Evaluating Corrosion Wastage and Structural Safety of Aging Ships

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ABSTRACT

Probabilistic approach has long been recognized as a preferred tool for the handling of the uncertainty of ship’s strength calculations. By factoring in corrosion wastage over time, such an approach can be expanded to account for time-dependency of structural strength. In ABS, analytical techniques had been developed to express the geometric properties of the hull girder and its components in the form of time-dependent distribution laws. Other analytical techniques were also developed to express the design wave-induced bending moment in probabilistic terms for any given life span. This paper shows, using examples, how these loads and geometric properties, all represented in the form of time-dependent distribution laws, could now be utilized to express hull girder bending stresses in the form of time-dependent distribution laws as well. Then, the probability of exceeding given permissible total stresses was calculated and suggestions for a reliability measure based on this probability of exceedence were made. They can be used as a quantitative decision-making assistance at time of initial design or steel renewal.

I. INTRODUCTION

Broadly speaking, corrosion wastage could be treated as a random phenomenon that affects the dimensions of plates, stiffeners and girders, just as the latter’s geometric properties could due to manufacturing and construction tolerances, etc. As such, all geometric properties of the hull girder and its components at any point in time in service due to corrosion could be treated in a probabilistic manner. This would permit the uncertainty related to the geometric properties be interacted with the uncertainty in predicting the loads acting on the hull structure. The former may be numerically evaluated by either analytical or approximate method [4], [6]. The latter is normally determined by separately calculating the wave-induced bending moment and the still water bending moment, and then combining them to obtain the total hull girder bending moment. Having assessed the uncertainty in the hull girder total bending moment and the uncertainty in the hull girder geometric properties, calculation of the total hull girder stresses may be performed in probabilistic terms at any ship’s age. Thus, the probability of exceeding the permissible total bending stresses given in the Classification Rules can be calculated and the potential risks for hull girder failure can be predicted. While the rational and the power of the probabilistic approach have been well recognized, there remain many challenges before it can be applied to everyday design and decision-making.

This paper reports one aspect of the current efforts by ABS in addressing such challenges. The focus has been on using analytical formulations, rather than numerical algorithms, to the largest extent so that almost no recourse is needed for numerical solutions. Using a bulk carrier example, main
features of this methodology are illustrated. This includes: 1) derivation of time-dependent distribution laws of total hull girder bending moment by combining that of still water and wave-induced bending moments; 2) derivation of time-dependent distribution laws of hull girder geometric properties (in the example, deck section modulus); 3) derivation of time-dependent distribution laws of hull girder stresses with reference to specific time span; 4) a proposed measure of reliability

II. CORROSION WASTAGE

Corrosion wastage depends on many factors such as ship’s operational life, quality of steel, methods of corrosion protection, operation conditions, etc. The combination of all these factors can vary substantially from case to case. There is an increasing interest in building up phenomenological models for the probabilistic description of the corrosion [14], [15] based on improved understanding of specific corrosion mechanisms. However, there still remain considerable uncertainties even in elegant theoretical models proposed. They are confined to some specific situations and cannot be applied to the general fleet.

Practically, all corrosion models have to be calibrated with gauging results. There are limited corrosion wastage database reported in public domain. The publications of Tanker Structure Cooperative Forum (TSCF) provide the industry with experience gained in tanker industry, and have been regarded as the most reliable source (see [21], [22]). In the last 10 years following TSCF publications, some collective studies on corrosion wastage were reported (see [23], [24]), which have improved and broadened the knowledge on corrosion wastage in commercial ships. These databases provide valuable data for development of analytical methods and make it possible to quantitatively discuss general corrosion in tankers.

There exist other types of corrosion, such as grooving/necking, pitting, etc. Unfortunately, there is virtually no collective data for these corrosion types, and the discussions remain, and will continue to remain for some years, mainly qualitative.

In a reliability-based approach, it is still acceptable to use simplistic corrosion progress model. Although the existing uncertainties in its prediction are too many, this approach could still contribute to a better understanding of an aging ship’s strength.

A significant number of detail records exist showing that the overall corrosion wear prevails in most cases [3]. This type of evenly distributed corrosion wear over each individual steel plate is considered in this paper. The mathematical model used in the calculations is shown in Fig. 1.
The first phase \((T=0-T_1)\) is when the protective coating is intact and there is no corrosion wastage of the structure.

