TECHNICAL NOTE

CHANGE OF STEEL'S YIELD STRESS OVER SHIP'S SERVICE LIFE AND ITS EFFECT ON THE FIRST YIELD HULL GIRDER BENDING MOMENT

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SUMMARY

The publication deals with the decrease of the yield and tensile stress of high tensile shipbuilding steel AH-32 over ship's service life and its effect on the first yield bending moment as a representative of the hull girder capacity. An example is given for a sample 25K DWT (25 thousand tons deadweight) bulk carrier. The probability of failure is calculated as the probability of the total hull girder bending moment exceeding the first yield bending moment. The probabilistic distributions of yield and tensile stress are obtained from laboratory test of the specimen of AH-32 steel (corroded plates of a 20 year old ship). It is found that although the decrease of yield stress may not be great, the increase of the probability of failure (i.e., the probability that the total hull girder bending moment will exceed the first yield bending moment) could be substantial.

1. INTRODUCTION

In time-variant reliability of ship's hull structure, the effect of time (i.e. service life) is a very important factor that should be taken into consideration when calculating the probability of failure according to a given failure mode. This is true for all major parameters determining the structural reliability such as loads, geometric properties of the structure and mechanical properties of the material. In this publication, possible decrease of the material's mechanical properties and its effect on the first-yield bending moment M_Y are considered.

There are numerous publications on the material properties of shipbuilding steels. For the sake of brevity, one could mention here only the thorough analysis of available data for ordinary shipbuilding steel and high-tensile steel published in [3], [4], [9]. All data refer to as-produced steel, i.e. to as-built ship.

The decrease of material's mechanical properties is due to different type of corrosion wastage which depends on many factors, the most important of them being the duration of ship's service life and operational environment. As far as corrosion is concerned, evenly distributed, pitting and grooving corrosion are considered as major contributors to ship's hull structure reliability degradation.

There are few publications on different corrosion types and their effect on the ultimate strength of plates and stiffeners. One can mention the work reported in [8], [11], [12], [13] on pitting corrosion and its effect on the ultimate strength of plates and stiffeners. The general conclusion in these publications is that the major cause for degradation of the ultimate strength is the reduction of the cross sectional area of plates and stiffeners due to corrosion. There is no surprise in this finding because the applied load is static. When corroded plate or stiffener is loaded by cyclic or dynamic loading the degradation of their fatigue strength and brittle fracture toughness may be significantly reduced. Laboratory or full-scale tests with cyclic or dynamic load applied on corroded steel plates or stiffeners are expensive, more complicated and time consuming. This explanation could probably well be the reason for the scarcity of publications on this topic.

At this junction, it is worth referring to the work done in the Technical University of Lisbon (see [15], [16], [17], [18], [19], [20], [21]). The experimental work done at the University targeted numerical evaluation of the corrosion effect on the ultimate strength of plates and a box girder. The tests were performed for moderate and severe corrosion. A conclusion was formulated that the decrease of the ultimate strength is due not only to reduction of the plates' thickness but also due to reduction of the material mechanical properties. For example, it was found that the modulus of elasticity of ordinary shipbuilding steel under severe corrosion decreases by 54.3% [17]. The elastic tensile limit is reduced by 54.9% which is interpreted as a proof that the material is getting more brittle.

Another source of information supporting the above mentioned findings for the effect of corrosion on steel's mechanical properties is the work reported in [14]. Steels from three manufacturers have been tested. The ultimate tensile stress and elongation were presented as a function of the test time. At the end of the tests reduction of the yield stress was recorded from 16% to 40% depending on the steel type. For the ultimate tensile stress the recorded reduction was from 30% to 40%.

The use of the hull girder ultimate strength as a major criterion for assessment of the probability of failure of the hull girder for given duration of ship's service life and given operational environment is a widely accepted mode. The capacity of the ship's hull girder depends on two random parameters – geometric properties of the hull and mechanical properties of the material. From all mechanical properties, the material yield stress, f_Y, is the most important for the calculation of the hull girder capacity that is farther used in the calculations of the hull girder reliability (when the loads are applied). For this reason information for the material yield stress as a random variable is very important not only for as-built ship but for corroded and old ship structure.

