*Reliability Engineering and System Safety* **26** (1989) 59–71

# Time-Dependent Reliability of the Primary Ship Structure

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(Received 18 September 1988; accepted 9 December 1988)

*ABSTRACT*

*A model is proposed to quantify the time variation of the reliability of the primary ship structure which results from the degrading effect of corrosion. The reliability function is calculated at discrete points during the ship's life, which are the basis to quantify the lifetime reliability. Example calculations are performed for a tanker and it is shown that, whenever strength degradation is present, the lifetime reliability calculated according to the present practice does not show the very distinct decrease of safety levels towards the end of the ship's lifetime.*

## 1 INTRODUCTION

Significant work has already been performed in reliability analysis of ship structures. The initial approaches adopted a level three formulation with one load and one resistance variable,[1–3] in which the variables are described by their probability distributions and the measure of safety is provided by the probability of failure.



*Reliability Engineering and System Safety* 0951-8320/89/$03·50 

Level 2 approaches followed later with applications of First Order Second Moment (FOSM) methods also to the one load and one strength variable problem.[4,5] The variables are described by their mean value and standard deviation and safety is quantified by the reliability index. Applications to multivariable problems were presented in Ref. 6 with a FOSM method and in Ref. 7 with an advanced FOSM technique. The latter can also account for information about the type of probability distribution applicable to each variable.

Structural reliability techniques and in particular FOSM methods have been developed to quantify time independent problems, i.e. to relate random variables. This has been possible because strength variables often have a small variation with time, being modelled as time invariant. On the other hand, all loading processes to which the hull is subjected are stationary during appropriately defined short periods, although becoming non-stationary for time periods that are one order of magnitude larger. However, on a time scale on the order of the service life of the structure, many non-stationary periods occur and the load processes can be modelled again as stationary.

Thus, with essentially constant strength variables and with stationary load processes, it has been possible to formulate time independent reliability problems that provide meaningful information concerning the reliability of marine structures[8] and of its relation with safety.[9]

Interest is now raised on a finer modelling of the time dependence of structural reliability. Several authors have explored the different time dependences of the various load processes of interest to determine the maximum combined value of the induced load effects. This work concentrates on the other aspect of time dependence, i.e. the influence of strength degradation on structural reliability. The time dependence of strength that is considered here is the result of corrosion of the ship plating. The effect on the compressive strength of plate elements was studied in Ref. 10 and its effect on the ship section modulus was considered in Ref. 11.

## 2 TIME-INDEPENDENT RELIABILITY OF THE PRIMARY HULL STRUCTURE

The structural design of the primary structure of ship hulls is based on the concept of providing enough flexural modulus to the midship section. The hull is modelled as a beam and its section modulus governs the levels of elastic stresses that are developed on the deck and bottom which turns out to be used as a measure of the capability of the cross section against collapse.

This model has obvious limitations but the purpose of the present work is not to dwell on those. This type of modelling is commonly adopted and provides a comparative measure of the reliability of ships of similar type. One can argue that ships of significantly different configuration will have different failure modes implying different degrees of approximation when using this approach.

The resisting capability of the ship hull is given as the product of the section modulus by the yield stress of the material. The demand is the combined effect of the still-water and the wave induced vertical bending moments.

Different approaches have been used to model the load variables. The still-water loads have been represented as a constant equal to its maximum permissible value,[2] or as a normally distributed variable.[4,6] The first approach is conservative especially for the smaller ships which experience still-water bending moments much lower than the maximum allowed value. The disregard of the randomness of the still-water load effects is also conservative except perhaps in the case of warships in which cargo variability is considerably less than in merchant ships.

The wave-induced loads have generally been modelled as a succession of stationary periods (sea states) during which wave and force amplitudes follow a Rayleigh distribution. The probability distribution of the wave induced load effects applicable to the long-term time frame of a ship's lifetime is obtained by weighting the various sea states by their probability of occurrence on a given ocean area or shipping route. The probability distribution that is obtained with this process is often fitted by a Weibull distribution, for practical reasons.[1,12] The exponential distribution, which is the special case of the Weibull with an exponent of unity has been shown to be a reasonable and practical approximation.

