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Estimation of Structural Service Life of Ships

THE AUTHORS

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ABSTRACT

A methodology for the structural life assessment of a ship's structure is suggested. The methodology is based on probabilistic analysis using reliability concepts and the statistics of extremes. In this approach, the estimation of structural life expectancy is based on selected failure modes. All possible failure modes of the ship must be investigated and the most likely paths to structural failure identified. For the purpose of illustration two failure modes are considered in this study. They are plate plastic deformation and fatigue cracking. Structural life based on these two failure modes is determined for an example vessel.

The methodology determines the probability of failure of the ship's structural components according to the identified failure modes as a function of time. The results can be interpreted as the cumulative probability distribution function (CDF) of structural life. Due to the unknown level of statistical correlation between failure modes, limits or bounds on the CDF of the structural life are established. The limits correspond to the extreme cases of fully correlated and independent failure modes. The CDFs of structural life are determined for two inspection strategies; namely, inspection every year and inspection every two years with a warranty inspection at the end of the first year.

The meaning of the results for the case investigated in this study is that, for example, given an inspection strategy of two years and a desired life of 15 years, there is a 72% chance that the vessel will not experience enough partial damage in the

failure modes identified to constitute reaching the "end of structural life" as defined.

INTRODUCTION

The estimation of structural life is not a simple task. Many factors affect the life of a ship, including design methods, ship type and service, structural details, materials, and construction methods and quality. Loads on the hull, including ship weight, water pressure, wave loads, and engine and propeller vibrations are important. Maintenance practices and inspection methods also play a vital role in determining how long the structure of a ship will survive.

The final decision as to when a vessel is no longer fit for continued service is an economic one. Many examples exist in the U.S. Navy and Coast Guard of extremely old ships which are still in effective service today. For the most part these ships are still operating not only because they have experienced good maintenance and material management practices, but also because the cost of retaining them was overshadowed by the cost of replacing them with new vessels.

It is not the intention of this paper to cover the economic decisions which go into determining a ship's fitness for further service. Rather, a probabilistic-based approach for evaluating the likelihood of reaching a desired service life is provided. This approach requires a considerable amount of information regarding a ship's characteristics, operational profile, and an engineering definition of when the economic "end of structural life" has been reached.

In order to demonstrate how this methodology might be used, an example ship type is investigated. The ship type used is a high performance semiplaning hull vessel. This type was chosen for investigation because of the recently published work [1] which provides the kind of information needed to perform the analysis.

FAILURE MODES

DEFINITION OF POTENTIAL FAILURE MODES

One of the first tasks that must be tackled for any type of vessel is to identify and categorize all of the potential failure modes of the structure. In this case, the potential failure modes of a typical high performance semiplaning hull vessel are described. It is from this initial survey of potential failure modes that the specific areas for further investigation will be chosen. The failure modes will be categorized according to the severity of consequences resulting from the failure. It should be noted that operator error, such as running aground, and damage due to hostile attack are not considered.

Catastrophic Failure Modes

These are failure modes in which the consequence of failure is the possible loss of the vessel. Such potential failure modes include:

1. Brittle fracture of the deck or bottom as a result of rapid crack growth from a smaller flaw.
2. Rupture of bottom plating as a result of impact with the water surface during slamming.

End of Serviceability Failure Modes

These failure modes are not as immediately dangerous as the catastrophic modes, but represent conditions which would make the vessel unserviceable for normal operations. They typically are so expensive to repair that it might be economically more feasible to take the vessel permanently out of service rather than repair it. Possible failure modes in this category are:

1. Ductile yielding of a gross panel of the deck or bottom such that significant plastic deformation has taken place. This can result in misalignment of shafts or gun-mount train rings, excessive vessel hogging or sagging, and areas of extremely large stress concentrations which could lead to catastrophic failure.
2. Buckling of deck or bottom panels. This mode is not just the buckling of panels of plating between stiffeners, but rather the overall buckling of gross panels between transverse stiffening. Invariably such deformations lead to reduced load carrying capacity among the remaining structural members and are precursors to some types of catastrophic failure.
3. Cracking of multiple structural details in a primary load carrying area. Again, it is not a catastrophic failure by itself, but rather an indication of potential weakness in the structure which might recur even if the symptoms are repaired.

Serviceability Limiting Failure Modes

Failure modes in this category are those which are troublesome enough that the vessel either must be taken out of service for a short time in order to effect repairs or which cause some limit on operational performance until the next scheduled repair period. Some possible failure modes in this category are:

1. Fatigue cracking of local details which run into the skin of the ship and penetrate it.
2. Fatigue cracking of engine mounts or other structural supports of machinery or equipment which might cause reduced operational capability.
3. Fracture of major structural components which could possibly lead to more serious consequences.

Non-Limiting Failure Modes

This category is for those failure modes which are most likely to cause a major degradation in the vessel's mission, but could possibly affect vessel performance. Some possible failure modes are:

1. Buckling of local plating between stiffeners in the underwater hull. Local plate buckling is not a reason to take a vessel out of service, but it could have an effect on the hydrodynamic performance of the vessel.
2. Yielding of local plating between stiffeners as a result of combined in-plane and out-of-plane loads. The

consequences are the same as for buckling of the plating.

3. Bimetallic corrosion at the deckhouse-hull connection in steel ships with aluminum deckhouses.

Nuisance Failure Modes

Nuisance failure modes are those which either affect the aesthetic appearance of the vessel or which taken individually do not represent problems which could be classified as being in one of the other categories. An example of this type of failure mode is the plastic deformation of the side shell plating (above the waterline) resulting from combined loads. This would give the classic "hungry horse" look to the vessel's sides. It represents no real threat to the performance of the vessel, but is considered unsightly.