The second phase \((T=T_1-T_2)\) is a gradual acceleration of corrosion as the coating breaks down. The final phase \((T > T_2)\) is when the coating has completely failed, and the corrosion rate reaches its maximum. The corrosion wastage at any time, \(\delta(T)\), is

\[
\delta(T) = \int_0^T \varepsilon(T) \, dT
\]

Data for the corrosion wear used in the paper are taken from [17]. However, the methodology is applicable to any set of data for evenly distributed corrosion wear.

### III. STILL WATER BENDING MOMENT

The early publications on statistical analysis of still water bending moments [5], [7], [10], [12], [13] and [18] showed that \(M_{SW}\) obeys the normal (Gaussian) distribution. Within the ship’s life, the p.d.f. of the still water bending moment depends on the ship’s type and loading patterns. As an example, the p.d.f. of a 25000 DWT bulk carrier for loaded conditions (hogging) is shown in Fig. 2 (p.o.e. stands for probability of exceedence).

Strictly speaking, the p.d.f. of the still water bending moments should be truncated. However, it is quite possible that in practice, the design values of \(M_{SW}\) may be exceeded. This may sometimes be revealed by careful analysis of the ship’s cargo plans (e.g., 10-30% exceedence relative to the design still water bending moments as reported in [19]).

In this paper, the distribution law of the still water bending moment is assumed the same through the ship’s life due to lack of information about its change with ship’s age. However, the methodology is general one and can be applied to any distribution law of the still water bending moment.

\[M_{SW,mean} = 53820 \text{ t.m}\]
\[M_{SW,st.dev.} = 10350 \text{ t.m}\]
\[M_{SW,design} = 69000 \text{ t.m}\]
with p.o.e. = 7.12%

Fig. 2 Probability density function of \(M_{SW}\) (hogging) for the 25000 DWT bulk carrier
IV. WAVE-INDUCED HULL GIRDER BENDING MOMENT

The wave-induced bending moment is calculated following the ABS Rules [1]:

\[
M_w = 19.37 \left[ 10.75 - \left( \frac{300 - L}{100} \right)^{1.5} \right] L^2 C_B 10^{-3} \text{ [t.m]}
\]  

(2)

For the 25000 DWT bulk carrier \( M_w \) is calculated as \( = 94795 \text{ t.m} \). It is widely accepted that the wave-induced bending moments follow the Weibull distribution (e.g., [16]):

\[
c.d.f. \quad F_{M_w}(M_w) = 1 - e^{-\left(\frac{M_w}{c}\right)^\lambda}
\]

(3)

\[
p.d.f. \quad f_{M_w}(M_w) = c \lambda e^{-\left(\frac{M_w}{c}\right)^\lambda} e^{-\left(\frac{M_w}{c}\right)^\lambda}
\]

(4)

The coefficient “c” is close to 1. For the purposes of the report, it is acceptable to assume \( c = 1 \). Thus, the Weibull distribution becomes exponential distribution (see Fig. 3):

\[
F_{M_w}(M_w) = 1 - e^{-\lambda M_w} \quad f_{M_w}(M_w) = \lambda e^{-\lambda M_w}
\]

(5)

To calculate the hull girder stresses in probabilistic terms at any given year or within any given time period, one should represent the wave-induced bending moment as direct function of any given duration of the ship’s operational life (see [8] and [9]). In the following examples in this paper two cases will be examined:

i) planned operational life of 20 years;
ii) extension of the ship’s life with 10 years after 15 years in operation.

Conventionally, the probability of wave-induced bending moment exceeding the Classification Rule-specified design wave-induced bending moment within 20 years is of order of \( 10^{-8} \).

Fig. 3 P.o.e. of \( M_w \) for operational life \( T_o=20 \) years with coefficient \( \lambda = 194321.10^{-9} \)
For consistency, the absolute value of the design wave-induced bending moment in the second case is determined in such a way that the p.o.e. is equal to $10^{-8}$. For the first case, the coefficient $\lambda$ is $194321.10^{-9}$ while for the second case $\lambda = 201633.10^{-9}$ (see [9]). The design wave-induced bending moments for various operational life is plotted in Fig. 4 all with p.o.e. = $1.10^{-8}$. One can observe the nonlinear relationship between the wave-induced bending moments vs. ship’s life.