The common approach is to combine the still-water and the wave induced load effects by just summing them.[1-5] However, being both random, their maxima will not be achieved at the same time which implies the need of a load combination factor that reduces one of the effects to account for that.

In Ref. 6 a study was made to express the total vertical bending moment $M_t$ in terms of the extreme values of the two components $M_{se}$ and $M_{we}$:

$$M_t = M_{se} + F_L M_{we} \tag{1}$$

where $F_L$ is the load combination factor. It was concluded that $F_L$ varies between 0·6 and 0·8 depending on the particular ship under consideration.

Another possibility of taking the load combination into account is to make use of the Turkstra rule[3] which basically says that the maximum combined value occurs when one of the loads reaches its maximum and the other is at its random point in time value, i.e. at its expected value. This was the approach adopted for code calibration in Ref. 14 where the total moment was defined as:

$$M_t = \max\left[(M_{se} + M_w), (M_s + M_{we})\right] \tag{2}$$

where $M_s$ and $M_w$ are the still-water and wave induced bending moments at a random point in time.

The formulation that has been first used in a second moment approach to the ship's hull reliability defines the safety margin $M$ as:[4]

$$M = M_c - M_s - M_w \tag{3a}$$

where $M_c$ is the hull resisting capacity

$$M_c = Z_0 F_y \tag{3b}$$

with $Z_0$ the midship section modulus and $F_y$ the yield stress of the material.

The reliability index is given by the ratios of the mean value to the standard deviation ($D_M$) of the safety margin

$$\beta = \frac{M}{D_M} = \frac{1}{V_M} \tag{4}$$

i.e. by the inverse of its coefficient of variation $V_M$. This method will be applied to a tanker of 128 400 tons of deadweight, which has a section modulus $Z_0$ of 35·8 $m^3$ referred to the deck.

The $10^{-8}$ characteristic value of wave induced bending moment in this tanker, as calculated in Ref. 6, is $5{\cdot}9 \times 10^6$ kNm. This value was obtained using an improved computation procedure developed in Ref. 6, which includes the bias due to the assumed shape of wave spectra, to the calculated transfer functions, to short-crestedness modelling, to wave directionality and to maneouvering in heavy weather.

That reference value corresponds to the North Atlantic wave climate given by Hogben *et al.*,[15] which should be accepted with some care since recent results[16,17] have shown that different compilations of wave data from the same ocean region lead to significantly different values of wave induced load effects. The mean value of the exponential distribution that has that calculated characteristic value is

$$\overline{M}_w = \frac{5{\cdot}9 \times 10^6}{\ln(10^8)} = 0{\cdot}32 \times 10^6 \text{ kN m}$$

In this approach the still-water component is represented as a normal distribution and the wave induced bending moments by an exponential one, which are the same assumptions adopted by Mansour.[4]

Data on still-water load effects has been analysed in Refs. 18 and 19, from where the statistical results of four sister tankers, summarised in Table 1, were taken.

**TABLE 1**
Mean Value of the Vertical Wave Induced Bending Moment at the Transverse Section in which it is Maximum and Corresponding Standard Deviation in Terms of the Maximum Permissible Still-water Bending Moment (100·0)

| *Ship identification* | *Mean bending moment* | *Standard deviation* |
|---|---|---|
| TK 18 | 28·2 | 24·3 |
| TK 19 | 26·7 | 21·7 |
| TK 20 | 42·5 | 12·8 |
| TK 21 | 34·0 | 24·2 |
| Average | 33·0 | 21·0 |

These results illustrate the variability that one can expect from sister ships operated by the same company in the same shipping routes. It is apparent that one of the ships (TK 20) experienced somewhat higher mean moments but with a smaller standard deviation. Thus the characteristic values obtained by combining both quantities would not be too different.