The goal of this publication is to show the corrosion effect on the first-yield hull girder bending moment considering the random nature of the geometric properties (plates, stiffeners, hull girder cross section) and material yield stress.

2. DATA FOR THE YIELD AND TENSILE STRESSES AS RANDOM VALUES

Data for the yield stress of corroded shipbuilding high tensile steel AH-32 (yield stress = 315 MPa) as a random variable are taken from Dalian University report [2]. Samples of twenty year old corroded steel plates have been tested there to find out the decrease of yield and tensile stress relative to the yield and tensile stress for as-built ship. The results are shown in Figure 1 and Figure 2.

The available data for the yield and tensile stress was analyzed by the computer program EasyFit [10]. First, the histograms were built and then - the probability density functions (PDFs) that best fit the data in the histograms were found. In the fitness process, Chi-squared, χ^2, criterion was used. For the yield stress of corroded steel, three parameter Weibull distribution was found to be the best fit (The corresponding parameters are given in Figure 1).

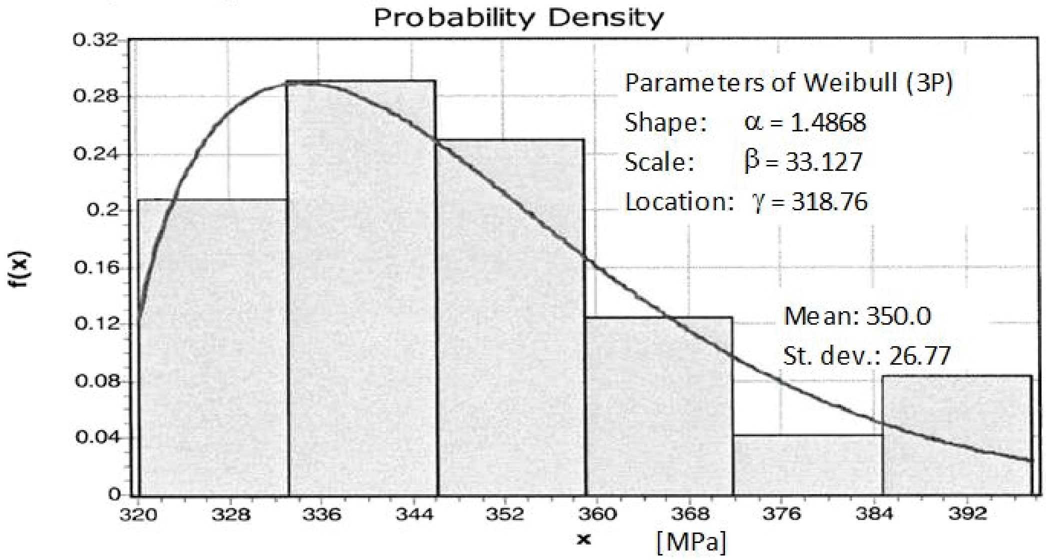

Figure 1. Histogram and PDF of the yield stress of corroded (20 year old) AH-32 steel. Weibull (3P) means three parameter Weibull distribution