Fig. 4  Design values of $M_W$ for different ship’s operational life, $M_{0,T_o}$, having the same probability of exceedence (p.o.e. = $1.10^{-8}$) for the 25000DWT bulk carrier

V. TOTAL HULL GIRDER BENDING MOMENT

As per the Rules of the classification societies, the design still water bending moments for hogging and sagging should be added to the wave-induced bending moments to obtain the total bending moments for hogging and sagging. Dividing the total bending moment by the hull girder section modulus yields the total bending stresses. These stresses should be smaller than the permissible stresses given in the Classification societies Rules. The probabilistic approach discussed in this paper uses the same procedure except that the calculations are performed in probabilistic terms and accounts are taken of the ship’s age.

Based on the principles of the composition of the distribution laws of the constituent variables (in this case – the still water bending moment, $M_{SW}$, and the wave-induced bending moment for hogging, $M_W$), the following formulae for the cumulative distribution function (c.d.f.) and the probability density function (p.d.f.) of the total bending moment, $M_t$, were derived (see [11] and [20]):

\[
F_{M_t}(M_t) = \int_{0}^{\infty} F_{M_{SW}}(M_t - M_W) f_{M_W}(M_W) d(M_W) 
\]

(6)

\[
F_{M_{SW}}(M_t - M_W) = \int_{0}^{M_t - M_W} f_{M_{SW}}(M_{SW}) d(M_{SW}) 
\]

(7)
\[ f_{M_t}(M_t) = \int_0^\infty f_{M_{SW}}(M_t - M_W) f_{M_W}(M_W) d(M_W) \]  
\[ f_{M_{SW}}(M_{SW}) = \frac{1}{\sigma_{M_{SW}} \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{M_{SW} - \bar{M}_{SW}}{\sigma_{M_{SW}}} \right)^2 \right] \]

where:
- \( f_{M_t}(M_t) \) = probability density function of \( M_t \)
- \( F_{M_t}(M_t) \) = cumulative distribution function of \( M_t \)
- \( f_{M_W}(M_W) \) = probability density function of \( M_W \) calculated with Eq. (5)
- \( \bar{M}_{SW} \) = mean value of \( M_{SW} \)
- \( \sigma_{M_{SW}} \) = standard deviation of \( M_{SW} \)

As an example, the probability density function of \( M_t \) for the 25000 DWT bulk carrier with operational life \( T_o = 20 \) years is shown in Fig. 5 and the probability of exceedence is shown in Fig. 6. Although the p.d.f. of \( M_t \) shown in Fig. 5 looks very much like Gaussian distribution, it is not Gaussian as can be seen in Fig. 6.

The p.d.f. and the c.d.f. of the total design hull girder bending moment, \( M_t \), for the second case (i.e., \( T_o = 10 \) years) are also calculated by Eqs. (6) - (9). The p.d.f. of \( M_t \) for time periods of 10 and 20 years are shown in Fig. 7.

![Fig. 5 P.d.f. of the total bending moment \( M_t \) for operational life \( T_o = 20 \) years](image-url)
To overcome the non-Gaussian characteristics of $M_t$, as is necessary for analytical calculation purpose, the p.d.f. and c.d.f. of $M_t$ for $T_o = 10$ and 20 years operational life were substituted with the following equations:

- For 20 years operational life, the p.d.f. of $M_t$ was presented by the equation

$$f_{M_t}(M_t) = \exp \left( \frac{a + cM_t + eM_t^2}{1 + bM_t + dM_t^2 + fM_t^3} \right)$$

(10)
For 10 years operational life, the c.d.f. of $M_t$ was presented by the Weibull equation

$$F_{M_t}(M_t) = a \left\{ 1 - \exp \left[ - \left( \frac{M_t + c \ln 2^{1/d} - b}{c} \right)^d \right] \right\}$$

(11)

Much analytical work and curve-fit exercises were performed to examine the types of equation that would best fit the p.d.f. and c.d.f. of $M_t$. Eqs. (10) and (11) were selected from many candidates based on accuracy and convenience for use.

One should emphasize here that the distribution laws of the design total bending moment refer to the whole time periods under consideration (i.e., for $T_o = 20$ and 10 years)

VI. HULL GIRDER SECTION MODULUS

Extensive studies had been made in ABS in probabilistic assessment of hull girder geometric properties [6]. In essence, the variability of the probabilistic distributions of hull girder geometric properties over time can be represented by a three-dimensional surface. As an example, the calculations are performed for the deck section modulus of the 25000 DWT bulk carrier. The envelope of the p.d.f. of $S_{M_{\text{deck}}}$ is shown in Fig. 8.