The recorded data has been normalised by the maximum permissible value of still-water bending moment in sagging which according to the Rules of Det norske Veritas is equal to $M_s = 3{\cdot}3 \times 10^6$ kN m.

The strength variables are the section modulus and the yield stress which are both assumed to be normally distributed random variables. The section modulus and its variability results from combining the geometric variables according to the method presented by Ivanov.[11] Usual assumptions were made for the variability of the geometric variables. The mean value of the section modulus resulted as 0·975 of its nominal value and its uncertainty was negligible (0·005). Assuming that the yield stress has a coefficient of variation of 0·10, its mean value will be 1·25 higher than its nominal value.[6]

The reliability index that results from applying these values to the formulation of eqn (4) is 7·1, which is slightly higher but in the range of values obtained by Mansour.[4]

In this formulation no reference is made to the life of the ship or to any other time period. In fact, it quantifies the probability of failure of the primary ship structure at a random point in time. This is equivalent to a hazard rate which will be introduced in the next section.

Another common formulation consists in defining the safety margin of the ship structure as:[5]

$$M = M_c - M_s - M_{we} \tag{5}$$

where $M_{we}$ is the most probable maximum wave induced bending moment during the ship's lifetime, i.e. it is the $10^{-8}$ characteristic value. This extreme wave induced bending moment is Gumbel distributed and has thus a coefficient of variation of 0·07 and a mean value of $1{\cdot}03M_{we}$.[6]

With this new formulation the resulting value of the reliability index is 2·63, which is in the range of values reported in Refs 5, 6 and 20. The significant difference in the value of the reliability indices that one obtains with the formulations of eqns (3) and (5) had already been pinpointed in Ref. 6 and confirmed later in Ref. 21.

If one is interested in the yearly reliability instead of the lifetime reliability, the value to be used in $M_{we}$ of eqn (5) is the most probable maximum wave induced bending moment in one year. This is the characteristic value that corresponds to 1/20 of the $10^8$ wave cycles, i.e. it is the value corresponding to the probability of exceedance of $5 \times 10^{-6}$. Thus

$$(M_{we})_1 = \frac{\ln(5 \times 10^6)}{\ln(10^8)}(M_{we})_{20} = 0{\cdot}837(M_{we})_{20}$$

where the subscripts of the parentheses indicate the number of years to which it is referred.

The yearly reliability index that results in this case is 3·43. Comparing this value with 7·1 and 2·63 that resulted for lifetime reliability from eqns 3 and 5, it can be concluded that the resulting reliability index is much more sensitive to the problem formulation than to the reference period.

## 3 TIME DEPENDENT RELIABILITY OF THE PRIMARY HULL STRUCTURE

A time dependent measure of the safety of a structure or any system is the reliability function $R(t)$ which is the probability that failure has not occurred prior to time $t$.

The hazard function $h(t)$ is the probability that the structure will fail in the interval $t$ to $t + dt$ given that it has survived up to time $t$. Thus, the reliability at $t + dt$ is related with the reliability at $t$ through the hazard function

$$R(t + \mathrm{d}t) = [1 - h(t)\,\mathrm{d}t]R(t) \tag{6}$$

Taking the limit as $\mathrm{d}t$ tends to zero gives the derivative of the reliability function

$$\mathrm{d}R(t)/\mathrm{d}t = -h(t)R(t) \tag{7}$$

which in turn can be integrated with respect to time to yield

$$R(t) = R_0\left[\exp - \int_{t_0}^{t} h(t)\,\mathrm{d}t\right] \tag{8}$$

where $t_0$ is the time at which the structure is put in service and $R_0$ is its reliability at that occasion, i.e. the probability that the structure does not fail until the end of construction or at the initiation of its operational life. In most cases the initial reliability of the structure is very close to unity implying that the reliability function depends on the integral of the hazard function (see Ref. 22).