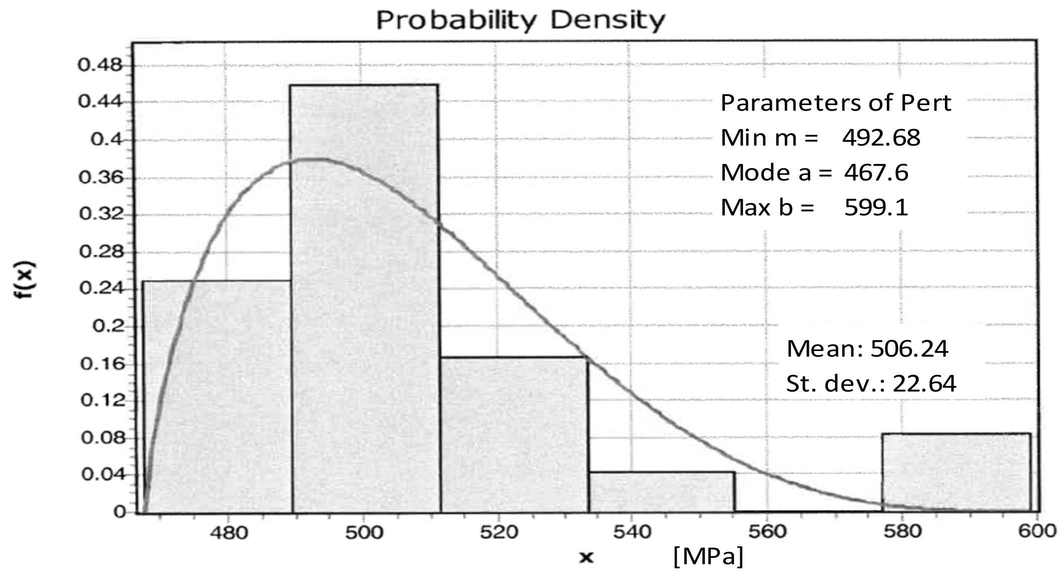

Figure 2. Histogram and PDF of tensile stress of corroded (20 year old) AH-32 steel

$$f(x,\alpha,\beta,\gamma)=\frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} e^{-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}} \quad (1)$$

where α = shape parameter, β = scale parameter, γ = location parameter.

For the ultimate tensile stress, Pert distribution was found to be the best (The corresponding parameters are given in Figure 2):

$$f(x)=\frac{1}{B(\alpha_1,\alpha_2)}\frac{(x-a)^{\alpha_1-1}(b-x)^{\alpha_2-1}}{(b-a)^{\alpha_1+\alpha_2-1}} \quad (2)$$

$$\alpha_1=\frac{4m+b-5a}{b-a} \qquad \alpha_2=\frac{5b-a-4m}{b-a} \quad (3)$$

$$a\le x\le b \quad (4)$$

Where a, b = boundary parameters (a < b); m = most likely value = mode parameter $a\le m\le b$; $B(\alpha_1,\alpha_2)$ = Beta function for (α_1,α_2)

$$B(\alpha_1,\alpha_2)=\int_0^1 t^{\alpha_1-1}(1-t)^{\alpha_2-1}\,dt \quad (5)$$

The corresponding PDFs of the yield and tensile stress for new steel (i.e., for as-built ship) were built with data for AH-32 steel of the same modern manufacturer as the tested corroded steel. All PDFs are shown in Figure 3 and Figure 4. One can observe the fact that the yield stress of corroded steel is greater than the Rule value [1] required for the yield stress of new steel.

Another observation is that the tensile stress of corroded AH-32 steel is also within the minimal and maximal Rule values for new steel.

3. HULL GIRDER ELASTIC SECTION MODULUS AS A RANDOM VARIABLE

Due to corrosion, the hull girder geometric properties decrease over ship's service life. Following the random nature of the corrosion, all geometric properties are also of a random nature. In this case, the hull girder elastic section modulus, Z_e, of the sample bulk carrier of 25K DWT [5] is used in the calculations. The PDF of the hull girder section modulus (deck) is shown in Figure 5 for 20 year service life. The reason for Z_e being greater than its nominal value is due to the used input data for the plates' thickness that could be greater than its nominal value.

4. FIRST YIELD BENDING MOMENT AS A RANDOM VARIABLE

When the hull girder section modulus and yield stress are known, the first yield bending moment, M_Y, can be calculated by the formula:

$$M_Y = Z_e . f_Y \quad (6)$$

where f_Y = yield stress, Z_e = elastic hull girder section modulus

When the PDFs of the hull girder elastic section modulus and yield stress are determined, the PDF of the first yield bending moment can be calculated by the convolution integral [7] :

$$f(M_Y)=\int_0^{\infty}\frac{1}{Z_e}f(Z_e)f\left(\frac{M_y}{Z_e}\right)dZ_e \quad \textbf{(7)}$$

where $f(M_Y)$ = PDF of M_Y; $f(Z_e)$ = PDF of Z_e; $f(M_Y/Z_e)$ = PDF of $f(f_Y)$ where f_Y is substituted by M_Y/Z_e.

