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# SSC-427

# LIFE EXPECTANCY ASSESSMENT OF SHIP STRUCTURES

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SHIP STRUCTURE COMMITTEE
2003

Ship
Structure
Committee

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**LIFE EXPECTANCY ASSESSMENT OF SHIP STRUCTURES**

This report illustrates analysis techniques that can be used to aid ship owners and operators in evaluating the life expectancy of their vessels. These techniques enable linking all aspects of a vessel's life cycle management including: design, construction, acquisition, repair, maintenance, and removal from service. Potential future applications include the improvement of vessel design and maintenance practices. Other applications include: inspection focus, repair prioritization, critical details identification, and determining the significance of each structural failure mode.

The report incorporates a bulk carrier and a tanker platform for demonstration of the project concepts. The reliability based life expectancy assessment process was applied to these two vessels in parallel application by considering the seven steps outlined in the introductory section of the report. These steps include: vessel particular identification, structural section and component definition, load assessment, definition of local detail characteristics, time dependant reliability assessment, system reliability analysis, and application of the results. Results of the time dependant reliability analysis and time histories of failure probability are presented and compared to illustrate differences and other factors such as the effect of maintenance level.

The report includes a review of the strengths and weaknesses of the analysis techniques and recommends further research areas to improve the viability of the demonstrated techniques.

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16. Abstract

The report presenting the results of this project includes the results of a literature review describing the state of knowledge in ship structure damage accumulation modeling in terms of fatigue and corrosion damage, ship structural limit states design, ship structure loading and load combination, and structural reliability analysis. Based upon the information collected in these reviews, this demonstration project assembled sample material degradation accumulation, vessel loading, structural limit state, and reliability analysis models. The demonstration considered corrosion degradation and its effects on hull girder first yield, component buckling and component fatigue crack initiation.

The report concludes with a review of the strengths and weaknesses of the analysis techniques and recommends further research areas to improve the viability of the techniques demonstrated in this report. In general, it is concluded that the techniques presented in this project can be applied, however, they require automation of the analysis process and the support of statistical data to describe issues such as structural degradation rates. A development plan for reliability-based life expectancy assessment software is presented as an illustration of how the technology developed in this project could be progressed.

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# CONVERSION FACTORS

## (Approximate conversions to metric measures)

| To convert from | To | Function | Value |
|---|---|---|---|
| **LENGTH** | | | |
| inches | Meters | divide | 39.3701 |
| inches | Millimeters | multiply by | 25.4000 |
| feet | Meters | divide by | 3.2808 |
| **VOLUME** | | | |
| cubic feet | cubic meters | divide by | 35.3149 |
| cubic inches | cubic meters | divide by | 61,024 |
| **SECTION MODULUS** | | | |
| $inches^2$ feet | $centimeters^2$ meters | multiply by | 1.9665 |
| $inches^2$ feet | $centimeters^3$ | multiply by | 196.6448 |
| $inches^3$ | $centimeters^3$ | multiply by | 16.3871 |
| **MOMENT OF INERTIA** | | | |
| $inches^2$ $feet^2$ | $centimeters^2$ $meters^2$ | divide by | 1.6684 |
| $inches^2$ $feet^2$ | $centimeters^4$ | multiply by | 5993.73 |
| $inches^4$ | $centimeters^4$ | multiply by | 41.623 |
| **FORCE OR MASS** | | | |
| long tons | Tonne | multiply by | 1.0160 |
| long tons | Kilograms | multiply by | 1016.047 |
| pounds | Tonnes | divide by | 2204.62 |
| pounds | Kilograms | divide by | 2.2046 |
| pounds | Newtons | multiply by | 4.4482 |
| **PRESSURE OR STRESS** | | | |
| $pounds/inch^2$ | $Newtons/meter^2$ (Pascals) | multiply by | 6894.757 |
| kilo $pounds/inch^2$ | mega $Newtons/meter^2$ (mega Pascals) | multiply by | 6.8947 |
| **BENDING OR TORQUE** | | | |
| foot tons | meter tons | divide by | 3.2291 |
| foot pounds | kilogram meters | divide by | 7.23285 |
| foot pounds | Newton meters | multiply by | 1.35582 |
| **ENERGY** | | | |
| foot pounds | Joules | multiply by | 1.355826 |
| **STRESS INTENSITY** | | | |
| kilo $pound/inch^2$ $inch^{1/2}$($ksi\sqrt{in}$) | mega Newton $MNm^{3/2}$ | multiply by | 1.0998 |
| **J-INTEGRAL** | | | |
| kilo pound/inch | $Joules/mm^2$ | multiply by | 0.1753 |
| kilo pound/inch | kilo $Joules/m^2$ | multiply by | 175.3 |
| **TEMPERATURE** | | | |
| Degrees Fahrenheit | Degrees Celsius | subtract<br>& divide by | 32<br>1.8 |

## ABSTRACT

This Ship Structure Committee project was developed to demonstrate vessel reliability based life expectancy estimation. This demonstration was intended to illustrate how these analysis techniques could be used to aid ship owners and operators in evaluating the life expectancy of their vessels and thus aid in linking all aspects of a vessel's life cycle management and planning including: design, construction, acquisition, repair and maintenance and removal from service. It is proposed that the potential applications could in the future be extended to the improvement of vessel design and maintenance practice. Some applications could include: inspection focusing, repair prioritization, identification of critical details, and gauging thesignificance of each structural failure mode.

The report presenting the results of this project includes the results of a literature review describing the state of knowledge in ship structure damage accumulation modeling in terms of fatigue and corrosion damage, ship structural limit states design, ship structure loading and load combination, and structural reliability analysis. Based upon the information collected in these reviews, this demonstration project assembled sample material degradation accumulation, vessel loading, structural limit state, and reliability analysis models. The demonstration considered corrosion degradation and its effects on hull girder first yield, component buckling and component fatigue crack initiation.

The sample application considered a bulk carrier and tanker structure as platforms for demonstration of the concepts involved in this project. The reliability based life expectancy assessment process was applied to these two vessels in parallel application by considering the seven step process outlined in the introductory sections of the report. These steps include: vessel particular identification, structural section and component definition, load assessment, definition of local detail characteristics, time dependant reliability assessment, system reliability analysis, and application of the results. Results of the time dependant reliability analysis, time histories of failure probability, are presented for the tanker and bulk carrier and compared to illustrate their difference and other factors such as the effect of maintenance level.

The report concludes with a review of the strengths and weaknesses of the analysis techniques and recommends further research areas to improve the viability of the techniques demonstrated in this report. In general, it is concluded that the techniques presented in this project can be applied, however, they require automation of the analysis process and the support of statistical data to describe issues such as structural degradation rates. A development plan for reliability-based life expectancy assessment software is presented as an illustration of how the technology developed in this project could be progressed.

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# 1. INTRODUCTION

The mandate of the Ship Structures Committee is to promote research and disseminate its results to the marine community in an effort to improve the quality of ship design, construction, maintenance and life cycle management.

This project was developed to aid ship owners and operators in evaluating the life expectancy of their vessels and thus aid in linking all aspects of a vessel's life cycle management and planning including: design, construction, acquisition, repair and maintenance and removal from service.

The decision-making processes in vessel life cycle management that ultimately determine the life expectancy of a vessel include the following issues:

- the quality of the ship's initial design and construction,
- the service in which it operates
- the owner's maintenance and repair strategies
- the rate of change of technology during the vessel's service life, and
- the prevailing economic circumstances affecting operations, upkeep, scrapping and new construction.

An owner's decisions regarding the purchase, continued operation or maintenance of a vessel are ideally based on developing the greatest return on each invested dollar. In order to estimate the costs associated with the operation of a vessel the initial cost, maintenance cost and probable residual value at the end of the operational period are necessary. These costs may be used to:

- estimate the required service life of a vessel such that its operational revenue exceeds its costs, or
- estimate the point in a vessel's life cycle at which repair and maintenance costs will start impacting on profitability.

Any technique developed to estimate the life cycle costs associated with the operation of a vessel could also be used to compare the efficiency of alternative structural designs for a given service or the cost effectiveness of designing ship structures for extended service lives (e.g., 40 vs. 20 year life).

In response to the desire to estimate the operating costs of structural systems, the Ship Structure Committee has assembled a project to develop techniques capable of estimating the life expectancy of a ship structure. In developing this project it has been recognized that the degradation of the ship structure and its loading are uncertain over any significant period of the vessel's service life, thus the techniques developed for estimating the life expectancy of a ship structure must be probabilistic in nature. The determination of life expectancy can be used to compute the time statistics for component or mode of failure needed in major expenditure decision analysis.

## 1.1 Report Layout

The following report presents the results of a research project aimed at demonstrating reliability based life expectancy assessment of ship structures. This report is presented as a demonstration of the concepts involved and as a first step towards the final development of these techniques. The report is presented in seven sections as follows:

- Section 1 - Project and Report Introduction
  Introduces the justification for the project and describes the layout of the report
- Section 2 - Project Objectives and Scope
  Defines the project objectives and scope of the investigation
- Section 3 - Vessel Life Expectancy Assessment Techniques
  Presents reliability based life expectancy assessment techniques along with its process, analytic approaches and defines the assessment data requirements
- Section 4 - Demonstration of Life Expectancy Assessment Techniques
  Presents two worked examples to demonstrate the analysis data, process and results
- Section 5 - A Critical Review of the Analysis Approach Limitations
  Discusses the benefits of the analysis techniques along with those areas in need of further development
- Section 6 - Conclusions and Recommendations
  Presents conclusions outlining what has been learned in this project and recommends areas for further development
- Appendix A - Vessel Life Expectancy Assessment Literature Review Report
  Describes the data and analytic techniques collected in the literature review for vessel life expectancy assessment
- Appendix B - Reliability Based Life Expectancy Assessment Software Development Plan
  Briefly describes the technical requirements and software development requirements to allow broad application of the approaches developed and described in this project.

## 2. PROJECT OBJECTIVES AND SCOPE

Traditionally the design of ship structures has been based upon simplified approaches making use of empirical or experience-based design formulae. Using these approaches, the designer is usually unaware of the level of safety and/or many of the underlying design assumptions. Once a vessel is in service, maintenance is often driven by third party (e.g., Class Society) rules for inspection and repair whose maintenance decisions are primarily experience or judgment based. However, recent developments in design techniques including reliability-based design and maintenance approaches are allowing the implementation or consideration of these analytic techniques to make more informed design and maintenance decisions.

When first conceived, the primary objective of this project was:

> *to develop a reliability-based approach for assessing the life expectancy of a vessel's structural system.*

This ability to evaluate a vessel's life expectancy, allows the project's second objective to be achieved:

> *to allow vessel owners or operators to relate vessel life expectancy to life cycle costs and thus indicate the impact of management decisions. Life expectancy can also be used in major expenditure decision analysis*

Potentially, the results of this project could be used in the future to improve design and maintenance techniques. Some applications could include:

<u>Inspection Focusing:</u>
As illustrated in the pictures of structural inspection in progress in Figure 2.1, on large ships there is a lot of structure to cover and inspection can be time consuming. One potential application of the work being performed in this project is to develop a means of focussing inspection on the areas which are most prone to failure or degradation. By highlighting areas of concern, more resources can be spent inspecting these areas and less on those which are more reliable.

<u>Repair Prioritization</u>
As illustrated in Figure 2.2, structural degradation can lead to extreme structural integrity issues. A potential application of the results of this study could be in the idenitifcation of areas which are prone to high degradation rates and thus suceptible to premature failure. This information could be used to develop proactive maintenance prioritisation techniques based upon maintenance needs.

<u>Identification of Critical Details</u>
As illustrated in Figure 2.3, structural details can promote degradation (cracking) and thus lead to failure. The results of an approach such as the one presented in this project could be used to identify details which pose problems and suggest modifications to improve thier performance.

<u>Failure Mode Significance</u>
Figure 2.4 illustrates global or hull girder buckling, a rare mode of failure. The techniques oulined in this project could be applied to develop a better understanding of the relative significance of each mode of failure and thus indicate appropriate levels of resouces which should be applied in either developing techniques to better uderstand them or prevent them.

**Figure 2.1: Ship Inspection**

**Figure 2.2: Unchecked Structural Degradation**

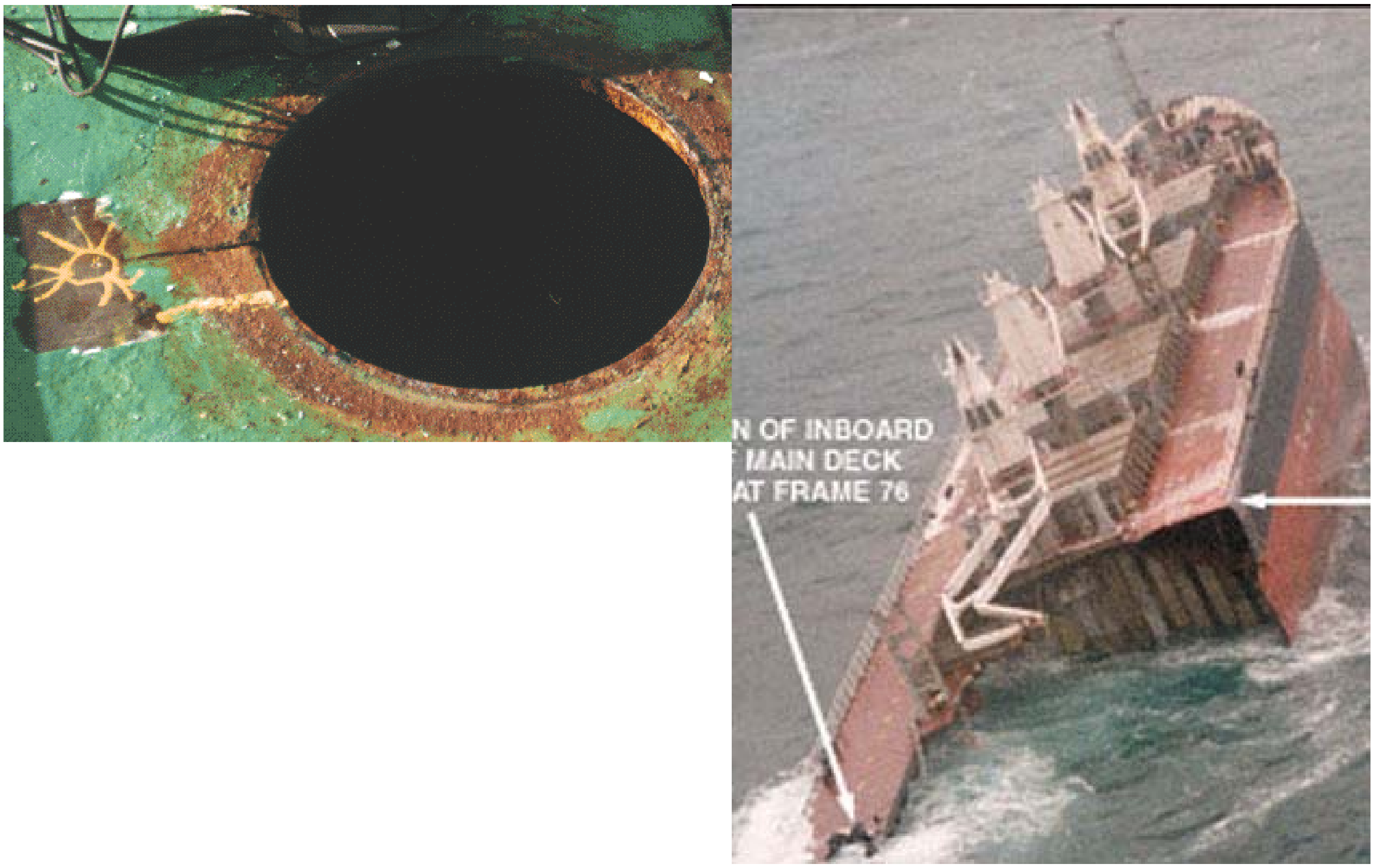



**Figure 2.3: Strength Deck Cracks Initiating at Grain Filling Ports**

**Figure 2.4: Global Buckling Failure**

## 2.1 Vessel Life Expectancy

In assessing the time dependent structural integrity or life expectancy of a ship structure using structural reliability techniques, one must consider the through life degradation of the structure and its potential failure modes. To estimate life expectancy, one should also consider the philosophies guiding ship construction, maintenance and repair in order to develop the repair strategies which will ultimately impact on the probable life expectancy of a ship structure.

The flow chart shown in **Figure 2.5** shows the components of a reliability-based life expectancy estimation approach used in ship structure life cycle management. The sections that follow provide additional detail on the major components of this approach.

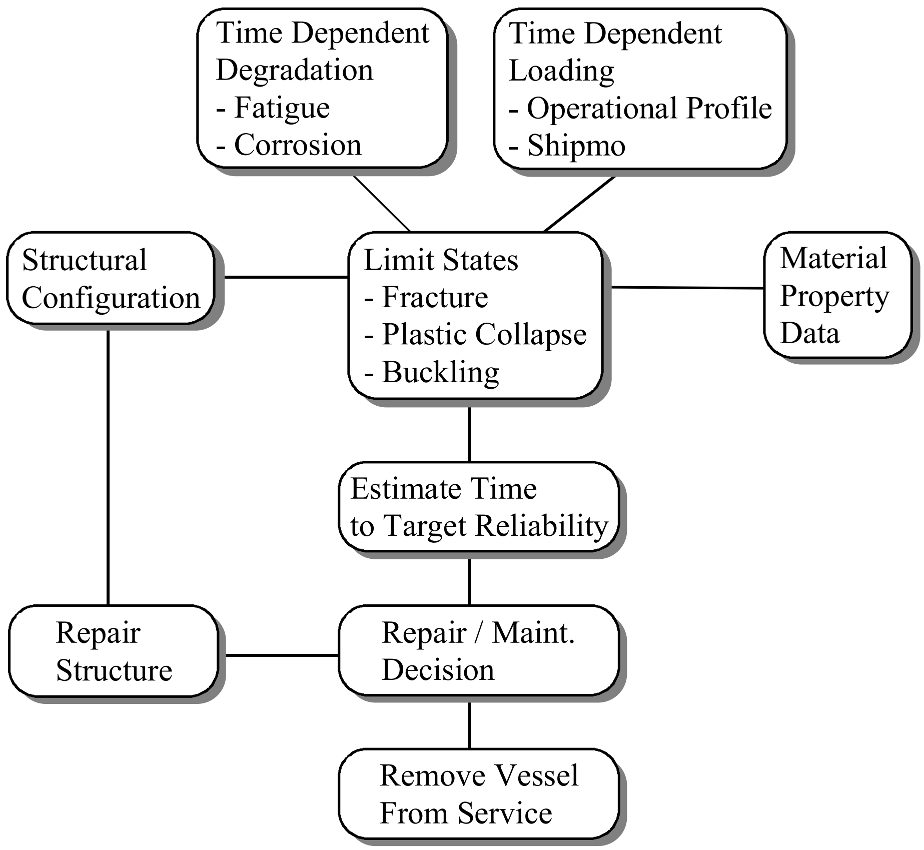



**Figure 2.5: Reliability-Based Vessel Life Cycle Management Process**

In general, the life cycle of a vessel may be divided into four phases including:

- Conception and Design
- Acquisition or Construction
- In-Service and Operation
- Disposal

In the concept development and design stages, decisions pertaining to the form of the vessel and details of the structural system are made. In principle, some of these decisions should be based on the design life of the vessel and thus directly impact its life expectancy. The life expectancy of the vessel is essentially a design parameter at this stage.

The quality of the fabrication and materials used in the construction of a vessel play a significant role in defining the life expectancy of a vessel. Misalignment, poor weld toe profiles, poor quality of paint application and cathodic protection systems, amongst other factors, can accelerate the degradation of a structural system.

The service life of a vessel is the time period in which the vessel is exposed to its service loads and accumulates damage. Damage may be in the form of corrosion, cracking or general structural deformation, all of which reduce the reliability of the structure. With the passage of time, the structure will require repair and maintenance actions to prevent progressive degradation leading to either a serviceability (inability to perform as intended) or an ultimate limit state (complete structural failure) failure.

The decision to remove a vessel from service, for reasons other than obsolescence, would be made based on a forecast that the expected maintenance and repair costs to maintain a given level of safety would exceed a tolerable level. Conventional replacement decision theory describes the operations and maintenance (O&M) cost history in terms of the "bathtub curve", consisting of three phases:

(1) an initial phase of higher costs associated with introducing new system or piece of equipment into service, i.e. "teething" troubles
(2) a stable phase of lower costs, characterized by random failure events;
(3) a final phase of accelerating costs as equipment or components wear-out.

It has been suggested that the "bath-tub curve" concept can be applied to ships, which essentially form a super-system of equipment and systems. The degree of variation between the phases is strongly dependent on the amount of planned maintenance, which when implemented effectively tends to "level out" the cost variation between individual years by preemptively replacing equipment before a more significant failure occurs. A particular feature of marine operations is the statutory survey (typically every five years), which tends to have additional costs associated with it; this can introduce a series of "mini-peaks" in the O&M cost history. In addition, ships may undergo one or more major refits, which may introduce new technology, systems, or structural configurations, each of which may introduce a new "teething" phase into the O&M cost history. Finally, ships are mobile assets that can change ownership or service, which then can affect the level of maintenance and the associated cost history. Ideally, an owner/operator would remove a vessel from service or perform a major refit prior to the third phase of the vessel's operational life.

# 3. VESSEL LIFE EXPECTANCY ASSESSMENT TECHNIQUE

The vessel life expectancy assessment approach developed in this project involves a seven step process including:

- Vessel Particular Identification,
- Structural Section and Component Definition,
- Load Assessment,
- Definition of Local Detail Characteristics,
- Time Dependant Reliability Assessment,
- System Reliability Analysis, and
- Application of the Results.

The sections that follow describe these steps and discuss their application, providing some additional information on their limitations and inherent assumptions. In addition, alternative approaches to those proposed for the case study examples are described.

It should be noted that the approach has been assembled with relatively simple limit state formulations and analysis techniques to demonstrate the application of time dependent reliability techniques for vessel life expectancy assessment. With this description, the approach may be improved to incorporate more advanced structural limit states (e.g., hull girder ultimate strength) or analysis techniques (e.g., finite element analysis).

The approach presented in this report was developed after the completion of a literature review to identify the state of practice. The project progress report outlining the results of the literature review is presented in Appendix A.

## 3.1 Vessel Particular Identification

In this step, the subject vessel is described in terms of its:

- Structural configuration and scantlings,
- Materials, and
- Hull form and weight distribution.

The structural configuration information, which may be described by general arrangement drawings, is used to subdivide the ship structure into discrete compartments with different environments (e.g., ballast tanks, work and cargo spaces). The scantlings will be used to define the structural components used in the reliability based limit state calculations along with the material property information. The scantling and section information will also be used to describe typical hull girder sections used to calculate section moduli.

The proposed sample time dependant reliability analysis is based on relatively simple limit state equations and thus the material property data requirements are modest. Future applications of the proposed approach may incorporate more complex limit state or structural analysis formulations and thus may require additional data. For the current example the material property data requirements include:

- Steel yield strength,
- Modulus of elasticity, and
- Welded connection S-N curves (statistically defined).

The statistically defined nominal stress S-N curves for this example have been taken from a typical design standard (e.g., BS 5400) which provides both the mean S-N relationship and a design relationship that represents the mean minus 2 standard deviations reference level.

### 3.1.1 Future Development

The description of the vessel particulars would be defined using a Graphical User Interface (GUI). It is expected that in software developed specifically for ship structure life expectancy assessment, much of the required material property or performance information would be stored in a database. The contents of the database would be made available to the user through a GUI allowing selections to be made from lists or pull-down menus.

## 3.2 Structural Section and Component Definition

The objective of this step in the assessment process is to subdivide the ship structure into a more manageable number of representative sections and components. This is accomplished by first dividing the structure into N longitudinal segments as shown in Figure 3.1. The division of the ship into segments should be performed such that the segments are small enough to be considered to have uniform applied loads and be subjected to common environmental effects (i.e., corrosion rates). Ship segment ends should ideally start and stop at the forward and aft ends of compartments with differing environments and or convenient mid-frame locations.

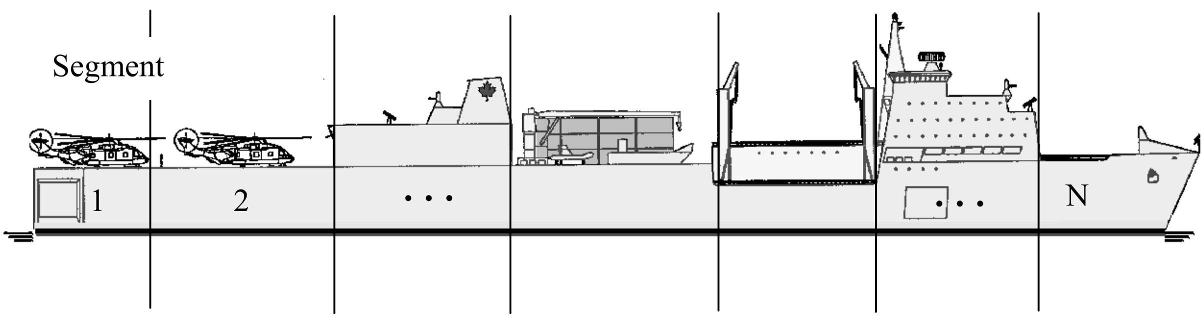



**Figure 3.1: Vessel Longitudinal Segment Definition**

The second step in the vessel subdivision process is to define one or more typical frame structures within each segment. This step would involve the definition of M typical frame sections similar to that shown in Figure 3.2. If the same number of frames is defined in each segment, then M x N frames have been defined in total. At this time, the number of frames that is characterized by a given frame is also recorded.

The third and final step in the subdivision process involves the identification of typical structural details. By grouping, structural details which:

- are structurally similar,
- are subjected to similar loads,
- operate under the same environmental conditions and
- start their life in the same condition.

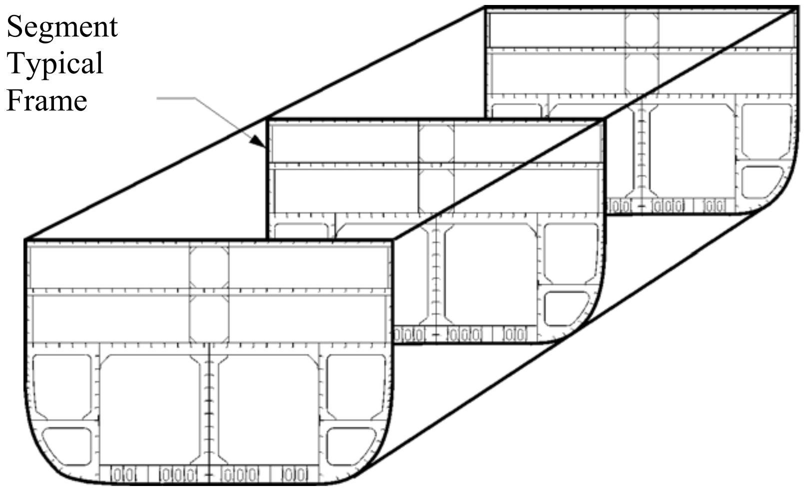



**Figure 3.2: Definition of Typical Frames for a Given Ship Segment**

This final subdivision step is accomplished as shown in Figure 3.3, in which the main deck longitudinal/frame intersections are grouped. In this structural detail, characterization process J typical structural details are defined. The number of structural details characterized by each structural detail will also be reported.

Based on this definition scheme, any structural detail characteristic could be related to its segment, frame and component based on a three dimensional subscript system (e.g., $Area_{m,n,j}$). In addition, the level of discretization detail would be determined by the user, and thus would be appropriate to their needs.

