

LIMIT MOMENTS UNDER CORROSION AT BULK-CARRIERS

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Abstract: On the base of linear corrosion model are done some analysis results of limit moments (Initial Yielding Bending Moment, Ultimate Yielding Bending Moment, Ultimate Bending Moment in Hogging and Sagging conditions) at a bulk-carrier hull girder transverse section in different stages (ages) of corrosion. For wide plate is obtained the load-end shortening (average stress-average strain) values, needed for the used ULTIM code, which considers the effects of welding initial deflections, residual stress and vertical shear force.

Keywords: corrosion ship, corrosion model, ultimate bending moment

1. INTRODUCTION. LIMIT MOMENTS

Unavoidable corrosion related problems merge the larger sphere of structural reliability. The oil tankers and especially the bulk-carriers are subject in a greater extent to corrosion, owing the corrosive nature of the cargo itself (coal, iron ore, various chemicals). Products such as sulfates, phosphates or coal may rapidly corrode the side shell frames and initiate cracks. The coal's corrosive nature is due to the sulfur content, which, reacting with the condensation moisture present in the ship's holds, produces a diluted water mix of sulfuric acid, which, in time, corrodes the structural members. For a bulk-carrier carrying coal and iron ore, one transverse structural member, initially 10 mm thick, may corrode (unequally on height direction) by 3...5 mm in a very short period.

As the corrosion process is going further, the structural resistance capability is diminished, enhancing the occurring of ultimate states such as fatigue cracking, buckling or various other damages like shell loosening, cracks and even ruptures [6]. The plating and stiffeners corrosion affects also the ship's general strength capability, leading to ultimate resistance worsening, presently a mandatory issue in the Classification Societies Rules [1].

To assess the ship's hull general bending strength, the limit moment concept may be used, following several initial premises. Assuming that we have no buckling due to compression, the moment corresponding to the yield stress occurring (in cross-section, the stresses are entirely elastic) is named Initial Yielding Bending Moment, $M_Y = \sigma_Y W_D$, where $\sigma_Y = R_{eH}$ is the material's yielding stress and W_D , is the strength modulus at deck's level. If in all cross-section's points the stress equals the yield stress figure, then the corresponding limit moment is named Fully Plastic Limit Bending Moment or Ultimate Yielding Bending Moment, $M_P = \sigma_Y W_{pl}$, where W_{pl} (plastic strength modulus) is the addition of the static moments related to the y_{pl} axis and computed using the cross-section's areas above and below this axis - axis which halves the cross-section. In achieving the plastic limit bending moment, the Prandtl material constitutive law is assumed (also Classification Societies Rules recommended). The M_P moment was initially proposed by Caldwell (some corrections added) as a ship's transverse section general bending verifying criteria [5]. The Ultimate Bending Moment of a hull girder transverse section in hogging and sagging conditions (M_{UH} and M_{US}) are defined as the maximum values of the curve of bending moment capacity M versus the curvature χ of the transverse section. The concept was first introduced by Smith [15]. Until the general collapse state is achieved, the various ship's section parts are successively attaining limit states such as buckling/plastic deformations, subsequently the approach being named as ship's section's progressive collapse.

2. INCLUDING WIDTH PLATES LOAD-END SHORTENING CURVES IN USED CODE

Limit bending moments and progressive collapse were evaluated using the ULTIM code ([3], [4]), written on the base of Smith approach algorithm (see App. 1 Ch. 5, Part 5, ABS 2006). The algorithm is coded in PASCAL programming language and a versatile pre and post processor is added. Among others, the program considers the effects of initial deflections, residual stress, corrosion, lateral pressure and vertical shear force (SHEAR module, [2]). The box girder cross section is automatically divided into hard corners and stiffened plating panel elements (one stiffener with its associated effective plating), for which a priori are modeled the tensile and the compressive behavior from the beginning to the collapse, as well as post-collapse.

Hard corners are sturdier elements composing the hull girder transverse section, which collapses mainly according to an elasto-plastic mode of failure (material yielding). These elements are generally constituted of two plates not lying in the same plane. Bilge, sheer strake-deck stringer elements, girder-deck connections and face plate-web connections on large girders are typical hard corners. For lengthened and shortened hard corners, the relevant load-end shortening curve σ - ε is to be obtained according Prandtl, $\sigma = \Phi R_{eH}$, where: Φ -edge function is equal to -1 for $\varepsilon < -1$, ε for $-1 < \varepsilon < 1$ and 1 for $\varepsilon > 1$; relative strain ε is equal to $\varepsilon_E / \varepsilon_Y$ (ε_E - element strain and ε_Y - strain at yield stress in the element, $\varepsilon_Y = R_{eH} / E$).

