

8 CONCLUSION

The case study in this paper demonstrates that the measured corrosion depth of a single-hull oil tanker after 25 years of service is in general much lower than the "rule" corrosion depth in most of the areas of the ship. However, the exception is the main deck area in cargo tanks where the corrosion wastage even exceeds in few places maximum values proposed by CSR.

The ultimate bending moment capacity analysis of a hull-girder indicates high corrosion degradation of the main deck that could jeopardize the ship structural strength. It is evident that the collapse strength of the main deck for "survey" state after 25 years of service is lower of the collapse strength calculated according to the CSR "rule" corrosion depth. However, the overall hull-girder properties are much higher for actual "survey" condition than for CSR "rule" corrosion state. This observation indicates that the ultimate bending moment capacity calculated according to the CSR "net" thickness approach is conservative.

The case study expectedly confirms that the HULS-1 single step method is more conservative leading to about 10% lower ultimate bending moment than PCA progressive collapse analysis method due to different approaches to the problem.

Finally, the case study provides the long-term non-linear corrosion wastage prediction model fitted to mean values of measured corrosion of the main deck plating. The long term corrosion wastage model of the main deck indicate more rapid degradation of load carrying capacity with respect to ultimate lateral pressure due to local bending of plating.

The corrosion wastage prediction can support planning future service of the considered ship. Moreover, as many old tankers are considered nowadays for conversion to FPSO vessels, the case study in the paper jointly with ship reliability methods and theoretical corrosion propagation models by Sun & Guedes Soares (2006) may be used for rational decisions about the feasibility of conversions.

REFERENCES

ABS, DNV, LLOYD'S REGISTER 2006. Common Structural Rules for Double Hull Oil Tankers.

Bureau Veritas, MARS 2000, (www.veristar.com)

Bureau Veritas, 2000, *Rules for Classification of Steel Ships*, Paris.

Garbatov, Y.; Guedes Soares, C., and Wang, G. Non-Linear Corrosion Wastage of Deck Plates of Ballast and Cargo Holds of Tankers . *Journal of Offshore Mechanics and Arctic Engineering*. 2007; 129(1):48-55

Gordo, J.M., Guedes Soares, C. & Faulkner, D. 1996. Approximate Assessment of the Ultimate Longitudinal Strength of the Hull Girder. *Journal of Ship Research*. 40(1):60-69.

Mage, P. 2006. *Safety of aged ship structure*, Graduation Thesis, University of Zagreb. (in Croatian)

Nieuwenhuijs, M.W, Segretain, J.F. & Baumans, P. 2006. First experience with Common Structural Rules for Bulk Carriers, *Proceedings of the 17th Symposium on Theory and Practice of Shipbuilding in memoriam prof. Leopold Sorta (SORTA)*, Rijeka, Croatia.

Paik, J.K. & al. 2006. Condition Assessment of Aged Ships, *Proceedings of 16th International Ship and offshore Structures Congress (ISSC)*,Vol.2, Southampton, UK, pp.269-320.

Steen, E. Østvold, T.K. & Valsgard, S. 2001. A New Design Model for Ultimate and Buckling Strength Assessment of Stiffened Plates, *Practical Design of Ships and Mobile Units (PRADS)*.

Sun, H.-H. & Guedes Soares, C. 2006. Reliability-Based Inspection of Corroded Ship-Type FPSO Hulls, *Journal of Ship Research*. 50(2): 171-180.

DNV 1978 SHIPS' LOAD AND STRENGTH MANUAL. Accession No, 00651001. Corp. Authors / Publisher, Det Norske Veritas information.