In designing a structure one is interested in avoiding the occurrence of a total failure during its lifetime. Thus the design parameter of interest would be the lifetime reliability $R(L)$

$$R(L) = R_0 \exp\left[ - \int_{t_0}^{L} h(t)\, dt \right] \tag{9}$$

In fact this has been the reference value adopted in most reliability studies up to now. This formulation allows one to consider the reliability without explicit reference to the time variable, making it possible to use FOSM methods, which have been developed for time invariant problems.[8]

The structural strength has been considered constant during the structure lifetime and in more detailed studies it has been described by more than one variable. The loading on the primary ship structure has been considered to be made up of the two main components: the still-water and the wave induced load effects, the first of which has been considered a constant, equal to its extreme value or at most a random variable. The wave induced load effects have been modelled as a sequence of independent and identically distributed random variables which represent the various waves or wave induced responses, i.e. the continuously varying surface elevation process is substituted by a sequence of peaks.

In transforming the time variation of the wave induced and still-water load effects into the time invariant variable necessary to the FOSM formulation various possibilities are available. One common formulation of the lifetime reliability has been to say that the strength of the ship must be enough to resist the load effects induced by a wave that can occur anytime during the ship's life.[1-4] This leads to the formulation of eqn (3). The other approach is to say that the ship structure must resist the most probable maximum wave induced load effect that occurs during its life,[5,6] which leads to eqn (5).

Although in both cases the objective is to have a measure of the probability of survival of the ship, the two different probabilistic models adopted for the wave induced loads, lead necessarily to two different indices (7·1 and 2·6 in the example of the last section).

Several other characteristic values of wave induced load effects could be thought of by defining the effects that occur with a probability of occurrence different from the most probable maximum, which has a probability of 63% of being exceeded during the ship's lifetime.

Still in the choice of the representative value of load effect to enter in a reliability formulation one can consider different models of combining load-effects to yield design values of the combined process, e.g. eqns (1) or (2).

Independently of which model is adopted, they all transform the time-varying load process into a characteristic value that is considered in the design and analysis. This procedure is justified because the loading can be considered stationary on a time scale significantly larger than one or two days which are typical durations of storms.

The problem addressed in this work concerns the degradation of the strength of a ship structure which can be observed during its lifetime as a result of corrosion. This is a process that leads to a monotonic loss of strength with time, decreasing the capability that the structure has for resisting the loads imposed.

The implication of a stationary load effect and a decreasing resisting capacity is that the hazard rate will be increasing, and the reliability function $R(t)$ will be decreasing during the ship's life.

Maintenance actions performed along the life of the ship have the effect of increasing the ship's capability at certain defined points in time. If this maintenance is performed with short intervals the range of variation of the structural strength can be reduced to a point that makes it accurate enough to consider that the structural strength is constant on the timescale of the ship's life.

Two ships can have the same lifetime reliability with different patterns of annual reliability along their life. A ship that would be subjected to maintenance actions ideally every year would be able to keep a constant value of annual reliability. On the other hand, a ship that is not subjected to maintenance has a larger annual reliability when new than when she is old. Thus, although the lifetime reliability can be equal to an accepted value in both cases, the yearly reliability can vary to unacceptably low values in the second case. The same thinking can be extended to the reliability relative to the duration of a voyage.

The key factor to formulate a reliability problem that is able to show the effect of the degradation of strength with time and that is still practical enough to use is the choice of the time duration to which structural reliability is referred to.

The still water loads have characteristic durations of the order of a few days. Wave induced loads have periods of stationarity of about 20 minutes. Although becoming nonstationary for larger periods, they are subjected to large-scale cyclic variations which can be considered to occur with equal probability. Typical reference periods are the three months duration of weather seasons or even a full year. One can state that the statistical descriptors of the wave processes during such a time scale show little variability from year to year.