Plating panels and ordinary stiffeners composing the hull girder transverse sections may collapse in one of the modes of failure specified in Tab 1.

Table 1

Element	Mode of failure
Lengthened transversely framed plating panel or ordinary stiffeners	Elasto-plastic collapse
Shortened ordinary stiffeners of longitudinally framed plating panel	Beam column buckling ; Torsional buckling ; Web local buckling of flanged profiles ; Web local buckling of flat bars
Shortened transversely framed plating panel	Plate buckling

The algorithm used in ULTIM code differs from the Smith method because it uses analytically derived average stress-average strain (Load-end shortening curves) relationships of longitudinally framed plating panel. The behavior of compressed elements has followed in principle the work of Adamchak,^{*)} but with modified relationships of stress-strain from the elastic range to the post-collapse region. It has been used the theory of plastic collapse mechanism, relating end shortening with central deflection to define the stress-strain relationship in the post collapse range, as was done by Adamchak, but the end conditions are changed. Thus, derivations consist on simply supported end conditions of panels, accounting for the effects of initial deflection and the eccentricity caused by the loss of plate stiffness. These changes are much more compatible with Hughes ([10]) whose evaluation of the collapse stress of compressed panels was followed.

In ULTIM code, only longitudinally framed plating panel was initially considered. Therefore is needed to derive and insert the characteristic values for the elasto-plastic load-end shortening (average stress-average strain) for panels with $\alpha < 1$ (Fig. 1). For classic bulk-carriers (without double walls), this type of panels appear at side structure. For the transversely framed *sides*, ABS recommend the formula (original notations are using)

$$\sigma_{CR5} = \min \left\{ \Phi R_{eH}, R_{eH} \left[\frac{s}{l} \left(\frac{2.25}{\beta_E} - \frac{2.25}{\beta_E^2} \right) + 0.1 \left(1 - \frac{s}{l} \right) \left(1 + \frac{1}{\beta_E^2} \right)^2 \right] \right\},$$

where Φ is the edge function and β_E the slenderness parameter, written in the form $\beta_E = 10^3 s / t_p (\varepsilon R_{eH} / E)^{1/2}$. We are used the ultimate stress determined with method suggested by Hughes ([10]), based on Valsgård approximation ([18]). For the transversally framed ultimate strengths decreases markedly because the middle portion of the plate receives less support from the sides and become more and more like a wide column, for which the buckling mode is a single half-wave pattern. The stress distribution within the plate will be as shown in fig. 1.

^{*)} Adamchak, J. C., *ULTSTR - A program for estimating the collapse moment of a ship's hull under longitudinal bending*, DTNSRDC 82/076

Ultimate compression strength of wide column is essential influenced by plate initial deformation. This was numerical obtained by Smith in the graphic forms, expressed with a good approximation by relation

$$(\sigma_{au})_{wc} = \sigma_Y \frac{0,63}{1 + 3,27 \delta_p / (\beta^2 t) \beta^2} , \quad (1)$$

where β is slenderness parameter, $\beta = a/t(\sigma_Y/E)^{1/2}$, E is Young modulus, σ_Y is yield stress and δ_p - initial deformation due to welding; for this, was used recommended Antoniou formula, $\delta_p = 0,065 t \beta^{1,65}$. When the applied load σ_a reaches the value given by (1) the center of the plate has collapsed and this region has an average value of stress equal to $(\sigma_{au})_{wc}$. As σ_a is further increased, this center region becomes wider but the level in it remains constant because $(\sigma_{au})_{wc}$ is independent of the width of the wide column. With increasing load, the stress in the side regions continues to increase and eventually these side regions undergo inelastic buckling and the plate collapses. Because it would be very difficult to determine the exact stress distributions, by Valsgård was suggested that at collapse each of the side regions is similar to one-half a square plate of length a , for which ultimate strength is obtained with the formula from the long plate ([10] – & 12.6),

$$(\sigma_{au})_L = 0,25 \sigma_Y \left(1,6 + \xi - \sqrt{\xi^2 - 10,4/\beta^2} \right) , \quad (2)$$

where $\xi = 1 + 2,75/\beta^2$. From the equilibrium between applied load and the internal average stresses we have $b(\sigma_{au})_{wp} = a(\sigma_{au})_L + (b-a)(\sigma_{au})_{wc}$, and the ultimate strength of a wide plates is

$$(\sigma_{au})_{wp} = \frac{a}{b} (\sigma_{au})_L + \left(1 - \frac{a}{b} \right) (\sigma_{au})_{wc} . \quad (3)$$

Residual stresses of about 10% from yielding were assumed in obtaining expressions (3).