The PDF of M_Y has been calculated in two versions:

- Using the PDF of the yield stress of corroded AH-32 steel (See Figure 3)
- Using the PDF of the yield stress of new AH-32 steel (See Figure 3)

The result of the calculations of the PDF of M_Y is shown in Figure 6 for the described two versions. One can observe the shift of the probabilistic distribution of M_Y for corroded AH-32 steel towards smaller values. Although the result is valid only for one example, it seems logical to expect such trend over ship's service life. All parameter characterizing the ship's hull girder capacity deteriorate over time. Is this valid for the yield stress? The prevailing opinion of the experts on material properties is that the yield and tensile stress do not diminish much or do not change at all. This opinion is based on the way the metal tests have been performed. The surface corrosive damages have been removed and the mechanical properties of the remaining metal have been tested. These kinds of tests of corroded metal produced the same or almost the same results as for new metal. However, this conclusion is incorrect because the effect of corrosion on the metal surface (i.e., the occurrence of micro stress concentration factors and embrittlement of the surface due to the hydrogen absorption) is ignored.

There are plenty of studies of the materials' mechanical properties of new steel (i.e., for as-built ship) but the publications on the material properties of corroded steel are only a few. However, even with the existing scarce information, one should make the next step - develop a methodology for analyzing the effect of possible decrease of the steel mechanical properties on the hull girder capacity.

When the PDF of M_Y and the PDF of the total hull girder bending moment M_t are known, one can calculate the probability $P(M_Y < M_t)$ which means that M_Y could be used as a "representative" of the hull girder capacity provided the accuracy of this approach is acceptable. As an example, the probability of failure of the hull of the sample bulk carrier was calculated for sagging conditions using the first yield bending moment M_Y as a criterion of the hull capacity. It can be done by either of the following formulae [6]:

$$P_f = \int_{-\infty}^{0} \left[f_{M,Y}\left(M_Y\right) \int_{M}^{0} f_{M,t}\left(M_t\right) dM \right] dM \qquad (8)$$

$$P_f = \int_{-\infty}^{0} f_{M,Y}\left(M_Y\right)\left[1 - F_{M,t}\left(M_t\right)\right] dM \qquad (9)$$

where P_f = probability of failure, $f_{M,t}(M_t)$ = PDF of M_t, $f_{M,Y}(M_Y)$ = PDF of M_Y, $F_{M,t}(M_t)$ = CDF of M_t for sagging.

Eq. (8) provides information about the probability of the capacity (in the example - measured by the first yield bending moment M_Y) being greater than the demand (i.e., M_t). In the paper, Eq. (8) is solved numerically for the sample bulk carrier to obtain quantitative assessment (although approximate) of the hull girder reliability represented by the probability $P(M_t < M_Y)$. All calculations in the example refer to ship's service life of

