CORROSION AND SHIP HULL ULTIMATE STRENGTH

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Abstract: For steel construction and marine structure in particular, the corrosion can be one of the collapse cause, due to excessive reduces of strengths areas and implicit decrease of ultimate moment, accomplished with the fatigue crack and progressive fracture evolution. At present, corrosion rata estimation has an empirical character, therefore the simplified models is use. The variables in frequently used corrosion models have probabilistic character. The means and the standard deviation for plate's thickness in different corrosion phases of linear and parabolic-linear models are presented in the paper. On the base of linear model are done some results for hogging ultimate bending moment at a bulk-carrier in different stages (ages) of corrosion.

Keywords: corrosion ship, corrosion model, ultimate bending moment

1. INTRODUCTION

Corrosion consists in partial or global metals destructing as a consequence of chemical, biochemical or electrochemical reaction that appears during interaction with environmental medium. Corrosion loss in industrial country was evaluated to 4-5 % from crude product ([6]). These loss manifested by direct irrecoverable metal loss (cca. 10-20 %) and by indirect consequences, much more difficult to appreciate: mass increase due to the corrosion added – needed to assure sufficient strength and correctly function in all live time, supplementary cost for over measure, difficulties in making up, deterioration of exploitation characteristic, increase of repair work, produce loss (fluid/gas), technological time lost, efficiency decrease, energy expend increase etc. Global, in industrial country, the cost of metal loss due to corrosion is tens dollars/year/man. The statistics on corrosion loss show that the naval branch is in front-rank, followed by civil engineering, chemical engineering, metallurgical engineering etc. Different ship corrosive medium – fluid or gaseous – can act independent or simultaneous. The implacable corrosion of ship structure is included in more general ship reliability and maintenance problematic – which is given special attention.

Corrosion rate depend on the structure type and the characteristic of corrosive medium in contact with the metal. Usual, it expresses in *mm/year* and allows at each moment T to determine the p plate thickness $t_{p,T}$,

$$\delta_{p,T} = -\frac{\mathrm{d}t_{p,T}}{\mathrm{d}T} \quad [mm/an] \quad \Rightarrow \quad t_{p,T} = t_{p,T_o} - \int_{T_o}^{T} \delta_{p,T}\,\mathrm{d}T \quad \Leftrightarrow \quad t_{p,T} = t_{p,T_o} - \Delta t_{p,T} \quad , \tag{1}$$

where t_{p,T_o} is initials p plate's thickness at $T = T_o$ (as-built thickness) and $\Delta t_{p,T}$ is the plate's thickness change due to corrosion at T time – which depends of corrosion adopted model. Minus sign appear because $t_{p,T}$ decrease when T increases. In [8] are given a series of values for corrosion rate, evaluated for different locations of the planetarium ocean and also is given the dependence of corrosion rate on the type of steel. In the Rule ([1], for instance) there are different regulation on the corrosion wear of ship hull plates.

2. CORRODED PLATE THICKNESS. CORROSION PATTERNS

Corrosion is an essential factor of deterioration for the steel structures, due to diminishing of the strength areas and progress of the fatigue cracks which generates fractures. A general formulation doesn't exist, yet, as it can be seen in [9], damages being dependent on different situations that include distinctive circumstances. The corrosion analysis revealed the existence of a significant number of parameters which influence corrosion and the difficulty in obtaining a corrosion pattern that can consider all this parameters. Nowadays, the corrosion rate estimation is mostly empirical, based on statistical data collected from different ship types, data used to develop some adapted models.