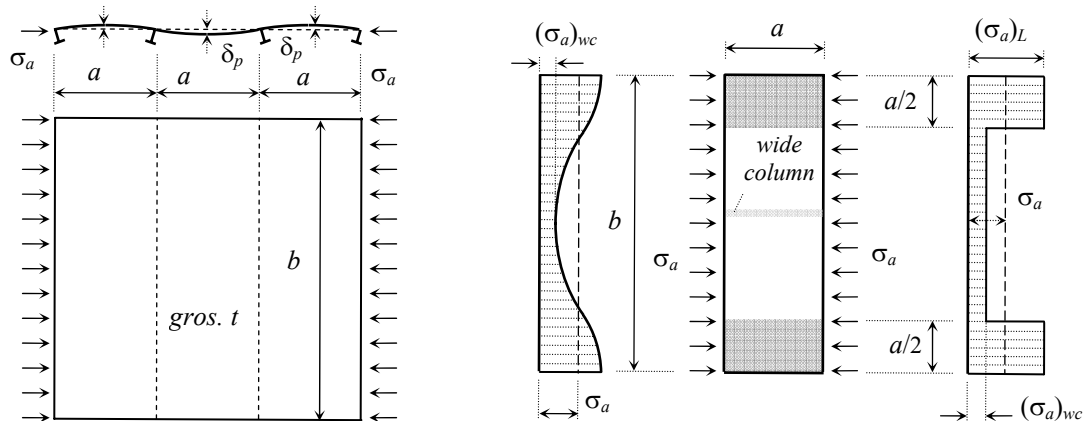


Fig. 1

The ultimate strain can be obtained by means of secant modulus from $(\sigma_{au})_{wp} = E_s(\epsilon_{au})_{wp}$, where E_s is expressed by means of reduction factor T , $E_s = TE = [(\sigma_{au})_L / \sigma_Y + 0,1]E$. Thus

$$(\epsilon_{au})_{wp} = \frac{(\sigma_{au})_{wp}}{E} \frac{1}{0,25 \left(2 + \xi - \sqrt{\xi^2 - 10,4/\beta^2} \right)} . \quad (4)$$

Example. For plate with $a = 840 \text{ mm}$, $b = 9070 \text{ mm}$, $t = 19 \text{ mm}$, $E = 208000 \text{ MPa}$, $\sigma_Y = 208000 \text{ MPa}$, having slenderness parameter $\beta = 1,5$ and $\delta_p = 2,4 \text{ mm}$, is obtained : $(\sigma_{au})_{wc} = 35,8 \text{ MPa}$, $\xi = 2,25$, $(\sigma_{au})_L = 193,2 \text{ MPa}$, $(\sigma_{au})_{wp} = 50,34 \text{ MPa}$, $(\epsilon_{au})_L = 0,00173$.

3. NUMERICAL RESULTS

The limit moments (Initial Yielding Bending Moment, Plastic Bending Moment, Ultimate Bending Moment in Hogging and Sagging conditions) are obtained for a bulk-carrier hull girder having $L = 225,3 \text{ m}$, $B = 32,24 \text{ m}$, $D = 20 \text{ m}$, inter-frame $l = 0,840 \text{ m}$ and $C_b = 0,863$, taking linear corrosion model ([14]) with $0,1 \text{ mm/year}$ corrosion rate. The initial deformation was considered equal to $\text{span}/750 = 3,2 \text{ mm}$. Using MODELER menu of ULTIM, was created material and geometrical model (plate thickness and stiffeners for new built ship), on base of which was automatically divided the middle transverse ship section (fig. 2, a). Design shear force was adopted the ABS value 53 MN . The obtained shear stress distribution (for new built ship) is shown in fig. 23, b.