The strength degradation induced by corrosion of plates is a very slowly varying process which only yields noticeable changes in the section modulus after some years. Thus it appears that an adequate reference period would be one year. This implies that the integral of eqn (9) would be separated in a series of integrals along periods of one year

$$R(L) = R_0 \exp\left[ -\int_{t_0}^{t_1} h(t)\,\mathrm{d}t - \int_{t_1}^{t_2} h(t)\,\mathrm{d}t - \cdots - \int_{t_n}^{L} h(t)\,\mathrm{d}t \right] \tag{10}$$

which can be recast in

$$R(L) = R_0 \prod_{i=1}^{n} R_i \tag{11a}$$

where $\Pi$ indicates the product of $n$ $R_i$s, given each by

$$R_i = \exp - \int_{t_{i-1}}^{t_i} h_i(t)\,\mathrm{d}t \tag{11b}$$

and $t_i - t_{i-1} = 1$ year. The hazard rate, although being monotonically increasing, is modelled as piecewise constant during each period of one year. Thus it takes the value $h_i$ at the $i$th year.

For a reference period of one year the reliability problem is defined in the usual way, based on a safety margin

$$M = C - S = g(x) \tag{12}$$

defined by a limit state function $g(x)$ which includes various variables $X_i$ that are of the resisting type ($C$) and of the load effect type ($S$). To illustrate its application, eqn (5) will be used to model this safety margin whose reliability will be quantified by eqn (4).

The level of safety is quantified by a reliability index that can be calculated by any of the methods available and which is related to the probability of failure by

$$P_{\mathrm{f}} = N(-\beta) \tag{13}$$

where $N$ is the Gaussian distribution function and the reliability index is given by eqn (4). The reliability relative to that reference period is

$$R_i = 1 - P_{\mathrm{f}} \tag{14}$$

These yearly reliabilities can be introduced in eqn (11) to yield the lifetime

**TABLE 2**
Lifetime (20 years) Reliability of the Tanker Hull Calculated with Various Formulations

| *Reference period* | $\beta$ *Eqn (4)* | *R(20) Eqn (8)* | *R(20) Eqn (11)* | *R(20) Eqn (15)* |
|---|---|---|---|---|
| 1 year | 3·43 | 0·999 61 | 0·992 24 | 0·992 21 |
| 2 years | 3·32 | 0·999 37 | 0·993 67 | 0·993 65 |
| 4 years | 3·15 | 0·998 99 | 0·994 94 | 0·994 93 |
| 20 years | 2·63 | 0·995 05 | 0·995 05 | 0·995 05 |

reliability. For high levels of reliability a good approximation for constant yearly reliability is

$$R(L) = R_0[1 - n(1 - R_i)] \tag{15}$$

where the lifetime is equal to $n$ years.

Table 2 indicates the results of calculating the lifetime reliability with various methods. It shows that one can use the reliability during shorter time intervals to determine the lifetime reliability which is indicated in the last line. The results of using time periods of different length are indicated in the last two columns, where it is apparent that one obtains better accuracy with four year periods than with yearly predictions. The differences are, however, due to round-off errors in the successive multiplications of numbers very close to unity.

To apply the method proposed here to the example of the tanker considered in Section 2, it is necessary to quantify the time variation of the hull section modulus of the tanker during its life. This has been determined by using the method of Ref. 11 with its assumptions about typical values of corrosion rates.

The results, which are summarised in Table 3, have been determined every four years for simplicity of calculations. The extreme situation of no repair during the ship's lifetime has been assumed although being aware that it is too severe. However, it shows more clearly the effect studied here and the changes that a maintenance program would bring become obvious.

Inspection of this table shows that the mean value of the section modulus decreases up to a value of 70% of the initial one after a 20-year period. The coefficient of variation due to the uncertainty of the geometric variables increases up to a value of 4% which is still small. This variability has to be combined with the one of the yield stress to give the variance of the moment capacity, as results from eqn (3b).