SELECTION OF FAILURE MODES

Only a few of the failure modes listed in the previous section are ones which would likely cause the vessel to be considered as unfit for further service. Some of the potential failure modes are not very likely to occur given the material used in its construction or the scantlings required by the design authorities responsible for the vessel. As a consequence, only a few of the failure modes might eventually lead to significant enough damage to threaten ultimately making the vessel unserviceable.

For the vessel type being used as an example in this paper, a considerable amount of information is available in Reference [1] to help identify the failure modes of interest. Because of the relatively robust scantlings of the structural framework of this class of high-performance vessels and the comparatively small in-plane loads shown in the quasi-static balance in extreme waves, gross panel buckling would not be considered as a potential problem. Rupture of bottom plating due to impact with waves was ruled out as a problem based on historical evidence and the enormous pressures required to rupture a steel plate of the geometry used in this class [1]. Again because of the relatively small in-plane loads experienced by this type of vessel, all buckling modes of failure were considered unlikely. This conclusion is supported by the history of a number of similar classes of vessels which are in the same fleet. In those classes, operating in similar environments as the vessel being investigated, the only buckling damage reported could be traced to collisions.

The process of elimination then leaves the most likely potential failure modes as ductile yielding of gross panels, ductile yielding of individual plate panels, and various fatigue related modes. Because of the relatively robust scantlings of the structural framework, ductile yielding of a gross panel is considered unlikely. however, the plating used on this class is somewhat thinner than that used on previous classes (7 lb vs. 7.5 lb plating), indicating a potential problem with individual plate panel deformation. This conclusion is supported by the casualty report records and background work reported in Reference [1].

Fatigue cracking of structural details is a problem on all types of seagoing vessels. Antoniou [2] reported that "there is practically no ship entirely free of cracks." In the U.S., Jordan and Cochran [3] and Jordan and Knight [4] estimated that there was an average of 86 structural detail failures per ship for those which they inspected. This potential failure mode was chosen for further investigation because it represents one of the most common types of structural failure and one which can grow to catastrophic proportions if not controlled.

Both potential failure modes identified for further study can be considered as serviceability-related modes of failure. That is, the failures will not lead directly to loss of the vessel, but may limit performance or endurance in some manner. Relating this limited serviceability to a definition for end of useful structural life is one of the most difficult problems faced in performing an estimation of structural life.

DEFINITION OF END OF STRUCTURAL LIFE

What determines an end of structural life is, usually, an economic factor. Once the cost of maintaining the structural system exceeds a specified budgeted amount, a decision must be made by the owners; either the additional repair spending is authorized or the structure is replaced. The scope of this study does not include an economic analysis of the structural system of the vessel, or its maintenance schedule and cost. Therefore, in order to demonstrate a methodology for estimating the structural service life for a portion of the example vessel, arbitrary constraints were selected to represent the owner's position on vessel replacement. These constraints were also chosen to demonstrate the broad range of possible forms for the constraints.

PLATE DEFORMATION

The end of structural life of a vessel is defined, for the plate deformation failure mode, as the need for replacement of more than five plate panels in a specified area at the end of any inspection and maintenance period (hereafter called inspection period). Plate panels are to be replaced when the ratio of plastic deformation w_p to plate thickness t_h is greater than or equal to 2.0.

This definition is based on the assumption that having to replace six or more plates in a critical region during any inspection period would cause the owner to use more resources than currently allocated for repair and steel replacement in the vessel's lifetime maintenance budget. The allowable deformation of the plate panel, $w_p/t_h = 2.0$ was chosen for the sake of demonstration. This value could easily have been more than 2.0, but realistically it would likely be less than 3.0. Defining a critical region introduces another level of complexity; now there is a specific number of panels to consider and the end of life is in terms of an event where more than five of the total panels in the region need to be replaced.

FATIGUE FAILURE

For this potential failure mode, the end of structural life of the vessel is defined as the development of at least one fatigue failure of a critical detail at the end of any inspection period within a specified critical portion of the vessel. The critical details would typically be identified by the owner's engineering staff as those which would cause a significant degradation in strength if cracked.

For the purposes of this paper, this definition of the "end of structural life" according to the fatigue failure mode is used. Other definitions could similarly be handled. Realistically, it is not likely that the cracking of one structural detail would be reason enough to consider taking a vessel out of service.

METHODOLOGY FOR STRUCTURAL LIFE ASSESSMENT

STRUCTURAL RELIABILITY ASSESSMENT

The performance function that expresses the relationship between the strength and load effect of a structural member according to a specified failure mode is given by

$$Z = g(X_1, X_2, \ldots, X_n) \tag{1}$$

in which the X_i's are the basic random variables, with g(.) being the functional relationship between the basic random variables and failure (or survival). The performance function can be defined such that the limit state, or failure surface, is given by $Z = 0$. The failure event is defined as the space where $Z < 0$, and the survival event is defined as the space where $Z > 0$. Thus, the probability of failure can be evaluated by the following integral:

$$P_f = \int\int, \ldots, \int f_X(X_1, X_2, \ldots, X_n)\, dx_1\, dx_2 \ldots dx_n \tag{2}$$

where f_x is the joint density function of X_1, $X_2, \ldots, X_n$, and the integration is performed over the region where $Z < 0$. Because each of the basic random variables has a unique distribution and they interact, the integral of equation (2) cannot be easily evaluated. However, a probabilistic modeling approach of Monte Carlo computer simulation with Variance Reduction Techniques (VRT) can be used to estimate the probability of failure [5,6].