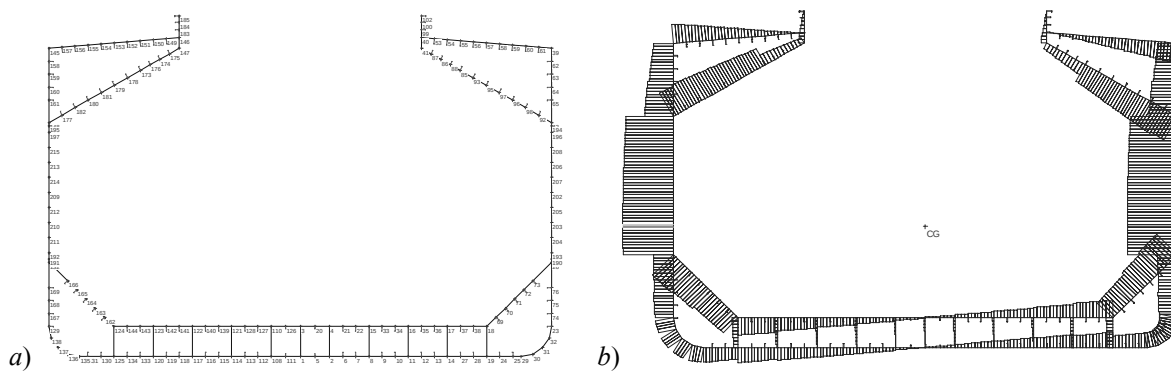


Fig. 2

The stress distributions corresponding to Initial Yielding, Ultimate Yielding and Ultimate Hogging and Sagging condition bending moments (for new built ship) are shown in fig. 3, a, b, c, d.

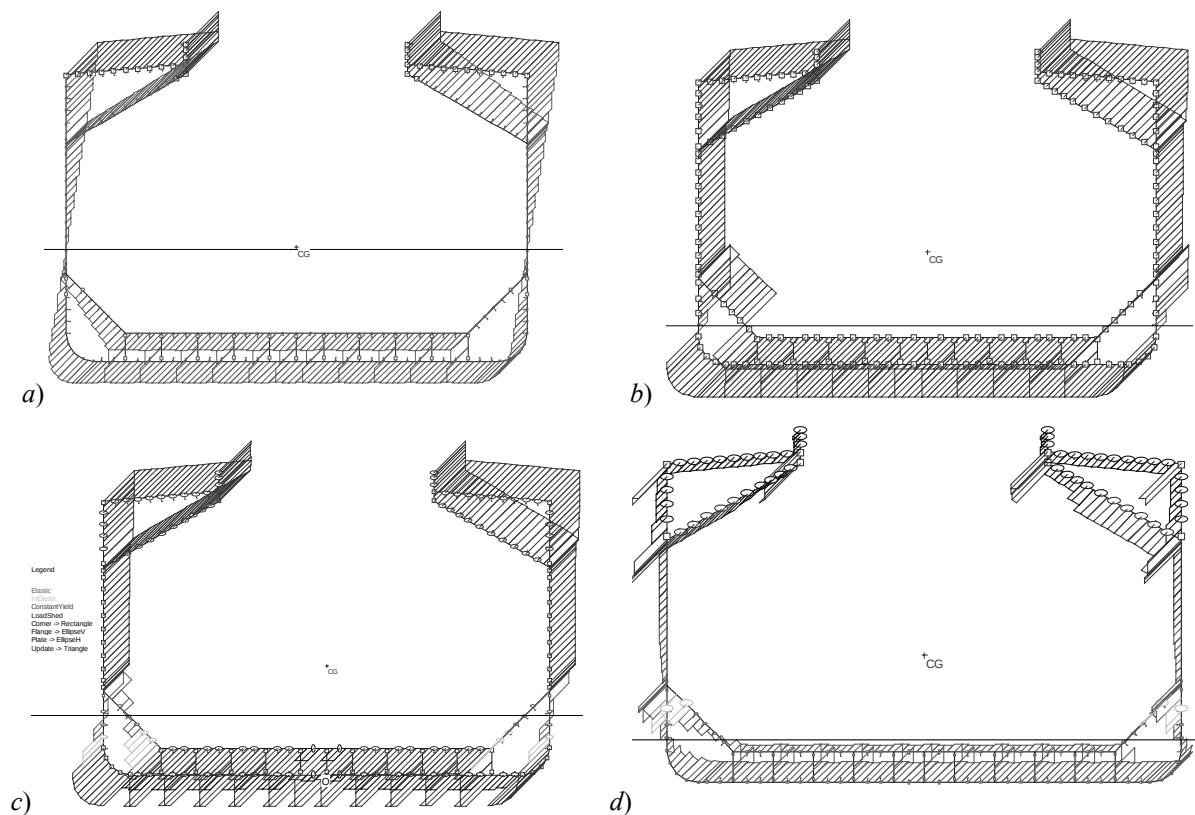


Fig. 3

If $\sigma_{Y tens} = \sigma_{Y compr}$, the moments M_Y and M_P have the same values in sagging and hogging, but stresses have opposite signs. It can be observed that for the values near M_P , neutral axis is situated little above double bottom. Therefore, all side plates will be in tension at hogging condition. For mentioned plates, the $(\sigma_{au})_{wp}$ and $(\varepsilon_{au})_{wp}$ values at sagging will be entered immediately after starting the initializing of ultimate moment calculus (SagInit). In fig. 4, a, b and c respectively are shown the evolution of bending moments and neutral axes versus curvature for Prandtl and real behaviors at hogging and sagging. At sagging is observed a pronounced decreasing of bending moment after reaching ultimate value, which diminishes as curvature increases.