Table 3 also shows the values of the yearly probability of failure resulting from the application of eqns (3b), (4), (5) and (13) where the section modulus

**TABLE 3**
Time Variation of the Mean Value and Coefficient of Variation of the Section Modulus of a Tanker Due to Uncertainty in the Geometric Variables, with a No Repair Assumption

| *Ship age (years)* | *Nominal sec. modulus* ($m^3$) | *Mean sec. modulus* ($m^3$) | *Coeff. of variation* | *Yearly probability of failure* |
|---|---|---|---|---|
| 0 | 35·8 | 34·9 | 0·005 | $0{\cdot}22 \times 10^{-3}$ |
| 4 | 34·5 | 33·6 | 0·008 | $0{\cdot}66 \times 10^{-3}$ |
| 8 | 32·8 | 31·8 | 0·013 | $1{\cdot}4 \times 10^{-3}$ |
| 12 | 30·8 | 29·8 | 0·020 | $5{\cdot}2 \times 10^{-3}$ |
| 16 | 28·5 | 27·6 | 0·029 | $17{\cdot}4 \times 10^{-3}$ |
| 20 | 25·9 | 24·9 | 0·039 | $108 \times 10^{-3}$ |

was taking the value appropriate to the ship's age. It can be observed that during the ship's life this probability increases by three orders of magnitude.

The lifetime reliability of the tanker structure can be calculated from the yearly reliabilities, including the effect of strength degradation. For simplification, reliabilities will be calculated for each four year period centered at the values indicated in Table 3. The reliability for the intact strength will be calculated for the period of the first two years. The resulting values of $R_i$ were 0·999 33, 0·997 48, 0·995 36, 0·986 42 and 0·957 28 corresponding to the ages of 0, 4, 8, 12 and 16 years respectively. The reliability for all the 18 years of a ship's life is determined by their product (eqn (11)) which results in 0·936 91, implying a probability of failure of 0·063.

If one did not want to calculate the structural reliability in limited time periods, two plausible approaches to account for strength degradation would be to consider a constant section modulus equal to its value at the midlife (9 years) or equal to its average value between the ages of zero and 18 years, which turn out to occur at an age of 10·5 years in this case. The probabilities of failure calculated for the two cases resulted in 0·018 and 0·025 respectively, which are about three times smaller than the one calculated with the four year reliabilities.

If the probability of failure in the 18 year period was calculated with the initial value of section modulus, which is the common procedure nowadays, a probability of failure of 0·003 would result, which is smaller than it should be by a factor of 21.

This example shows clearly that the usual practice of calculating the lifetime reliability is unconservative even if some plausible allowance is made for strength reduction due to the effect of corrosion. More accurate results are obtained combining the reliability for shorter reference periods, of four years or less.

Furthermore, the yearly probabilities of failure can have values much higher than predicted by the average lifetime value. Situations can occur in which the latter is acceptable but not the first value. This shows the need for using yearly reliabilities as design and operational reference values.

## 4 CONCLUSIONS

A formulation was presented to quantify the time variation of the reliability of the ship primary structure which is able to account for the effect of strength degradation due to corrosion. This formulation is related with the common approaches of assessing structural reliability with FOSM methods.

It is proposed that the reliability function can be quantified at discrete points during the ship's life, and that lifetime reliability can be calculated by integrating appropriately these values.

It is shown that the usual practice of calculating the lifetime reliability directly leads to unconservative results which are not able to account properly for the effect of strength degradation.

## ACKNOWLEDGEMENTS

This work has been conducted in the scope of the project 'Development of Codes for the Design of Marine Structures', which is partially funded by INIC, the National Institute for Scientific Research through CEMUL, the Centre for Mechanics and Materials of the Technical University of Lisbon. It has been presented at the WEMT 88 Symposium on Advances in Ship Operations, held at Trieste, Italy, from 12 to 14 October 1988.

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