Linear model, with constant corrosion rate, is the simplest model. From (1) results linear time dependence for thickness of p corroded plate ($T_{\max}$ is p plate lifetime equal to ship lifetime or to plate renewal period),

$$t_{p,T} = t_{p,T_o} - \delta_p (T - T_o) \quad , \quad T_1 < T < T_{\max} \quad . \tag{2}$$

Experimental data shows that nonlinear models are much more suitable for ship structure corrosion. Southwell ([11]) and Yamamoto ([13]) has observed and processed the results obtained for the ships in different locations, and show that due to corrosion plate thickness reduces nonlinear, very rapidly in the beginning of exploitations – initial phase of corrosion, after which plate reducing is relatively stabilized (stationary phase of corrosion). The observations also show that it exists a pre initial phase (noted **0** in figure 2), with duration $T_1 - T_o$, named coating longevity, in which corrosion don't exist, due to integrally anti corrosion protection, (100 % effectiveness), i. e. $t_{p,T_1} = t_{p,T_o}$. Exponential model proposed on basis of these observations (fig. 2) is defined by relations

$$t_{p,T} = 0 \quad , \quad T \le T_1, \quad , \quad t_{p,T} = t_{p,T_o} - \Delta t_{p,\infty} \left[1 - \exp\left(-\frac{T - T_1}{T_1} \right) \right] \quad , \quad T > T_1 \quad , \tag{3}$$

where $\Delta t_{p,\infty}$ is the variation of plate thickness (thickness of corrosion deposit). Such models are flexible and can be applied in any circumstance, only if are known $\Delta t_{p,\infty}$ and T_1 ([4], [7]).

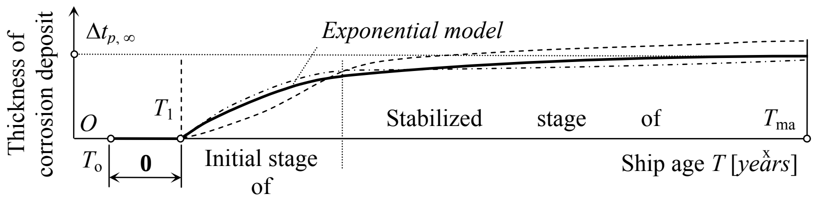


Fig. 1 Corrosion deposit thickness evolution. Exponential model

A simplification of the nonlinear model can be obtained by inserting a particular value ($T_2 > T_1$) which delimits the rapidly corrosion process stage of the relative stable stage and by portions linearization of corrosion rate. Thus is obtained the model from fig. 2, with **I** and **II** stages (plus pre initial stage **0**). Stage **I** is the corrosion evolutional stage. It extends in the $T_2 - T_1$ interval (starting with the beginning of the corrosion protection deterioration) and is defined by linear corrosion rate ascending (during this stage the plate's thickness reducing is more and more pronounced),

$$\delta_{p,T,\mathrm{I}} = \delta_{p,\mathrm{II}} \frac{T - T_1}{T_2 - T_1} \quad , \quad T_1 < T \le T_2 \quad , \tag{4}$$

where T_2 is the completely damaged corrosion protection time, when corrosion rate reach its maximum value δ_p, equal to corrosion rate at the beginning of the stage **II**. Based on the (1) and (4) formulas, can be obtained the parabolic expression of the thickness reducing in time,

$$t_{p,T,\mathrm{I}} = t_{p,T_o} - \frac{1}{2}\delta_p \frac{(T - T_1)^2}{T_2 - T_1} \quad , \quad T_1 < T \le T_2 \;\Rightarrow\; t_{p,T_2} = t_{p,T_o} - \frac{1}{2}\delta_p (T_2 - T_1) \quad . \tag{5}$$

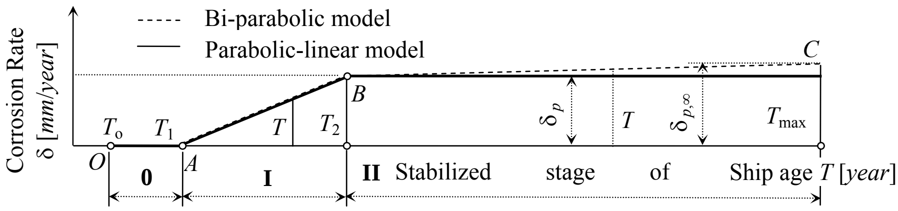


Fig. 2 Simplified nonlinear models

For stage **II**, that extend the interval [T_2 , T_{max}), can be also used linear ascending rate corrosion but in a small proportion of the one used in stage I, therefore obtaining an bi-parabolic model - more conservative than the exponential model. If the corrosion rate is constant during this stage (fully stabilized corrosion), a linear-parabolic model is obtained – easily to use in calculus [4] though it uses three parameters (T_1, T_2, δ_p). Variation of plate thickness during the stage **II** of the linear-parabolic model is obtained with a similar formula with (2),