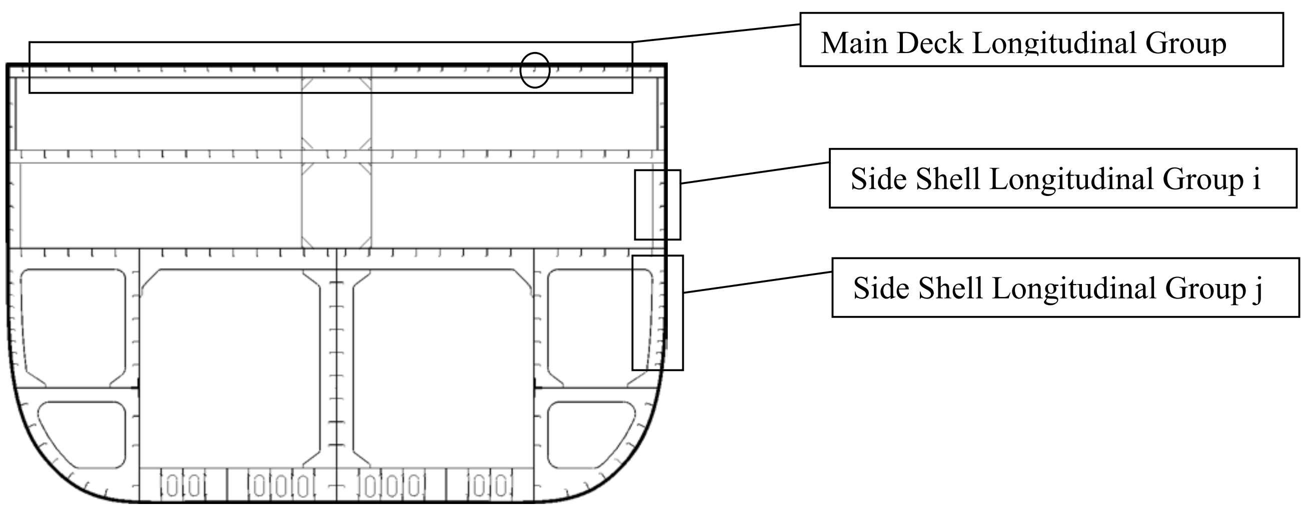



**Figure 3.3: Definition of Typical Structural Details**

### 3.2.1 Future Development

This structural segment, frame and component definition could be completed in a database environment in which a pictorial representation of the longitudinal structure is presented. The user could specify the number of frames in the hull, the frame spacing, location of the segment boundaries and typical frames. The number of typical frame groups and proportion of the segment's frames represented by each typical frame could be defined. Finally, the user could group and define typical structural details for each frame by picking from a pictorial listing of structural details.

Based on the approach outlined for structural discretization, it is possible to include any appropriate level of detail. For instance, every frame and structural component may be described or a more approximate approach which takes advantage of the ability to group like components and frames, assuming that their performance will be similar, can be applied.

## 3.3 Load Assessment

The objective of this step in the assessment process is to define the loads applied to the vessel. This is accomplished through a statistical analysis of the loads generated based on a defined operational profile to estimate load distributions for fatigue and ultimate strength calculations. In addition, the still water load distribution will be estimated for the vessel.

The still water load distribution may be estimated based on the hull geometry and weight distribution data. The uncertainty in still water loads at a given vessel longitudinal location can be considered by characterizing the still water moment with a normal distribution. It has been suggested (Ayyub & Assakkaf 2000) that the ratio of the mean to nominal still water moments are 0.4 to 0.6 for commercial vessels and 0.7 for warships. The variability in terms of the coefficient of variation was estimated as 0.3 to 0.9 for commercial vessels and 0.15 for warships.

An operational profile may be defined simply by stating a general area of operation (e.g., North Atlantic) and an endurance or service speed. At the other extreme, a full operational profile for a specific loading condition or a mission may state how much time the vessel will spend in various areas of the world, and at what times in the year, as well as the distribution of its speed and headings. This data can be then combined with a statistical representation of the wave climate in the areas of operation to provide a complete picture of the vessel's "sea operational profile". The net result is a matrix expressing the probability of occurrence of a given wave height, period and ship speed condition. This wave encounter data statistical analysis computation may be completed using software such as LOS$^3$A, for example.

The next step in the load analysis process is to evaluate vessel response to wave encounters (load cycle amplitude) and thus develop a load level exceedance probability for the operational profile. The net result of this portion of the analysis process is to develop a load spectrum specific to the vessel operational profile. If more than one operational profile is defined for a vessel, the procedure is repeated and an *overall* load spectrum is obtained as a weighted sum of the individual operational profiles based on the proportions of time spent in each operational profile.

### 3.3.1 Load Analysis Data Requirements

Two "sets" of data are required for long-term load calculations including the vessel operational profile and reference loads for all operational conditions. The operational profile information required includes:

- The projected route of the vessel described in terms of areas of operation and the percent time spent in these areas,
- Vessel loading conditions or mission and relative time spent in each mode; (loading conditions are appropriate for commercial vessels, while the mission may be more appropriate for military or patrol vessels),
- Vessel average speed ranges and relative amount of time spent at each speed in a particular sea state or wave height. In statistical terms this refers to joint probability distribution (or conditional probability distribution) of speed and sea state (wave height),
- Joint probability distribution (or conditional probability) of relative heading and sea state (wave height), and
- Statistical representation of the wave climate for each area of operation

The ship loads information includes load Response Amplitude Operators (RAO's) and corresponding load zero crossing periods in irregular seaways for all relevant combinations of ship speed, relative heading and sea state. Load RAO values refer to a particular (predetermined) load location (e.g., midships) and for a specific loading mode (e.g., vertical bending moment).

In order to make the calculations feasible, each of the parameters in the operational profile is discretized in some manner. For example, the route can be divided into Marsden Zones (or zones of latitude and longitude transited by the vessel) and the time spent in these zones. Loading can be treated in terms of standard conditions. Relative heading can be simplified into head, bow beam, quartering and following seas; and speed can be treated as sets of speed ranges.

When a new design will follow the same operational profile as an existing ship, the existing ship's operation may be studied and characterized from operational logs. For new designs, operational profiles can be generated from the operator's plans. The level of discretization of operational profile and/or environmental data should correspond to the certainty in the operational profile information.

The process of developing a detailed operational profile requires the development of input joint probability or conditional probability diagrams, including ship speed versus sea state (or wave height), and relative heading versus sea state (or wave height). These are obtained either from historical data or perhaps from operating directions for the vessel.

Vessel response RAO values are usually obtained utilizing state of the art load calculating software. Two types of sea load calculating programs have been successfully used in this project. One is the linear strip theory program ShipmoPC, Version 3.0, and the other is PRECAL, a frequency domain panel code for load calculations, however, many seakeeping codes could be used.

### 3.3.2 Load Analysis Process

Exceedance probabilities for load cycle are calculated using the procedure given in (FTL 1998). The load amplitudes can be discretized into N number of loads, or calculations can be performed for load ranges. In any case, the long-term exceedance probability for load cycle amplitude in all seaways for *n* route legs is:

$$Q(X_{cycle})_{Route} = \sum_{m=1}^{n}\sum_{i=1}^{N_H}\sum_{j=1}^{N_V}\sum_{k=1}^{N_\phi}\sum_{l=1}^{N_T} p_m(leg)\cdot p(V_j \mid H_i)\cdot p(\phi_K \mid H_i)\cdot p(H_i T_{zl})\cdot \frac{f_z}{f_{zRoute}}\cdot e^{\left(\frac{-X_{cycle}^2}{2\cdot RMS^2{}_{load}}\right)}$$

where $X_{cycle}$ is load amplitude, $p_m(leg)$ is the leg probability reflecting time spent traversing individual sea area relative to total time at sea, $f_z$ is zero crossing frequency in a seaway, and $f_{zRoute}$ is average long-term zero crossing frequency.

Terms $p(V_j|H_i)$, $p(\phi_k|H_i)$ and $p(H_i, T_z)$ are conditional probability of speed vs. wave height, relative heading vs. wave height and joint probability of wave height and wave zero crossing period, respectively.

Three major assumptions are inherent in this approach:

- stationarity of wave conditions, i.e., wave parameters given by significant wave height and zero crossing period are assumed fixed for a certain period of time (usually two to three hours),
- wave loading process is narrow banded. This permits load amplitude in a random seaway to be modeled using a Rayleigh distribution,
- when an operational profile is developed in the absence of historical data, speed, sea state (wave height) and relative heading are assumed to be independent quantities. This may not always be the case as in severe sea states the practice is to reduce speed and to orient the ship in preferred directions. From the fatigue point of view, the bulk of damage arises from the exposure to moderate conditions. Because the amount of time spent in these severe sea states is not as significant as that spent in more moderate conditions, the assumption of independence is reasonable.

The cumulative probability distribution of lifetime loading is calculated form the knowledge of number of cycles in the ship life $N_{cycle}$ as:

$$F_{X_{life}}(X_{life\backslash}) = [F_{X_{cycle}}(X_{cycle})]^{N_{cycles}}$$

The calculated lifetime load spectrum can be presented in either tabular or graphical form. Also, as previously mentioned, calculations can be done for individual load amplitudes or for load amplitude ranges. For example, Figure 3.4 shows in graphical form load exceedance probabilities based on individual load cycle amplitudes.

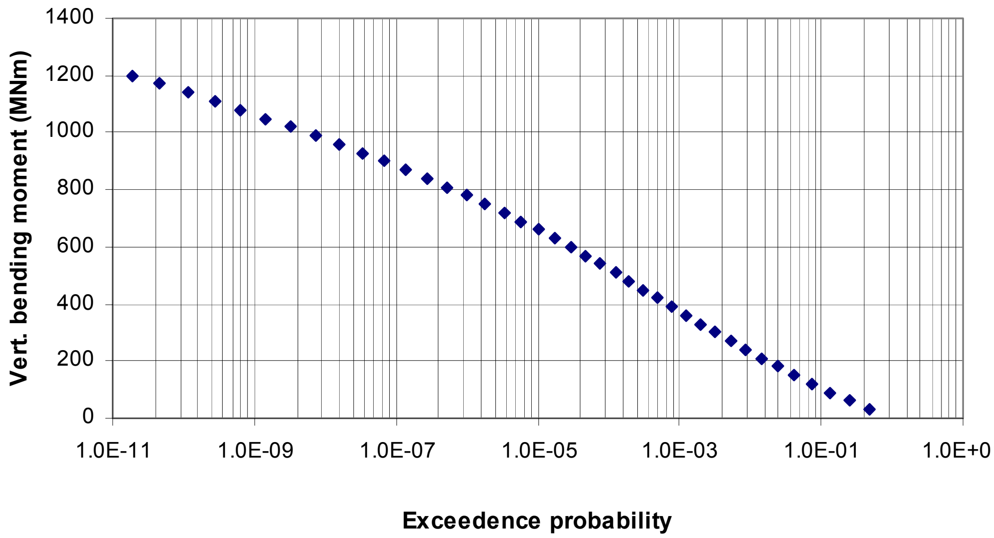



**Figure 3.4: Example Load Spectrum**

This type of data presentation is well suited if short-term analysis is sought, i.e., finding an individual load cycle corresponding to a certain probability of exceedance in the ship lifetime.

Results presented in this format are suitable for fatigue calculations by assuming that the load cycles are fully reversing and by assuming that the load occurrence rate follows a Poisson process. If the mean loading rate of occurrence is λ and is assumed relatively constant for extended periods of time, the number of occurrences (*n*) of the load in time *t* is given by

$$P[n \text{ in } t] = \frac{(\lambda t)^n}{n!} e^{-\lambda t}$$

If the duration of each load is very short, the cumulative distribution function of the maximum load is given by (Ellingwood 1995 and Wen 1990)

$$F_{\max}(x) = \exp[-\lambda t(1 - F_i(x))]$$

where $F_i(x)$ is the cumulative probability distribution function for the applied load.

In fatigue analysis, it is also necessary to make an assumption as to the nature of the load cycle such as moments are fully reversing or pressures are half sinusoidal (e.g., peak to zero).

### 3.3.3 Future Development

The definition of operational profiles and in general the load calculations may be completed using the LOS$^3$A software in which a map based system is used to define the operational profile. RAO’s can be generated using Shipmo’7 for the vessel sections and operating conditions of interest.

By assembling the software in a modular fashion, any RAO generating software may be used with the LOS$^3$A software to estimate the applied load spectrum.

## 3.4 Definition of Local Detail Characteristics

In this stage of the problem solution process, the characteristics of the previously defined structural details (see Section 3.2) are assigned. The characteristics of interest to this investigation include:

- nominal stress transfer functions,
- cross-section geometry,
- stress concentration effects, and
- corrosion rate and coating quality information.

### 3.4.1 Nominal Stress Transfer Function

The nominal stress transfer coefficient is used to identify the local nominal stress applied to each component. In the approach that will be implemented, the nominal stress transfer coefficient is the vertical distance of component m,n,j from the vessel keel ($Y_{m,n,j}$). This information will be used to estimate the location of the section neutral axis ($Ycg_{m,n}$) and the moment of inertia ($I_{m,n}$). The difference between the neutral axis height from the keel and the component distance from the keel will be used to estimate the component nominal stress ($\sigma_{m,n,j}$) considering the section moment $M_{m,n}$ as follows:

$$\sigma_{m,n} = M_{m,n} \frac{\left(Ycg_{m,n} - Y_{m,n,j}\right)}{I_{m,n}}$$

The section moment of inertia and neutral axis location may be updated with time as corrosion damage accumulates.

### 3.4.2 Component Cross-Section Geometry

Section properties ($Ycg_{m,n}$ and $I_{m,n}$) will be estimated based on the geometry of the structural components. Local component geometries will be defined in terms of the as-built area of plating and stiffeners as shown below.

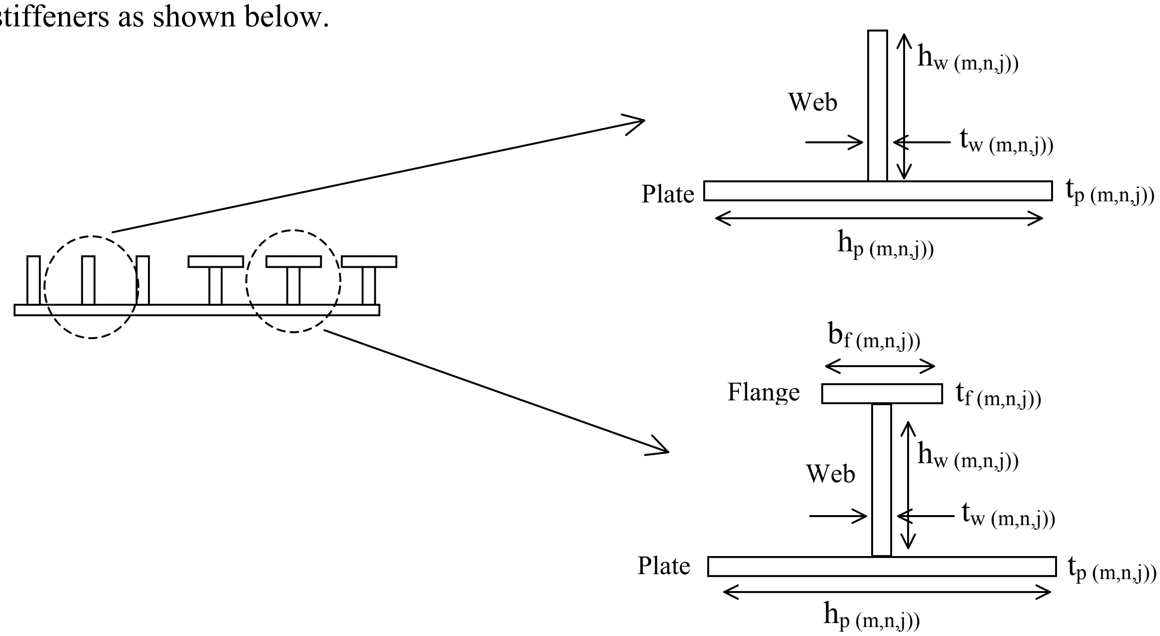



**Figure 3.5: Component Geometric Definition**

The basic structural component geometry is defined in terms of the component stiffener and plate thickness and lengths as defined above. In assigning these section properties, effective thicknesses will have to be assigned for stiffeners with flanges to ensure that the stiffener area is preserved. In calculating section moments of inertia, the contribution of the component moment of inertia about its own axis will be neglected. The centroid of the component area will be defined by the keel offset ($Y_{m,n,j}$) defined previously for nominal stress calculation.

### 3.4.3 Stress Concentration Effects

Local stress concentration effects will be considered in terms of a nominal stress fatigue detail category assigned to each component ($Cat_{m,n,j}$). Detail category selection will be based on the details outlined in standard fatigue design manuals such as BS5400. Figure 3.6 provides a sample of the fatigue details that will be the basis of the estimation of fatigue life.

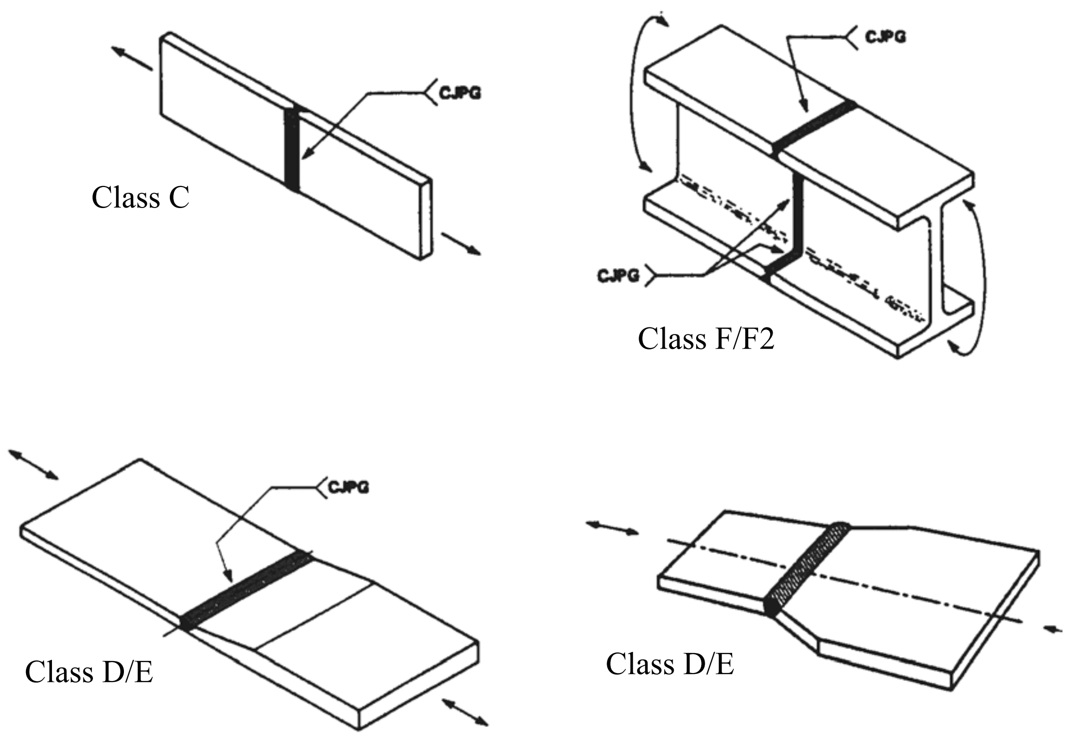



**Figure 3.6: Nominal Stress Detail Classification**

The variability in construction quality will be incorporated in the analysis by considering the S-N curve statistical variability. In this approach, the intercept of the S-N curve will be randomly assigned to each component ($WQ_{m,n,j}$) as a representation of weld quality. The statistical variation of the fatigue performance of an F2 detail is shown in Figure 3.7. The offset of the S-N curves based on given deviations from the mean in Figure 3.7 illustrates the fatigue crack initiation rate variability that can be considered in the simulation of fatigue damage.

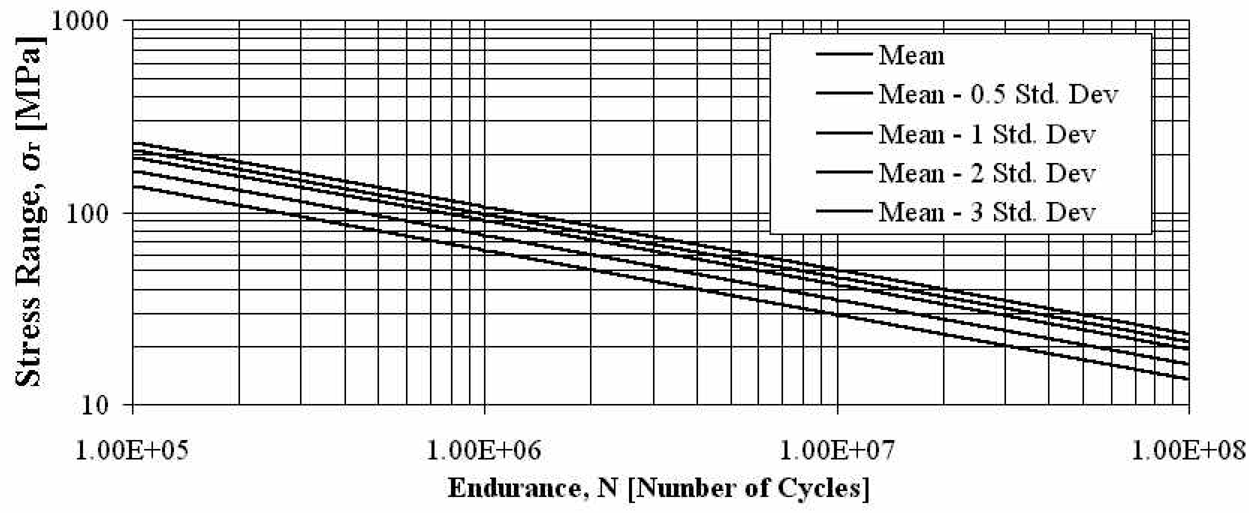



**Figure 3.7: Detail Category F2 S-N Curve Intercept Variation**

### 3.4.4 Corrosion Rate and Coating Quality

Detail corrosion rate and coating quality data will be used in evaluating the long-term section properties of the vessel. Corrosion cannot start while the paint coatings are intact. A mean life of the coatings on each component ($To_{m,n,j}$) will be assigned based on location and environment. Variability in these values will be assigned based on a normal distribution related to the variability in the paint application quality.

Annual mean corrosion rates ($CR_{m,n,j}$) will be assigned to each component based on location and environment. In addition, a coefficient of variation in corrosion rate ($COVcr_{m,n,j}$) will be assigned to each component.

Based on this approach, the average reduction ($R_{m,n,j}$) in section thickness will be expressed in terms of the duration of service (t) and a normally distributed random corrosion severity factor (Q) as follows:

$$R_{m,n,j} = t\,(CRm,n,j + Q\ COVcr_{m,n,j})$$

The potential for pitting or weld zone preferential corrosion will be evaluated by assigning a pitting corrosion rate randomly to those components whose coatings have broken down. The rate of pitting corrosion will be based on the corrosion data collected in the project (see Section 4.4). Pitting corrosion will affect the integrity of the structure by reducing the effectiveness of the stiffening element (e.g., having it trip) and promoting a loss of water tightness. The latter effect will not influence the structural integrity of the vessel but will be tracked as an independent degradation mode.

### 3.4.5 Future Development

The development of a software program to perform the above structural characterization would only be useful if the effort required by the user to enter data is minimized. For this, a Windows based GUI should be developed to simplify the data entry process.

In future, it would likely be beneficial to increase the level of detail of the structural component description to explicitly include the stiffener flanges and other bracketing attachments. This improvement in the level of detail will allow more accurate consideration of component failure modes and the consideration of other load effects such as lateral bending, local pressures or torsion. Ultimately, it would be possible to consider the application of finite element analysis techniques, however, this step requires a significant increase in the data preparation process. To facilitate or automate the FE model generation process, local component finite element models based on the parametric modeling techniques such as those develop by FTL for DREA could be considered (FTL 1998).

It is also suggested that while the current model has been developed based on a nominal stress S-N analysis for fatigue initiation, it can be improved. The modular approach envisaged for the development of the software would allow for the replacement of the nominal stress approach with a hot-spot stress approach that would allow the explicit consideration of construction quality in terms of residual stresses, eccentricity and weld quality. This improvement, however, only refines the crack initiation analysis and does not consider propagation. It would be possible to incorporate a fracture mechanics based crack growth algorithm to consider the growth of cracks and ultimately failure in a fracture mode.

## 3.5 Time Dependant Reliability Analysis

Time dependant reliability analysis will include the independent effects of corrosion and fatigue degradation. The time dependant reliability analysis will be completed in a step-wise simulation process based on reliability analyses at discrete constant time intervals. The simulation process includes the following steps:

1) Assemble as built section properties,
2) Estimate effects of corrosion and update section properties,
3) Consider loss of water tightness,
4) Use load spectrum to estimate probability of fatigue failure,
5) Use load spectrum to estimate probability of section failure,
6) Use load spectrum to estimate the probability of component failure,
7) Collect failure probability data and increment service life clock by the constant time step and repeat steps 2 through 6 until the end of the vessel service life, and
8) Repeat Steps 2 through 6 until convergence of failure probabilities is achieved.

### 3.5.1 As Built Section Properties and Corrosion Degradation

The section properties for individual components will include their cross sectional area and lateral stability. The cross-sectional area of a stiffened panel component ($A_{m,n,j}$) will be estimated in terms of the thickness reduction ($R_{m,n,j}$) as:

$$A_{m,n,j} = A_{0\ m,n,j}\left(\frac{T_{0\ m,n,j} - R_{m,n,j}}{T_{0\ m,n,j}}\right)$$

where $A_0$ and $T_0$ are the section original area and thickness, respectively

The hull girder neutral axis location and moment of inertia will be estimated based on the first and second moments of component areas about the section neutral axis.

### 3.5.2 Probability of Fatigue Failure

The formulation which will be used to estimate the time dependant fatigue reliability of a structural component (Ayyub & Souza 2000) is based on an S-N type of approach and can be applied in a nominal or hot spot stress fatigue analysis. In this formulation, the reliability function for fatigue analysis is based on the hypothesis that as fatigue is a process of cumulative damage, the conditional probability that failure will occur in the next loading cycle should be monotonically increasing with the life spent. Using a Weibull distribution to express fatigue reliability, a function expressing the reliability ($L(t_L \mid N = n)$) for a given time interval (0 to $t_L$) may be developed as follows:

$$L\left(t_L \middle| N = n\right) = \exp\left[-\left(\frac{n}{E(N)}\Gamma\left(1+\frac{1}{k}\right)\right)^k\right]$$

where n is the number of load cycles in the time interval (0 to $t_L$), E(N) is the mean fatigue life, and k is shape factor for the Weibull probability distribution.

The mean fatigue life is defined considering that fatigue failure occurs when the mean damage, defined by Miner's rule, is equal to 1.0 and is expressed as:

$$E(N) = \frac{E(A)}{E\left(S^b\right)} \qquad \text{and} \qquad E\left(S^b\right) = \int_0^\infty S^b f_s(s)ds$$

where E(A) is the mean value of the S-N curve parameter, $E(S^b)$ is the mean value of the random stress range variable $S^b$, E(N) is the mean fatigue life value and $f_s(s)$ is the probability density function of the stress range acting on the structure.

The Weibull distribution shape parameter (k) may be expressed as:

$$k = COV(N)^{-1.08}$$

where COV(N) is the coefficient of variation of the fatigue life and is used to capture the variability introduced by the strength and loading random variables.

### 3.5.3 Probability of Section or Component Failure

The approach that will be used to estimate the time dependant reliability of a component or section has been presented by (Ayyub & Souza 2000). In this work, the reliability at a given time (L(t)) is estimated considering the action of n random load events in a given time interval (0 to $t_L$), as follows:

$$L(t_L) = \int_0^{\infty} \exp\left\{ -\lambda t_L \left[ 1 - \frac{1}{t_L} \int_0^{t_L} F_s(rg(t))dt \right] \right\} f_{Ro}(r)dr$$

where, $\lambda$ is the mean load interval, $F_s(x)$ is the load magnitude probability function, rg(t) is the time dependant degraded strength of the structure and $f_{Ro}$ is a probability density function describing the variability of the initial component or section strength. The initial component strength distribution would be determined using an advanced Monte Carlo simulation technique.

This time dependant reliability analysis will be used to evaluate the probability of section yielding and component buckling. The project will investigate pitting corrosion to consider a loss of water tightness limit state.

### 3.5.4 Time Dependant Probability of Failure Data and Convergence

The vessel service lifetime dependant reliability analysis process described in the preceding section is based on a probabilistic simulation approach. Therefore the results of each service life analysis will yield different time histories of failure probabilities. In order to make use of this information, multiple service life simulations will need to be made and the results collected. With increasing number of simulations the time dependant reliability history will converge to a stable result. The accuracy or convergence tolerance will have to be explored in order to ensure reliable results.

The number of vessel life expectancy simulations will be minimized through the application of an advance Monte Carlo simulation technique. At this time, it is expected that a Latin Hypercube technique will be employed.

### 3.5.5 Future Development

Further development of the life expectancy assessment approach could extend the scope of the analysis to include in-service repair strategies. This improvement would involve the establishment of simple repair strategies (renewal/ repair) for cracks or corrosion given a threshold remaining thickness or crack size at which repairs are completed. The maintenance rules used for corrosion, for example, could include:

- sand blasting and painting for a range of residual thicknesses for which the reduction in thickness associated with the sand blasting is considered along with the coating reapplication
- replacement of plating for thickness reductions below a given value.

In these cases, it would also be desirable to consider the probability of detection of the degradation, allowing continued degradation until the damage is detected.

## 3.6 System Reliability Analysis

The objective of this step in the analysis process is to estimate time dependant probabilities of failure of ship structures from the simulated component and section probabilities of failure. In this analysis a first passage approach may be applied to determine the time dependant probability of the first failure. Using the data developed in the time dependant reliability analysis the probability of a component failure, a section failure, or vessel failure may be estimated.