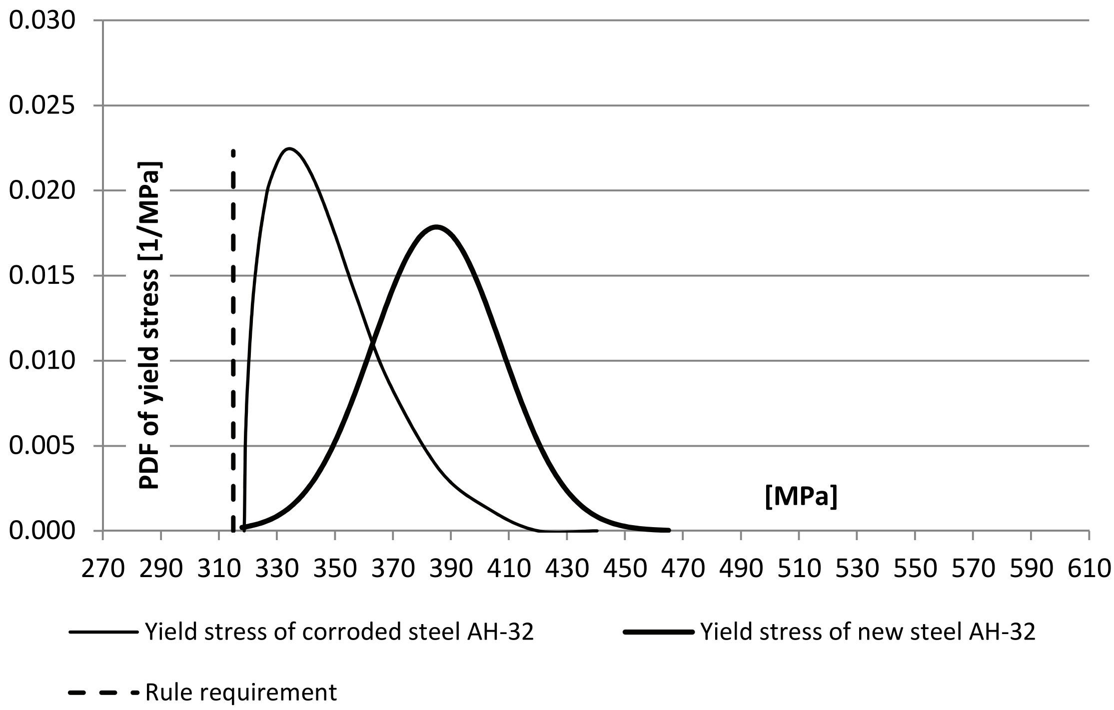

Figure. 3 PDFs of yield stress for corroded and new AH-32 steel

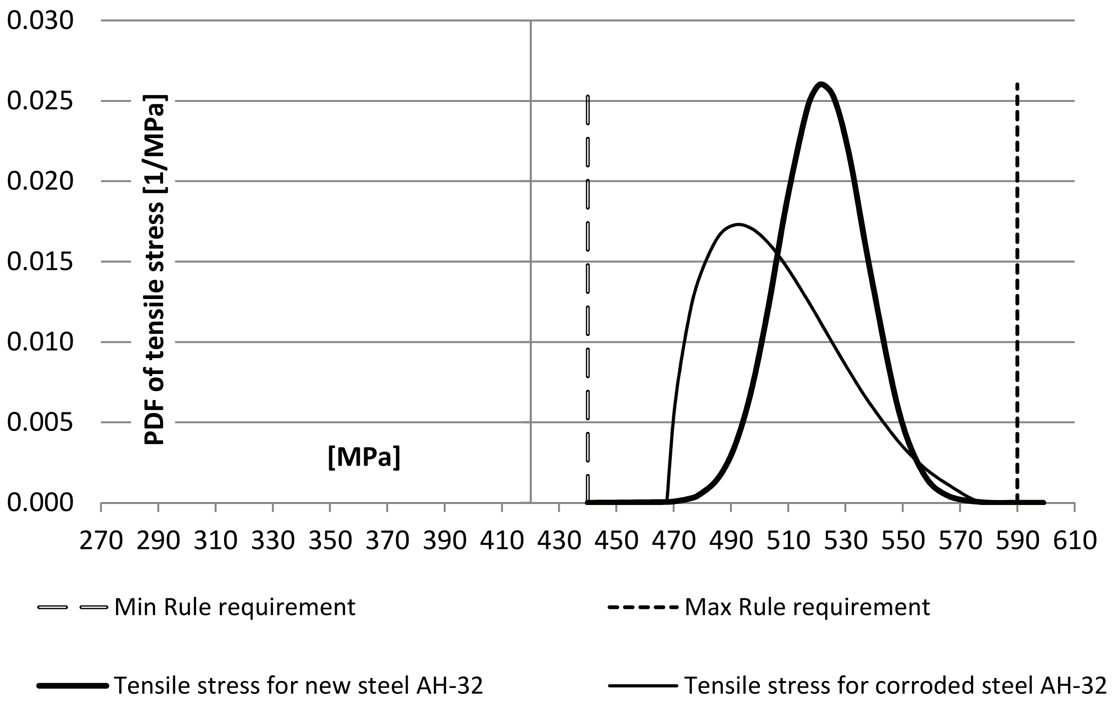

Figure. 4 PDFs of tensile stress for corroded and new AH-32 steel

20 years, i.e. the effect of time is included in both material and geometric properties of the hull.