The strength (or resistance) R of a structural component and the load effect L are generally functions of time. Therefore, the probability of failure is also a function of time. The time effect can be incorporated in the reliability assessment by considering the time dependence of one or both of the strength and load effects. In the following sections the modeling of time dependence of strength and load effects is briefly discussed.

TIME DEPENDENCE IN STRUCTURAL RELIABILITY ASSESSMENT

Time Dependence of Load Effects

There are generally three approaches which can be used to model the time dependence of the load effect:

1. Stochastic Process Modeling. In this approach, the load effect is modeled as a stochastic process. Informally defined, a stochastic process L(t) is a random variable that is a function of time t. In this case, the instantaneous value of the load at the point in time t is of interest. Therefore, the time duration aspect is not present in the modeling process. The determination of the probability of failure in a time period from the probability of failure at a point in time can be arithmetically difficult, and this method is not suitable for structural life assessment based on reliability theory.
2. Extreme Value Modeling. The statistical characteristics of the extreme load in a time period t can be determined using the basic concepts of extreme statistics [7]. Then, the resulting extreme value probability distribution can be used in the reliability assessment methodology to determine the probability of failure. By varying the time period t from zero to the design structural life, a plot of the probability of failure as a function of time can be developed. This method can be used in reliability and structural life assessment according to certain failure modes, for example, plate plastic deformation, member buckling, etc.
3. Cumulative Value Modeling. For certain failure modes, e.g., fatigue and brittle fracture, the failure event occurs because of the accumulation of damage due to repeated application of loads of variable amplitudes with varying frequencies. The variable amplitude and frequency loading that causes failure can be transformed into an equivalent constant amplitude loading necessary to cause failure. The number of load cycles to failure can be related to the number of years of structural service. Therefore, the cumulative value loading and resulting probability of failure are functions of the number of load applications, which means that they are functions of time.

The time dependence of the loading can come from a number of sources. For the case of fatigue the time dependence is obvious. For the case of plate deformation the time dependence results from increased exposure to extreme events over longer time periods. Another contributing factor could be the general tendency of ships to increase in displacement with age, the result of adding new equipment, carrying more stores and spares than originally planned, and increasing crew size. The net effect of these changes can be illustrated as shown in Figure 1.

Time Dependence of Strength

The strength or resistance of a structure is also a function of time. Generally, all structural members in ships become weaker in the course of time due to material

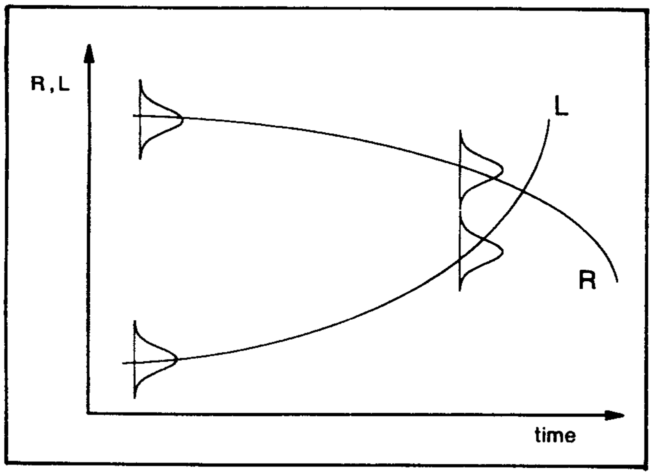

Figure 1. Time Dependent Strength *R* and Load Effect *L*.

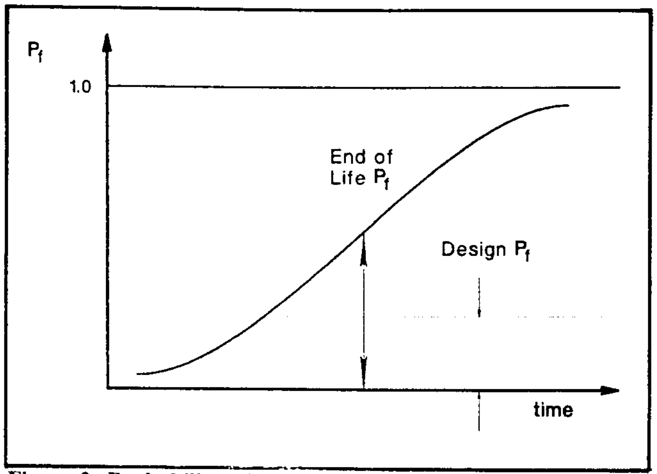

Figure 2. Probability of failure as a function of time.

corrosion and deterioration. In this study, the failure modes of interest are based on structural strength that is not time dependent. Therefore, strength is considered to be a constant amplitude random variable.

Time Dependence of Risk Measures and Structural Life Definition

Based on the load effect L(t) and strength R(t) shown in Figure 1, the probability of failure can be computed according to a specified failure mode using, for example, Monte Carlo computer simulation with variance reduction techniques. The resulting probability of failure $P_f(t)$ is a function of time as shown in Figure 2. Mathematically, the probability of failure can vary from zero to one. Realistically, the probability of failure varies from an initial (design) probability of failure based on design values to a final probability of failure at the end of useful structural life. The resulting mathematical variation of the probability of failure with time can be viewed as the cumulative distribution function of the structural life SL of a component according to a specified failure mode. Actually, the curve satisfies all the conditions of a cumulative probability distribution function. This relationship can be expressed as follows:

$$F_{SL}(t) = \text{Prob}(SL < t) = P_f(t) \qquad (3)$$

where $F_{SL}(t)$ is the cumulative distribution function of structural life.