### 3.6.1 Component Probability of Failure Time History

The probability of a component failure at any time may be estimated based on the individual component probabilities of failure. This assessment will be based on a systems reliability approach that estimates the probability of:

- any component failure

$$P_{f\ comp} = 1 - \prod_{m,n,j}^{M,N,J} \left(1 - P_{f\ m,n,j}\right)$$

- a component failure in a given frame (n) within a section (m)

$$P_{f\ comp\ m,n} = 1 - \prod_{j}^{J} \left(1 - P_{f\ m,n,j}\right)$$

- a component failure in a given vessel section (m)

$$P_{f\ comp\ m} = 1 - \prod_{n,j}^{N,J} \left(1 - P_{f\ m,n,j}\right)$$

### 3.6.2 Section Probabilities of Failure

The probability of a section failure defined by the probability of any failure in a section may be estimated using system reliability techniques. This assessment may be completed for

- any failure in a given section

$$P_{f\ section} = P_{f\ section\ m,n} + 1 - \prod_{j}^{J} \left(1 - P_{f\ m,n,j}\right)$$

- any section failure in the vessel

$$P_{f\ vessel} = 1 - \prod_{j}^{J} \left(1 - P_{f\ section\ m,n}\right)$$

### 3.6.3 Vessel Probability of Failure Time History

The probability of any number of failures in the entire vessel could be tracked. Or perhaps the time history of each failure mode could be tracked as shown pictorially in Figure 3.8. This summary format could be used in the design process to identify inequalities in the design margins of safety afforded to each limit state and thus direct further attention to ensure more uniform reliability levels.

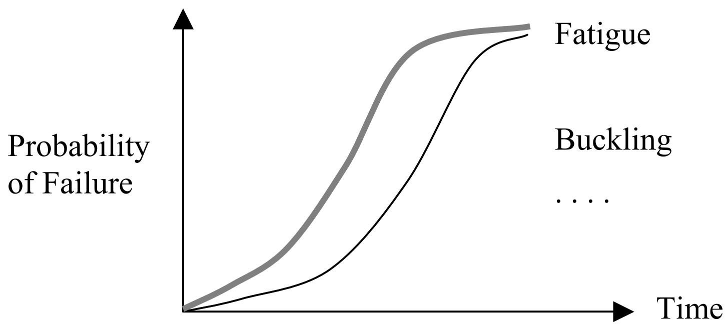



**Figure 3.8: Potential Time Based Reliability Results**

Alternatively, the number of components or sections with failure probabilities exceeding a specified threshold at any given point in time could be determined. This would be an indicator of the state of wear of the vessel.

### 3.6.4 Future Development

In the future, life expectancy assessment software could be configured to estimate the optimal time between maintenance actions. This approach could define work areas and identify the accumulation of sufficient degradation within a work area to trigger a work action in a similar fashion as reliability centered maintenance.

## 3.7 Application of the Results

The results generated by the reliability-based life expectancy assessment will indicate the relative rate at which damage is accumulating with time. This information may be used to define the increase in maintenance costs that will indicate the end of a vessel's useful life.

In this project, the model developed based on the techniques described in the previous sections was applied in two limited applications. These applications are used to demonstrate the analysis techniques and to define areas in need of improvement. These example problems include a tanker and a tramp bulk carrier. This work is described in more detail in Section 4 that describes the sample applications and results.

#### 3.7.1 Future Development

It would be desirable to incorporate graphical displays that could illustrate the analysis results. These displays could include plots of the various component, section, ship, and failure mode reliability histories in terms of first failure or cumulative failure probabilities. In addition, it would be instructive to graphically display failure probabilities mapped onto the ship structure in such a way as to effectively illustrate the areas of greatest concern and help focus inspection and maintenance activities.

As noted, the current analysis approach development work will not consider maintenance or repair costs, however, with the implementation of maintenance strategy rules, it would be possible to use the analysis techniques developed here to estimate lifecycle costs. By including inspection and repair cost data, even in a relative sense, the merits of alternative maintenance practices could be compared. With more detailed repair and maintenance cost data, repair and maintenance strategies could be compared using a cost benefit analyses.

# 4. DEMONSTRATION OF VESSEL LIFE EXPECTANCY ASSESSMENT

The sample application is presented in terms of the seven steps used to describe the approach in the previous sections, including:

- Vessel Particular Identification
- Structural Section and Component Definition,
- Load Assessment,
- Definition of Local Detail Characteristics,
- Time Dependant Reliability Assessment,
- System Reliability Analysis, and
- Application of the Results.

The results may be compared and the analysis process is described in a step-wise fashion.

## 4.1 Vessel Particular Identification

### 4.1.1 MV Bulk Carrier Particulars

The MV Bulk Carrier is a geared "handy-size" bulk carrier operating on short-term contracts (tramp service) taking it all over the world. The vessel entered service in 1987 and completed a major refit in a Chinese shipyard in 1998. It continues to trade worldwide. The particulars of the MV Bulk Carrier are provided below.

**Length:** 190 m

**Beam:** 27.6 m

**Depth:** 14.8 m

**Block Coefficient ($C_B$):** 0.8

**Displacement:** 47 043 tonnes

**Max Draft:** 10.93 m

**Service Speed:** 15 knots

**Power Plant:** 12,000 HP Slow Speed Diesel

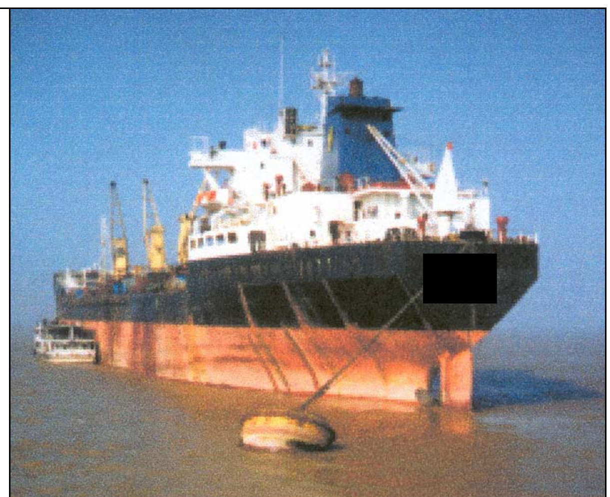


**Figure 4.1: Bulk Carrier Particulars**

### 4.1.2 VLCC Tanker Particulars

This tanker was designed for fabrication in a European yard for service from Europe to the Middle East. The tanker is double hulled with 24 cargo tanks capable of carrying up to 2 million barrels of oil. The particulars of the VLCC tanker are provided below.

| | |
|---|---|
| **Length:** 324.5 m<br>**Beam:** 57 m<br>**Depth:** 31.1 m<br>**Block Coefficient ($C_B$):** 0.842<br>**Displacement:** 295,100 tonnes (GRT)<br>**Design Draft:** 21.1 m<br>**Service Speed:** 15.4 knots<br>**Power Plant:** Single screw prop. Driven by two 23,000 kW two stroke diesel engine |  |

**Figure 4.2: Tanker Particulars**

## 4.2 Structural Section and Component Definition

### 4.2.1 Bulk Carrier Section and Component Definition

The bulk carrier has been divided into 10 segments, defined primarily by the extent of the holds as illustrated in Figure 4.3. Each segment has been further divided into two frame types; frame type 1 is a section in way of the open hatch and frame type 2 is a section in way of the deck plate between the hatches. Frame type 1 has 13 component types, and frame type 2 has 14 component types, as illustrated in Figure 4.4a and Figure 4.4b. The number of repetitions of each frame type and assumed loading in each segment are as described in Table 4.1.

**Table 4.1: Bulk Carrier Frame Type Distribution**

| Segment | Frame Type 1 | Frame Type 2 | Segment | Frame Type 1 | Frame Type 2 |
|---|---|---|---|---|---|
| 1 | | 17 | 6 | 11 | 17 |
| 2 | | 31 | 7 | 11 | 10 |
| 3 | 15 | 7 | 8 | 13 | 10 |
| 4 | 11 | 17 | 9 | 10 | 10 |
| 5 | 11 | 10 | 10 | | 18 |

Each structural component consists of a longitudinal bulb flat and hull plate and these component types may be repeated within a section several times. The hull plate is not considered to be one continuous structural piece, but is defined as flanges of the bulb flats; the width of the flange is the average center-to-center distance between adjacent bulb stiffeners. Table 4.2 provides a breakdown of the components illustrated in Figure 4.4a and 4.4b for frame types 1 and 2, respectively. Table 4.2 only shows the components for the starboard side of the ship. The ship is symmetric about its longitudinal centerline and thus each component is repeated.

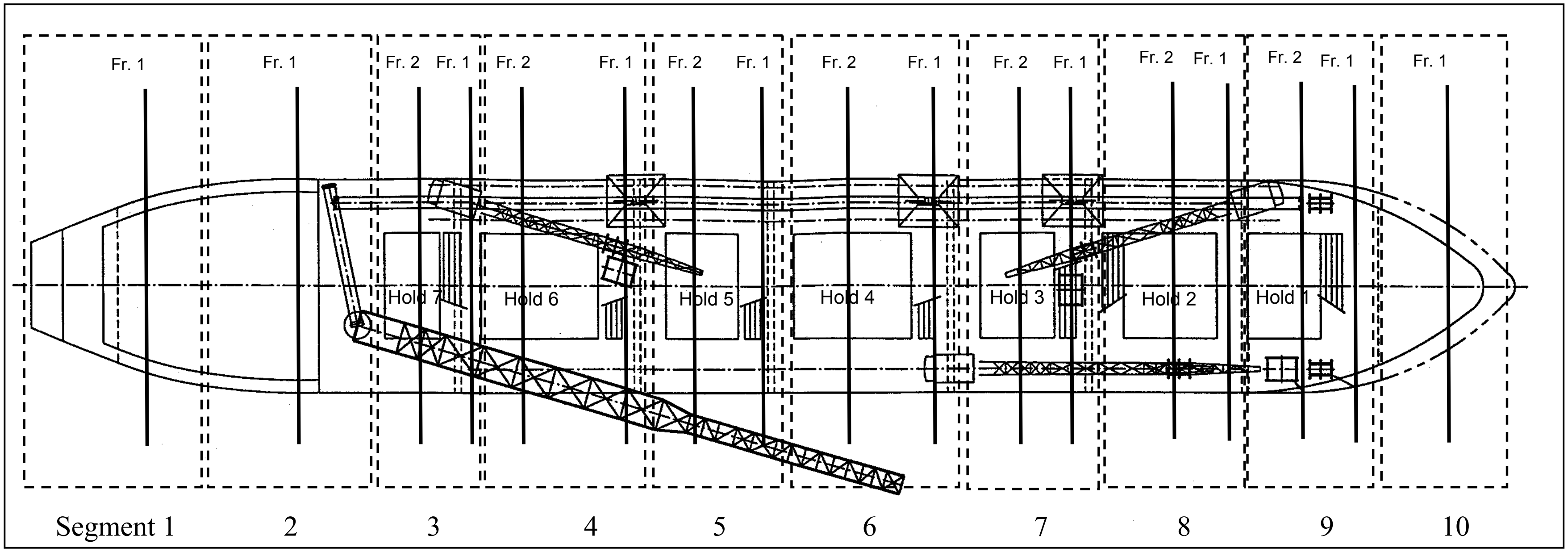



**Figure 4.3: General Arrangement of Segments and Frames in the Bulk Carrier**
(Only the general location of the frame types for each segment has been shown for clarity)

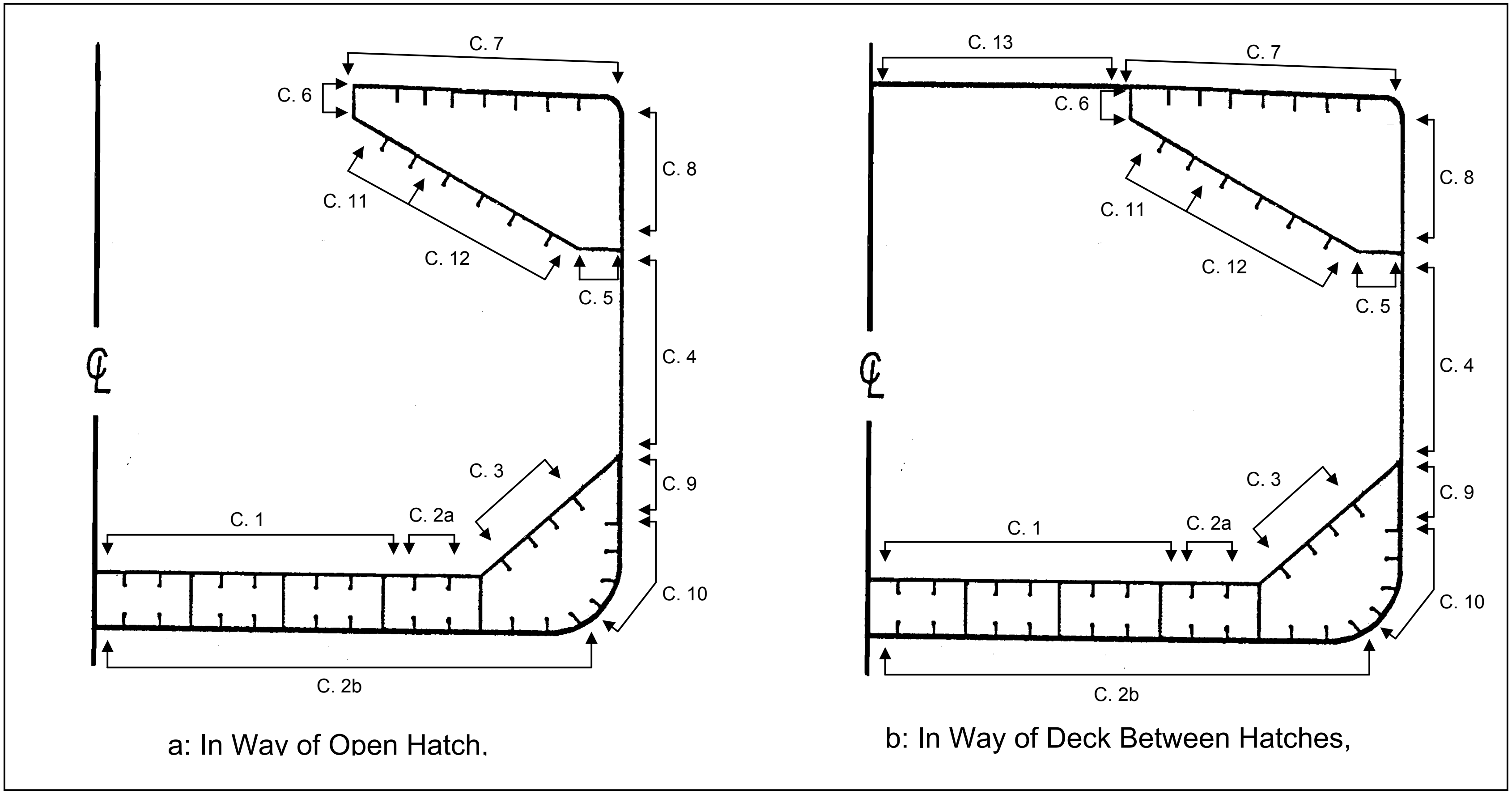



**Figure 4.4: Section View of the Bulk Carrier Describing Component Location**
(Figure 4.4a is the section in way of an open hatch; 4.4b is the section in way of the deck between hatches. Both sections shown are the starboard side of the ship; the ship is symmetric about its longitudinal centerline.)

**Table 4.2: Bulk Carrier Component Characteristics for Frame Types 1 and 2****

| Segment | Frame Type | Component | N.A. Location* | Plate $b_p$ | Plate $t_p$ | Web $t_w$ | Web $h_W$ | Number | ***Corrosion / Coating Class |
|---|---|---|---|---|---|---|---|---|---|
| I | 1 | 1 | 1500 | 850 | 20 | 12 | 320 | 9 | 6 / 5 |
| I | 1 | 2a | 1500 | 850 | 20 | 11 | 280 | 2 | 6 / 5 |
| I | 1 | 2b | 0 | 850 | 20 | 11 | 280 | 11 | 8 / 5 |
| I | 1 | 3 | 3092 | 850 | 18 | 11 | 280 | 4 | 6 / 5 |
| I | 1 | 4 | 7550.00 | 811 | 18 | | | 7 | 11 /4 |
| I | 1 | 5 | 10735 | 1000 | 18 | | | 1 | 8 / 5 |
| I | 1 | 6 | 14775 | 650 | 18 | | | 1 | 7 / 5 |
| I | 1 | 7 | 15100 | 850 | 18 | 12 | 320 | 7 | 6 / 5 |
| I | 1 | 8 | 12770 | 370 | 18 | | | 11 | 7 / 5 |
| I | 1 | 9 | 3804 | 209 | 18 | | | 12 | 7 / 5 |
| I | 1 | 10 | 1925 | 850 | 18 | 11 | 280 | 4 | 7 / 5 |
| I | 1 | 11 | 13087 | 1000 | 18 | 17.5 | 300 | 2 | 8 / 5 |
| I | 1 | 12 | 11492 | 1000 | 18 | 12 | 320 | 4 | 8 / 5 |
| I | 1 | 13 | 15100 | 400 | 18 | | | 17 | 9 / 4 |
| I | 2 | 1 | 1500 | 850 | 20 | 12 | 320 | 9 | 6 / 5 |
| I | 2 | 2a | 1500 | 850 | 20 | 11 | 280 | 2 | 6 / 5 |
| I | 2 | 2b | 0 | 850 | 20 | 11 | 280 | 11 | 8 / 5 |
| I | 2 | 3 | 3092 | 850 | 18 | 11 | 280 | 4 | 6 / 5 |
| I | 2 | 4 | 7550.00 | 811 | 18 | | | 7 | 11 /4 |
| I | 2 | 5 | 10735 | 1000 | 18 | | | 1 | 8 / 5 |
| I | 2 | 6 | 14775 | 650 | 18 | | | 1 | 7 / 5 |
| I | 2 | 7 | 15100 | 850 | 18 | 12 | 320 | 7 | 6 / 5 |
| I | 2 | 8 | 12770 | 370 | 18 | | | 11 | 7 / 5 |
| I | 2 | 9 | 3804 | 209 | 18 | | | 12 | 7 / 5 |
| I | 2 | 10 | 1925 | 850 | 18 | 11 | 280 | 4 | 7 / 5 |
| I | 2 | 11 | 13087 | 1000 | 18 | 17.5 | 300 | 2 | 8 / 5 |
| I | 2 | 12 | 11492 | 1000 | 18 | 12 | 320 | 4 | 8 / 5 |

* Distance from bottom of hull (keel)
** All dimensions in mm, Geometric parameters described in Figure 3.5
*** See Section 4.4 for a definition of these codes.

### 4.2.2 Tanker Section and Component Definition

The Tanker has also been divided into 10 segments, defined primarily by the extent of the holds. There are two frame types defined for the tanker, both having the same scantlings, geometry and component lay out. The difference between the frame types being in their fatigue behavior as outlined in Section 4.4. The number of repetitions of each frame type in each segment is outlined in Table 4.3.

**Table 4.3: Tanker Frame Type Distribution**

| Segment | Frame Type 1 | Frame Type 2 | Segment | Frame Type 1 | Frame Type 2 |
|---|---|---|---|---|---|
| 1 | 9 | 1 | 6 | 6 | 1 |
| 2 | 6 | 1 | 7 | 7 | 1 |
| 3 | 6 | 1 | 8 | 6 | 1 |
| 4 | 7 | 1 | 9 | 7 | 1 |
| 5 | 6 | 1 | 10 | 3 | 1 |

Each frame is divided into 44 component types that may be repeated within the segment. The segments of the Tanker are illustrated in Figure 4.5. Figure 4.6 is the midship section of the Tanker, which is typical over the length of the ship considered in this model.

Each component used to describe the tanker structure consists of a T-bulb or bulb-flat longitudinal and hull plate and may be repeated several times. The hull plate is not considered to be one continuous structural piece, but is defined as another flange on the T-bulbs or a flange on the flat bulb; the width of the flange is the center-to-center distance between the T-bulb stiffeners. Table 4.4 provides a breakdown of the components of the midship section. Table 4.4 only shows the components for the starboard side of the ship. The ship is symmetric about its longitudinal centerline thus components are repeated.

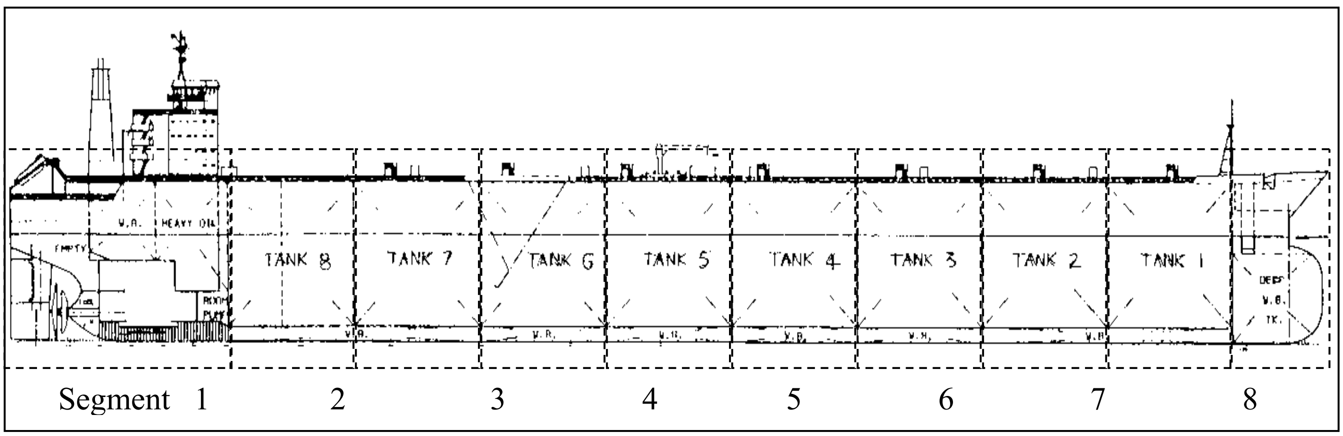



**Figure 4.5: General Arrangement of Segments in the Tanker**

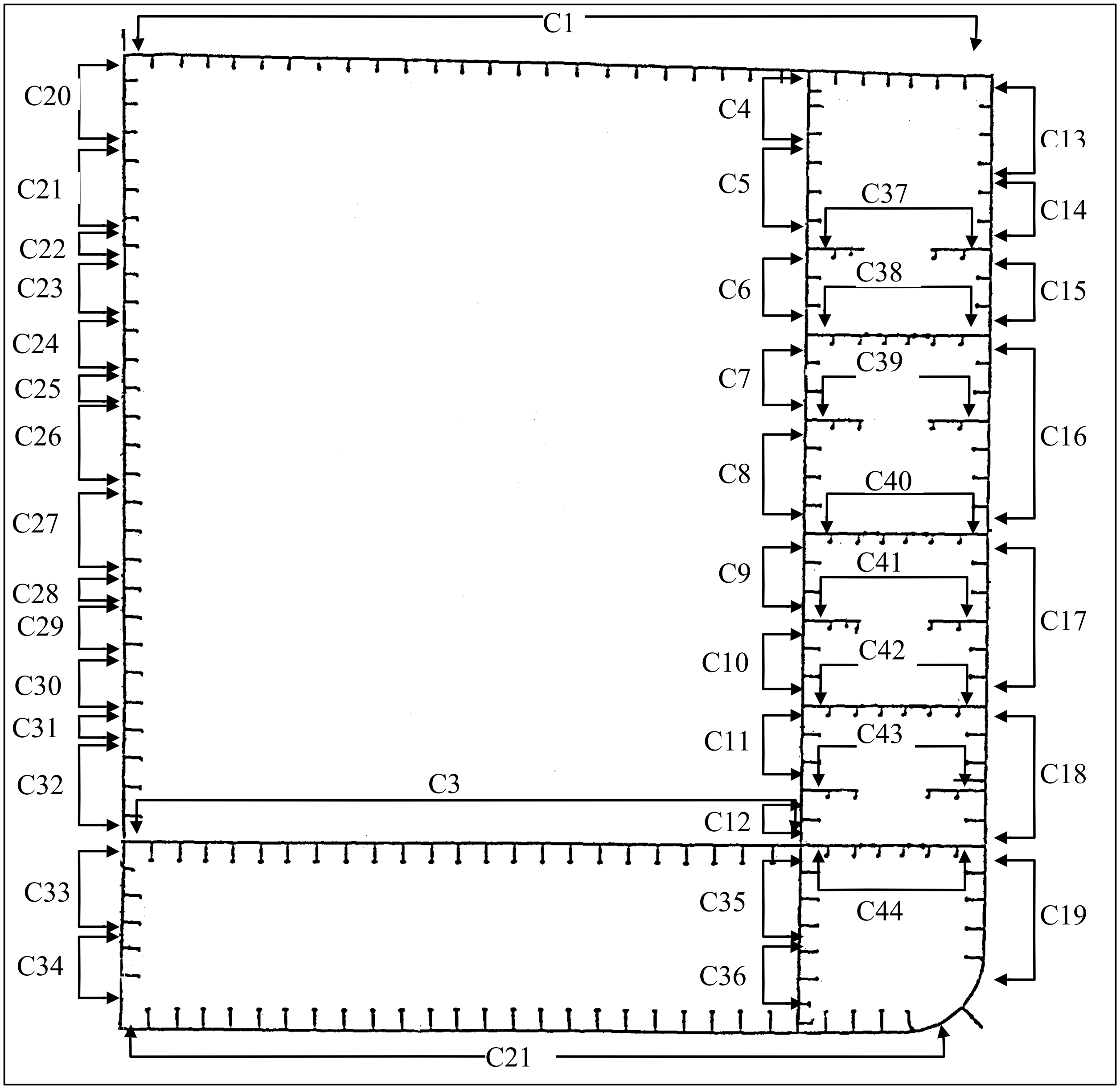



**Figure 4.6: Section View of the Tanker Describing Component Location**
(The midship section shown is the starboard side of the ship, the ship is symmetric about its longitudinal centerline)

**Table 4.4: Tanker Component Characteristics for a Typical Frame****

| Segment | Frame Type | Component | N.A. Location* | Plate $h_p$ | Plate $t_p$ | Web $t_w$ | Web $h_w$ | Flange $b_F$ | Flange $t_f$ | Number | Corrosion / Coating Class |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 1 | 1 | 31175 | 950 | 20 | 25 | 350 | | | 30 | 2 / 6 |
| I | 1 | 2 | 0 | 1055 | 27 | 15 | 700 | 150 | 20 | 27 | 6 / 5 |
| I | 1 | 3 | 6180 | 978 | 27 | 12 | 600 | 150 | 20 | 23 | 8 / 5 |
| I | 1 | 4 | 27851 | 823 | 18 | 25 | 350 | | | 3 | 7 / 5 |
| I | 1 | 5 | 25335 | 795 | 17 | 12 | 400 | 150 | 12 | 3 | 7 / 5 |
| I | 1 | 6 | 22820 | 1450 | 14 | 12 | 400 | 150 | 12 | 2 | 7 / 5 |
| I | 1 | 7 | 20304 | 725 | 17 | 12 | 500 | 150 | 15 | 2 | 7 / 5 |
| I | 1 | 8 | 18627 | 1450 | 17 | 12 | 500 | 150 | 15 | 2 | 7 / 5 |
| I | 1 | 9 | 16170 | 1450 | 18 | 12 | 500 | 150 | 15 | 2 | 7 / 5 |
| I | 1 | 10 | 13270 | 1450 | 19 | 12 | 550 | 150 | 12 | 2 | 7 / 5 |
| I | 1 | 11 | 10370 | 1450 | 20 | 12 | 550 | 150 | 12 | 2 | 7 / 5 |
| I | 1 | 12 | 7697 | 1450 | 21 | 12 | 600 | 150 | 20 | 2 | 7/ 5 |
| I | 1 | 13 | 29528 | 838 | 20 | 25 | 350 | | | 3 | 7 / 5 |
| I | 1 | 14 | 25097 | 1257 | 20 | 10 | 300 | 150 | 15 | 2 | 7 / 5 |
| I | 1 | 15 | 22581 | 931 | 20 | 12 | 500 | 150 | 15 | 2 | 7 / 5 |
| I | 1 | 16 | 19681 | 931 | 20 | 12 | 550 | 150 | 20 | 5 | 7 / 5 |
| I | 1 | 17 | 21981 | 931 | 22 | 12 | 650 | 150 | 20 | 4 | 7 / 5 |
| I | 1 | 18 | 7697 | 966 | 25 | 12 | 600 | 150 | 20 | 3 | 7 / 5 |
| I | 1 | 19 | 6708 | 1505 | 25 | 12 | 650 | 150 | 20 | 4 | 7 / 5 |
| I | 1 | 20 | 29311 | 823 | 16 | 25 | 350 | | | 3 | 3 / 6 |
| I | 1 | 21 | 26516 | 795 | 17 | 12 | 300 | 150 | 20 | 3 | 3 / 6 |
| I | 1 | 22 | 24653 | 966 | 14.5 | 12 | 300 | 150 | 20 | 1 | 3 / 6 |
| I | 1 | 23 | 21858 | 966 | 14.5 | 12 | 400 | 150 | 20 | 2 | 3 / 6 |
| I | 1 | 24 | 20926 | 966 | 17 | 12 | 400 | 150 | 20 | 2 | 3 / 6 |
| I | 1 | 25 | 19994 | 966 | 17 | 12 | 450 | 150 | 20 | 1 | 3 / 6 |
| I | 1 | 26 | 18131 | 966 | 17.5 | 12 | 450 | 150 | 20 | 3 | 3 / 6 |
| I | 1 | 27 | 15336 | 966 | 18.5 | 12 | 500 | 150 | 20 | 3 | 3 / 6 |
| I | 1 | 28 | 13473 | 966 | 19.5 | 12 | 500 | 150 | 20 | 1 | 3 / 6 |
| I | 1 | 29 | 12541 | 966 | 19.5 | 12 | 550 | 150 | 20 | 2 | 3 / 6 |
| I | 1 | 30 | 10678 | 966 | 20 | 12 | 550 | 150 | 20 | 2 | 3 / 6 |
| I | 1 | 31 | 9746.59 | 966 | 20 | 12 | 600 | 150 | 20 | 1 | 3 / 6 |
| I | 1 | 32 | 7883.25 | 966 | 21 | 12 | 600 | 150 | 20 | 3 | 3 / 6 |
| I | 1 | 33 | 5088 | 1003 | 22 | 12 | 550 | 150 | 20 | 3 | 7 / 5 |
| I | 1 | 34 | 2293 | 1003 | 21 | 12 | 550 | 150 | 20 | 2 | 7 / 5 |
| I | 1 | 35 | 5088 | 1003 | 22 | 12 | 650 | 150 | 25 | 3 | 7 / 5 |
| I | 1 | 36 | 2293 | 1003 | 23 | 12 | 650 | 150 | 25 | 2 | 7 / 5 |
| I | 1 | 37 | 25097 | 1000 | 12 | 10 | 215.3 | 44 | 24.7 | 4 | 8 / 5 |
| I | 1 | 38 | 22581.5 | 1000 | 12 | 10 | 215.3 | 44 | 24.7 | 6 | 8 / 5 |
| I | 1 | 39 | 19681.5 | 1000 | 12 | 10 | 215.3 | 44 | 24.7 | 4 | 8 / 5 |
| I | 1 | 40 | 16170 | 1000 | 12 | 10 | 215.3 | 44 | 24.7 | 6 | 8 / 5 |
| I | 1 | 41 | 13270 | 1000 | 12 | 10 | 215.3 | 44 | 24.7 | 4 | 8 / 5 |
| I | 1 | 42 | 10370 | 1000 | 12 | 10 | 215.3 | 44 | 24.7 | 6 | 8 / 5 |
| I | 1 | 43 | 7697 | 1000 | 12 | 10 | 215.3 | 44 | 24.7 | 4 | 8/ 5 |
| I | 1 | 44 | 6020 | 1000 | 12 | 10 | 215.3 | 44 | 24.7 | 6 | 8 / 5 |

* Distance from bottom of hull (keel)
** All dimensions in mm, Geometric parameters described in Figure 3.5

## 4.3 Load Assessment

The loading used in the analysis includes the still water moment, service load (moment) distribution, and extreme load (moment) distribution. In these sample applications, only a single loading condition is considered, however, the implications of a more detailed consideration of a range of loading conditions could be accommodated.