5. TOTAL HULL GIRDER BENDING MOMENT

There are several methods for calculation of the total hull girder bending moment published in the shipbuilding literature. Their analysis is not the subject of this publication. One should only mention that all of them target determination of the total hull girder bending moment as a number but not in the form of probabilistic distribution. In the example, the total hull girder sagging bending moment for the sample bulk carrier was calculated by the extreme value statistics based on the parent distribution for the still water bending moment (Gaussian distribution) and wave-induced bending moment (Weibull distribution). The effect of truncation was not considered.

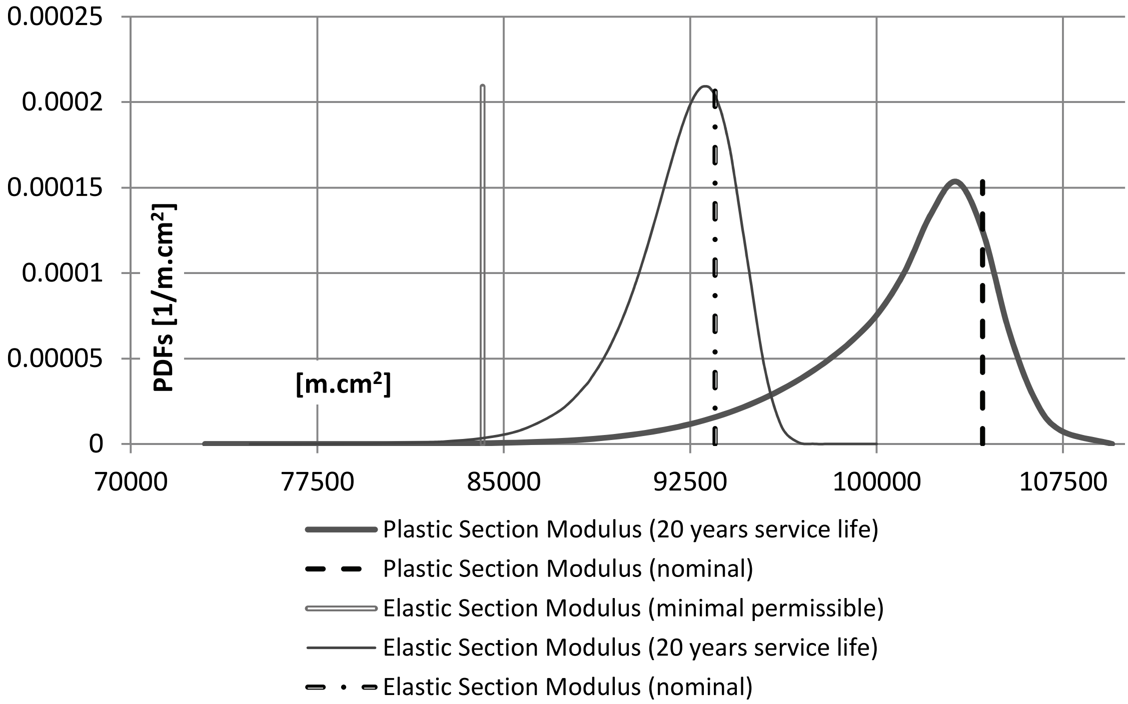

Figure 5. PDFs of the hull girder section moduli of a sample bulk carrier of 25K DWT