STATISTICS OF EXTREMES

Extreme values based on observational data are very important in structural safety assessment. The prediction of future conditions, especially extreme conditions, are necessary in engineering planning and design. The prediction is based on an extrapolation from previously observed data.

Consider a set of observations $(x_1, x_2, \ldots, x_n)$ from an identically distributed and independent set of random variables $(X_1, X_2, \ldots, X_n)$. The distribution of X_i is called the initial (or parent) distribution, which has the cumulative probability distribution function $F_X(x)$ and the density probability function $f_X(x)$. The maximum value of the observed values is a random variable M_n which can be represented as

$$M_n = \text{Maximum}(X_1, X_2, \ldots, X_n) \qquad (6)$$

The exact cumulative and density probability distribution functions of the maximum value are given by, respectively [7]:

$$F_{M_n}(m) = [F_X(m)]^n \qquad (7)$$

$$f_{M_n}(m) = n[F_X(m)]^{n-1} f_X(m) \qquad (8)$$

It can be shown that for relatively large values of *n*, the extreme distribution approaches an asymptotic form that is not dependent on the exact form of the initial distribution, but rather depends on the tail characteristics of the initial distribution in the direction of the extreme. The central portion of the initial disribution has little influence on the asymptotic form of the extreme distribution. These facts are of great practical interest and importance.

For probability distributions of exponential tails, the extreme distribution approaches an extreme value distribution of double exponential form as $n \to \infty$, for example, a normal or lognormal probability distribution approaches a Type I extreme value distribution as $n \to \infty$. In this case, the difference between an exact distribution for M_n and the Type I extreme value distribution is relatively small. The difference diminishes as $n \to \infty$. Practically, the difference is negligible for *n* larger than approximately 25 [7].

For the purpose of the structural life expectancy assessment, the mathematical model for extreme distribution must be a function of *n* in order to relate the outcome of the analysis of extreme statistics to time. Extreme value distributions, like Type I or Type II extreme value distributions [7], are used in this study to model extreme load effects. Since the mathematical model is

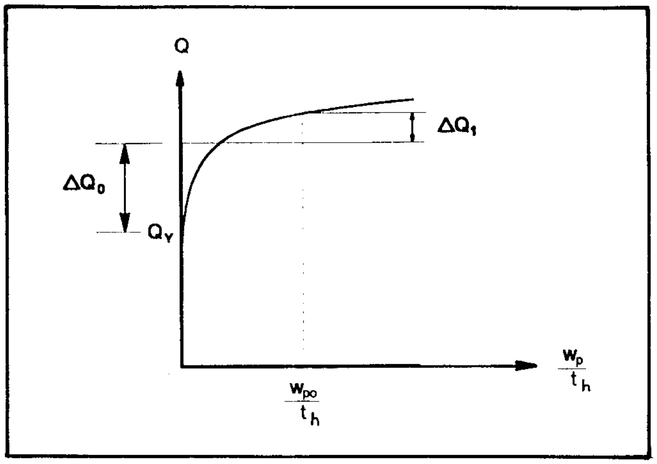

Figure 3. Load vs. Permanent Set for plates of finite aspect ratio [8].

not sensitive to the type of the initial distribution, as long as it is within the same general class, the mathematical model used in this study is based on an initial distribution that follows the class of normal probability distributions.

STRUCTURAL LIFE ASSESSMENT OF COMPONENTS

PLATE DEFORMATION

The structural life of a ship according to the plate deformation failure mode as previously defined can be determined in several steps that are discussed in the following sections.

Limit State Equation

The limit state equation for the local plate deformation failure mode can be expressed in a general form as

$$g(x) = R(X_1, X_2, \ldots, X_{n-m}) - L(X_{n-m+1}, \ldots, X_n) \quad (9)$$

in which $R(X_1, X_2, \ldots, X_{n-m})$ is the strength of the structural component or system according to the specified failure mode, $X_1, \ldots, X_{n-m}$ are the basic strength random variables, $L(X_{n-m+1}, \ldots, X_n)$ is the load effect on the structural component or system in the specified failure mode, and $X_{n-m+1}, \ldots, X_n$ are the basic load variables. Since $X_1, \ldots, X_n$ are random variables, $g(X)$ is a random variable. In this study, the limit state equation for plate yielding is given by

$$g(x) = \text{Resistance} - \text{Still Water Load} - \text{Dynamic Load} \quad (10)$$

Each of the terms in the above equation are expressed in units of pressure. The still water load is the hydrostatic pressure at the depth of interest. The dynamic pressure is the extreme dynamic pressure based on the results from full scale experiments conducted on one of the vessels of this class [1]. The resistance term is an empirical expression developed by Hughes [8,9] based on elastoplastic methods and is given as:

$$\text{Resistance} = \frac{F_y^2}{E} \{Q_y + T(R_w)[\Delta Q_0 + \Delta Q_1 R_w]\} \quad (11)$$

where

F_y is the yield stress of the material

E is the modulus of elasticity of the material

Q_y is the initial yield load calculated from elastic theory

ΔQ_0 accounts for curved transition portion of load deflection curve (see Figure 3)

ΔQ_1 accounts for subsequent straight portion of load deflection curve

R_w is the ratio of the deflection w_p at a given loading to the deflection at the completion of the edge hinge formation w_{p0}

$T(R_w) = [1 - (1-R_w)^3]^{1/3}$ for $R_w \leq 1$

$= 1$ for $R_w > 1$.

This expression was calibrated with available experimental data [8]. It tends to provide a lower bound on stresses required for a specified deflection, but is extremely accurate for w_p/t_h ratios of less than 4.