Since the still water loading condition only affects the ultimate strength of the vessel, only the most severe loading condition is reported.

### 4.3.1 Bulk Carrier Loading

The longitudinal distribution of loads to be applied to the bulk carrier has been idealized to consider a midship and a forward/aft load magnitude. The loads to be applied to each structural segment of the vessel are outlined in Table 4.5. It would be possible to consider different loading conditions for each frame or segment and thus produce more detailed analysis results. The two loading zone condition is used in these examples simply to demonstrate the analysis approach.

**Table 4.5: Bulk Carrier Segment Loading Conditions**

| Segment | Loading | Segment | Loading |
|---|---|---|---|
| 1 | Fwd/Aft | 6 | Midship |
| 2 | Fwd/Aft | 7 | Midship |
| 3 | Midship | 8 | Midship |
| 4 | Midship | 9 | Fwd/Aft |
| 5 | Midship | 10 | Fwd/Aft |

The most severe still water bending moment was estimated for the bulk carrier by calculating the load distributions for a range of loading conditions. Figure 4.7 is a sample loading distribution calculated for an alternate hold loading condition for the bulk carrier. In considering the load estimates for a range of loading conditions, the maximum hog and sag still water bending moments shown in Table 4.6 for each of the two loading zones were derived.

**Table 4.6: Bulk Carrier Maximum Still Water Loads**

| | Loading Zone | SWB Moment [kNm] |
|---|---|---|
| Sag | Midship | 537,755 |
| | Forward/Aft | 97,640 |
| Hog | Midship | 223,180 |
| | Forward/Aft | 273,180 |

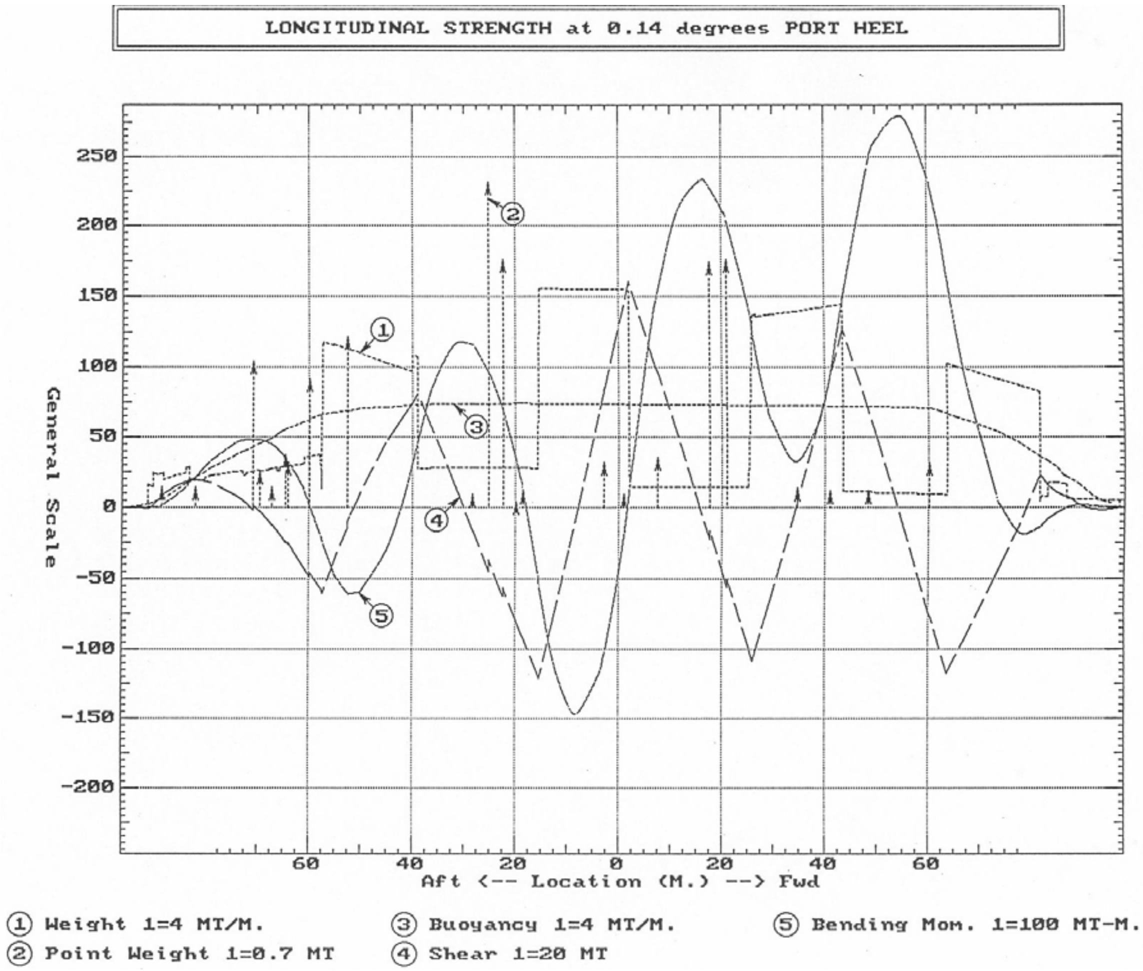



**Figure 4.7: Bulk Carrier Still Water Loads for Alternate Hold Loading Arrangement**

Wave bending moments for the bulk carrier were calculated for design operational profiles related to the intended usage of the ship. The combined statistical effects of this service were evaluated as described in SSC 406 - Sea Operational Profiles for Structural Reliability Assessments. The bulk carrier in this example operates on short term contracts which take the vessel all over the world in a year round basis, as shown in the data collection (Glen et. al. 1999). Consequently, the routes for her are the world shipping routes. A typical route from Norfolk (North America) to Hong Kong (Asia) is analyzed in this report. This route includes Marsden Zones 23, 33, 48 56 66, 67, 84, 85, 90, 75, 59, 60, 61, 62 and 40.

The operational characteristics are based upon the joint probability distributions of vessel speed and sea state, shown in Table 4.7 and the joint probability of relative heading and sea state, shown in Table 4.8. This data, as described in SSC 406 describes how hard the vessel is being operated in terms of the likely hood to change direction or speed in light of wave conditions.

**Table 4.7: Bulk Carrier Joint Probability of Speed and Sea State**

| Speed (Knots) | Sea State 1 | 2 | 3 | 4 | 5 | 6 | 7 | SUM |
|---|---|---|---|---|---|---|---|---|
| 10.-12 | 0.0079 | 0.0000 | 0.0000 | 0.0073 | 0.0133 | 0.0331 | 0.0000 | **0.0616** |
| 12.-14 | 0.0310 | 0.0320 | 0.2172 | 0.2144 | 0.1986 | 0.1532 | 0.0000 | **0.8464** |
| 14.-16 | 0.0000 | 0.0199 | 0.0265 | 0.0290 | 0.0068 | 0.0098 | 0.0000 | **0.0920** |
| SUM | **0.0389** | **0.0519** | **0.2437** | **0.2507** | **0.2187** | **0.1961** | **0.0000** | **1.0000** |

**Table 4.8: Bulk Carrier Joint Probability of Relative Heading and Sea State**

| Heading (Degree) | Sea State 1 | 2 | 3 | 4 | 5 | 6 | 7 | SUM |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.0034 | 0.0100 | 0.0327 | 0.0332 | 0.0242 | 0.0202 | 0.0000 | **0.1236** |
| 45 | 0.0028 | 0.0072 | 0.0253 | 0.0256 | 0.0194 | 0.0159 | 0.0000 | **0.0963** |
| 90 | 0.0038 | 0.0116 | 0.0370 | 0.0376 | 0.0272 | 0.0227 | 0.0000 | **0.1400** |
| 135 | 0.0216 | 0.0190 | 0.1172 | 0.1209 | 0.1141 | 0.1037 | 0.0000 | **0.4964** |
| 180 | 0.0067 | 0.0065 | 0.0321 | 0.0343 | 0.0317 | 0.0324 | 0.0000 | **0.1437** |
| SUM | **0.0383** | **0.0542** | **0.2443** | **0.2516** | **0.2166** | **0.1950** | **0.0000** | **1.0000** |

Vessel response to wave encounters were estimated using the linear strip theory program SHIPMO 7 (McTaggart 1997) under the relevant combinations of speed, relative heading, wave height and wave period. More specifically, the ship speeds set in SHIPMO7 were 0, 6, 10, 12, 14 and 16 knots. The heading angles were set at 0, 45, 90, 135 and 180 degrees, where 180 degree represents head seas. Sea states were expressed with BRETSCHNEIDER spectrum in terms of wave significant wave heights and peak wave periods. Since the responses and loads are assumed to be linear with respect to wave height, only one wave height was calculated, while the wave zero crossing periods ranged from 3.5 second to 12.5 seconds.

The midship wave induced bending moment statistical distributions, developed using LOS$^3$A (FTL 1999), considering an 85% duty cycle (15% of ship's life spent tied up along side), are described statistically in Table 4.9 and Figures 4.8 and 4.9. The operational profile load analysis indicated that the vessel would be expected to have a mean load zero crossing period of 7.85225 seconds and based upon this and the annual load probability statistics were able to be developed. Table 4.9 presents the probabilities associated with each vertical wave bending moment magnitude or cycle as well as lifetime load magnitude exceedance probabilities. Figure 4.8 simply displays these load magnitudes and their corresponding probabilities graphically.

**Table 4.9: Bulk Carrier Vertical Bending Moment Exceedance Probabilities @ Midship**

| Vert. Bend. Moment (MNm) | P(exceed) Load Cycle | P(exceed) in life | Number of cycles | Vert. Bend. Moment (MNm) | P(exceed Load Cycle | P(exceed) in life | Number of cycles |
|---|---|---|---|---|---|---|---|
| 20 | 8.029E-01 | 1.000E+00 | 6.800E+05 | 620 | 5.669E-04 | 1.000E+00 | 1.300E+02 |
| 40 | 6.404E-01 | 1.000E+00 | 9.300E+05 | 640 | 4.563E-04 | 1.000E+00 | 9.300E+02 |
| 60 | 5.017E-01 | 1.000E+00 | 4.200E+05 | 660 | 3.684E-04 | 1.000E+00 | 9.800E+02 |
| 80 | 3.856E-01 | 1.000E+00 | 1.700E+05 | 680 | 2.983E-04 | 1.000E+00 | 2.300E+02 |
| 100 | 2.951E-01 | 1.000E+00 | 1.900E+05 | 700 | 2.423E-04 | 1.000E+00 | 6.200E+02 |
| 120 | 2.265E-01 | 1.000E+00 | 4.500E+05 | 720 | 1.974E-04 | 1.000E+00 | 1.400E+02 |
| 140 | 1.746E-01 | 1.000E+00 | 8.900E+05 | 740 | 1.615E-04 | 1.000E+00 | 7.500E+02 |
| 160 | 1.350E-01 | 1.000E+00 | 4.600E+05 | 760 | 1.325E-04 | 1.000E+00 | 4.300E+02 |
| 180 | 1.046E-01 | 1.000E+00 | 1.300E+05 | 780 | 1.092E-04 | 1.000E+00 | 1.800E+02 |
| 200 | 8.106E-02 | 1.000E+00 | 7.600E+04 | 800 | 9.030E-05 | 1.000E+00 | 7.600E+01 |
| 220 | 6.291E-02 | 1.000E+00 | 8.000E+04 | 820 | 7.496E-05 | 1.000E+00 | 1.100E+01 |
| 240 | 4.890E-02 | 1.000E+00 | 2.900E+04 | 840 | 6.245E-05 | 1.000E+00 | 7.500E+01 |
| 260 | 3.809E-02 | 1.000E+00 | 1.200E+04 | 860 | 5.222E-05 | 1.000E+00 | 6.500E+01 |
| 280 | 2.973E-02 | 1.000E+00 | 2.200E+04 | 880 | 4.382E-05 | 1.000E+00 | 7.400E+01 |
| 300 | 2.327E-02 | 1.000E+00 | 5.200E+04 | 900 | 3.689E-05 | 1.000E+00 | 9.900E+01 |
| 320 | 1.824E-02 | 1.000E+00 | 9.700E+04 | 920 | 3.115E-05 | 1.000E+00 | 3.700E+01 |
| 340 | 1.433E-02 | 1.000E+00 | 5.500E+04 | 940 | 2.639E-05 | 1.000E+00 | 8.500E+01 |
| 360 | 1.127E-02 | 1.000E+00 | 2.200E+04 | 960 | 2.242E-05 | 1.000E+00 | 4.200E+01 |
| 380 | 8.880E-03 | 1.000E+00 | 6.000E+03 | 980 | 1.909E-05 | 1.000E+00 | 6.000E+00 |
| 400 | 7.005E-03 | 1.000E+00 | 5.700E+03 | 1000 | 1.630E-05 | 1.000E+00 | 7.600E+01 |
| 420 | 5.533E-03 | 1.000E+00 | 9.800E+03 | 1020 | 1.394E-05 | 1.000E+00 | 5.100E+01 |
| 440 | 4.376E-03 | 1.000E+00 | 7.300E+03 | 1040 | 1.195E-05 | 1.000E+00 | 2.900E+01 |
| 460 | 3.465E-03 | 1.000E+00 | 7.500E+03 | 1060 | 1.026E-05 | 1.000E+00 | 1.100E+01 |
| 480 | 2.748E-03 | 1.000E+00 | 9.700E+03 | 1080 | 8.821E-06 | 1.000E+00 | 5.400E+00 |
| 500 | 2.182E-03 | 1.000E+00 | 3.600E+03 | 1100 | 7.595E-06 | 1.000E+00 | 2.100E+00 |
| 520 | 1.735E-03 | 1.000E+00 | 8.800E+03 | 1120 | 6.546E-06 | 1.000E+00 | 8.000E-01 |
| 540 | 1.382E-03 | 1.000E+00 | 4.900E+03 | 1140 | 5.648E-06 | 1.000E+00 | 1.100E+00 |
| 560 | 1.102E-03 | 1.000E+00 | 1.900E+03 | 1160 | 4.877E-06 | 1.000E+00 | 2.700E+00 |
| 580 | 8.812E-04 | 1.000E+00 | 5.300E+02 | 1180 | 4.214E-06 | 1.000E+00 | 5.600E+00 |
| 600 | 7.059E-04 | 1.000E+00 | 6.300E+02 | 1200 | 3.643E-06 | 1.000E+00 | 9.400E+00 |

*(Table 4.9 continued)*

| Vert. Bend. Moment (MNm) | P(exceed) Load Cycle | P(exceed) in life | Number of cycles | Vert. Bend. Moment (MNm) | P(exceed) Load Cycle | P(exceed) in life | Number of cycles |
|---|---|---|---|---|---|---|---|
| 1220 | 3.151E-06 | 1.000E+00 | 4.100E+00 | 2120 | 3.212E-09 | 3.414E-02 | 4.700E-03 |
| 1240 | 2.727E-06 | 1.000E+00 | 9.500E+00 | 2140 | 2.710E-09 | 2.888E-02 | 9.300E-03 |
| 1260 | 2.360E-06 | 1.000E+00 | 5.500E+00 | 2160 | 2.285E-09 | 2.440E-02 | 4.700E-03 |
| 1280 | 2.043E-06 | 1.000E+00 | 2.100E+00 | 2180 | 1.924E-09 | 2.059E-02 | 8.000E-04 |
| 1300 | 1.768E-06 | 1.000E+00 | 9.100E+00 | 2200 | 1.619E-09 | 1.735E-02 | 7.500E-03 |
| 1320 | 1.531E-06 | 1.000E+00 | 6.600E+00 | 2220 | 1.360E-09 | 1.460E-02 | 4.700E-03 |
| 1340 | 1.325E-06 | 1.000E+00 | 4.300E+00 | 2240 | 1.142E-09 | 1.228E-02 | 2.400E-03 |
| 1360 | 1.147E-06 | 1.000E+00 | 2.400E+00 | 2260 | 9.582E-10 | 1.031E-02 | 4.000E-04 |
| 1380 | 9.926E-07 | 1.000E+00 | 7.000E-01 | 2280 | 8.030E-10 | 8.645E-03 | 6.800E-04 |
| 1400 | 8.588E-07 | 9.999E-01 | 2.900E-01 | 2300 | 6.722E-10 | 7.242E-03 | 2.700E-04 |
| 1420 | 7.429E-07 | 9.997E-01 | 3.000E-02 | 2320 | 5.622E-10 | 6.060E-03 | 8.000E-05 |
| 1440 | 6.424E-07 | 9.990E-01 | 9.500E-01 | 2340 | 4.696E-10 | 5.066E-03 | 8.000E-05 |
| 1460 | 5.554E-07 | 9.975E-01 | 1.000E-02 | 2360 | 3.919E-10 | 4.229E-03 | 2.400E-04 |
| 1480 | 4.799E-07 | 9.944E-01 | 1.900E-01 | 2380 | 3.268E-10 | 3.527E-03 | 5.300E-04 |
| 1500 | 4.145E-07 | 9.887E-01 | 4.800E-01 | 2400 | 2.721E-10 | 2.938E-03 | 9.400E-04 |
| 1520 | 3.579E-07 | 9.791E-01 | 8.700E-01 | 2420 | 2.264E-10 | 2.445E-03 | 4.500E-04 |
| 1540 | 3.089E-07 | 9.646E-01 | 3.400E-01 | 2440 | 1.882E-10 | 2.033E-03 | 3.000E-05 |
| 1560 | 2.665E-07 | 9.439E-01 | 8.800E-01 | 2460 | 1.562E-10 | 1.688E-03 | 6.900E-04 |
| 1580 | 2.297E-07 | 9.166E-01 | 4.800E-01 | 2480 | 1.295E-10 | 1.400E-03 | 4.000E-04 |
| 1600 | 1.979E-07 | 8.824E-01 | 1.400E-01 | 2500 | 1.073E-10 | 1.160E-03 | 1.600E-04 |
| 1620 | 1.705E-07 | 8.417E-01 | 8.400E-01 | 2520 | 8.880E-11 | 9.597E-04 | 6.000E-05 |
| 1640 | 1.467E-07 | 7.954E-01 | 5.900E-01 | 2540 | 7.340E-11 | 7.934E-04 | 9.400E-05 |
| 1660 | 1.262E-07 | 7.446E-01 | 3.600E-01 | 2560 | 6.060E-11 | 6.551E-04 | 5.500E-05 |
| 1680 | 1.085E-07 | 6.906E-01 | 1.700E-01 | 2580 | 4.998E-11 | 5.403E-04 | 4.000E-05 |
| 1700 | 9.320E-08 | 6.350E-01 | 1.000E-02 | 2600 | 4.118E-11 | 4.452E-04 | 4.500E-05 |
| 1720 | 8.001E-08 | 5.790E-01 | 6.500E-02 | 2620 | 3.389E-11 | 3.664E-04 | 6.600E-05 |
| 1740 | 6.864E-08 | 5.240E-01 | 4.200E-02 | 2640 | 2.785E-11 | 3.012E-04 | 1.000E-06 |
| 1760 | 5.885E-08 | 4.708E-01 | 3.600E-02 | 2660 | 2.287E-11 | 2.473E-04 | 4.700E-05 |
| 1780 | 5.042E-08 | 4.203E-01 | 4.500E-02 | 2680 | 1.876E-11 | 2.028E-04 | 3.000E-06 |
| 1800 | 4.316E-08 | 3.729E-01 | 6.700E-02 | 2700 | 1.537E-11 | 1.662E-04 | 6.600E-05 |
| 1820 | 3.692E-08 | 3.292E-01 | 9.900E-02 | 2720 | 1.257E-11 | 1.360E-04 | 3.600E-05 |
| 1840 | 3.156E-08 | 2.891E-01 | 4.100E-02 | 2740 | 1.028E-11 | 1.111E-04 | 1.100E-05 |
| 1860 | 2.695E-08 | 2.528E-01 | 9.100E-02 | 2760 | 8.390E-12 | 9.073E-05 | 7.000E-07 |
| 1880 | 2.300E-08 | 2.202E-01 | 4.900E-02 | 2780 | 6.842E-12 | 7.398E-05 | 4.000E-06 |
| 1900 | 1.961E-08 | 1.911E-01 | 1.200E-02 | 2800 | 5.573E-12 | 6.026E-05 | 3.000E-07 |
| 1920 | 1.671E-08 | 1.653E-01 | 8.100E-02 | 2820 | 4.534E-12 | 4.903E-05 | 9.000E-06 |
| 1940 | 1.423E-08 | 1.426E-01 | 5.400E-02 | 2840 | 3.684E-12 | 3.984E-05 | 9.800E-06 |
| 1960 | 1.210E-08 | 1.227E-01 | 3.100E-02 | 2860 | 2.990E-12 | 3.234E-05 | 2.300E-06 |
| 1980 | 1.028E-08 | 1.053E-01 | 1.110E-01 | 2880 | 2.424E-12 | 2.621E-05 | 6.200E-06 |
| 2000 | 8.733E-09 | 9.011E-02 | 4.400E-03 | 2900 | 1.963E-12 | 2.123E-05 | 1.200E-06 |
| 2020 | 7.409E-09 | 7.699E-02 | 1.000E-04 | 2920 | 1.588E-12 | 1.717E-05 | 7.200E-06 |
| 2040 | 6.280E-09 | 6.565E-02 | 7.900E-03 | 2940 | 1.283E-12 | 1.387E-05 | 3.900E-06 |
| 2060 | 5.318E-09 | 5.589E-02 | 7.500E-03 | 2960 | 1.035E-12 | 1.119E-05 | 1.200E-06 |
| 2080 | 4.500E-09 | 4.749E-02 | 8.700E-03 | 2980 | 8.340E-13 | 9.018E-06 | 2.000E-08 |
| 2100 | 3.804E-09 | 4.030E-02 | 1.100E-03 | 3000 | 6.713E-13 | 7.259E-06 | 2.600E-07 |

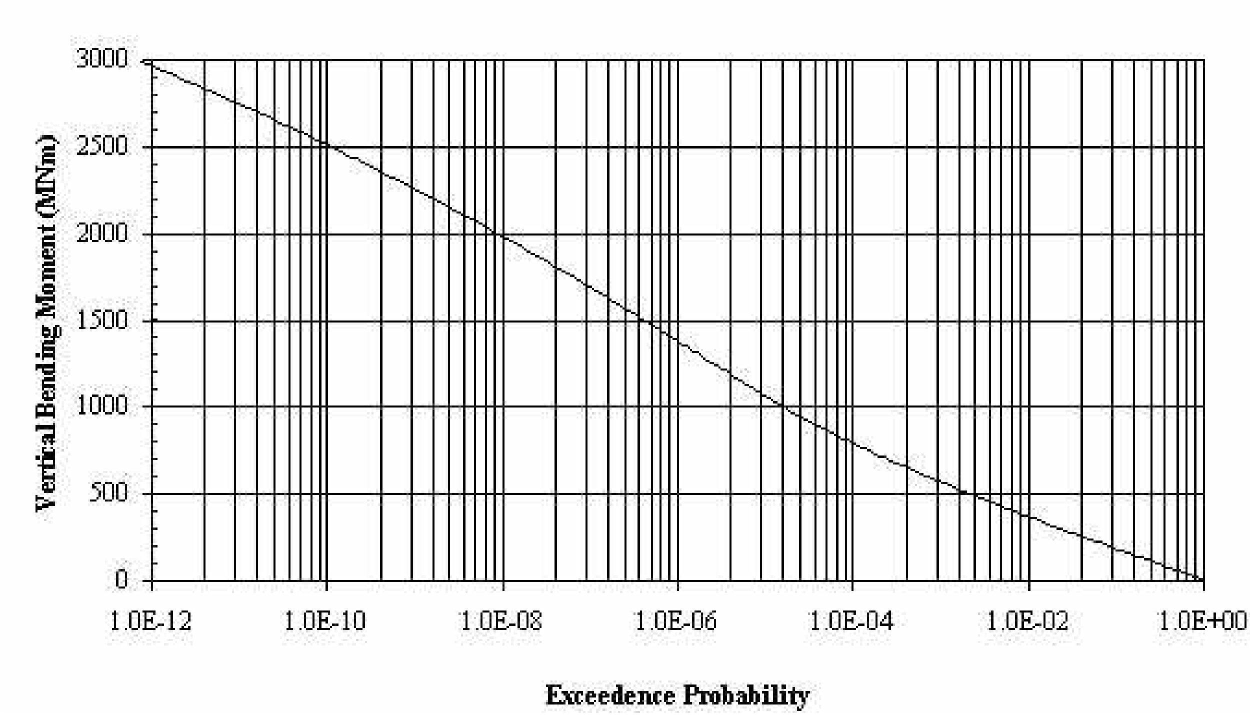



**Figure 4.8: Bulk Carrier Load Cycle Midship Vertical Bending Moment Exceedance Probability**

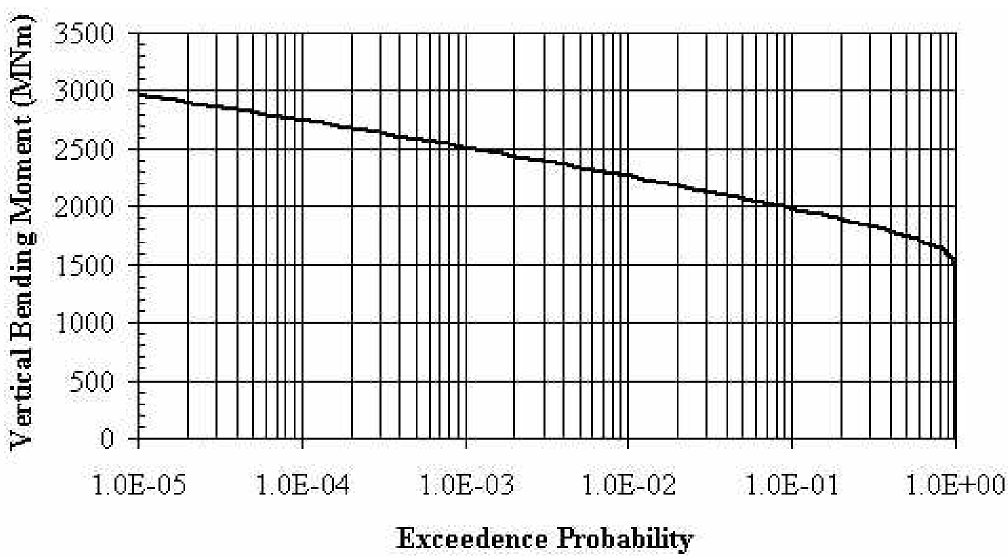



**Figure 4.9: Bulk Carrier Lifetime Midship Vertical Bending Moment Exceedance Probability (20 yrs)**

Load cycle exceedance probabilities indicate the probability of exceeding a given moment magnitude in a single load cycle. This data along with the 20-year design life and the mean zero crossing period (wave period) are used to estimate annual and thus life time statistics. Lifetime load exceedance probabilities = probability of exceeding a given moment magnitude in the lifetime of the vessel (e.g., 20 years). Figure 4.10 presents the load magnitude return periods for the bulk carrier.

| Return Period [y] | Midship Moment [MNm] |
|---|---|
| 0 | 0 |
| 5 | 1,780 |
| 10 | 1,860 |
| 15 | 1,920 |
| 20 | 1,940 |
| 25 | 1,980 |
| 30 | 2,000 |

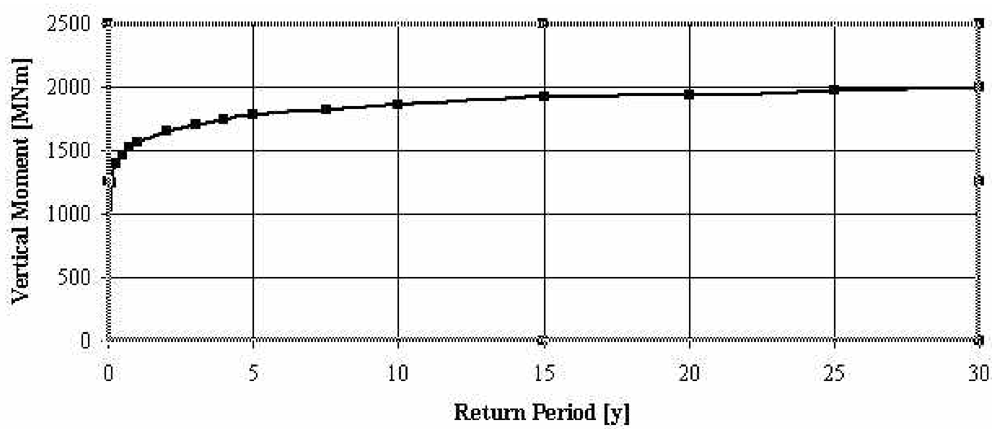



**Figure 4.10: Bulk Carrier Extreme Load Return Period**

In this analysis, it was assumed that the wave induced bending moments in the forward and aft loading zones were 80% of those estimated for the mid ship section. This assumption was made simply to reduce computational effort and is considered conservative. The vessel segments in the forward and aft segments of the ship should not encounter significant wave induced bending moments because of the relative length of the vessel compared to frequently encountered wave periods. This analysis does, however, ignore local load cycles such as slamming loads.