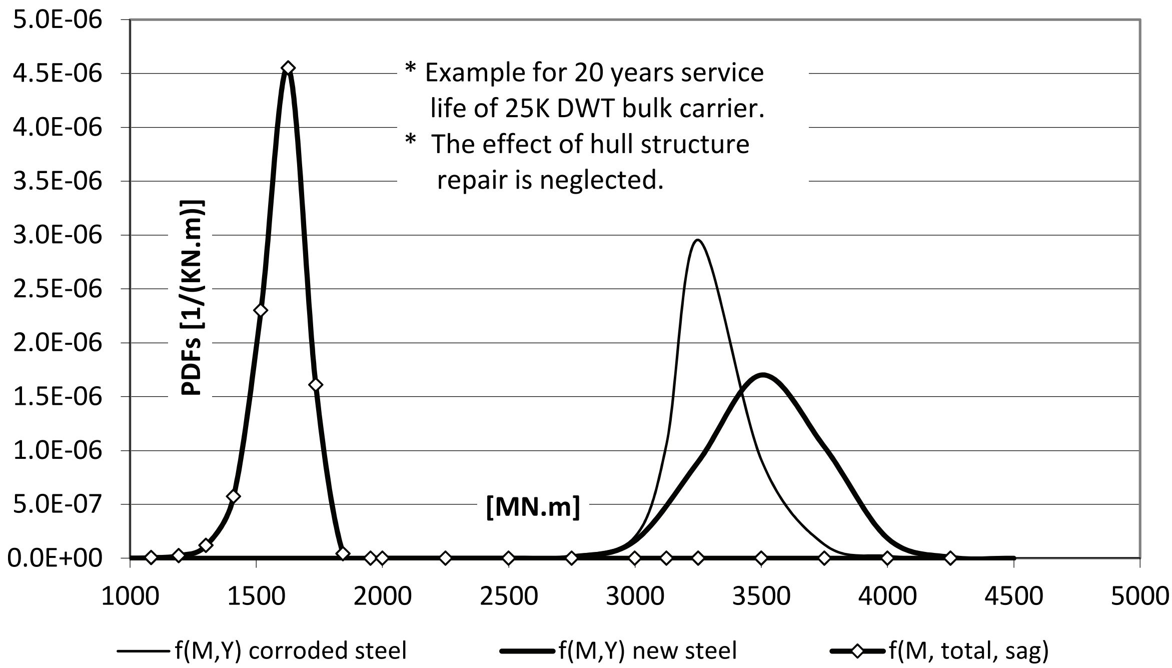

Figure 6. PDFs of the total hull girder bending moment and first-yield bending moment for corroded and new AH-32 steel (the calculations are performed with KN.m although for convenience their values in the abscissa axes are given in MN.m