The p.d.f. of $S_{M_{\text{deck}}}$ should be truncated due to physical reasons ($S_M$ cannot be infinite). It requires calculating a coefficient $C_A$ that should be used to correct the ordinates of the p.d.f. [6]. In this paper, the upper limit of $S_{M_{\text{deck}}}$ is assumed 1.05 of $S_{M_{\text{deck}}, \text{nominal}}$ while the lower limit is assumed 0.8 of $S_{M_{\text{deck}}, \text{nominal}}$. Having built the envelope, one can calculate the probability that $S_{M_{\text{deck}}}$ could be between any limits during any given time interval with the formula

Fig. 8 Envelope of the p.d.f of $S_{M_{\text{deck}}}$ for the 25000 DWT bulk carrier
\[
P\left(\text{SM}_1 \leq \text{SM} \leq \text{SM}_2; T_1 \leq T \leq T_2\right) = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \left[ C_{A,T} \int_{\text{SM}_1}^{\text{SM}_2} P_T(\text{SM}) d(\text{SM}) \right] dT
\]

where:

- SM\(_1\) = lower limit of SM
- SM\(_2\) = upper limit of SM
- T\(_1\) = lower limit of T
- T\(_2\) = upper limit of T
- CA,T = coefficient for correction of the ordinates of P\(_T(\text{SM})\) at any year T
- P\(_T(\text{SM})\) = Gaussian probability density function of SM at any year T

In physical terms, Eq. (12) represents the ratio between the volume below the envelope within the given limits and the total volume below the envelope. The cross section of the envelope at any ship’s age gives the probability density function of SM\(_{\text{deck}}\) for this year.

In the paper, the envelope of SM\(_{\text{deck}}\) is used in two ways: i) To calculate the probability of SM\(_{\text{deck}}\) exceeding a given value within the planned operational life (see the darker surface in Fig. 9) or any given time interval; ii) To obtain the probability density function of SM\(_{\text{deck}}\) at any given year (see Fig. 10).

As an example, two p.d.f. of SM\(_{\text{deck}}\) are shown in Fig. 11 for operational life T\(_0\)=10 and 20 years. It is interesting to note that the distribution law of SM\(_{\text{deck}}\) for the whole time period does not obey Gaussian distribution although at each year it is Gaussian. One possible explanation of this fact is that the envelope of the p.d.f. is not smooth because of the knuckle in the envelope (see Fig. 8) at the end of the coating longevity.
To overcome the non-Gaussian characteristics of SM\textsubscript{deck} necessary for calculation in probabilistic terms of the total hull girder bending stresses, the p.d.f. of SM\textsubscript{deck} were replaced by equations in the following way:

![Graph showing the p.d.f. of SM\textsubscript{deck} at several years of the ship’s operational life](image)

**Fig. 10** P.d.f. of SM\textsubscript{deck} at several years of the ship’s operational life

![Graph showing the p.d.f. of SM\textsubscript{deck} for To = 10 and 20 years operational life](image)

**Fig. 11** P.d.f. of SM\textsubscript{deck} for To = 10 and 20 years operational life
For 20 years operational life, the cumulative distribution function of SM_{deck} was first analytically presented by the Weibull equation. Then it was differentiated and the following equation of the probability density function of SM_{deck} was derived:

\[
f_{SM_{deck}}(SM_{deck}) = \frac{b e^{-\left(\frac{SM_{deck} + d \ln \left(\frac{1}{e} - c \right)}{d}\right)}}{d^e} \left(\frac{SM_{deck} + d \ln \left(\frac{1}{e} - c \right)}{d}\right)^{e-1}
\]

(13)

For 10 years operational life, the probability density function of M_t was represented by the equation

\[
\ln \left[f_{SM_{deck}}(SM_{deck})\right] = a + bSM_{deck} + cSM_{deck}^2 + dSM_{deck}^3 + eSM_{deck}^4 + fSM_{deck}^5
\]

(14)

As for M_t, much analytical work and curve-fit exercises were performed to examine the types of equation that would best fit the p.d.f. of SM_{deck}. Eqs. (13) and (14) were selected from many candidates based on accuracy and convenience for use.