$$t_{p,T,\text{II}} = t_{p,T_2} - \delta_p (T - T_2) \;\;,\;\; T_2 < T < T_{\max} \;\Rightarrow\; t_{p,T,\text{II}} = t_{p,T_o} - \delta_p \left(T - \frac{T_1 + T_2}{2} \right) \;\;,\;\; T_2 < T < T_{\max} \;\;. \tag{6}$$

At the $T_{\max}$ time, the plate will have the thickness $t_{p,T_{\max}} = t_{p,T_o} - \delta_p \left(T_{\max} - \dfrac{T_1 + T_2}{2} \right)$.

3. MEAN VALUES ANE STANDARD DEVIATION FOR CORRODATED PLATE THICKNESS

Corrosion processes are frequently subject to the uncertainties caused by the environmental conditions, material characteristics and loading. Consequently, the strength characteristics (including ultimate bending moments) becomes statistical parameters that are dependent of the corroded structural elements geometry (plates and girders) [5], [10]. For the probabilistic formulation of the corrosion models is necessary to define the mean values and variance (standard deviation) of thickness plates in different stages, taking into account that the variables which they depend (t_{p,T_o} , δ_p , T_1 şi T_2) have also probabilistic character. If a random variable z is a linear combination of two random variables, x and y, when z has the mean value $\overline{z} = a\overline{x} + b\overline{y}$ and the standard deviation $D_z = a^2 D_x + 2abC_{cy} + b^2 D_y$. If x, y are statistical independent, that is uncorrelated (covariance C_{xy} = 0), when $D_z = a^2 D_x + b^2 D_y$. Mean thickness of the p plate at T time is given by the formula $\overline{t_{p,T}} = \overline{t_{p,T_o}} - \overline{\Delta t_{p,T}}$ where $\overline{t_{p,T_o}}$, $\overline{\Delta t_{p,T}}$ are means of the initial thickness, respectively thickness of corrosion deposit. Having the fact that t_{p,T_o} and $\Delta t_{p,T}$ are statistical independent, results that the thickness standard deflection at time T has the expression $D_{t_p,T} = D_{t_p,T_o} + D_{\Delta t_{p,T}}$, where D_{t_p,T_o} , $D_{\Delta t_{p,T}}$ are the standard deflection of the initial thickness and corrosion wear of the p plate at time T, respectively. The formulas can be generalized for the linear combination between more then two random parameters. In order to obtain the variance of plate thickness having a known corrosion model, Taylor series expansion is used, with linear terms retaining.

For *linear model*, $t_{p,T}$ has the mean $\overline{t_{p,T}} = \overline{t_{p,T_o}} - \overline{\delta_p}(T - \overline{T_1})$, where $\overline{t_{p,T_o}}$, $\overline{\delta_p}$, $\overline{T_1}$ are mean of random variables t_{p,T_o} , δ_p , T_1 and the variance $D_{t_{p,T}} = \left(\dfrac{\partial t_{p,T}}{\partial t_{p,T_o}} \right)^2_{t_{p,To} = \overline{t_{p,To}}} D_{t_{p,T_o}} + \left(\dfrac{\partial t_{p,T}}{\partial \delta_p} \right)^2_{\delta_p = \overline{\delta_p}} D_{\delta_p} + \left(\dfrac{\partial t_{p,T}}{\partial T_1} \right)^2_{T_1 = \overline{T_1}} D_{T_1}, \overline{T_1} < T < T_{\max}$, where $D_{t_{p,T_o}}$, D_{δ_p} , D_{T_1} are variance of t_{p,T_o} , δ_p , T_1 and $\dfrac{\partial t_{p,T}}{\partial t_{p,T_o}} = 1$, $\dfrac{\partial t_{p,T}}{\partial \delta_p} = -(T - T_1)$, $\dfrac{\partial t_{p,T}}{\partial T_1} = \delta_p$.