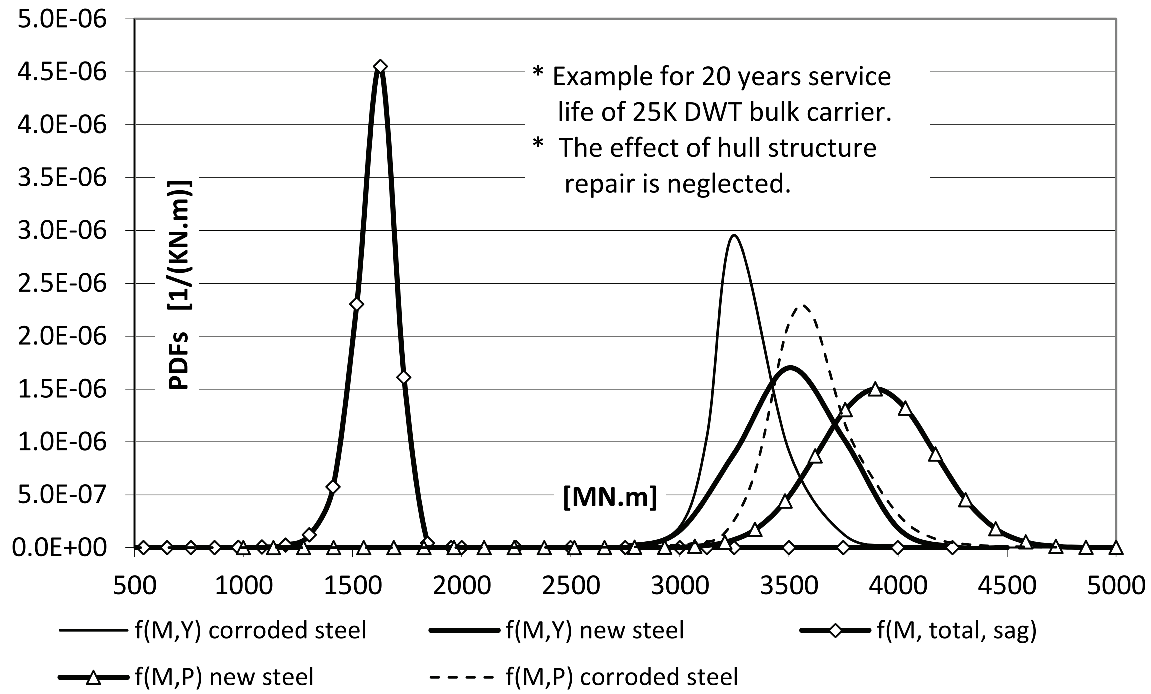

Figure 7. PDFs of M_Y and M_P for corroded and new AH-32 steel (the calculations are performed with KN.m although for convenience their values in the abscissa axes are given in MN.m)

6. DISCUSSION OF THE RESULTS AND CONCLUSION

Eq. (8) was numerically solved for two PDFs of the yield stress f_Y : the first one – when data for new AH-32 steel (modern manufacturer) is used, and the second one – when data for corroded AH-32 steel from the same steel manufacturer is used. When the probability of non-failure $R = 1 - P_f$ is calculated in Bells (Bell = - log(P_f)), the result for the first case is $R \approx 9.3$, and for the second case: $R \approx 3.7$.

The mean value of the yield stress of the new steel (first case) is 385.0 MPa while the mean value of the yield stress of corroded steel (second case) is 348.7 MPa. Hence, the reduction of the mean value of the yield stress of corroded steel is about 10%. However, the reduction of R is about 2.5 times which indicates the high sensitivity of the hull girder capacity to even relatively small decrease of the yield stress. It results from the fact that the reliability depends on the shape of the probabilistic distributions of the corresponding parameters in the areas of the asymptotic tails. In that area, even small change of the probabilistic distribution may cause significant changes in the final result for R.

A parametric study was also performed which showed that the probability of non-failure, R, is two to three times more sensitive to changes of the mean value than to changes of the standard deviation of the steel yield stress.

Although the numerical results are obtained only from one example, they might be interpreted as showing the high sensitivity of the hull girder capacity (measured by the first yield bending moment) to reduction of the yield stress over ship's service life. This emphasizes the need for greater efforts to obtain information for the effect of material aging (or corrosion) on basic mechanical properties of the ship's hull material.

Another topic that deserves special attention is the effect of truncation of PDFs. None of the parameters determining P_f or R is infinite. Therefore, the PDF of any parameter should be truncated which will certainly change its parameters (see, e.g., [6]). Since P_f and R depend mostly on the values of the corresponding PDFs in their tails, one can expect that even small change of the PDF tail may cause significant change of P_f and R.

Similar work was also done on the effect of decreased yield stress on pure plastic bending moment M_P (It is the theoretical maximal bending moment that can be sustained by the hull structure if no buckling occurs.). M_P is calculated as a product of the yield stress (for corroded and new AH-32 steel) and the hull girder plastic section modulus shown in Figure 5. For the sake of brevity, details of the calculations for M_P are not given here because the numerical results were similar to those for the analyzed case of first yield bending moment M_Y. This could be expected as one can see in Figure 7 which illustrates the shift of PDFs for M_Y and M_P when change of the PDFs of f_Y is considered.

It is a fact that there are only a few data on the mechanical properties of shipbuilding steels affected by corrosion. This explains the reasoning that this phenomenon is not taken into consideration when calculating the ship's hull girder strength. Under these circumstances, a question may arise as to whether we should wait until the time when sufficient statistical data are available for the decrease of steels' mechanical properties for different levels of corrosion, for their spatial distribution, etc. or if we should start performing a preliminary sensitivity analysis to evaluate the effect of possible decrease of steels' mechanical properties on ships' hull girder strength? When cautiously applied, verified and calibrated against data from real ships' operation, the latter approach is more reasonable and preferable.

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