VII. CALCULATION OF THE TOTAL BENDING STRESSES FOR “AS-BUILT” AND AGING SHIPS

Technically, the calculations could be performed using p.d.f. or c.d.f. of SM_{deck} with reference to a given year or to a given time period. Since the p.d.f. or c.d.f. of M_t is with reference to given time periods (T_o=10 and 20 years), for the same time reference should be used for calculation of the total bending stresses. For purposes of comparison, two sets of calculations of the total hull girder bending stresses were performed for each time period of 10 and 20 years:

A. The distribution law of the design total hull girder bending moment refers to the whole time period while the distribution law of SM_{deck} at the beginning of the time period is used. This case is close to the present practice for calculating the hull girder bending stresses.

B. The distribution laws of both the design total hull girder bending moment and SM_{deck} refer to the whole time period.

Again, the composition of the laws of the distribution of the constituent variables (in this case – the total design hull girder bending moment, M_t, and the deck section modulus, SM_{deck}) is applied to obtain the cumulative distribution function (c.d.f.) and the probability density function (p.d.f.) of the total hull girder bending stresses in the deck:

\[
F_{s_t,SM_{deck}}(s_t,SM_{deck}) = \int_0^\infty F_{M_t}(s_t,SM_{deck}) \cdot f_{SM_{deck}}(SM_{deck}) \, d(SM_{deck})
\]

(15)

where:

- \( F_{s_t,SM_{deck}}(s_t,SM_{deck}) \) = c.d.f. of \( s_t,SM_{deck} \)
- \( F_{M_t}(s_t,SM_{deck}) \) = c.d.f. of \( M_t \), which is expressed through the product of the bending stress in the deck, \( s_t,SM_{deck} \), and the deck section modulus, \( SM_{deck} \). It is calculated either by integrating Eq. (10) or directly by Eq. (11)
f_{SM\_deck}(SM\_deck) = \text{p.d.f. of SM\_deck}. \text{At the beginning of each time period it is Gaussian (see Fig. 10) and is determined with the equation}

\[
f_{SM\_deck}(SM\_deck) = \frac{1}{\sigma_{SM\_deck}} \exp\left[-\frac{1}{2} \left( \frac{SM\_deck - \bar{SM\_deck}}{\sigma_{SM\_deck}} \right)^2 \right]
\]

\(\bar{SM\_deck}\) = mean value of SM\_deck \quad \sigma_{SM\_deck} = \text{standard deviation of SM\_deck}

For the whole time periods of 10 and 20 years, \(f_{SM\_deck}(SM\_deck)\) is determined either by Eq. (13) or Eq. (14)

\[
f_{s_{t,\_deck}}(s_{t,\_deck}) = \int_{SM\_deck,\_min}^{SM\_deck,\_max} f_{M_t}(M_t = s_{t,\_deck}SM\_deck)f_{SM\_deck}(SM\_deck)SM\_deck d(SM\_deck) \] (17)

where:
\[
f_{s_{t,\_deck}}(s_{t,\_deck}) = \text{p.d.f. of s}_{t,\_deck}
\]

The results of the calculations of \(s_{t,\_deck}\) for the two cases with 10 and 20 years operational life are shown in Fig. 12 together with the permissible total bending stresses of 1784 kg/cm\(^2\) given in the Classification Rules [1]. One can clearly observe in Fig. 12 two trends: a) the probability density functions (p.d.f.) of \(s_{t,\_deck}\) is shifted towards the permissible total bending stresses when the distribution laws refer to the whole time period under consideration, b) within one set of calculations (A or B), the difference between the p.d.f. is not big, especially relative to the permissible stresses located in the asymptotic tails (numerical results of the calculations for set A and B are given in the next Section). In the authors’ view, the use of distribution laws of the hull girder geometric properties corresponding to the whole time interval is preferable because it is more consistent with the approach to calculating the loads acting on the hull structure.

VIII. A MEASURE OF RELIABILITY

In mathematical terms, the calculation of the probabilities of exceedence of the permissible stresses requires very high accuracy because the permissible stresses are in the asymptotic tails of the p.d.f. (see Fig. 12). Even very small change of the ordinates of the distribution laws in the asymptotic tails leads to substantial change of the probability of exceedence of given limit. Therefore, to make the calculations more stable, a measure of the probability of exceedence proposed in [2] is used. It is based on the proposal of Prof. V. V. Bolotin to measure the reliability of structures with very high reliability:

\[
R = -\log_{10}(\text{p.o.e.}) \quad \text{[Bells]} \] (18)