For *parabolic-linear model* – stage **I**, $t_{p,T}$ has the mean $\overline{t_{p,T,\mathrm{I}}} = \overline{t_{p,T_o}} - \frac{1}{2}\overline{\delta_p}\frac{(T-\overline{T}_1)^2}{\overline{T}_2-\overline{T}_1}$, $\overline{T}_1 < T \le \overline{T}_2$, where $\overline{T}_1$ and $\overline{T}_2$ are the mean for the times which the corrosive protection become inefficient respective completely damaged, and $\overline{\delta_p}$ is the mean of the stabilized corrosion rate. Using Taylor series and retaining only the linear terms, variance of p plate thickness at time T time of stage **I** have expression

$$D_{t_{p,T,\mathrm{I}}} = \left(\frac{\partial t_{p,T,\mathrm{I}}}{\partial t_{p,T_o}}\right)^2_{t_{p,T_o}=\overline{t_{p,T_o}}} D_{t_{p,T_o}} + \left(\frac{\partial t_{p,T,\mathrm{I}}}{\partial \delta_p}\right)^2_{\delta_p=\overline{\delta_p}} D_{\delta_{p,\mathrm{II}}} + \left(\frac{\partial t_{p,T,\mathrm{I}}}{\partial T_1}\right)^2_{T_1=\overline{T}_1} D_{T_1} + \left(\frac{\partial t_{p,T,\mathrm{I}}}{\partial T_2}\right)^2_{T_2=\overline{T}_2} D_{T_2} \quad , \tag{7}$$

where

$$\frac{\partial t_{p,T,\mathrm{I}}}{\partial t_{p,T_o}} = 1 \;\; ; \;\; \frac{\partial t_{p,T,\mathrm{I}}}{\partial \delta_p} = -\frac{1}{2}\frac{(T-T_1)^2}{T_2-T_1} \;\; ; \;\; \frac{\partial t_{p,T,\mathrm{I}}}{\partial T_1} = -\frac{1}{2}\delta_p\left(\frac{T-T_1}{T_2-T_1}\right)\left(\frac{T-T_1}{T_2-T_1}-2\right) \;\; ; \;\; \frac{\partial t_{p,T,\mathrm{I}}}{\partial T_2} = \frac{1}{2}\delta_p\left(\frac{T-T_1}{T_2-T_1}\right)^2 \; . \tag{8}$$

The mean of p plate thickness at T time of stage **II** has expression $\overline{t_{p,T,\mathrm{II}}} = \overline{t_{p,T_o}} - \overline{\delta_p}\left(T - \frac{\overline{T}_1+\overline{T}_2}{2}\right)$, $\overline{T}_2 < T < T_{\max}$.

Variance is done by (7), where $\frac{\partial t_{p,T,\mathrm{I}}}{\partial t_{p,T_o}} = 1$; $\frac{\partial t_{p,T,\mathrm{I}}}{\partial \delta_p} = -\left(T - \frac{T_1+T_2}{2}\right)$; $\frac{\partial t_{p,T,\mathrm{I}}}{\partial T_1} = \frac{\delta_p}{2}$; $\frac{\partial t_{p,T,\mathrm{I}}}{\partial T_2} = \frac{\delta_p}{2}$.