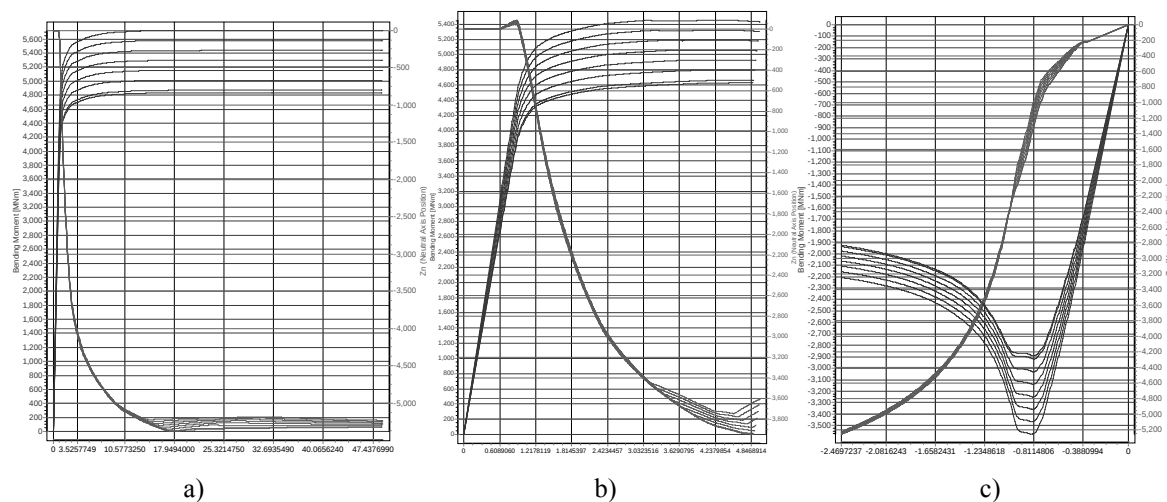


Fig. 4

The values of M_Y , M_P , M_{UH} , M_{US} for different ages of considered bulk-carrier obeyed to linear corrosion with 0.1 mm/year corrosion rate are centralized in table 2. On the data from table 2 are drawn more expressive diagrams from fig. 5.

Table 2

Ship age [year]	M_Y [MNm]	M_P [MNm]	M_{UH} [MNm]	M_{US} [MNm]
0	4070.496	5717.079	5452.410	3575.978
4	3978.041	5579.262	5321.276	3468.367
8	3885.790	5438.168	5190.490	3359.895
12	3793.587	5296.789	5059.480	3250.273
16	3701.434	5155.086	4928.142	3141.031
20	3609.329	5013.016	4796.253	3030.682
24	3517.272	4870.526	4663.294	2918.871
25	3494.266	4834.832	4629.972	2890.769

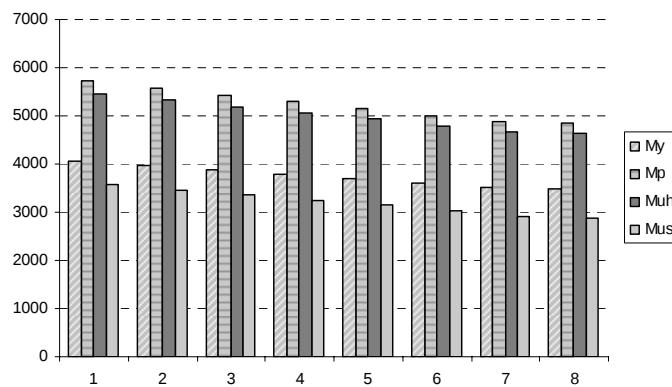


Fig. 5

4. CONCLUSIONS

With corrosion increasing, all the pattern of moment-curvature graphics remains the same. For linear corrosion model, the limits have also linear decreasing. From the MUS – curvature diagrams results that the contribution of side plates to ultimate sagging moment is insignificant.

The Ultimate Bending Moment in Sagging conditions is smaller than Ultimate Bending Moment in Hogging with about 30 %. Both these values are inferior in comparison with values Caldwell's Ultimate Yielding Bending Moment.

The Initial Yielding Bending Moment is smaller than Ultimate Bending Moment in Sagging that can seem a paradox. This is because of panels buckling from upper neutral axe of section.

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