Using Bells as a measure of the “reliability” (defined as the probability \(P(s_{t,\_deck} < [s])\)), the following results for the p.o.e. of the permissible total bending stresses for each of the four probability density functions in Fig. 12 were obtained (for comparison, the results are also shown in the traditional format of probability of exceedence):
Fig. 12  Probability density functions (p.d.f.) of the total bending stresses in the deck for the two sets of calculations for operational life of 10 and 20 years

A. The distribution law of the design total hull girder bending moment refers to the whole time period while the distribution law of SM_{deck} at the beginning of the time period is used

For 20 years operational life:
\[ P(s_t < [s_t]) = 4.27 \text{ Bells} \quad P(s_t > [s_t]) = 5.34 \times 10^{-5} \]

For 10 years operational life:
\[ P(s_t < [s_t]) = 4.17 \text{ Bells} \quad P(s_t > [s_t]) = 6.72 \times 10^{-5} \]

B. The distribution laws of both the design total hull girder bending moment and SM_{deck} refer to the whole time period

For 20 years operational life:
\[ P(s_t < [s_t]) = 2.18 \text{ Bells} \quad P(s_t > [s_t]) = 0.0067 \]

For 10 years operational life:
\[ P(s_t < [s_t]) = 2.37 \text{ Bells} \quad P(s_t > [s_t]) = 0.0043 \]
One can observe in the first set of calculations, A, (i.e., when the distribution law of $M_t$ refers to the whole time period of 10 or 20 years, but that of $M_{d_{deck}}$ is determined for the beginning of each time period) that the difference between the probability of exceedence (p.o.e.) of the permissible total bending stresses for 10 and 20 years service life (measured in Bells) is about 2.4%. In the second set of calculations, B, (i.e., when the distribution laws of $M_t$ and $M_{d_{deck}}$ refer to the whole time period of 10 or 20 years) this difference (measured in Bells) is about 8.7%. The numbers might be slightly influenced by the unavoidable inaccuracy (although the accuracy of the curve-fit is extremely high) when the ordinates of the probability density functions or cumulative distribution functions were substituted by analytical equations, as aforementioned. However, even with this in mind, one can conclude that the differences between the p.o.e. of the permissible total bending stresses in the Classification Rules for new design within one set of calculations are quite small, especially when compared with the uncertainties in the loads, corrosion wear, construction tolerances, etc.

However, the difference between the probabilities of exceedence (measured in Bells) of the same permissible total bending stresses in the two sets of calculations, A and B, is much greater (between 176 - 196%). It does not mean that the reliability of the hull structure has changed by the same numbers. The probability of exceedence (i.e., the probability of failure) is method-dependent. Direct comparison between results obtained by two different methods is not meaningful. Comparisons can be made only between results obtained by the same method. In this sense, any set of calculations (A or B) is acceptable, provided all parameters are presented in probabilistic terms, as described in this paper.

In other words, whatever set of calculations is used (A or B), it is reasonable to use the permissible bending stresses given in the Classification Rules for new design in assessing the strength of old ships, provided the calculations are performed in probabilistic terms, as described in the paper. In plain language, there is no need to develop a new set of permissible stresses for aging ships, provided all parameters determining the ship’s strength are calculated in probabilistic terms in the same way as for new design.

It is interesting to mention that the probability of exceedence of the wave-induced bending moment given in the Rules is $1.10^{-8}$. However, when all other uncertainties are taken into consideration (still water bending moment, geometric properties of structural components and hull girder), the probability of exceedence of the permissible total bending stresses increases up to $4.3 – 6.7 \times 10^{-3}$.

The accuracy of the calculations with the analytical method presented in this paper was double checked by repeating all calculations with Monte Carlo simulation method. The maximum difference between the results obtained by the two methods is 2%. The analytical method provides accurate solution in closed form within very short time, including in areas of the asymptotic tails. Thus, the traditional application of the Monte Carlo method in such problems can be avoided, especially when high accuracy requires long computational time.

**CONCLUSIONS**

This paper illustrates that time-consuming numerical analyses need not necessarily be the only workable tool for solving probabilistic formulations. An analytical method has been developed for calculation of the probability of exceedence of given permissible total hull girder stresses. It explicitly accounts for the uncertainties associated with age related hull structure degradation due to corrosion, probabilistic nature of still water and wave-induced bending moments. This probability of exceedence can be used as a measure – at the new design stage or at any point in the service life of the ship – to account for the desired level of structural safety. The method does not require
application of specially developed computer programs for calculating the reliability of the hull structure. It is believed that such an approach will facilitate the application of time-dependent Reliability theory in ship structural design, maintenance and repair.

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