Extreme Load Effects

In this study, only loads and load effects in head-seas are considered. No other heading is considered because the stress records in Reference [1] indicate that they result in much smaller stresses than the head-seas condition. Tests and stress measurements at the locations of interest were reported by Reference [1]. Eight combinations of ship speed and sea state for the head-seas condition are considered as described in Table 1. The combination of high sea state and high speed was not included because historical records indicate that this type of vessel is almost never operated under those conditions. The percentages shown in Table 1 for each combination represent the assumed usage of the ship in the corresponding speed/sea state combination. The total of the percentages in the table is about 20%, which is the expected percent usage of the ship in head seas.

Table 1. Percentage of Operating Time at Various Combinations of Speed and Sea State in Head Seas

Sea State	Ship Speed Low (12 kts)	Medium (24 kts)	High (29 kts)
Low (1 & 2)	Case 1 4.0%	Case 2 1.7%	Case 3 1.0%
Medium (3 & 4)	Case 4 4.7%	Case 5 1.3%	Case 6 0.7%
High (5)	Case 7 5.3%	Case 8 1.0%	Not Considered

Table 2. Statistical Characteristics of the Maximum Stress

Case No.	Interval (sec)	Mean Value (psi)	Coefficient of Variation
1	30	2027	0.0993
2	30	2181	0.0993
3	30	2303	0.0993
4	30	7136	0.0993
5	30	7818	0.0993
6	30	3556	0.0993
7	30	8821	0.0993
8	10	15462	1.0121

In order to use the theory of statistics of extremes, the parent distribution for the measured stress needs to be defined. The stress due to the still-water pressure component should not be considered in the statistics of extreme analysis. The parent distribution of the stress is defined as the probability distribution of the random variable which is defined as the maximum stress in each stress record. Based on this definition, the statistical characteristics of the parent distributions of stress for the eight cases were determined. The results are summarized in Table 2. For cases 1 through 7 the lengths of the stress records were 30 seconds, while the record length for case 8 was 10 seconds [1]. The mean values and coefficients of variation (COV) for cases 6 and 8 were based on the maximum values taken from 10 and 23 records of stress time-history, respectively [1]. Each record represents the stress time-history for 30- and 10-second intervals of measurement, respectively. For the other cases, one record per case was used; therefore, the maximum value in each record was considered as the mean value of the maximum stress for the corresponding case and the coefficient of variation was assumed to be the same as the COV for case 6, i.e., 0.0993.

A transformation from measured stress to uniform lateral pressure was performed using the approach shown in Reference [1]. Essentially, that approach uses a formulation from Mansour [10] to determine a uniformly distributed pressure which causes the measured stresses in the plating. Then the mean value of the maximum pressure can be determined using the theory of extremes.

Table 3. Statistical Characteristics of Pressure

	Maximum Pressure		Extreme Pressure		
Case No.	Mean (psi)	COV	No. of Intervals	Mean (psi)	COV
1	1.75	0.0993	216000	2.55	0.0177
2	1.89	0.0993	91800	2.71	0.0186
3	1.99	0.0993	54000	2.83	0.0192
4	6.17	0.0993	253800	8.99	0.0175
5	6.76	0.0993	70200	9.66	0.0189
6	3.07	0.0993	37800	4.35	0.0196
7	7.63	0.0993	286200	11.13	0.0174
8	13.37	1.0121	162000	74.30	0.0477

Table 4. Statistical Characteristics of Pressure for Case 8

	Maximum Pressure		Extreme Pressure		
Usage Period (Years)	Mean (psi)	COV	No. of Intervals	Mean (psi)	COV
0.2	13.37	1.0121	2160	60.49	0.0732
0.5	13.37	1.0121	5400	63.70	0.0657
1	13.37	1.0121	10800	66.02	0.0610
2	13.37	1.0121	21600	68.24	0.0569
5	13.37	1.0121	54000	71.07	0.0523
10	13.37	1.0121	108000	73.13	0.0493
15	13.37	1.0121	162000	74.30	0.0477
50	13.37	1.0121	540000	77.67	0.0435
100	13.37	1.0121	1080000	79.54	0.0414

It is reasonable to assume that the maximum dynamic pressure has the same coefficient of variation (COV) as the maximum measured stress. The mean value and COV of the extreme pressure were then determined for a ship usage period of 15 years at a rate of 3,000 hours per year and according to the percent use presented in Table 1. The selection of the usage period of 15 years and 3,000 hours of operation per year were for the purpose of illustration. The results are summarized in Table 3.

It is evident from Table 3 that case 8 is the most critical sea state/ship speed combination. Therefore, for this case the statistics of the maximum and extreme pressures were determined for usage periods of 0.2, 0.5, 1, 2, 5, 10, 15, 50 and 100 years. The results are shown in Table 4.

Since the stresses due to still-water pressure were not measured, the mean value of the still-water pressure was determined from hydrostatics to be 2.667 psi. The coefficient of variation and distribution type of still-water pressure are assumed to be 0.20 and normal, respectively (after [6]). The still-water pressure is considered a random variable because Reference [1] does not provide information on the vessel draft and displacement at the time the strain gages were zeroed. The total pressure applied to the plate is the still-water pressure plus the extreme dynamic pressure.

Strength Characteristics

The statistical characteristics of the strength of the material used in the ship, and the dimensions of the plate of interest in this study are based on those given in Reference [1] and are shown in Table 5.