ECHIVALENT ANGLE PROFILE FOR BULB SECTION

In order to use the above formulas for the laminate girders is necessary to assimilate those with plate. In accordance with ABS rules [1], a bulb section may be taken as equivalent to a built-up section. The dimensions of the equivalent angle section are to be obtained, in *mm*, from the following formula:

$$t_w = t_w^{'} \;\; , \;\; h_w = h_w^{'} - \frac{h_w^{'}}{9.2} + 2 \;\; ; \;\; b_f = \alpha\left(t_w^{'} + \frac{h_w^{'}}{6.7} - 2\right) \;\; , \;\; t_f = \frac{h_w^{'}}{9.2} - 2 \;\; , \tag{9}$$

where $\alpha = 1{,}1 + (120 - h_w^{'})^2/3000$ or $\alpha = 1$, as $h_w^{'}$ is $\le$ or $>$ 120 *mm*.

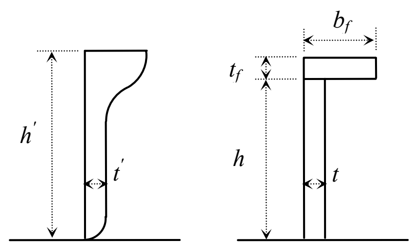


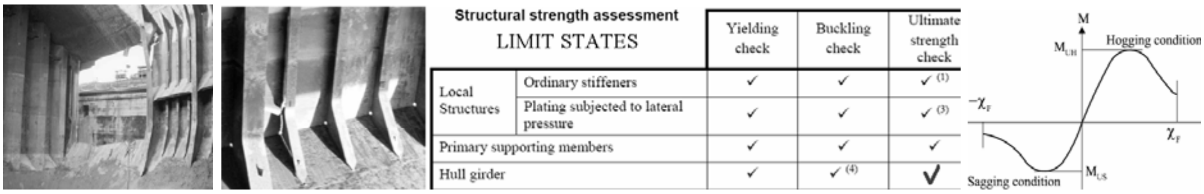
Fig. 3

Example. The bulb HP 300×12 DIN are geometrical characteristics $t_w^{'}$ = 12 *cm*, $h_w^{'}$ = 300 *cm* ; z_n = 18,7 *cm* (measured from base plate), A = 49,7 cm^2, I_x = 4460 cm^4 (x – central axis parallel with base plate).

For equivalent profile are obtained: t_w = 12 *cm*, h_w = 265,4 *cm* b_f = 54,78 *cm*, t_f = 30,61 *cm*; z_G = 18,37 *cm*; A = 48,62 cm^2; I_x = 4289 cm^4. As can be seen, the errors are little, on conservative side.

CORROSION EFECT ON ULTIMATE BENDING MOMENT

The corrosion of ship's hull plate decreases the local and general strength capacity (fig. 4, *a*, [3]. In accordance with Register Rules, ultimate bending moment M_u is one of most important structural limit strength assessment criteria, being in present a compulsory check, as can be seen in figure 4, *b* [1]. It is to be checked that the hull girder ultimate bending capacity is in compliance with the formula $\gamma M \leq M_u$, where M is design bending moment for the ship in intact, flooded and harbour conditions and γ_R is the safety factor.



a) *b*) *c*)

Fig. 4 a) Buck-carrier's corroded plates; b) local/general strength check; c) moment capacity versus curvature