### 4.3.2 Tanker Loading

The longitudinal distribution of loads to be applied to the tanker has been idealized to consider a midship and a forward/aft load history. The loads applied to each structural segment of the vessel are outlined in Table 4.10. It would be possible to consider different loading conditions for each frame or segment and thus produce more detailed analysis results. The two loading zone condition is used in these examples simply to demonstrate the analysis approach.

**Table 4.10: Tanker Segment Loading Conditions**

| Segment | Loading | Segment | Loading |
|---|---|---|---|
| 1 | Fwd/Aft | 6 | Midship |
| 2 | Fwd/Aft | 7 | Midship |
| 3 | Midship | 8 | Midship |
| 4 | Midship | 9 | Fwd/Aft |
| 5 | Midship | 10 | Fwd/Aft |

The most severe still water bending moment distributions were developed for the tanker in a similar fashion as for the bulk carrier. The maximum hog and sag still water bending moment distributions estimated for the tanker are shown in Table 4.11 for each of the two loading segments.

**Table 4.11: Tanker Maximum Still Water Loads**

| | Loading Zone | SWB Moment [kNm] |
|---|---|---|
| Sag | Midship | 5,651,990 |
| | Forward / Aft | 1,638,540 |
| Hog | Midship | 3,489,200 |
| | Forward / Aft | 1,128,407 |

Wave bending moments for the tanker were calculated for design operational profiles related to the intended usage of the ship. The combined statistical effects of this service were evaluated as described in SSC 406 - Sea Operational Profiles for Structural Reliability Assessments. The routes for the tanker used in this example may cover the seas in Europe, Africa and Middle East area. A typical route is assumed herein to include Marsden Zones 17, 16, 25, 36, 58, 68, 84, 85, 90, 75, 59, 69, 60, 50, and 39. The vessel is supposed to run at service speed of 15.4 knots under design draft.

The operational characteristics are based upon the joint probability distributions of vessel speed and sea state, shown in Table 4.12 and the joint probability of relative heading and sea state, shown in Table 4.13. This data, as described in SSC 406 describes how hard the vessel is being operated in terms of the likelihood to change direction or speed in light of wave conditions.

**Table 4.12: Tanker Joint Probability of Speed and Sea State**

| Speed | Significant Wave Height (m) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (knot) | 0~1 | 1~2 | 2~3 | 3~4 | 4~5 | 5~6 | 6~7 | 7~8 | 8~9 | 9~10 | 10~11 | 11~12 | 12~13 | 13~14 | 14~15 |
| 0 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.200 | 0.600 | 0.800 | 1.000 |
| 6 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.100 | 0.300 | 0.300 | 0.400 | 0.200 | 0.000 |
| 10 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.080 | 0.100 | 0.200 | 0.600 | 0.700 | 0.500 | 0.000 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 | 0.000 | 0.000 | 0.050 | 0.100 | 0.120 | 0.200 | 0.300 | 0.300 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 15 | 0.900 | 0.950 | 1.000 | 1.000 | 0.950 | 0.900 | 0.800 | 0.700 | 0.500 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 16 | 0.100 | 0.050 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| SUM | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** |

**Table 4.13: Tanker Joint Probability of Relative Heading and Sea State**

| Heading | Significant Wave Height (m) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Degree | 0~1 | 1~2 | 2~3 | 3~4 | 4~5 | 5~6 | 6~7 | 7~8 | 8~9 | 9~10 | 10~11 | 11~12 | 12~13 | 13~14 | 14~15 |
| 0 | 0.146 | 0.176 | 0.213 | 0.250 | 0.284 | 0.313 | 0.337 | 0.354 | 0.366 | 0.373 | 0.375 | 0.374 | 0.369 | 0.363 | 0.338 |
| 45 | 0.308 | 0.317 | 0.323 | 0.326 | 0.329 | 0.332 | 0.336 | 0.343 | 0.351 | 0.361 | 0.372 | 0.385 | 0.397 | 0.410 | 0.434 |
| 90 | 0.261 | 0.266 | 0.259 | 0.247 | 0.233 | 0.219 | 0.207 | 0.196 | 0.188 | 0.182 | 0.178 | 0.176 | 0.176 | 0.177 | 0.189 |
| 135 | 0.191 | 0.163 | 0.141 | 0.124 | 0.110 | 0.097 | 0.087 | 0.076 | 0.067 | 0.058 | 0.049 | 0.041 | 0.033 | 0.026 | 0.014 |
| 180 | 0.095 | 0.078 | 0.064 | 0.053 | 0.045 | 0.038 | 0.034 | 0.031 | 0.028 | 0.027 | 0.026 | 0.025 | 0.025 | 0.025 | 0.025 |
| SUM | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** | **1.000** |

Vessel response to wave encounters were estimated using the linear strip theory program SHIPMO 7 (McTaggart 1997) under the relevant combinations of speed, relative heading, wave height and wave period. More specifically, the ship speeds set in SHIPMO7 were 0, 6, 10, 13, and 15 knots. The heading angles were set at 0, 45, 90, 135 and 180 degrees, where 180 degree represents head seas. Sea states were expressed with BRETSCHNEIDER spectrum in terms of wave significant wave heights and peak wave periods. Since the responses and loads are linear with respect to wave height, only one wave height was calculated, while the wave zero crossing periods ranges from 3.5 second to 12.5 seconds.

The midship wave induced bending moment statistical distributions, developed using LOS$^3$A (FTL 1999), considering an 85% duty cycle, are described statistically in Table 4.14 and Figures 4.11 and 4.12. The operational profile load analysis indicated that the vessel would be expected to have a mean load zero crossing period of 8.26358 seconds and based upon this and the annual load probability statistics were able to be developed. Table 4.14 presents the probabilities associated with each vertical wave bending moment magnitude or cycle as well as lifetime load magnitude exceedance probabilities. Figures 4.11 and 4.12 simply display these load magnitudes and their corresponding probabilities graphically.

**Table 4.14: Tanker Vertical Bending Moment (MNm) Exceedance Probabilities @ Midship**

| Vert. Bend. Moment | P(exceed) Load Cycle | P(exceed) in Life | Number of Cycles | Vert. Bend. Moment | P(exceed) Load Cycle | P(exceed) in Life | Number of Cycles |
|---|---|---|---|---|---|---|---|
| 100 | 7.117E-01 | 1.000E+00 | 6.400E+05 | 5100 | 2.049E-04 | 1.000E+00 | 3.400E+02 |
| 200 | 5.240E-01 | 1.000E+00 | 4.100E+05 | 5200 | 1.819E-04 | 1.000E+00 | 1.900E+02 |
| 300 | 3.960E-01 | 1.000E+00 | 5.800E+05 | 5300 | 1.616E-04 | 1.000E+00 | 5.000E+01 |
| 400 | 3.060E-01 | 1.000E+00 | 9.900E+05 | 5400 | 1.436E-04 | 1.000E+00 | 3.600E+01 |
| 500 | 2.401E-01 | 1.000E+00 | 5.700E+05 | 5500 | 1.277E-04 | 1.000E+00 | 3.200E+01 |
| 600 | 1.908E-01 | 1.000E+00 | 2.400E+05 | 5600 | 1.135E-04 | 1.000E+00 | 4.000E+01 |
| 700 | 1.531E-01 | 1.000E+00 | 9.800E+04 | 5700 | 1.010E-04 | 1.000E+00 | 5.800E+01 |
| 800 | 1.239E-01 | 1.000E+00 | 7.000E+03 | 5800 | 8.991E-05 | 1.000E+00 | 8.600E+01 |
| 900 | 1.009E-01 | 1.000E+00 | 5.700E+04 | 5900 | 8.005E-05 | 1.000E+00 | 2.200E+01 |
| 1000 | 8.255E-02 | 1.000E+00 | 3.800E+04 | 6000 | 7.129E-05 | 1.000E+00 | 6.500E+01 |
| 1100 | 6.787E-02 | 1.000E+00 | 4.200E+04 | 6100 | 6.351E-05 | 1.000E+00 | 1.400E+01 |
| 1200 | 5.603E-02 | 1.000E+00 | 6.500E+04 | 6200 | 5.660E-05 | 1.000E+00 | 6.900E+01 |
| 1300 | 4.643E-02 | 1.000E+00 | 3.000E+03 | 6300 | 5.045E-05 | 1.000E+00 | 2.900E+01 |
| 1400 | 3.862E-02 | 1.000E+00 | 5.200E+04 | 6400 | 4.497E-05 | 1.000E+00 | 9.300E+01 |
| 1500 | 3.224E-02 | 1.000E+00 | 1.000E+04 | 6500 | 4.010E-05 | 1.000E+00 | 6.100E+01 |
| 1600 | 2.701E-02 | 1.000E+00 | 7.600E+04 | 6600 | 3.577E-05 | 1.000E+00 | 3.300E+01 |
| 1700 | 2.270E-02 | 1.000E+00 | 4.800E+04 | 6700 | 3.190E-05 | 1.000E+00 | 8.000E+00 |
| 1800 | 1.914E-02 | 1.000E+00 | 2.500E+04 | 6800 | 2.846E-05 | 1.000E+00 | 8.500E+01 |
| 1900 | 1.619E-02 | 1.000E+00 | 5.000E+03 | 6900 | 2.540E-05 | 1.000E+00 | 6.500E+01 |
| 2000 | 1.373E-02 | 1.000E+00 | 9.500E+03 | 7000 | 2.266E-05 | 1.000E+00 | 4.800E+01 |
| 2100 | 1.168E-02 | 1.000E+00 | 6.100E+03 | 7100 | 2.022E-05 | 1.000E+00 | 3.200E+01 |
| 2200 | 9.956E-03 | 1.000E+00 | 4.900E+03 | 7200 | 1.805E-05 | 1.000E+00 | 1.800E+01 |
| 2300 | 8.510E-03 | 1.000E+00 | 5.500E+03 | 7300 | 1.611E-05 | 1.000E+00 | 5.000E+00 |
| 2400 | 7.292E-03 | 1.000E+00 | 7.500E+03 | 7400 | 1.438E-05 | 1.000E+00 | 3.700E+00 |
| 2500 | 6.262E-03 | 1.000E+00 | 8.000E+02 | 7500 | 1.284E-05 | 1.000E+00 | 3.600E+00 |
| 2600 | 5.390E-03 | 1.000E+00 | 5.100E+03 | 7600 | 1.146E-05 | 1.000E+00 | 4.700E+00 |
| 2700 | 4.649E-03 | 1.000E+00 | 3.000E+02 | 7700 | 1.023E-05 | 1.000E+00 | 6.600E+00 |
| 2800 | 4.018E-03 | 1.000E+00 | 6.200E+03 | 7800 | 9.129E-06 | 1.000E+00 | 9.500E+00 |
| 2900 | 3.480E-03 | 1.000E+00 | 2.700E+03 | 7900 | 8.148E-06 | 1.000E+00 | 3.100E+00 |
| 3000 | 3.019E-03 | 1.000E+00 | 9.700E+03 | 8000 | 7.272E-06 | 1.000E+00 | 7.400E+00 |
| 3100 | 2.624E-03 | 1.000E+00 | 7.100E+03 | 8100 | 6.490E-06 | 1.000E+00 | 2.300E+00 |
| 3200 | 2.284E-03 | 1.000E+00 | 4.900E+03 | 8200 | 5.792E-06 | 1.000E+00 | 7.700E+00 |
| 3300 | 1.992E-03 | 1.000E+00 | 3.000E+03 | 8300 | 5.168E-06 | 1.000E+00 | 3.700E+00 |
| 3400 | 1.739E-03 | 1.000E+00 | 1.300E+03 | 8400 | 4.611E-06 | 1.000E+00 | 0.000E+00 |
| 3500 | 1.521E-03 | 1.000E+00 | 9.100E+02 | 8500 | 4.114E-06 | 1.000E+00 | 6.800E+00 |
| 3600 | 1.332E-03 | 1.000E+00 | 6.800E+02 | 8600 | 3.669E-06 | 1.000E+00 | 3.900E+00 |
| 3700 | 1.168E-03 | 1.000E+00 | 6.100E+02 | 8700 | 3.272E-06 | 1.000E+00 | 1.300E+00 |
| 3800 | 1.025E-03 | 1.000E+00 | 6.800E+02 | 8800 | 2.918E-06 | 1.000E+00 | 9.000E+00 |
| 3900 | 9.011E-04 | 1.000E+00 | 8.700E+02 | 8900 | 2.602E-06 | 1.000E+00 | 7.000E+00 |
| 4000 | 7.928E-04 | 1.000E+00 | 1.700E+02 | 9000 | 2.319E-06 | 1.000E+00 | 5.100E+00 |
| 4100 | 6.982E-04 | 1.000E+00 | 5.500E+02 | 9100 | 2.067E-06 | 1.000E+00 | 3.500E+00 |
| 4200 | 6.155E-04 | 1.000E+00 | 1.000E+01 | 9200 | 1.842E-06 | 1.000E+00 | 2.000E+00 |
| 4300 | 5.431E-04 | 1.000E+00 | 5.400E+02 | 9300 | 1.640E-06 | 1.000E+00 | 7.000E-01 |
| 4400 | 4.796E-04 | 1.000E+00 | 1.300E+02 | 9400 | 1.461E-06 | 9.999E-01 | 5.200E-01 |
| 4500 | 4.239E-04 | 1.000E+00 | 7.600E+02 | 9500 | 1.301E-06 | 9.998E-01 | 4.800E-01 |
| 4600 | 3.749E-04 | 1.000E+00 | 4.400E+02 | 9600 | 1.158E-06 | 9.995E-01 | 5.500E-01 |
| 4700 | 3.318E-04 | 1.000E+00 | 1.600E+02 | 9700 | 1.030E-06 | 9.988E-01 | 7.200E-01 |
| 4800 | 2.939E-04 | 1.000E+00 | 9.200E+02 | 9800 | 9.168E-07 | 9.975E-01 | 9.700E-01 |
| 4900 | 2.605E-04 | 1.000E+00 | 7.000E+02 | 9900 | 8.154E-07 | 9.951E-01 | 3.100E-01 |
| 5000 | 2.310E-04 | 1.000E+00 | 5.100E+02 | 10000 | 7.250E-07 | 9.911E-01 | 7.200E-01 |

*(Table 4.14 **continued)***

| Vert. Bend. Moment | P(exceed) Load Cycle | P(exceed) in Life | Number of Cycles | Vert. Bend. Moment | P(exceed) Load Cycle | P(exceed) in Life | Number of cycles |
|---|---|---|---|---|---|---|---|
| 10100 | 6.444E-07 | 9.850E-01 | 2.000E-01 | 15100 | 1.004E-09 | 6.524E-03 | 5.400E-04 |
| 10200 | 5.726E-07 | 9.760E-01 | 7.300E-01 | 15200 | 8.702E-10 | 5.655E-03 | 6.700E-04 |
| 10300 | 5.086E-07 | 9.636E-01 | 3.100E-01 | 15300 | 7.536E-10 | 4.899E-03 | 9.100E-04 |
| 10400 | 4.516E-07 | 9.473E-01 | 9.400E-01 | 15400 | 6.521E-10 | 4.241E-03 | 2.500E-04 |
| 10500 | 4.009E-07 | 9.266E-01 | 6.100E-01 | 15500 | 5.640E-10 | 3.668E-03 | 6.800E-04 |
| 10600 | 3.557E-07 | 9.015E-01 | 3.200E-01 | 15600 | 4.874E-10 | 3.171E-03 | 1.800E-04 |
| 10700 | 3.155E-07 | 8.720E-01 | 6.000E-02 | 15700 | 4.210E-10 | 2.740E-03 | 7.400E-04 |
| 10800 | 2.797E-07 | 8.385E-01 | 8.200E-01 | 15800 | 3.634E-10 | 2.365E-03 | 3.700E-04 |
| 10900 | 2.479E-07 | 8.013E-01 | 6.200E-01 | 15900 | 3.134E-10 | 2.040E-03 | 4.000E-05 |
| 11000 | 2.197E-07 | 7.610E-01 | 4.300E-01 | 16000 | 2.702E-10 | 1.759E-03 | 7.600E-04 |
| 11100 | 1.945E-07 | 7.185E-01 | 2.700E-01 | 16100 | 2.327E-10 | 1.516E-03 | 5.200E-04 |
| 11200 | 1.722E-07 | 6.744E-01 | 1.200E-01 | 16200 | 2.004E-10 | 1.305E-03 | 3.100E-04 |
| 11300 | 1.524E-07 | 6.295E-01 | 9.300E-02 | 16300 | 1.724E-10 | 1.123E-03 | 1.200E-04 |
| 11400 | 1.348E-07 | 5.845E-01 | 7.800E-02 | 16400 | 1.482E-10 | 9.652E-04 | 6.600E-05 |
| 11500 | 1.191E-07 | 5.400E-01 | 7.600E-02 | 16500 | 1.273E-10 | 8.293E-04 | 3.000E-05 |
| 11600 | 1.053E-07 | 4.965E-01 | 8.600E-02 | 16600 | 1.093E-10 | 7.120E-04 | 1.200E-05 |
| 11700 | 9.300E-08 | 4.545E-01 | 6.000E-03 | 16700 | 9.377E-11 | 6.109E-04 | 1.100E-05 |
| 11800 | 8.211E-08 | 4.144E-01 | 3.500E-02 | 16800 | 8.040E-11 | 5.238E-04 | 2.400E-05 |
| 11900 | 7.246E-08 | 3.764E-01 | 7.200E-02 | 16900 | 6.888E-11 | 4.488E-04 | 4.900E-05 |
| 12000 | 6.391E-08 | 3.407E-01 | 1.700E-02 | 17000 | 5.897E-11 | 3.843E-04 | 8.400E-05 |
| 12100 | 5.635E-08 | 3.073E-01 | 6.700E-02 | 17100 | 5.046E-11 | 3.288E-04 | 2.900E-05 |
| 12200 | 4.966E-08 | 2.765E-01 | 2.400E-02 | 17200 | 4.314E-11 | 2.811E-04 | 8.100E-05 |
| 12300 | 4.374E-08 | 2.480E-01 | 8.500E-02 | 17300 | 3.686E-11 | 2.402E-04 | 4.000E-05 |
| 12400 | 3.850E-08 | 2.219E-01 | 5.100E-02 | 17400 | 3.147E-11 | 2.050E-04 | 5.000E-06 |
| 12500 | 3.388E-08 | 1.981E-01 | 2.100E-02 | 17500 | 2.685E-11 | 1.749E-04 | 7.500E-05 |
| 12600 | 2.980E-08 | 1.765E-01 | 9.400E-02 | 17600 | 2.289E-11 | 1.491E-04 | 4.900E-05 |
| 12700 | 2.619E-08 | 1.569E-01 | 7.100E-02 | 17700 | 1.950E-11 | 1.271E-04 | 2.700E-05 |
| 12800 | 2.301E-08 | 1.393E-01 | 5.000E-02 | 17800 | 1.660E-11 | 1.082E-04 | 8.000E-06 |
| 12900 | 2.021E-08 | 1.234E-01 | 3.200E-02 | 17900 | 1.412E-11 | 9.203E-05 | 2.000E-06 |
| 13000 | 1.773E-08 | 1.091E-01 | 1.600E-02 | 18000 | 1.201E-11 | 7.823E-05 | 8.200E-06 |
| 13100 | 1.556E-08 | 9.641E-02 | 1.000E-03 | 18100 | 1.020E-11 | 6.646E-05 | 6.500E-06 |
| 13200 | 1.364E-08 | 8.504E-02 | 8.900E-03 | 18200 | 8.657E-12 | 5.641E-05 | 6.400E-06 |
| 13300 | 1.195E-08 | 7.492E-02 | 7.900E-03 | 18300 | 7.343E-12 | 4.785E-05 | 7.900E-06 |
| 13400 | 1.047E-08 | 6.593E-02 | 6.820E-02 | 18400 | 6.224E-12 | 4.056E-05 | 6.000E-07 |
| 13500 | 9.160E-09 | 5.795E-02 | 9.700E-03 | 18500 | 5.272E-12 | 3.435E-05 | 4.400E-06 |
| 13600 | 8.013E-09 | 5.088E-02 | 2.200E-03 | 18600 | 4.462E-12 | 2.908E-05 | 9.100E-06 |
| 13700 | 7.006E-09 | 4.463E-02 | 5.700E-03 | 18700 | 3.773E-12 | 2.459E-05 | 4.600E-06 |
| 13800 | 6.122E-09 | 3.911E-02 | 9.900E-03 | 18800 | 3.189E-12 | 2.078E-05 | 8.000E-07 |
| 13900 | 5.346E-09 | 3.424E-02 | 4.800E-03 | 18900 | 2.693E-12 | 1.755E-05 | 7.500E-06 |
| 14000 | 4.666E-09 | 2.995E-02 | 4.000E-04 | 19000 | 2.272E-12 | 1.481E-05 | 4.800E-06 |
| 14100 | 4.070E-09 | 2.617E-02 | 6.500E-03 | 19100 | 1.916E-12 | 1.249E-05 | 2.500E-06 |
| 14200 | 3.548E-09 | 2.286E-02 | 3.100E-03 | 19200 | 1.614E-12 | 1.052E-05 | 5.000E-07 |
| 14300 | 3.091E-09 | 1.994E-02 | 1.000E-04 | 19300 | 1.359E-12 | 8.858E-06 | 8.600E-07 |
| 14400 | 2.692E-09 | 1.739E-02 | 7.500E-03 | 19400 | 1.143E-12 | 7.452E-06 | 4.500E-07 |
| 14500 | 2.342E-09 | 1.515E-02 | 5.300E-03 | 19500 | 9.613E-13 | 6.264E-06 | 2.600E-07 |
| 14600 | 2.037E-09 | 1.319E-02 | 3.300E-03 | 19600 | 8.075E-13 | 5.262E-06 | 2.600E-07 |
| 14700 | 1.771E-09 | 1.147E-02 | 1.500E-03 | 19700 | 6.778E-13 | 4.417E-06 | 4.200E-07 |
| 14800 | 1.538E-09 | 9.973E-03 | 0.000E+00 | 19800 | 5.684E-13 | 3.704E-06 | 7.000E-07 |
| 14900 | 1.335E-09 | 8.663E-03 | 7.000E-04 | 19900 | 4.764E-13 | 3.105E-06 | 1.000E-07 |
| 15000 | 1.158E-09 | 7.520E-03 | 5.500E-04 | 20000 | 3.989E-13 | 2.600E-06 | 6.000E-07 |