Table 5. Strength Characteristics

Strength Property	Mean Value	COV
Yield Stress	47.8 ksi	0.13
Modulus of Elasticity	29,774 ksi	0.038
Plate Thickness	0.161 in	0.01
Plate Width	11.75 in	0.05
Plate Length	23.5 in	0.05

Table 6. Probability of Deforming a Single Plate

Usage Period (Years)	Probability of Failure, P_{fp}	COV (P_{fp})
0.2	0.03004	0.0490
0.5	0.05092	0.0401
1	0.06765	0.0351
2	0.09403	0.0294
5	0.13950	0.0284
10	0.17200	0.0244
15	0.20310	0.0215
50	0.27760	0.0155
100	0.32900	0.0121

Assessment of Probabilities of Failure

The probabilities of plastic deformation (P_{fp}) of a plate according to the limit state of equation (10) can be determined using Monte Carlo simulation with variance reduction techniques. Conditional Expectation with Antithetic Variates variance reduction techniques [6] were used in the analysis. A computer program was developed for this purpose. The average simulated probabilities of failure (P_{fp}), coefficients of variation of the estimate of the probability of failure COV(P_{fp}) and the numbers of simulation cycles for different usage periods of the ship are shown in Table 6.

Assessment of Structural Life According to Plate Deformation

The end of structural life due to plate plastic deformation was defined as plastic deformation more than twice the thickness of the plate in at least six plates within the critical region. The critical region was defined as that area of the vessel's bottom and side plating which experiences the most pressure as a result of regular operation as well as extreme events such as bottom slamming. The selection was done based on a finite element analysis provided in Reference [1]. This critical area of the vessel has a total of 28 plates. These plates are assumed to experience the same loading and have approximately the same strength characteristics, and therefore have approximately the same probability of failure. The vessel is assumed to have the following inspection and maintenance strategy (hereinafter called inspection strategy): The ship is inspected at the end of the first year because it is the end of the warranty period, then the ship is inspected every I years. It is assumed that the probability of failure of a plate within the warranty period is the same as the probability of failure of a plate within a usage period that is equal to the warranty period. It is also assumed that any damage found during the inspection is restored to a "like new" condition. In order to demonstrate the effect of inspection interval, values of I of one and two years are considered.

Given the probability of failure of a plate (P_{fp}) within the inspection period I as defined previously, the probability of failure of six plates out of 28 plates ($P_{f6/28,I}$) can be determined using the probability mass function of the binomial distribution [11]. The binomial distribution is based on a Bernoulli sequence of trials, i.e., failure of plates which are assumed to be statistically independent. Actually, the events of plate failure are statistically correlated with relatively small correlation coefficients. The probability of failure of the plates is a function of the correlation level. Therefore, it can be estimated in the form of upper and lower limits which correspond to coefficients of correlation (ϱ) of one and zero, respectively. Since the events of plate failure are statistically correlated with relatively small correlation coefficients, the probability of failure of the plates in plastic deformation is closer to the lower limit. The calculations for both limits were performed; however, the results of the lower limit are used in this study. The results of P_{fp} and $P_{f6/28,I}$ for inspection intervals of one and two years, and for the lower and upper limits are summarized in Table 7.

Table 7. Probability of Deforming 6 Out of 28 Plates

Inspection Interval I (years)	Upper Limit, $\varrho = 1$		Lower Limit, $\varrho = 0$	
	P_{fp}	$P_{f6/28,I}$	P_{fp}	$P_{f6/28,I}$
1	0.06765	0.06765	0.06765	0.009895
2	0.09403	0.09403	0.09403	0.042719

The probability of failure of the ship due to plate deformation within its structural life (SL) depends on the inspection strategy of the ship. For the assumed inspection strategy, the probability of failure within the structural life can be determined. Using the probabilities of plate failure from Table 7, the probabilities of failure of the ship due to plate plastic deformation P_{fSL} were determined for I = 1 and 2 years, and SL = 1, 3, 5, 11, 15, 21, 31, 51 and 101 years. The results are shown in Figure 4.

The lower limit on the probability of failure in structural life assessment is a more accurate estimate than the upper limit. It is evident from Figure 4 that by reducing the inspection interval, expected structural life can be increased. This is due to the fact that at the end of each inspection interval, any reported deformation damage is to be fixed before sending the ship to sea for the next usage period. However, it should be noted that these results are highly dependent on the underlying assumptions, for example, the number of hours of operation per year, the percent usage in each sea state/speed combination, loading conditions, definition of end of structural life, and strength characteristics.

FATIGUE

Fatigue and brittle fracture in ship structures is considered as one of the most critical failure modes. The structural life of the ship according to fatigue and brittle fracture failure mode as previously defined can be determined in several steps that are discussed in the following sections.

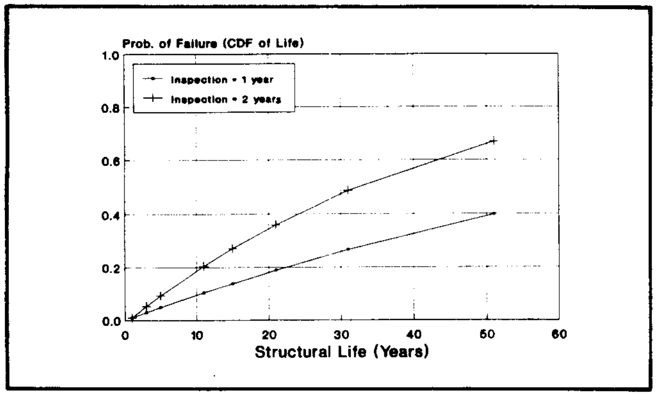

Figure 4. Lower limit of structural life based on plate deformation.