The ultimate bending capacities of a hull girder transverse section, in hogging and sagging conditions, are defined as the maximum values of the curve of bending moment capacity M versus the curvature χ of the transverse section (see Fig 4, c). The curvature χ is positive for hogging condition and negative for sagging condition. The curve M-χ is to be obtained by means of an incremental-iterative approach. In this approach, the ultimate hull girder bending moment capacity M_u is defined as the peak value of the curve M-χ. The curve is to be obtained through an incremental-iterative approach. Each step of the incremental procedure is represented by the calculation of the bending moment which acts on the hull transverse section as the effect of an imposed curvature. For each step, the value χ is to be obtained by summing an increment of curvature to the value relevant to the previous step. This increment of curvature corresponds to an increment of the rotation angle of the hull girder transverse section around its horizontal neutral axis. This rotation increment induces axial strains ε in each hull structural element, whose value depends on the position of the element. In hogging condition, the structural elements above the neutral axis are lengthened, while the elements below the neutral axis are shortened. Vice-versa in sagging condition. The stress σ induced in each structural element by the strain ε is to be obtained from the load-end shortening curve σ-ε of the element, which takes into account the behaviour of the element in the non-linear elasto-plastic domain. The distribution of the stresses induced in all the elements composing the hull transverse section determines, for each step, a variation of the neutral axis position, since the relationship σ-ε is non-linear. The new position of the neutral axis relevant to the step considered is to be obtained by means of an iterative process, imposing the equilibrium among the stresses acting in all the hull elements. Once the position of the neutral axis is known and the relevant stress distribution in the section structural elements is obtained, the bending moment of the section around the new position of the neutral axis, which corresponds to the curvature imposed in the step considered, is to be obtained by summing the contribution given by each element stress. The hull girder transverse sections are constituted by the elements contributing to the hull girder longitudinal strength, considered with their net offered scantlings. If ultimate bending moment is evaluate at the any time in the ship life, must be taken into account the corroded thickness of plates.

For illustration only, is presented the corrosion effect on ultimate bending moment at the bulk-carrier, having $L = 225.3\,m$, $B = 32.24\,m$, $D = 20\,m$, $C_b = 0.863$, taking *linear corrosion model* with 0,1 *mm/an* corrosion rate. Using the ULTIM code ([2]), table 1 contain the ultimate M_{UH} and section area, obtained for new build and corroded ship at 4, 8, 12, 16, 20 year ages, and figure 5 presents the corresponding graphic.

Table 1

New built BULK, HOGGING.SEC Area = 3664797.793 mm^2 Ultimate BM = 5452.410 *MNm*	4 years BULK, HOGGING.SEC Area = 3583670.724 mm^2 Ultimate BM = 5321.276 *MNm*	8 years BULK, HOGGING.SEC Area = 3502543.655 mm^2 Ultimate BM = 5190.490 *MNm*
12 years BULK, HOGGING.SEC Area = 3421416.586 mm^2 BM = 5059.480 *MNm*	16 years BULK, HOGGING.SEC Area = 3340289.517 mm^2 Ultimate BM = 4928.142 *MNm*	20 years BULK, HOGGING.SEC Area = 3259162.448 mm^2 Ultimate BM = 4796.253 *MNm*

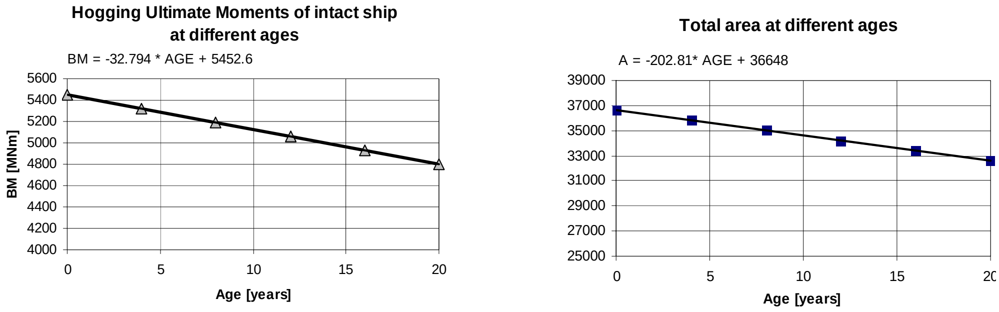


Fig. 5 Ultimate moment M_{UH} and section area versus ship age

CONCLUSIONS

For linear corrosion model the ultimate moment is practical linear decreasing – in examined case, with 32,8 *MNm* annual rate (about 0,6 %/*year*). The section area has also linear decrease, with 203 $cm^2/year$ (about 0,55 %/*year*). By means of simple calculus, the results may be transposing for any other corrosion model than linear.

Presented expressions for statistic parameters (means and variance) can be used in probabilistic approach of ultimate bending moment, using the existing data for annual corrosion rates of different ship types.

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