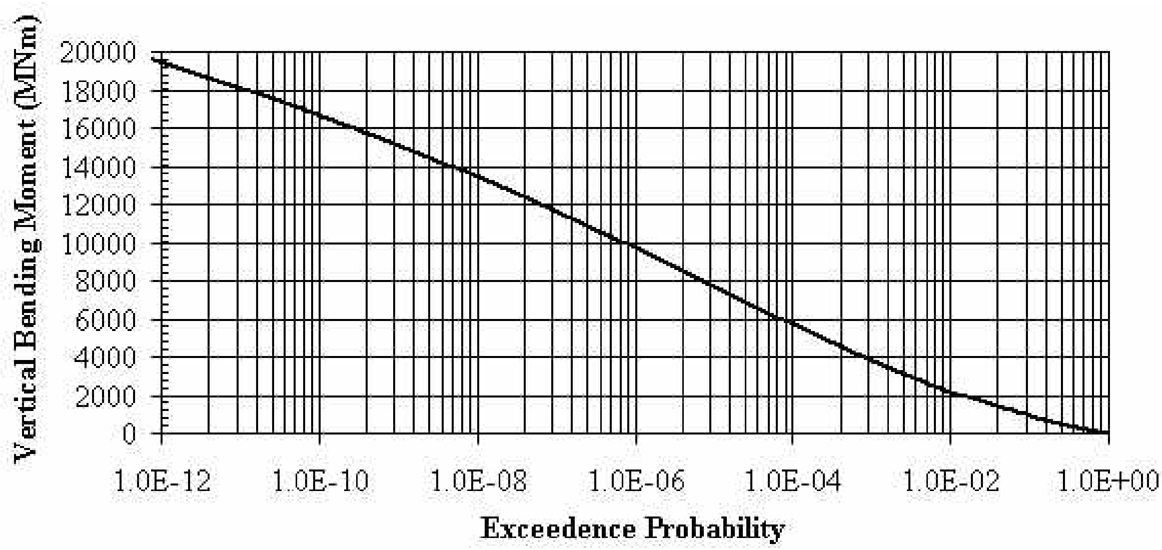



**Figure 4.11: Tanker Load Cycle Midship Vertical Bending Moments Exceedance Probabilities**

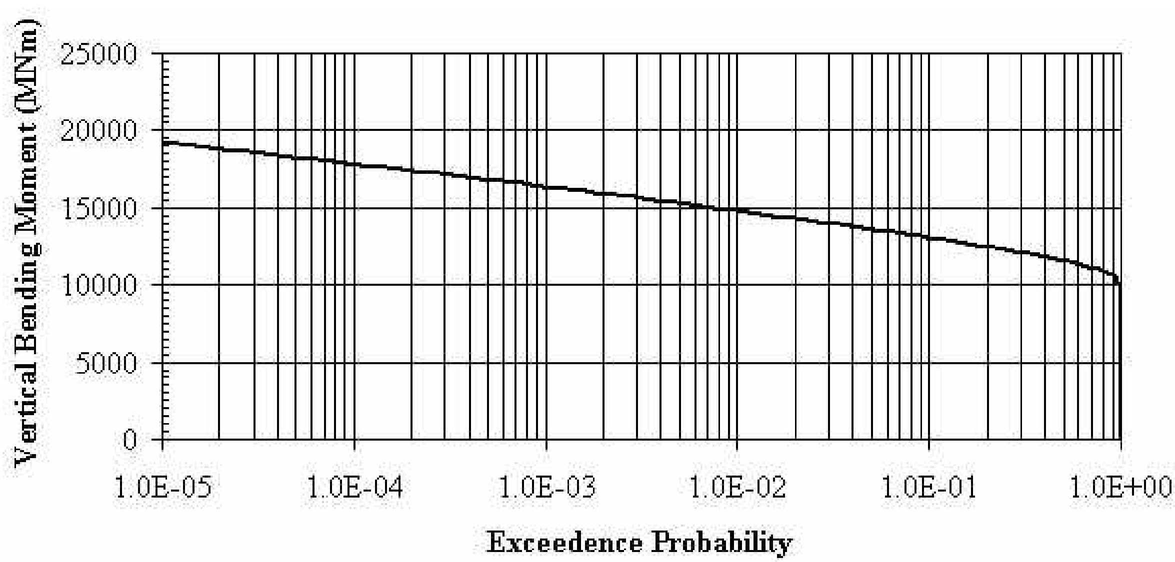



**Figure 4.12: Tanker Lifetime Midship Vertical Bending Moment Exceedance Probability**

Load cycle exceedance probabilities indicate the probability of exceeding a given moment magnitude in a single load cycle. This data along with the 20-year design life and the mean zero crossing period (wave period) are used to estimate annual and thus life time statistics. Lifetime load exceedance probabilities = probability of exceeding a given moment magnitude in the lifetime of the vessel (e.g., 20 years). Figure 4.13 presents the load magnitude return periods for the bulk carrier.

| Return Period [y] | Midship Moment [MNm] |
|---|---|
| 0 | 0 |
| 5 | 12,100 |
| 10 | 12,600 |
| 15 | 12,900 |
| 20 | 13,200 |
| 25 | 13,300 |
| 30 | 13,500 |

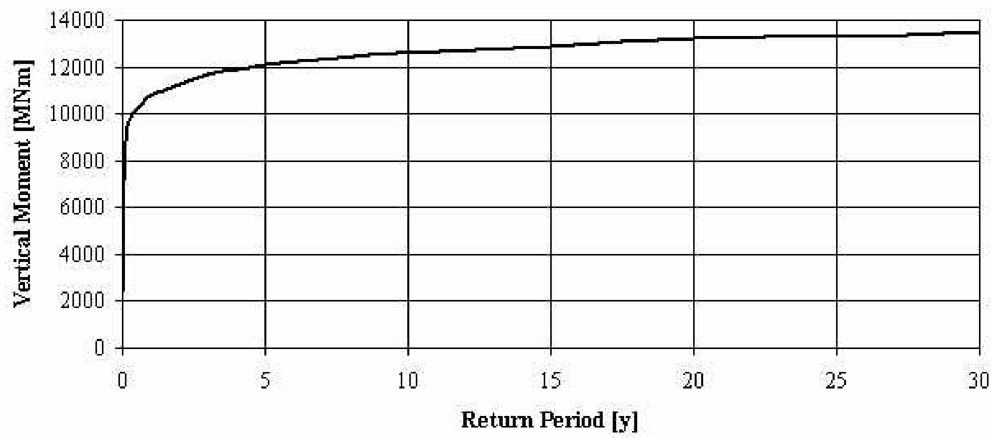



**Figure 4.13: Tanker Extreme Load Return Period**

In this analysis, it was assumed that the wave induced bending moments in the forward and aft loading zones were 80% of those estimated for the mid ship section. This assumption was made simply to reduce computational effort and is considered conservative since the vessel segments in the forward and aft segments of the ship should not encounter significant wave induced bending moments because of the relative length of the vessel compared to frequently encountered wave periods.

## 4.4 Definition of Local Detail Characteristics

Next, the characteristics of the previously defined structural details (see Section 3.2) are assigned. The characteristics of interest to this investigation include:

- nominal stress transfer functions,
- cross-section geometry,
- stress concentration effects, and
- corrosion rate and coating quality information.

### 4.4.1 Bulk Carrier Local Detail Characteristics

The structural geometry of the bulk carrier defined in Table 4.2 is used in this example to calculate a hull girder moment of inertia and section modulus for each cross section. These section properties are updated as degradation accumulates. The initial section properties are shown in Table 4.15.

**Table 4.15: Bulk Carrier As Built Midship Section Properties**

| Moment of Inertia [$mm^4$] | Neutral Axis Distance to Keel [mm] | Section Modulus Deck [$mm^3$] | Section Modulus Keel [$mm^3$] |
|---|---|---|---|
| 7.45E+13 | 5938.5 | 8.14E+09 | 1.26E+10 |

The material properties used in the analysis were based on the nominal properties of the steel used to fabricate the vessel. The vessel was constructed with AH 32 steel having the following material properties:

- 315 MPa yield stress
- 440 MPa UTS
- 207 GPa modulus of elasticity

The fatigue performance of the welded connections in this analysis were assessed using a nominal stress approach in which the following S-N data is used:

$$N \sigma_r^m = K_0 \Delta^d$$

where:

| | |
|---|---|
| $\sigma_r$ | is the applied stress range [MPa] |
| N | is the predicted number of cycles to failure of a stress range $\sigma_r$ |
| $K_0$ | is the constant term relating to the mean line of the statistical analysis results |
| m | is the inverse slope of the mean line log $\sigma_r$ - log N curve |
| $\Delta$ | is the reciprocal of the anti-log of the standard deviation of log N |
| d | is the number of standard deviations below the mean line |

Two fatigue detail classes were considered for this example application in which the following constants are used:

| | | | |
|---|---|---|---|
| Class F | $K_0 = 1.73\text{x}10^{12}$ | $\Delta = 0.605$ | m = 3.0 |
| Class F2 | $K_0 = 1.23\text{x}10^{12}$ | $\Delta = 0.592$ | m = 3.0 |

A review of the structural connections used in the bulk carrier indicated that, at the level of detail being used in this analysis, all components in the bulk carrier should be assigned an F2 fatigue class or category.

The corrosion degradation modeling approach used in the examples considers coating life, general corrosion and pitting or localized rates. Since observed detail corrosion rate and coating quality data is not available from survey results, the data used in evaluating the long-term section properties of the vessel was randomly assigned. A mean life of the coatings of on each component ($To_{m,n,j}$) was assigned based on location and environment. Variability in these values was randomly assigned based on a normal distribution that theoretically represents the variability in the paint application quality. Data collected from the literature indicates that the mean life of coatings ranges from 5 to 10 years. This range in coating life is related to the component location and environment. In the examples, the coating life normal distribution statistics outlined in Table 3.1 are used.

**Table 4.16: Coating Life Statistics**

| Locations | Coating Life [y] | | Coating |
|---|---|---|---|
| | Mean | Coef. of Variation | Class |
| Living Space | 10 | 0.2 | 1 |
| Exterior Deck | 9 | 0.2 | 2 |
| Interior Deck | 10 | 0.2 | 3 |
| Dry Cargo Space | 1 | 0.3 | 4 |
| Ballast Tank | 5 | 0.3 | 5 |
| Liquid Cargo Space | 7 | 0.3 | 6 |

Annual mean corrosion rates ($CR_{m,n,j}$) can be assigned to each component based on location and environment. In addition, a coefficient of variation in corrosion rate ($COVcr_{m,n,j}$) can be assigned to each component. The corrosion rate mean and coefficient of variation data can be drawn from the data collected from the literature and used in the example problems.

**Table 4.17: Corrosion Rate Statistics**

| Structure Type | Liquid Cargo [mm/y] | | | Ballast [mm/y] | | | Ullage/Dry Space | | |
|---|---|---|---|---|---|---|---|---|---|
| | Class | Mean | COV | Class | Mean | COV | Class | Mean | COV |
| Deck | 1 | 0.05 | 1.7 | 5 | 0.19 | 1.1 | 9 | 0.02 | 0.6 |
| Deck Stiffener | 2 | 0.09 | 2 | 6 | 0.16 | 1.4 | 10 | 0.02 | 0.6 |
| Side | 3 | 0.06 | 0.6 | 7 | 0.07 | 0.04 | 11 | 0.02 | 0.6 |
| Bottom | 4 | 0.05 | 1.7 | 8 | 0.19 | 1.1 | 12 | 0.02 | 0.6 |

The potential for pitting or weld zone preferential corrosion can be evaluated by assigning a pitting corrosion rate randomly to those components whose coatings have broken down. The rate of pitting corrosion assignment can be based on the corrosion data collected in the literature review. Pitting corrosion affects the integrity of the structure by reducing the effectiveness of the stiffening element (i.e., having it trip) and promoting a loss of water tightness. The latter effect will not influence the structural integrity of the vessel but will be tracked as an independent degradation mode. The pitting corrosion rate data available for use in the examples is shown in Table 4.18.

**Table 4.18: Pitting Corrosion Rate Data**

| Structure Type | Liquid Cargo [mm/y]* | | Ballast [mm/y] | | Ullage/Dry Space | |
|---|---|---|---|---|---|---|
| | Mean | COV | Mean | COV | Mean | COV |
| All Connections | 1.5 | 0.11 | 2 | 0.2 | 0 | 0 |

The assignment of coating life and corrosion rate classes are applied to the component types based upon their location. The details of these assignments are outlined in Table 4.2 according the values given in Tables 4.17 and 4.18.

In general, paint renewals are completed on five-year intervals for the outer hull and fifteen years for ballast tanks. It is noted that the cargo holds in the tanker are not painted. This generalization is put forward simply as an indicator of the level of maintenance typical for commercial vessels. In the sample applications presented in this report, three level of maintenance are explored to demonstrate their effect on vessel life expectancy assessment.

### 4.4.2 Tanker Local Detail Characteristics

The structural geometry of the Tanker defined in Table 4.4 is used in this example to calculate a hull girder moment of inertia and section modulus for each cross-section. These section properties are updated as degradation accumulates. The initial section properties are shown in Table 4.16.

**Table 4.19: Tanker As Built Midship Section Properties**

| Moment of Inertia [$mm^4$] | Neutral Axis Distance to Keel [mm] | Section Modulus Deck [$mm^3$] | Section Modulus Keel [$mm^3$] |
|---|---|---|---|
| 1.41E+15 | 13205.8 | 7.84E+10 | 1.07E+11 |

The material properties used in the analysis were based on the nominal properties of the steel used to fabricate the vessel. The vessel was constructed with Grade A and AH 36 steel. The main deck of the vessel is fabricated with higher strength steel. In the sample analysis, the following material properties were applied:

- 353 MPa yield stress
- 490 MPa UTS
- 207 GPa modulus of elasticity

The fatigue and corrosion data used to characterize structural degradation in the tanker is the same as that used in the bulk carrier. However, this basic data is assigned differently for the tanker.

A review of the structural connections used in the tanker indicated that, at the level of detail being used in this analysis, all components in frame type 1 should be assigned an F fatigue class or category while those in frame type 2 were assigned an F2 fatigue class or category. The frame types and their distribution in the tanker are described in Table 4.3.

The assignment of coating life and corrosion rate classes are applied to the component types based upon their location. The details of these assignments are outlined in Table 4.4 according the values given in Tables 4.17 and 4.18.

## 4.5 Time Dependant Reliability Assessment

The time dependant reliability is calculated in the sample applications considering five elements. The general approach is presented in the next five sections after which the results of applying this process to the bulk carrier and tanker structure are described.

### 4.5.1 Structural and Limit State Analysis

The structural analysis performed in the example problems is based on a hull girder analogy supplemented by local stress concentration effects. The stress concentration effects are detail specific and are incorporated in the assigned nominal stress fatigue class or categories.

The section properties for individual components include their cross sectional area and lateral stability. The cross-sectional area of a stiffened panel component ($A_{m,n,j}$) is estimated in terms of the thickness reduction ($R_{m,n,j}$) as:

$$A_{m,n,j} = A_{0\ m,n,j}\left(\frac{T_{0\ m,n,j} - R_{m,n,j}}{T_{0\ m,n,j}}\right)$$

where $A_0$ and $T_0$ are the section original area and thickness, respectively

The hull girder neutral axis location and moment of inertia are estimated based on the first and second moments of component areas about the section neutral axis.

In the example applications, the applied failure criteria include a combination of performance and prescriptive limit states expressing component and sectional failure criteria as outlined in Table 4.20.

**Table 4.20: Example Limit States**

| Criteria Type | Component | Section |
|---|---|---|
| Prescriptive | Local Diminution (general corrosion)<br>Water Tightness (pitting limit) | Average Diminution (general corrosion) |
| Performance | Buckling<br>Fatigue Crack Initiation | Section Yielding |

The time dependant effects of general corrosion are considered in the estimation of section modulus and thus affect the yield and buckling probabilities. Fatigue crack initiation is evaluated using a nominal stress based Miner's summation. The analysis included in the sample applications does not consider the effects of either general or pitting corrosion on fatigue initiation rate.

All of the limit states (failure criteria or performance functions) are formulated to include factors of safety and thus will be expressed as follows:

$$\alpha R - L < 0 \qquad \text{[Failure Condition]}$$

where L and R are the load and resistance effects, respectively and $\alpha$ is the factor of safety applied to the resistance. The factors of safety were included in the analysis to allow the approach to be used in conjunction with design rules that conservatively define failure before the capacity of the structure is completely used up. The factors of safety applied in the sample problem have values less than or equal to unity as outlined in Table 4.21.

**Table 4.21: Proposed Limit State Criteria and Factors of Safety**

| Failure Criteria | Load (L) | Resistance (R) | Safety Factor ($\alpha$) |
|---|---|---|---|
| Prescriptive | | | |
| Local Diminution | $t_o$ - $t_i$ | 0.30 $t_o$ | 0.75 |
| Water Tightness | $t_o$ - $t_i$ | 0.80 $t_o$ | 0.75 |
| Average Diminution | Average[$t_o$ - $t_i$] | 0.20 $t_o$ | 0.75 |
| Performance | | | |
| Buckling | Comp. bending stress $\sigma_i = M\ Y_i / I_i$ | Stability Limits (outlined below) | 1 |
| Fatigue Crack Initiation | Miners Damage Sum | 1 | 1 |
| Section Yielding | Max. bending stress $\sigma_i = M\ Y_i / I_i$ | $\sigma_y$ (yield stress) | 1 |

Buckling Criteria (Lewis 1988)

Only two buckling modes will be considered, for the sake of simplicity, including:

- Elastic inter stiffener plate buckling

$$\sigma_i = k_c \frac{\pi^2 E}{12(1-\upsilon^2)}\left(\frac{t_i}{b}\right)^2$$

- Stiffener Flexural Buckling

$$\sigma_i = \frac{\pi^2 E I_i}{A_i l^2}\left[1 + \frac{\pi^2 E I_i}{l^2 G A_{si}}\right]^{-1}$$

This ignores stiffener torsional buckling and grillage buckling, however, formulations for these buckling modes may be considered in the future using the approach outlined in these examples.

where:

$\nu$ Poisson's ratio (= 0.3)
$\sigma_y$ material yield stress
$\sigma_i$ component compressive stress
$A_i$ time dependant area of plating and stiffener
$A_{si}$ time dependant shear area
$b$ stiffener spacing
$E$ modulus of elasticity (= 207 GPa)
$G$ shear modulus (= 80.4 GPa)
$I_i$ time dependant section moment of inertia
$k_c$ compressive buckling coefficient (= approx 7.5)
$M$ section design moment related to the design probability of exceedance ($1 \times 10^{-8}$)
$t_o$ nominal original thickness
$t_i$ time dependant thickness
$Y_i$ time dependant distance relative to the neutral axis

### 4.5.2 Treatment of Coating Life and Corrosion

In the sample problem's treatment of coating life and corrosion, the scantlings of the vessel are estimated at discrete times in the vessel's life to develop an appreciation for the effects of corrosion on the probabilities of failure. The discrete representations of the reduced scantlings (plate thickness, stiffener flange and web thickness as described in Tables 4.2 and 4.4) are used in the calculations described in the previous section to evaluate the effect of corrosion on structural failure probabilities.

Three corrosion rates are investigated in this analysis considering low, medium and high rates. The three levels correspond to the mean - 1 standard deviation, mean and mean + 1 standard deviation rates considering the data outlined in Tables 4.16 and 4.17 assigned to each component. This treatment was used as a means of demonstrating the effects of high, medium and low levels of maintenance applied to a vessel.

In addition to the strength or structural limit states, the sample problem considers prescriptive limit states related to local diminution or wastage. These corrosion limit states are addressed by calculating the probability of failure given by the following equation:

$$P_f = 1 - \text{Pr}[\text{Corrosion Reduction}(\max(0, \textit{time} - T_0)) > t_0\, \delta\, \alpha]$$

where $T_0$ is the coating life and *time* is the duration of service for which the corrosion induced thickness reduction is calculated for each component thickness. The limit on acceptable wastage is expressed in the limit state equation in terms of the original section thickness $t_o$, the resistance factor ($\delta$) (see Table 4.21), and a user defined safety factor ($\alpha$) also shown in Table 4.21.

The random variable of interest has two components: the one related to corrosion rate and the other related to the coating life. In these example applications, it was noted that coating life had less variability (lower COV) than corrosion rate, so it is may be neglected when compared to the corrosion rate variability. Using this assumption, the random distribution used to calculate probabilities of diminution failures may be considered in terms of a normal distribution with the following parameters:

$$\text{Mean} = \text{Mean corrosion reduction}(\max(0, t - T_0)), \text{ and}$$

$$\begin{aligned}\text{Sigma} &= \text{Mean(corrosion reduction) COV(corrosion rate)} (\max(0, t - T_0)) \\ &= \text{corrosion reduction} * \text{COV(corrosion rate)}\end{aligned}$$

The sample applications consider three levels of maintenance high, normal and low. These levels of maintenance or paint quality are used to assign deterministic coating lives. In the sample applications it was assumed that that coatings are not renewed (re-applied) and that their lives are for high maintenance/quality (mean+1 standard deviation), normal (mean), low (mean-1 standard deviation).

In this approach, the probability of failure is calculated by estimating the probability of exceeding a corrosion reduction of $t_0\, \delta\, \alpha$.

This analysis approach may be used to calculate failure probabilities for local diminution and loss of water tightness using the corrosion rate (Table 4.16) and local pitting data (Table 4.18), respectively.

The average diminution limit state is evaluated using the corrosion rate data from Table 4.16 and averaging the corrosion reductions estimated for all of the components at a section as follows:

$$P_{f\,av} = \frac{\sum_{i=1}^{N} n_i (b_{fi} p_{ff_i} + b_{pi} p_{fp_i} + h_{wi} p_{fw_i})}{\sum_{i=1}^{N} n_i (b_{fi} + b_{pi} + h_{wi})}$$

where *N* is the number of different components at a frame, $n_i$ is the number of component repetitions, and the remaining variables are component initial thickness and reduction.

*4.5.2.1 Bulk Carrier Corrosion Diminution Time Dependant Reliability*

In the time dependant reliability analysis for corrosion, three limit states were examined as outlined in Tables 4.20 and 4.21. These tables identify the limit states and provided the allowable limits of corrosion for failure to be declared. In general, the three limit states investigated included:

- Water Tightness - Failure is considered to have occurred when local pitting reduces the plate thickness to less than 20% of its original thickness.
- Local Diminution - Failure is considered to have occurred when general corrosion reduces the plate thickness to less than 70% of its original thickness.
- Average Diminution - Failure is considered to have occurred when general corrosion reduces the average plate thickness at a frame to less than 80% of the average original thickness at a frame.

These limit states are evaluated considering a factor of safety of 0.75, therefore, the minimum plate thickness is divided by 0.75 to calculate the failure limit in the reliability calculation.

As noted in the last column of Table 4.2, components were individually assigned corrosion rate and coating life codes according to their location and environment. The coating life (1 to 6) and corrosion rate (1 to 12) codes are listed in Tables 4.16 and 4.17, respectively. The application of these codes to the bulk carrier frame is shown in Figure 4.14 below.

Note:

Coating and Corrosion codes presented in figure as:

(Corrosion/Coating)

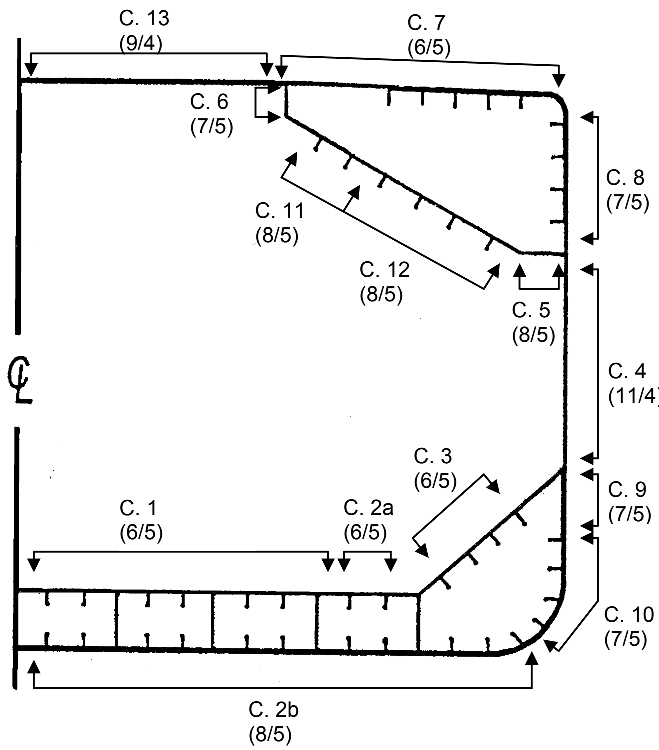



**Figure 4.14: Bulk Carrier Component Coating and Corrosion Codes**

The application of coating life and corrosion rate codes, shown above, includes only five unique combinations of codes and thus will only develop five unique time-based reliability results in this analysis. The coating life and corrosion rate code combinations used include:

- 6/5 for components 1, 2a, 3, and 7
- 7/5 for components 6, 8, 9, and10
- 8/5 for components 2b, 5, 11, and 12
- 9/4 for component 13
- 11/4 for component 4

Therefore, in the remainder of this section, only the results for components 1, 6, 2b 13 and 4 will be presented and discussed. Based upon the structure, data and limit states discussed earlier the estimated time dependant pitting or water tightness probability of failure is shown in Figure 4.15. These results illustrate that normally maintained (or normal quality paint) the probability of pitting failure, loss of water tightness, is low except for those surfaces (components 1 and 2b) that have relatively short coating lives.

| Years | Component | | | | |
|---|---|---|---|---|---|
| | 1 | 6 | 2b | 13 | 4 |
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 10 | 4.49E-02 | 0.00E+00 | 7.22E-02 | 0.00E+00 | 0.00E+00 |
| 15 | 3.12E-01 | 0.00E+00 | 3.92E-01 | 0.00E+00 | 0.00E+00 |
| 20 | 4.64E-01 | 0.00E+00 | 5.48E-01 | 0.00E+00 | 0.00E+00 |
| 25 | 5.44E-01 | 0.00E+00 | 6.24E-01 | 0.00E+00 | 0.00E+00 |
| 30 | 5.92E-01 | 0.00E+00 | 6.68E-01 | 0.00E+00 | 0.00E+00 |
| 35 | 6.23E-01 | 0.00E+00 | 6.96E-01 | 1.11E-16 | 1.11E-16 |
| 40 | 6.44E-01 | 0.00E+00 | 7.16E-01 | 1.41E-12 | 1.41E-12 |

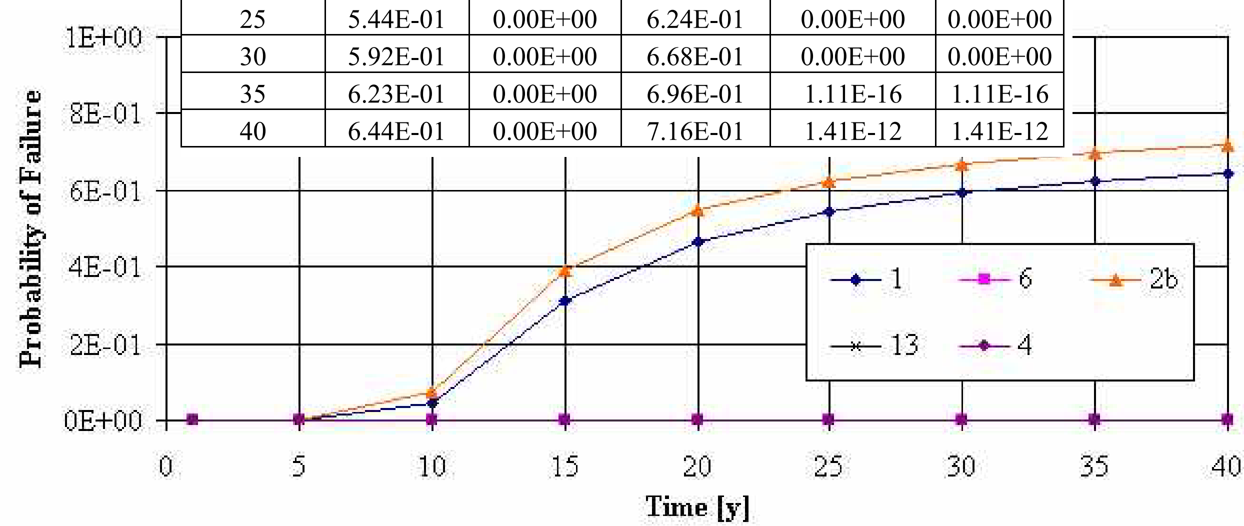
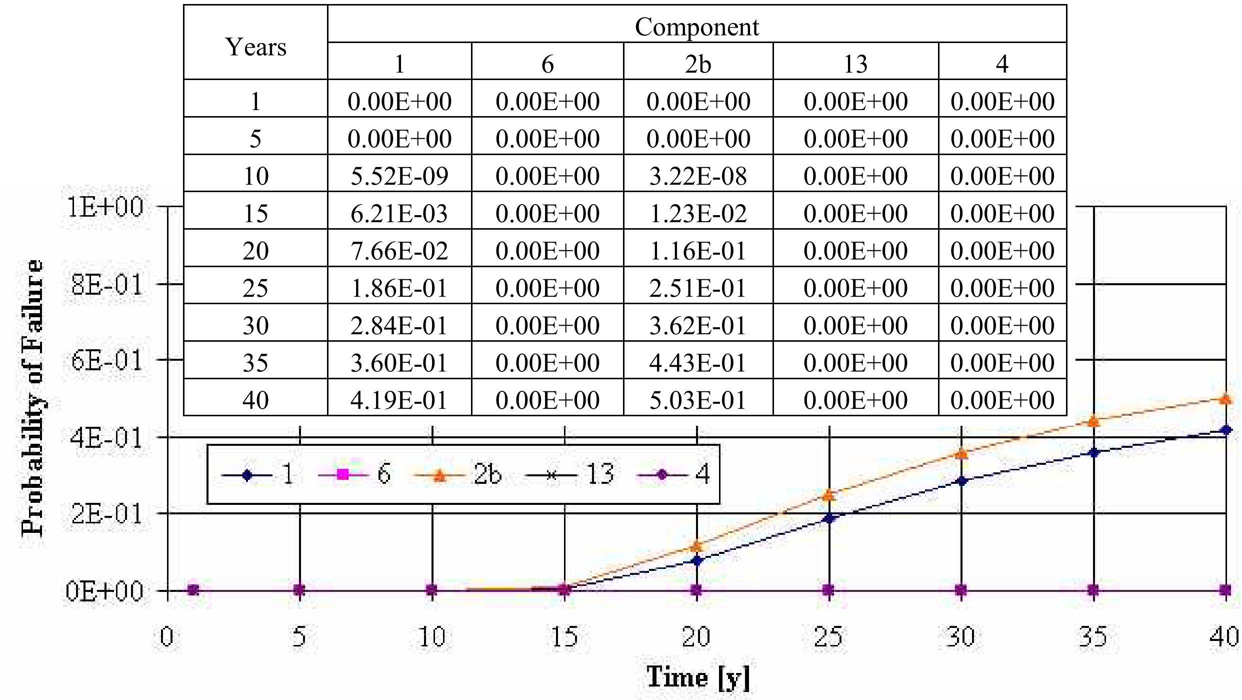



**Figure 4.15: Bulk Carrier Component Probability of Pitting Failure**

It is noted that each component is comprised of two elements, a plate and a stiffener, with different thickness. Corrosion diminution reduces thickness and a unit reduction in component thickness represents a greater percentage of component thickness for a thinner component, therefore, at the same corrosion rate the probability of corrosion failure for the stiffener and plate is greatest for the thinnest element. In the sample problems, the component probability of pitting or diminution failure is taken as the greater of the stiffener and plate probabilities of failure. This means that the component probability of failure is the same as that of its thinnest element. This assumption may not be correct for those cases in which the stiffener is thinner than the plate element, when considering pitting, since the loss of water tightness is not dependant on stiffener pitting.