Identification of Fatigue Details

For the purpose of illustration, a structural detail type in the example vessel was identified as susceptible to fatigue and brittle fracture due to wave loading and water pressure. The structural detail type is shown in Figure 5. The critical fatigue detail within the structural detail is the weld between the longitudinal stiffener with two-inch scallops and the shell plating. This detail can be classified as fatigue detail no. 36 according to the classification by Munse, et al. in SSC-318 [12]. The detail is referred to, in this study, as "Detail 36."

Limit State Equation

The fundamental relationship for the analysis undertaken in this part of the study can be expressed in the form of a simple limit state equation as

$$Z = \text{Resistance} - \text{Load} \tag{12}$$

For the purpose of fatigue analysis, equation (12) is usually handled in one of two ways; either using stress range vs. number of cycles to failure (S-N) fatigue test data, or from the principles of fracture mechanics. For this study, an S-N relationship approach was undertaken because of the popularity of the approach, and because the procedure is fairly well established. Munse et al. [12] provides an in-depth discussion concerning this approach as well as much of the needed S-N data to accomplish the tasks.

For the case of fatigue analysis of structural details, the resistance is expressed in terms of the strength characteristics of the various fatigue details that make up the particular structural detail of interest. The S-N curves provide information concerning the stress range to life relationship usually expressed in terms of constant amplitude stress range. A least squares regression line through the mean values of life at each stress range tested provide a curve which can be expressed in a log-log linear form as [13]

$$\log N = \log C - m \log S_R \tag{13}$$

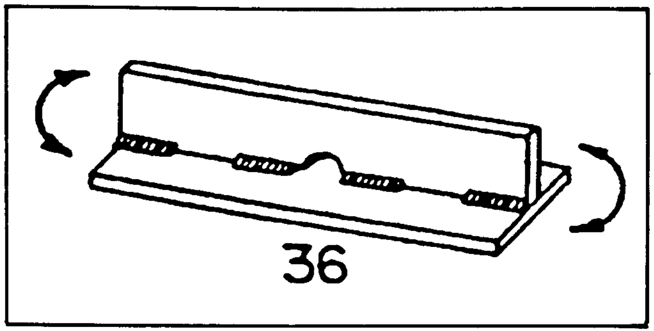

Figure 5. Structural Detail Number 36.

where S_R is the constant amplitude stress range at N cycles to failure; the regression coefficients are the negative inverse of the S-N curve slope, *m,* and the intercept, log *C*. The loading term in equation (12) is represented by an *equivalent constant amplitude stress range* for the lifetime load histogram for the fatigue detail of interest. Because the loading in equation (12) is represented as a single value, the solution for the probability of having a fatigue failure in a given lifetime reduces to

$$P_{ff} = P(N_d \leq N) \tag{14}$$

Here N is a random variable representing the number of loading cycles which the detail of interest can survive at the equivalent constant amplitude loading from the lifetime histogram. The term N_d represents the number of loading cycles expected in the life of the vessel based on the lifetime load histogram. The solution to equation (14) becomes nothing more than evaluating the cumulative distribution function (CDF) of the random variable N at the value N_d.

Load Effect Histograms

In order to evaluate equation (12) an expression for the loading expected in the vessel's lifetime needs to be developed. The ideal form for the loading information is a histogram (or probability density function, PDF) relating stress ranges to frequency of occurrence. Such a histogram or PDF can then easily be related to an equivalent constant amplitude stress range, as shown by Munse [12].

The stress records [1] for the eight cases in Table 1 were evaluated to determine the stress range cycles encountered. A "Rainflow Counting Method" [14] was used to build a frequency histogram of stress ranges from time-histories of stress for each case. The individual histograms were then weighted by their respective percent usage factors from Table 1 and combined to form a stress range frequency histogram for head-seas. The total lifetime load stress range histogram is shown in Figure 6.

Fatigue Strength Characteristics

The S-N curves and their statistical characteristics are taken from Munse, et al. in SSC-318 [12]. The fatigue

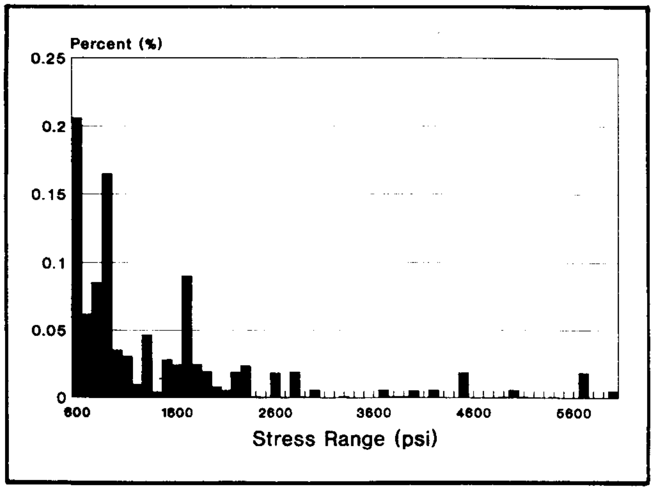

Figure 6. Lifetime stress range histogram for head seas.