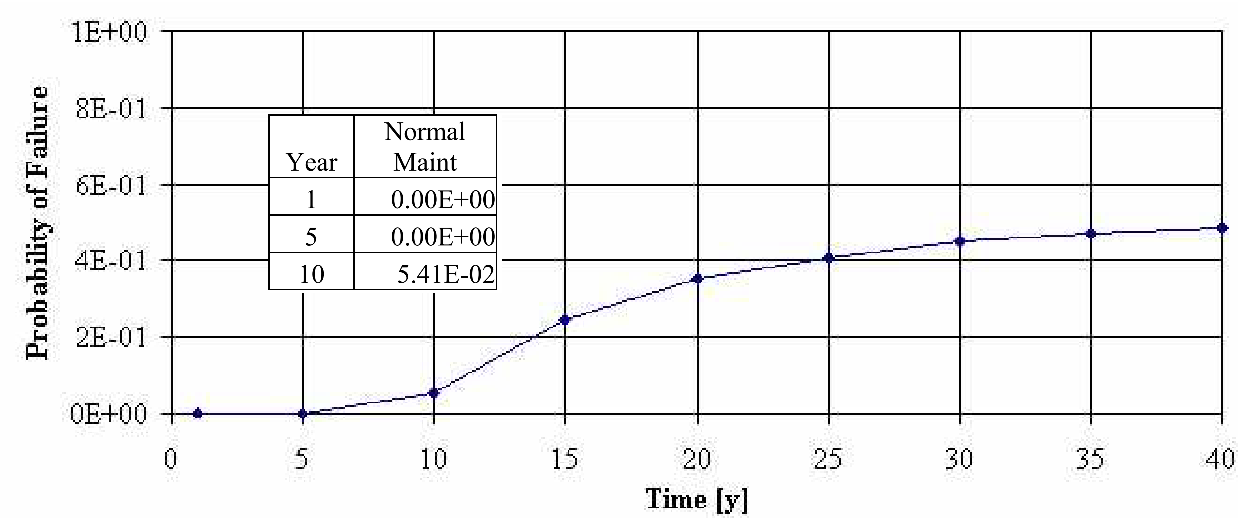
Estimated time dependant component probabilities of failure are also estimated for the local diminution limit state and presented in Figure 4.16 for a normal maintenance (or paint quality) scenario. This result indicates that, as in the pitting case, the components with significant failure probabilities are those with short coating lives.




| Years | Component | | | | |
|---|---|---|---|---|---|
| | 1 | 6 | 2b | 13 | 4 |
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 10 | 5.52E-09 | 0.00E+00 | 3.22E-08 | 0.00E+00 | 0.00E+00 |
| 15 | 6.21E-03 | 0.00E+00 | 1.23E-02 | 0.00E+00 | 0.00E+00 |
| 20 | 7.66E-02 | 0.00E+00 | 1.16E-01 | 0.00E+00 | 0.00E+00 |
| 25 | 1.86E-01 | 0.00E+00 | 2.51E-01 | 0.00E+00 | 0.00E+00 |
| 30 | 2.84E-01 | 0.00E+00 | 3.62E-01 | 0.00E+00 | 0.00E+00 |
| 35 | 3.60E-01 | 0.00E+00 | 4.43E-01 | 0.00E+00 | 0.00E+00 |
| 40 | 4.19E-01 | 0.00E+00 | 5.03E-01 | 0.00E+00 | 0.00E+00 |

**Figure 4.16: Bulk Carrier Component Probability of Diminution Failure**

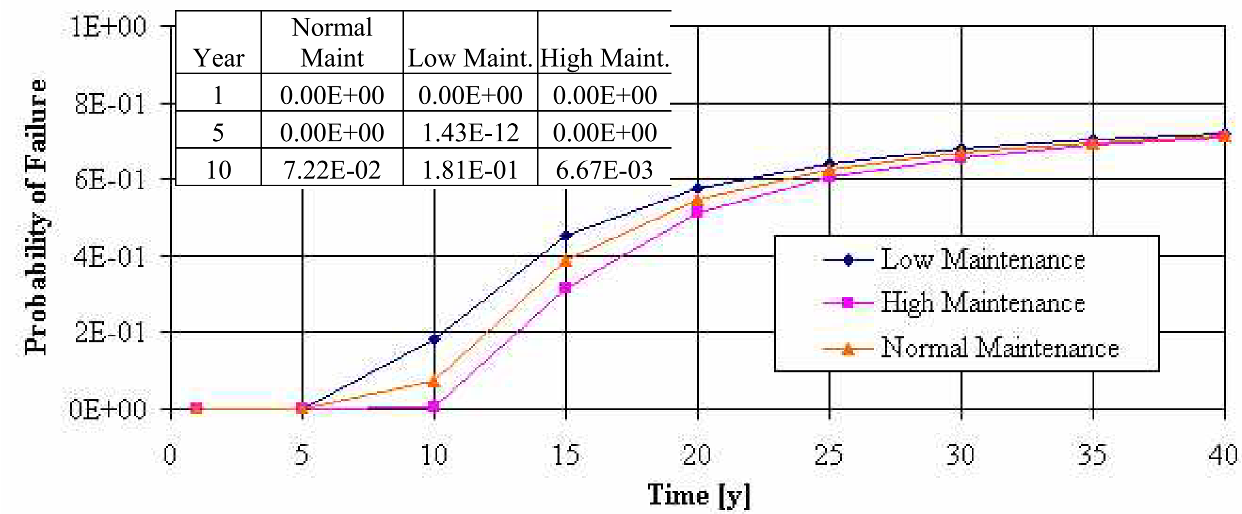
In a similar fashion, the time dependant probability of failure by frame average diminution was calculated. The time dependant probability of failure for this limit state is presented in Figure 4.17. The frame average time dependant reliability is very similar to that of the component diminution probability of failure time history since the frame is comprised primarily of components with coating lives and corrosion rates similar to those of component types 1 and 2b.




| Year | Normal Maint |
|---|---|
| 1 | 0.00E+00 |
| 5 | 0.00E+00 |
| 10 | 5.41E-02 |

**Figure 4.17: Bulk Carrier Probability of Frame Average Diminution Failure**

The sensitivity of failure probabilities to maintenance level or coating quality was investigated by considering high, medium and low coating lives. These results are shown in Figure 4.18 for pitting failure of component type 2b. Similar results can be generated for each of the corrosion degradation modes.



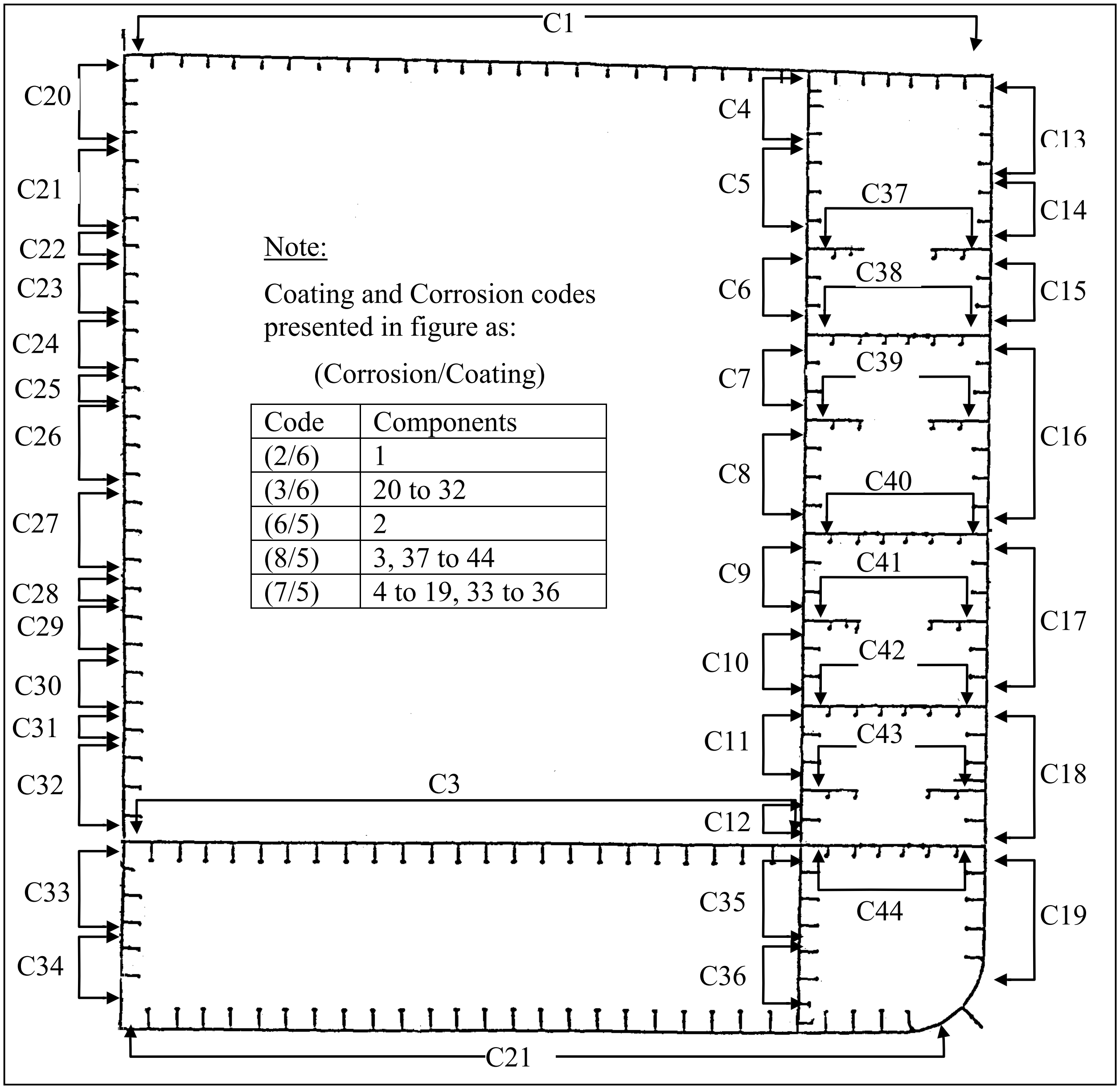

| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 1.43E-12 | 0.00E+00 |
| 10 | 7.22E-02 | 1.81E-01 | 6.67E-03 |

**Figure 4.18: Sensitivity of Bulk Carrier Pitting Time Dependant Reliability to Maintenance**

The results in Figure 4.18 illustrate that lower quality coatings or lower levels of coating maintenance, as expected, result in earlier and more rapid corrosion. However, it is noted that, as in this example, without coating renewal (repainting) in the long-term there is little benefit from higher maintenance levels or better quality paints. The difference between paint qualities or paint maintenance levels was assumed to affect the life of the coating by plus or minus one standard deviation in this analysis. It is possible to explore this effect further by associating high and low quality paint by larger deviations from the mean life; however, the data available in this project was not able to link paint quality with the statistical variation of the coating life.

*4.5.2.2 Tanker Corrosion Diminution Time Dependant Reliability*

The tanker corrosion time dependant reliability analysis was based upon the same limit states, coating life and corrosion data as the bulk carrier (Tables 4.20 and 4.21). As noted in the last column of Table 4.4, components were individually assigned corrosion rate and coating life codes according to their location and environment. The coating life (1 to 6) and corrosion rate (1 to 12) codes are listed in Tables 4.16 and 4.17, respectively. The application of these codes to the tanker frame is shown in Figure 4.19 below.




Note:

Coating and Corrosion codes presented in figure as:

(Corrosion/Coating)

| Code | Components |
|---|---|
| (2/6) | 1 |
| (3/6) | 20 to 32 |
| (6/5) | 2 |
| (8/5) | 3, 37 to 44 |
| (7/5) | 4 to 19, 33 to 36 |

**Figure 4.19: Tanker Component Coating and Corrosion Codes**

The application of coating life and corrosion rate codes, shown above, includes only five unique combinations of codes and thus will only develop five unique time-based reliability results in this analysis. Therefore, in the remainder of this section only the results for components 1, 20, 2, 3 and 4 will be presented and discussed. Based upon the structure, data and limit states discussed earlier the estimated time dependant pitting or water tightness probability of failure is shown in Figure 4.20. These results illustrate a range of pitting rates for the normal maintenance level (or normal quality paint), this is due to the range of environments existing on the tanker which result in a larger number of coating lives than observed in the Bulk Carrier.

| Years | Component | | | | |
|---|---|---|---|---|---|
| | 1 | 20 | 2 | 3 | 4 |
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 10 | 2.44E-15 | 0.00E+00 | 1.07E-02 | 4.70E-02 | 0.00E+00 |
| 15 | 4.33E-03 | 0.00E+00 | 2.14E-01 | 3.51E-01 | 0.00E+00 |
| 20 | 7.74E-02 | 8.45E-10 | 3.86E-01 | 5.19E-01 | 0.00E+00 |
| 25 | 1.87E-01 | 5.04E-05 | 4.84E-01 | 6.04E-01 | 0.00E+00 |
| 30 | 2.79E-01 | 3.67E-03 | 5.44E-01 | 6.53E-01 | 0.00E+00 |
| 35 | 3.47E-01 | 2.84E-02 | 5.84E-01 | 6.84E-01 | 0.00E+00 |
| 40 | 3.98E-01 | 8.63E-02 | 6.12E-01 | 7.05E-01 | 0.00E+00 |

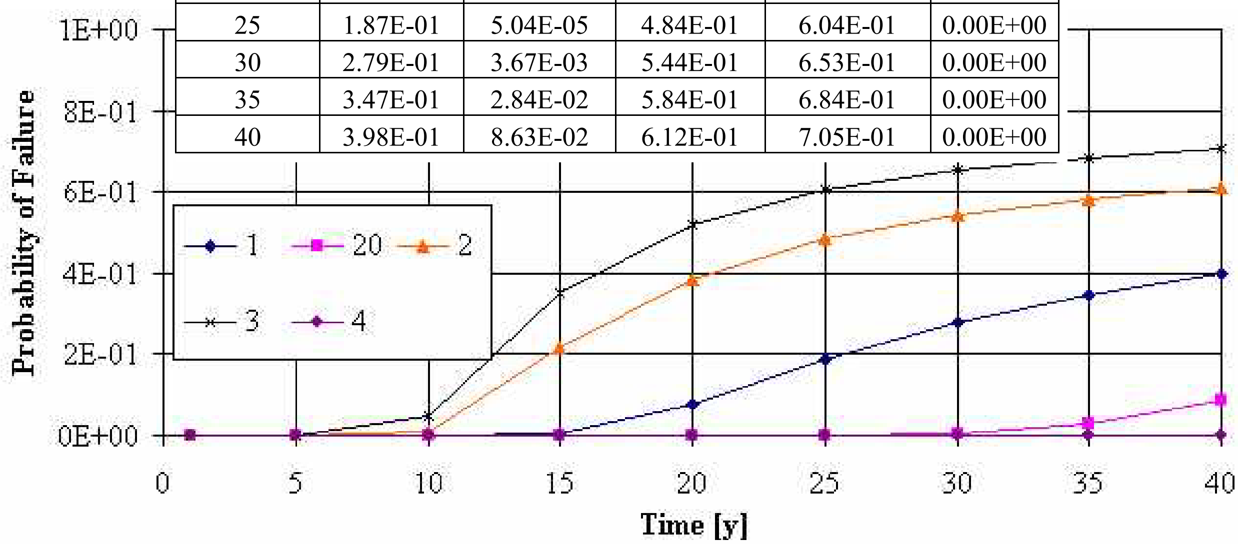
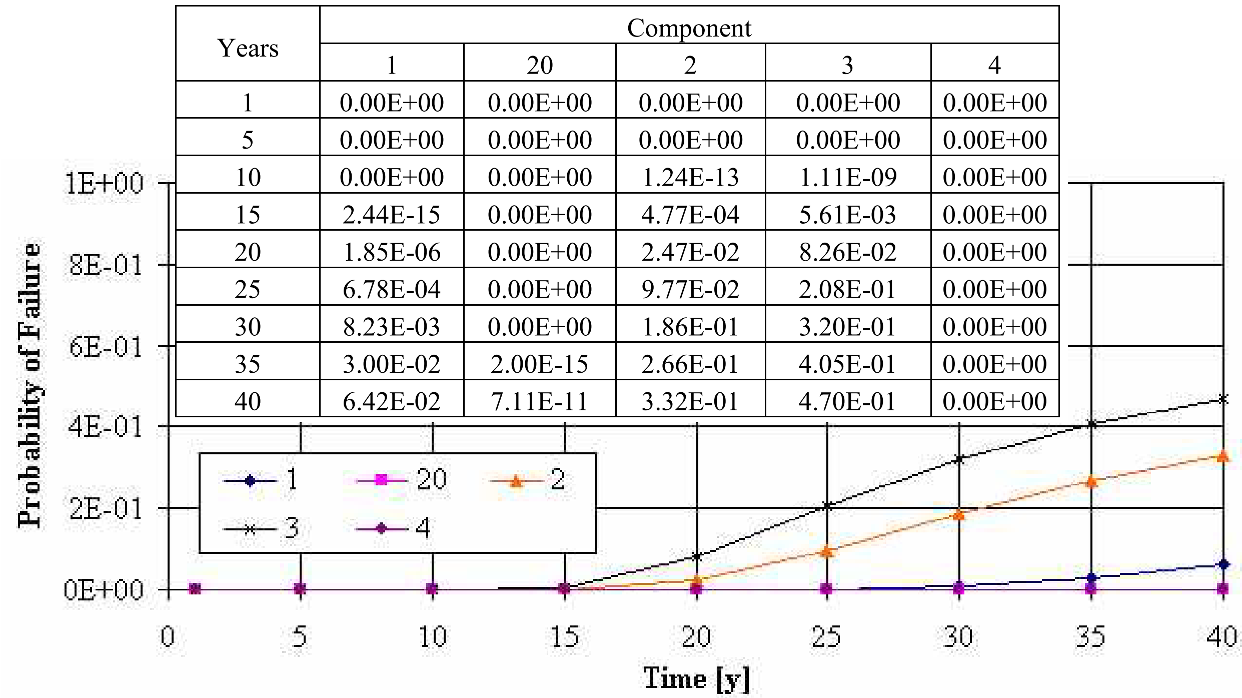



**Figure 4.20: Tanker Component Probability of Pitting Failure**

As in the bulk carrier analysis, each component is comprised of two elements, a plate and a stiffener, with different thickness. The component probability of pitting or diminution failure is taken as the greatest of the stiffener and plate probabilities of failure. This means that the component probability of failure is the same as that of its thinnest element.

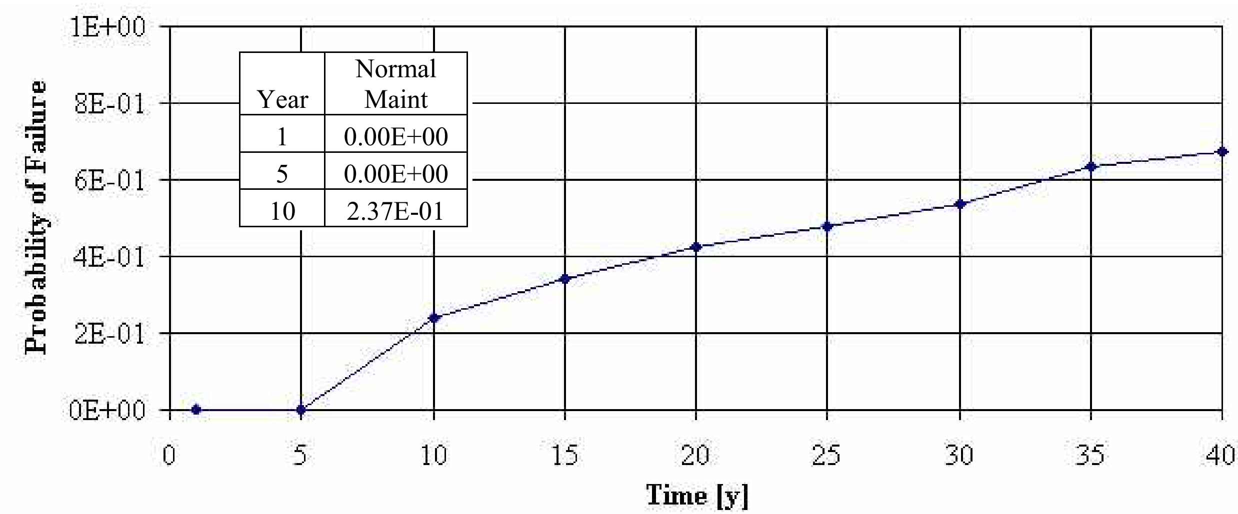
Estimated time dependant component probabilities of failure are also estimated for the local diminution limit state and presented in Figure 4.21 for a normal maintenance (or paint quality) scenario. This result indicates that, as in the pitting case, the components with more significant failure probabilities are those with shorter coating lives.




| Years | Component | | | | |
|---|---|---|---|---|---|
| | 1 | 20 | 2 | 3 | 4 |
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 10 | 0.00E+00 | 0.00E+00 | 1.24E-13 | 1.11E-09 | 0.00E+00 |
| 15 | 2.44E-15 | 0.00E+00 | 4.77E-04 | 5.61E-03 | 0.00E+00 |
| 20 | 1.85E-06 | 0.00E+00 | 2.47E-02 | 8.26E-02 | 0.00E+00 |
| 25 | 6.78E-04 | 0.00E+00 | 9.77E-02 | 2.08E-01 | 0.00E+00 |
| 30 | 8.23E-03 | 0.00E+00 | 1.86E-01 | 3.20E-01 | 0.00E+00 |
| 35 | 3.00E-02 | 2.00E-15 | 2.66E-01 | 4.05E-01 | 0.00E+00 |
| 40 | 6.42E-02 | 7.11E-11 | 3.32E-01 | 4.70E-01 | 0.00E+00 |

**Figure 4.21: Tanker Component Probability of Diminution Failure**

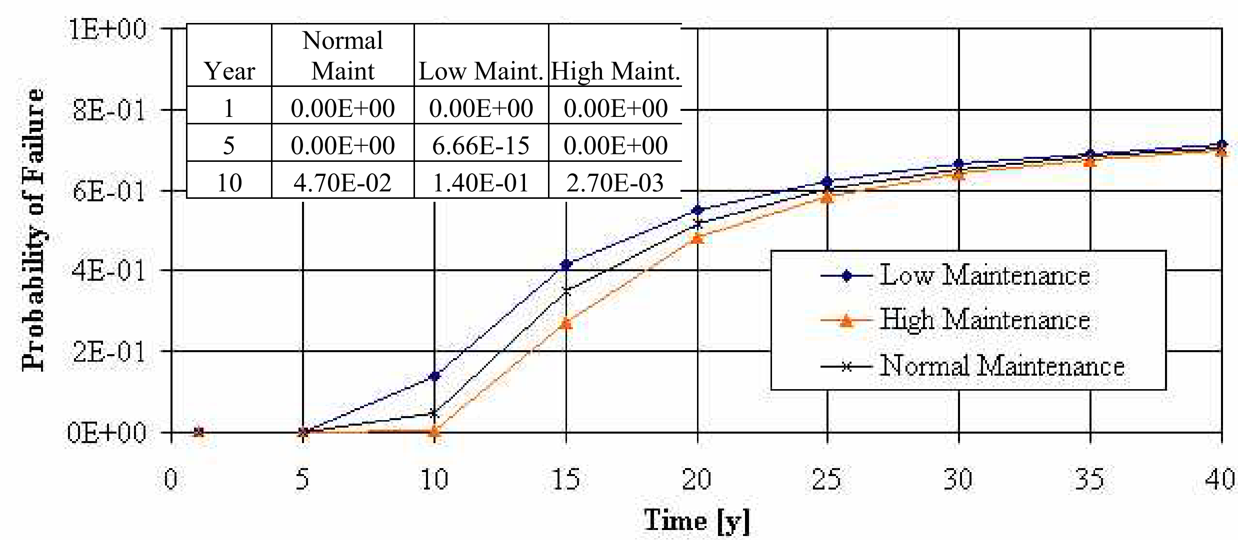
In a similar fashion, the time dependant probability of failure by frame average diminution was calculated. The time dependant probability of failure for this limit state is presented in Figure 4.22. The frame average time dependant reliability is not similar to any one of the component diminution probability of failure time histories as was the case in the bulk carrier sample problem. The frame average time dependant reliability is a composite of many component types and thus does not resemble any one component failure probability time history.




| Year | Normal Maint |
|---|---|
| 1 | 0.00E+00 |
| 5 | 0.00E+00 |
| 10 | 2.37E-01 |

**Figure 4.22: Tanker Probability of Frame Average Diminution Failure**

The sensitivity of failure probabilities to maintenance level or coating quality was investigated by considering high, medium and low coating lives. These results are shown in Figure 4.23 for pitting failure of component type 1. Similar results can be generated for each of the corrosion degradation modes or component types.




| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 6.66E-15 | 0.00E+00 |
| 10 | 4.70E-02 | 1.40E-01 | 2.70E-03 |

**Figure 4.23: Sensitivity of Tanker Pitting Time Dependant Reliability to Maintenance**

As shown for the bulk carrier, the results in Figure 4.23 illustrate that lower quality coatings or lower levels of coating maintenance, as expected, result in earlier and more rapid corrosion. It is also noted that the tanker structure was shown to be more susceptible to corrosion than the bulk carrier since it included more spaces with environments that accelerate corrosion.

### 4.5.3 Buckling and Hull Girder Yield Limit States

In this element of the analysis, the probability of component buckling or section yielding are evaluated and the safety factor is assumed to be unity as outlined in Table 4.21, therefore the limit state or performance function being evaluated is simply the difference between the structural capacity and the applied load (e.g. Z = R - L).

The load in this element of the analysis is evaluated as the sum of the still water and wave induced bending moment associated with the loading zone being analyzed.

$$L = L_{SW} + L_{WWM}$$

where:

$L_{SW}$ is the vessel midship or fwd/aft loading zone still water moment assumed to be a normally distributed random variable with a COV of variation of 10%

$L_{WWM}$ is the wave bending moment described in terms of a Weibull distribution

$$F(x;\alpha,\beta)=1-\exp\left(-\left(\frac{x}{\alpha}\right)^{\beta}\right)$$

The Weibull distribution central and shape parameters, $\alpha$ and $\beta$, respectively, are developed based upon the extreme load data presented in Tables 4.9 and 4.14 for the bulk carrier and tanker. Table 4.22 presents the wave bending load Weibull distribution parameters used in the analysis.

**Table 4.22: Wave Bending Moment Weibull Distribution Parameters**

| Vessel | $\alpha$ | $\beta$ |
|---|---|---|
| Bulk Carrier | 83.91 MNm | 1.0660 |
| Tanker | 334.73 MNm | 0.8445 |

With this information, the limit state equation may be re-expressed for the buckling limit state in terms of applied and resisting stress levels and thus develop an expression for the random structural safety parameter Z, as follows:

$$Z = B \bullet min\,[\sigma_{i1},\ \sigma_{i2}] - (M_{SW} + M_{wwm})\ y/I$$

where y, I, $\sigma_{i,1}$ and $\sigma_{i,2}$ are the location of the component relative to the neutral axis, section moment of inertial, critical elastic inter stiffener plate buckling stress and critical stiffener flexural buckling stress at the section of interest. These parameters are related to the vessel scantlings and are thus time dependant. The minimum failure stress is evaluated for each component since only one mode of buckling will occur at a time.

The buckling limit state equation also incorporates a limit state a bias parameter (B) with a mean of 1 and a coefficient of variation of 10%. This parameter is used to consider the conservatism inherent in the analytically expressed buckling failure criteria equations.