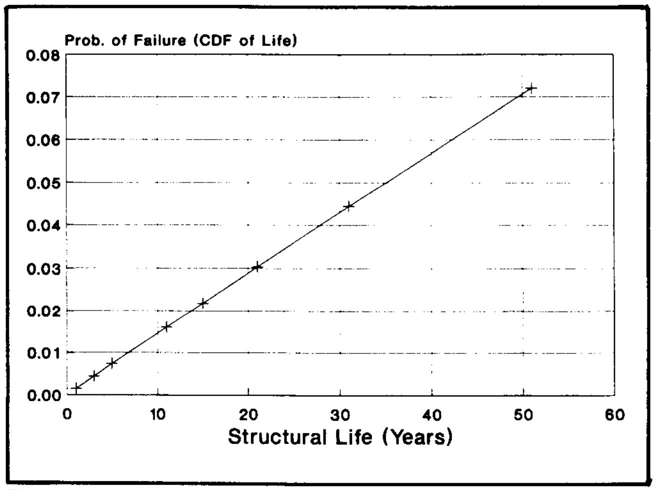

Figure 7. Structural life based on the fatigue failure mode.

strength characteristics of Detail 36 are m = 6.966, Log C = 15.15 and $V_N = 0.63$. The *Weibull* probability distribution is used to model fatigue strength. The parameters of the distribution are $w = 6.82 \times 10^8$ and $k = 0.969$.

The standard deviation of the fatigue life data can easily be found; however, the scatter of the data about the mean fatigue line is not the only uncertainty involved in the S-N analysis. A measure of the total uncertainty (coefficient of variation, COV) in fatigue life, v_R, is usually developed to include the uncertainty in fatigue data, errors in the fatigue model, and any uncertainty in the individual stresses and stress effects. Ang and Munse [15] suggested that the total COV in terms of fatigue life could be given by:

$$v_R^2 = v_N^2 + v_F^2 + v_C^2 + (m v_S)^2 \qquad (15)$$

where v_R is the total COV of resistance in terms of cycles to failure, v_N is the variation in the fatigue test data about the mean S-N line, v_F is the variation due to errors in the fatigue model and use of Miner's rule, v_C is the variation due to uncertainty in the mean intercept of the regression line that includes effects of fabrication, workmanship, and uncertainty in slope, v_S is the variation due to uncertainty in the equivalent stress range that includes effects of errors in the stress analysis, and m is the slope coefficient of the mean S-N regression line.

Values of m and v_N can be obtained from sets of S-N curves for the type of detail being investigated; a number of which are tabulated by Munse in SSC-318 [12]. Reasonable values for the remaining uncertainties are available in the literature [7, 11, 12, 16). Typically, v_S is taken to be 0.1, v_C is assumed to be 0.4, and v_F is taken as 0.15.

Assessment of Probabilities of Failure

The probability of a fatigue detail failing to reach the design usage period can be determined using the cumulative distribution function of the *Weibull* distribution. The resulting probabilities of failure of Detail 36 are 0.00150 and 0.00293 for one and two year usage periods, respectively. The total number of critical local fatigue details depends on the section of the ship identified as critical. For the purpose of illustration, assume that the number of local details in the critical region of the ship is 76. All 76 local fatigue details are assumed to have the same load effect and strength. The end of structural life for this mode of failure is defined as the failure of at least one local fatigue detail at the end of an inspection interval. Similar to the method used for plate deformation mode of failure, the probability of failure of at least one detail out of the number of details at the end of inspection periods of one and two years can be determined using the binomial probability distribution. The resulting probabilities are 0.01075 and 0.01996 for one- and two-year inspection periods, respectively, under these assumptions.

Assessment of Structural Life According to Fatigue Failure

The structural life of a ship detail is dependent on the inspection strategy. As in the case of plate deformation, two strategies are considered. In the first, the ship is inspected at the end of every year during its entire structural life. In the second strategy, the ship is inspected at the end of the warranty period, i.e., the end of the first year, and then at the end of every two years during its structural life. The structural life also depends on the correlation level between the fatigue details, which is unknown. The calculations for structural life were performed for the two limiting cases that correspond to correlation levels of statistically independent (coefficient of correlation = 0.0), and fully correlated (coefficient of correlation = 1.0). Since fatigue damage is cumulative in nature, and the same welding process and source of loading apply to all fatigue details, the coefficient of correlation between fatigue details of the same type can be assumed to be large, i.e., close to the fully correlated limiting value. Based on the underlaying assumptions, it was determined that the resulting probabilities of failure of the ship in fatigue are almost independent of the inspection strategy. The results are shown in Figure 7.

CONCLUSIONS

The assessment of the structural service life of a ship is a complicated and difficult task. The ability to determine with some confidence the expected service life of a structure holds the potential for large economic gains. These gains could be seen in more effective utilization of initial construction material and resources, more effective maintenance and repair strategies, and possibly more return value in disposal at the end of the structure's life. It therefore seems reasonable that work in this area should be pursued.

The structural service life of the example vessel analyzed in this paper according to the defined "end of structural life" was determined for two failure modes. In the plate deformation failure mode, Figure 4 indicates that for inspection intervals of two years, there is a 72% chance that the vessel will not sustain enough damage in 15 years of operation to constitute reaching the "end of structural life" as defined. For the fatigue failure mode, Figure 7 indicates that for inspection intervals of two years, the probability of reaching 15 years of life without experiencing a fatigue failure of one of the identified critical details is 98%. Both of these results are based on the definitions of "end of structural life" provided in this paper.

The methodology and examples provided in this paper are meant to be a catalyst for further discussion and investigation into the subject. While not meant to be taken literally, they do show one manner in which probabilistic methods can be used to address the subject of life assessment. The results of the approach are highly dependent on the assumptions with which the model works. In particular, the operational profile of the vessel and the definition of "end of structural life" drive the entire procedure. Exercising the methodology by performing a parametric analysis could possible provide the user with additional insights into the problem of life assessment. Those insights might lead to additional savings through improved maintenance or inspection strategies.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of the U.S. Coast Guard, U.S. Naval Academy, and the Univrsity of Maryland.

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