The limit state equation for section yielding is expressed in much the same way as component buckling and thus describes the random structural safety parameter (Z), using similar variables.

$$Z = \sigma_y - (M_{SW} + M_{wwm})\ y_{max}/I$$

where $\sigma_y$ , $y_{max}$ and I are the structure's material yield strength, extreme distance from the neutral axis and section moment of inertia.

The strength of a component or reliability (1-probability of failure) of a section or component is evaluated as the minimum of those calculated for the buckling or yield limit states.

The reliability (1- probability of failure) of a component or section is evaluated using an extreme shock reliability model. This model considers extreme load events causing component or section failure.

$$R(t) = \int_0^\infty \exp\left\{ -\lambda t \left[ 1 - \frac{1}{t} \int_0^t F_S(rg(\tau))\, d\tau \right] \right\} f_{R_0}(r)\, dr$$

If the time dependant degradation (corrosion) is not taken into account (e.g. $g(t) = 1$), since this effect will be evaluated at discrete times, the equation may be re-expressed as follows:

$$R(t) = \int_0^\infty \exp\{ -\lambda t [1 - F_S(r)] \} f_{R_0}(r)\, dr$$

In this formulation, the strength (resistance) of the structure is expressed in terms of the random buckling or yield stress minus the random still water stress component ($\sigma - \sigma_{sw}$). The strength limit state equation considers buckling if the still water moment induces a compressive stress, whereas, the limit state equation considers the yield criterion if the still water moment induces a tensile stress. This variable limit state equation assumes that the buckling stress is lower than the compressive yield stress.

Since the resistance is normally distributed, its mean and standard deviation may be estimated using a first order reliability approximation. In this estimate, the random resistance mean is calculated by evaluating the limit state equation using the random variable mean values (e.g., Mean($\sigma$) – Mean($\sigma_{SW}$)). The random resistance standard deviation is calculated as follows:

$$((STD(\sigma))^2 + (STD(\sigma_{SW}))^2)^{1/2}$$

In the analysis, it was assumed that the actual material yield strength was 110% of the nominal value. This increase in yield strength is considered to account for the difference between lower bound nominal (reported in section 4.4) and actual material yield strengths.

The loading ($F_s(r)$) considered in the extreme shock reliability model in terms of a Weibull cumulative probability function ($F_S(r) = 1 - \exp(- r/\alpha)^{\beta}$) in which the statistical parameters are evaluated using the data in Table 4.22 ($\alpha_{Load}$, $\beta_{Load}$), as follows:

$$\alpha = \alpha_{Load}\ (y/I)\ 10^6 \text{ GPa} \qquad \text{and} \qquad \beta = \beta_{Load}$$

where y and I are the neutral axis location and moment of inertia of the section of interest. The frequency of load events ($\lambda$) in the extreme shock reliability model is expressed in terms of the reciprocal of the mean zero crossing (wave) period (1/T) discussed in Section 4.3 for the tanker and bulk carrier.

With all of this information, the extreme shock reliability model may be rewritten as:

$$R(t) = \int_0^{\infty} \exp\left\{ - \lambda t \exp\left( - \left( \frac{r}{\alpha} \right)^{\beta} \right) \right\} f_{R_0}(r)\, dr$$

and using this approach component probabilities of failure (1-R(t)) are estimated:

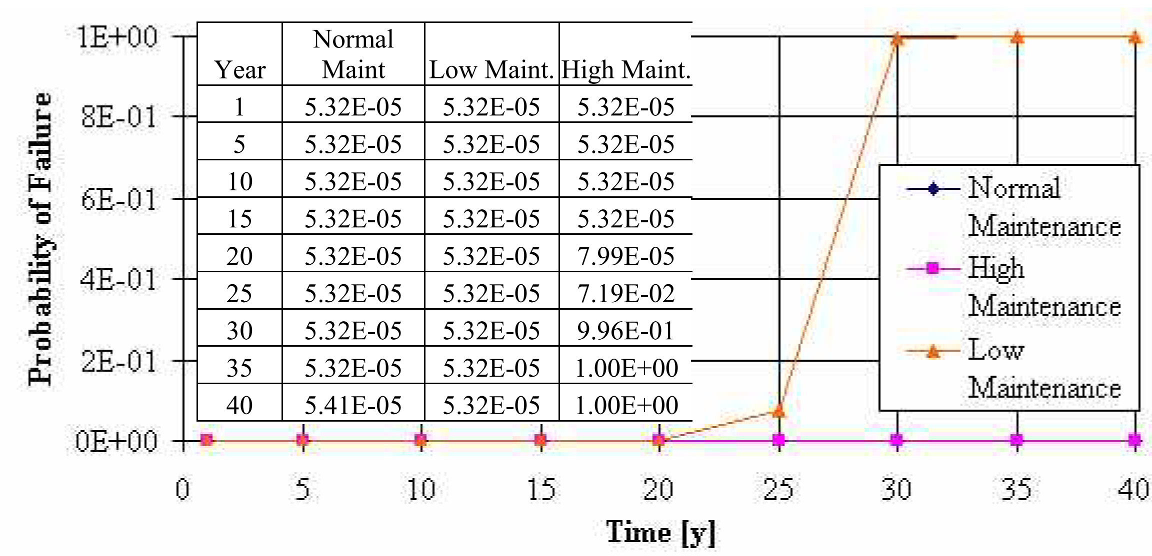
- For components located above the N.A., the probabilities of failure are the maximum of:
  - Failure probability associated with buckling under sag condition, and
  - Failure probability associated with yield under hog condition.
- For components located below the N.A., the probabilities of failure are the maximum of:
  - Failure probability associated with buckling under hog condition, and
  - Failure probability associated with yield under sag condition.

### *4.5.3.1 Bulk Carrier Buckling and Ultimate Strength Time Dependant Reliability*

In evaluating the time dependant reliability of component ultimate strength limit states, yielding and buckling, the effect of component corrosion is considered. The same coating life and corrosion rate data assigned to the bulk carrier frame in the previous section were used in evaluating the time dependant probability of failure due to component yielding and buckling.

The results developed for this limit state illustrate that over the 40-year analysis period, there is not enough diminution to significantly change the section modulus of the hull girder. Therefore the probability of first yield failure of components ($P_f = 5.32 \times 10^5$) is essentially not time dependant. Rather this is a function of the applied loading that is dependent on the vessel operational conditions and longitudinal position within the vessel. This result illustrates the fact that the section modulus of a vessel's hull girder is primarily a function of the distance of material from the hull girder neutral axis rather than individual component cross-sectional areas and the first yield criteria is essentially a hull girder based mode of failure.

The probability of component failure in compression due either to yielding or buckling is more susceptible to component diminution and is thus a function of time. The effect of coating maintenance level (paint quality) is shown in Figure 4.24 as an illustration of the time dependant component probability of failure due to buckling (component 7). Early in a component's life when its cross sectional area has not been reduced significantly, the dominant mode of failure is first yield. Later in the component's life when its cross sectional area is reduced, the potential for buckling becomes more significant. The susceptibility of an individual component to failure in a buckling mode is a function of its geometry and relative spacing with respect to its neighbors.




| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 5.32E-05 | 5.32E-05 | 5.32E-05 |
| 5 | 5.32E-05 | 5.32E-05 | 5.32E-05 |
| 10 | 5.32E-05 | 5.32E-05 | 5.32E-05 |
| 15 | 5.32E-05 | 5.32E-05 | 5.32E-05 |
| 20 | 5.32E-05 | 5.32E-05 | 7.99E-05 |
| 25 | 5.32E-05 | 5.32E-05 | 7.19E-02 |
| 30 | 5.32E-05 | 5.32E-05 | 9.96E-01 |
| 35 | 5.32E-05 | 5.32E-05 | 1.00E+00 |
| 40 | 5.41E-05 | 5.32E-05 | 1.00E+00 |

**Figure 4.24: Bulk Carrier Component Failure Probability in Compression**

Probabilities of failure were estimated for components in the midship and fwd / aft segments of the vessel. Since it was assumed that the scantlings remained constant, it was noted that the probabilities of failure for the forward and aft segment was lower than that estimated for the mid ship area. This difference in reliability is attributed to the difference in applied loading that, in these sample calculations, is based solely on hull girder bending effects.

*4.5.3.2 Tanker Buckling and Ultimate Strength Time Dependant Reliability*

In evaluating the time dependant reliability of component ultimate strength limit states, yielding and buckling, the effect of component corrosion is considered. The same coating life and corrosion rate data assigned to the tanker frame in the previous section were used in evaluating the time dependant probability of failure due to component yielding and buckling.

The results developed for this limit state illustrate that over the 40-year analysis period, there is not enough diminution to significantly change the section modulus of the hull girder. Therefore, the probability of first yield failure of components is essentially not time dependant rather they are a function of the applied loading that is dependant on the vessel operational conditions and longitudinal position within the vessel.

The probability of component failure in compression due either to yielding or buckling is more susceptible to component diminution and is thus a function of time. The effect of coating maintenance level (paint quality) is shown in Figure 4.25 as an illustration of the time dependant component probability of failure due to buckling (component 37). Early in a component's life when its cross sectional area has not been reduced significantly, the dominant mode of failure is first yield. Later in the component's life when its cross sectional area is reduced, the potential for buckling becomes more significant. The susceptibility of an individual component to failure in a buckling mode is a function of its geometry and relative spacing with respect to its neighbors.

| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 1.36E-02 | 1.36E-02 | 1.36E-02 |
| 5 | 4.04E-02 | 5.11E-02 | 4.04E-02 |
| 10 | 1.22E-01 | 7.24E-01 | 9.94E-02 |

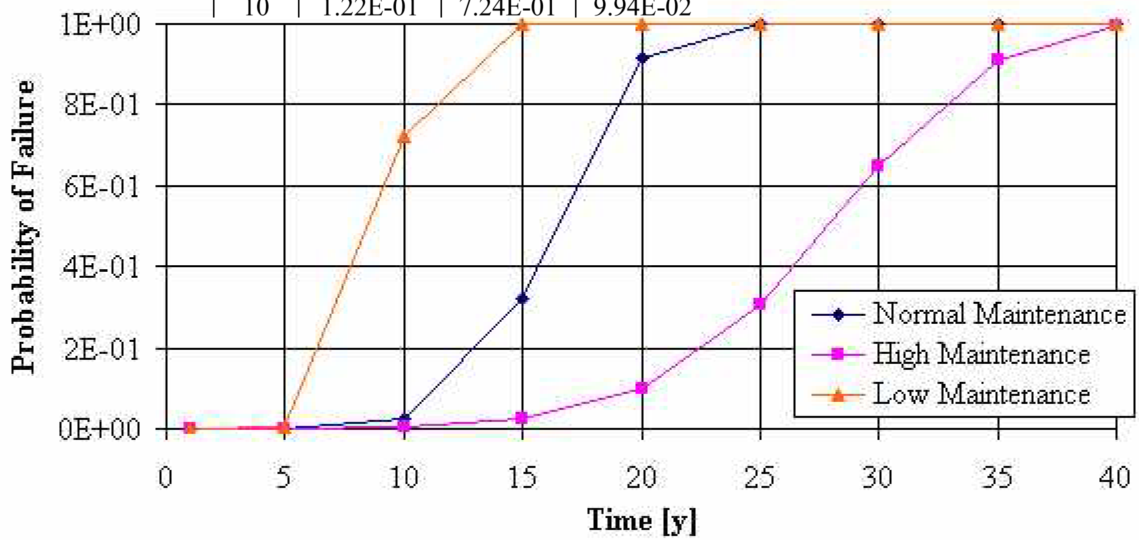



**Figure 4.25: Tanker Component Failure Probability in Compression**

Probabilities of failure were estimated for components in the midship and fwd / aft segments of the vessel. Since it was assumed that the scantlings remained constant, it was noted that the probabilities of failure for the forward and aft segment was lower than that estimated for the mid ship area. This difference in reliability is attributed to the difference in applied loading that in these sample calculations is based solely on hull girder bending effects.

The results presented in these sample applications indicate that the tanker structure is more susceptible to strength failure modes (component yielding and buckling). This result is primarily a function of the applied loading and the tanker structure is significantly longer and thus experiences larger wave induced bending moments.

### 4.5.4 Fatigue Crack Initiation

In evaluating the potential for fatigue crack initiation, a nominal stress approach is used in a Miner's linear damage accumulation model. In this approach, it is assumed that the wave-induced moments are fully reversing and thus the stress range experienced by structural components is twice that calculated for the wave encounter.

$$\sigma = 2*(M_{wwm}\ y/I)$$

Where $\sigma$ is the stress range, $M_{wwm}$ is a wave bending moment calculated for the vessel loading zone, and y and I are the component's distance from the neutral axis and the vessel moment of inertia at the location of interest.

The limit state for fatigue damage accumulation considers the margin of safety against Miner's summation reaching unity.

$$Z = N_s - N_t$$

$$Z = \frac{K_0 \Delta^d}{\sigma^m} - N_t$$

In this formulation $K_0$, $\Delta$ and m are fatigue material parameters described in Section 4.4.1 for each fatigue classification assigned to the structural components. The parameter d in the limit state equation is used as a means of representing the variability of workmanship or fatigue life and expresses the number of standard deviations below the mean fatigue performance S-N curve a given details performance is expected to be. $N_t$ is the expected number of load cycles experienced by a detail in a given time period based upon the previously defined wave encounter period ($\lambda$). In this cumulative damage model, the wave encounter period is assumed to be normally distributed with a coefficient of variation of 1 and having the mean values presented in Section 4.3 for the bulk carrier and tanker.

The probability of failure for a given component, Pf = Pr (Z < 0), is evaluated using a first order mean value approximation considering the probability of failure as a result of all of the stress cycles in a given range of stress cycle magnitude, as follows:

$$P_{f_i} = P_{ri}\left( N_t > \frac{K_0 \Delta^d}{\sigma_i^{\ m}} \right) = 1 - F_{N_t}\left( \frac{K_0 \Delta^d}{\sigma_i^{\ m}} \right)$$

where $\sigma_i$ is the middle of the interval between successive deciles of the Weibull stress distribution. The stress distribution is derived from the wave bending statistical distribution using the hull girder bending analogy. The probability of fatigue failure for a given component is then calculated as a function of the sum of fatigue stress range intervals failure probabilities, as follows.

$$P_f = \frac{\sum_{i=1}^{10} P_{f\,i}}{10}$$

### *4.5.4.1 Bulk Carrier Fatigue Crack Initiation Time Dependant Reliability*

Ideally in a fatigue analysis, the load environment and characteristics of each connection detail would be considered individually. However, in the bulk carrier sample application only the cruciform connection details at web frames and bulkheads are considered. These web frame and bulkhead connection details are in general, the most prone to fatigue crack initiation and are assigned nominal stress S-N fatigue categories of F and F2, respectively. In the sample application structural description of the bulk carrier two frame types were defined to account for frames in way of hatch openings and those away from hatch openings. Therefore, in any segment of the bulk carrier three fatigue crack initiation lives are calculated for each component:

- at a frame in way of a hatch opening (Frame type 2 - fatigue category F),
- at a frame away from the hatch opening (Frame type 1 - fatigue category F), and
- at a bulkhead (frame type 1 - fatigue category F2).

These three fatigue life behaviors are repeated for the loads associated with the midship and forward/aft segments of the vessel. All six of these time dependant reliabilities are illustrated for component type 7 in Figure 4.26. These results indicate that the probability of fatigue failure is most significant at the midship Type 2 web frames, where the wave induced bending moments are highest and the vessel section modulus is the lowest. In the sample application, it was assumed that the deck area between hatches is fully effective thus these frames have a higher section modulus.

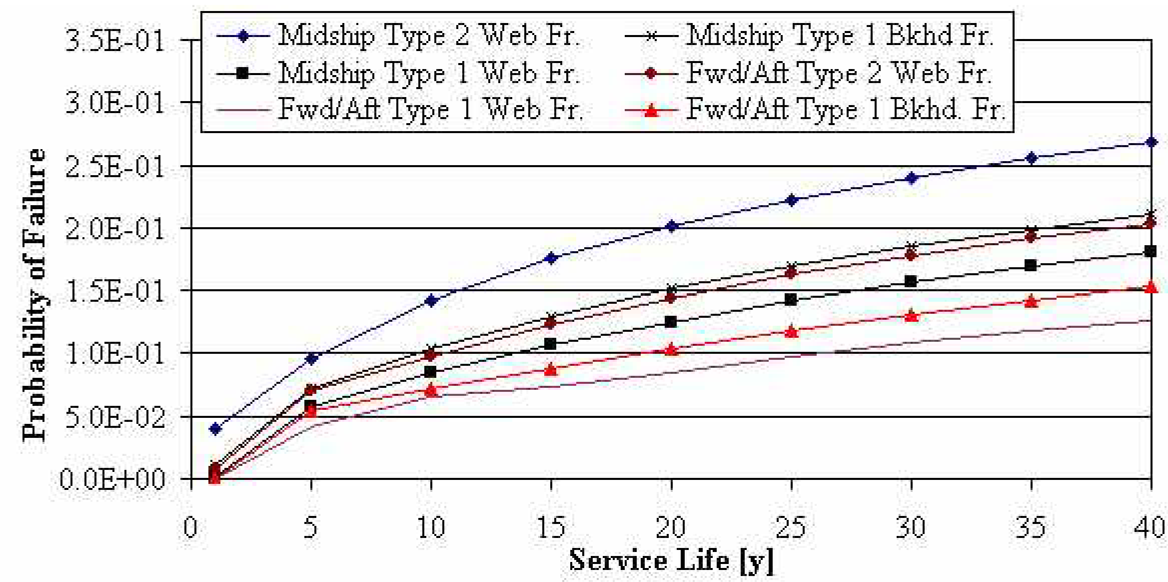



**Figure 4.26: Bulk Carrier Frame Type Time Dependant Reliability Comparison**

A comparison of the behavior of Type 1 web frames and Type 1 bulkhead frames, in Figure 4.26, illustrates the effect of different fatigue detail categories for the same loading conditions. This comparison could also be used as a demonstration of the effect of weld quality. In these sample applications, the mean fatigue life curves were used, however, lower quality welds with more weld faults (e.g., undercut, lack of fusion defects, etc.) could be assigned more severe fatigue classification by applying a fatigue performance below the mean level (e.g., mean - N standard deviations). This reduction in fatigue performance would conceptually have a similar effect as assigning the lower fatigue category as shown in the difference between the Type 1 web frame and Type 1 bulkhead frames in Figure 4.26.

*4.5.4.2 Tanker Fatigue Crack Initiation Time Dependant Reliability*

As in the bulk carrier fatigue analysis the tanker sample fatigue assessment was simplified to consider only the cruciform connection details at web frames and bulkheads. These web frame and bulkhead connection details are in general, the most prone to fatigue crack initiation and are assigned nominal stress S-N fatigue categories of F and F2, respectively. Therefore, in any segment of the tanker, two fatigue crack initiation lives are calculated for each component:

- at a web frame (fatigue category F), and
- at a bulkhead (fatigue category F2).

These two fatigue life behaviors are repeated for the loads associated with the midship and forward/aft segments of the vessel. All four of these time dependant reliabilities are illustrated for component type 1 in Figure 4.27. These results indicate that the probability of fatigue failure is most significant at the midship bulkheads, where the wave induced bending moments are highest and the lowest fatigue life category is assigned.

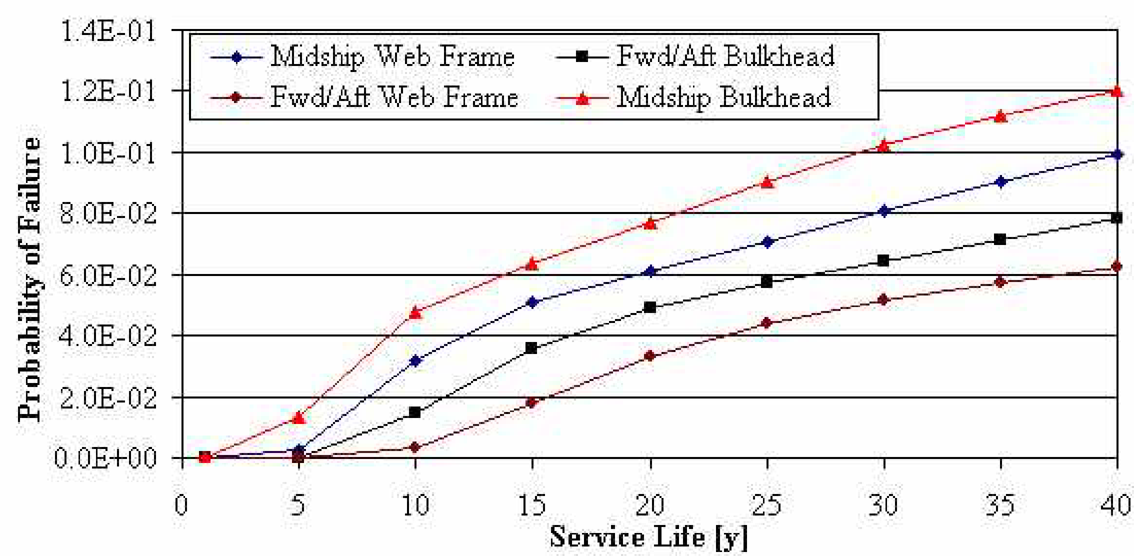



**Figure 4.27: Tanker Frame Type Time Dependant Reliability Comparison**

Similar comparisons made between the bulk carrier frame types can be made for the tanker. Figure 4.27 illustrates the effect of fatigue performance category and loading level on the probability of fatigue failure. As noted before the application of fatigue detail category data could be used to denote weld quality.

In general, the tanker structure components are less susceptible to fatigue as demonstrated by their lower probabilities of fatigue failure when compared to those of the bulk carrier. It is noted however, that since the fatigue analysis did not consider the combined effects of fatigue and corrosion (e.g., increased stresses at thinner sections to local pitting stress concentrations) this result may be somewhat misleading since, as discussed in Section 4.5.2.2, the tanker structure is more susceptible to corrosion damage.

## 4.6 System Reliability Analysis

In the previous section, the time history of component probability of failure was presented. In this section those results are used to estimate system reliabilities used to better understand the performance of the larger structures based upon the performance of their components. As a general rule, the failure of a larger structure (e.g., a frame) is deemed to occur if any one of its components fails (a weakest link approach). In reality, vessel structural failure would not occur due to the failure of a single component, however, if a broader definition of failure were adopted such as “failure to resist any degradation” then a weakest link approach is valid.

The results presented in this section based upon the weakest link analogy will result in relatively high probabilities of failure due to the fragility or non-redundancy of the system. The systems reliability analysis could be completed to consider a range of system redundancies including multiple pass component failure criteria to indicate system failure (e.g., system failure occurs when more than three components fail).

The sample applications in the previous sections have focused on component failure and in this section the probability of failure of frames segments and the entire vessel are considered. In assembling these various levels of system reliability it is assumed, in general, that:

- Component failure modes are fully correlated within a frame.
- Frame failure occurs when its first component fails
- Frames within the Fwd/Aft segments are fully correlated
- Frames within the Midship segments are fully correlated
- Segments fail when one frame in the segment fails
- Fwd/Aft and Midship segments are non-correlated
- Vessel failure occurs when one segment fails

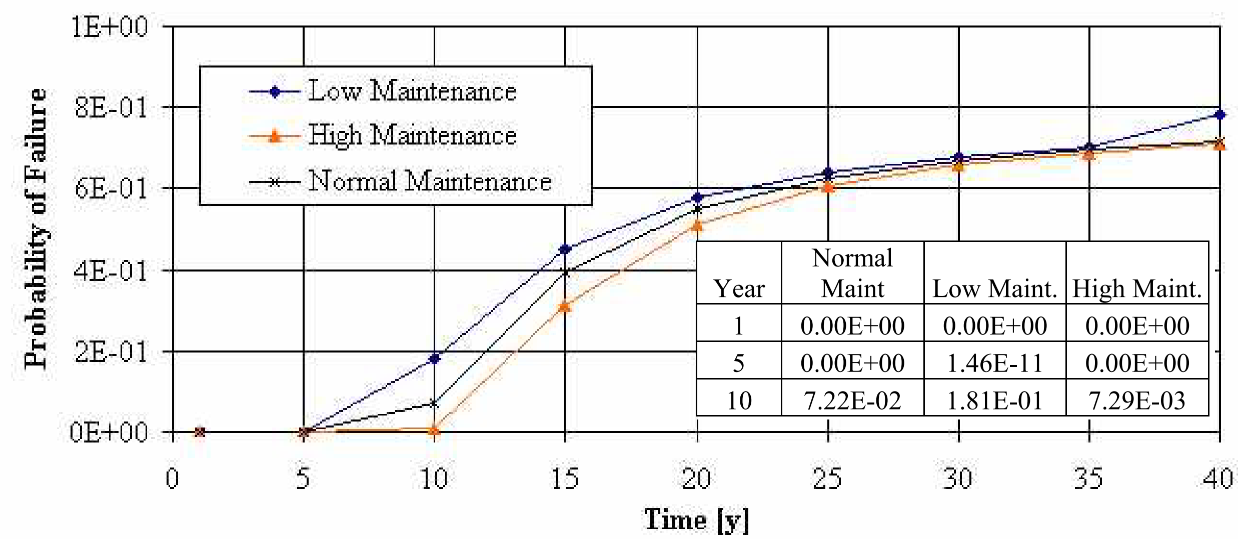
Based upon the above definitions the system reliability analysis results presented in the sections which follow were developed.

### 4.6.1 Corrosion Diminution System Reliability

#### *4.6.1.1 Bulk Carrier Corrosion Diminution System Reliability*

In the bulk carrier sample application, only one frame type was defined, with respect to pitting corrosion, therefore, the probability of frame failure shown in Figure 4.28 is the same as the probability of segment failure and thus vessel failure. The results illustrate that during the initial stages of the vessel's life, the quality of the paint or coating maintenance has a significant effect on the probability of failure, however, without paint renewal the long term probability of pitting corrosion is not affected by paint quality or maintenance level. If paint and steel renewals were completed, the probability of corrosion failure would reset to zero provided that steel renewals returned the plate to its original thickness.

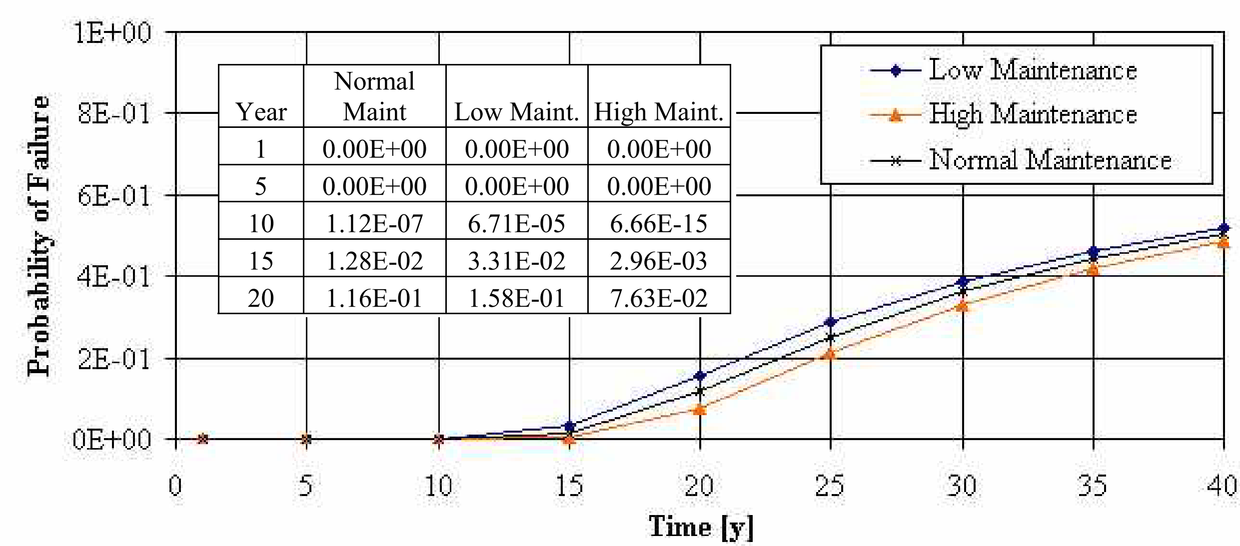
If the paint was reapplied but steel renewals were not completed, the time history for corrosion failure would have another area with near zero probability of failure after which the probability of failure would rise more steeply than shown in Figure 4.28. The more rapid increase in failure probability is due to the fact that once the coating life has ended, the reduction of scantlings to their allowable limit starts with some wastage from the previous service period.




| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 1.46E-11 | 0.00E+00 |
| 10 | 7.22E-02 | 1.81E-01 | 7.29E-03 |

**Figure 4.28: Bulk Carrier Frame Pitting Corrosion Diminution Failure Probability**

Paint quality or coating maintenance has the same effect on the component corrosion failure mode as it had on pitting as shown in Figure 4.29. The only difference is that the beneficial effects of higher quality paint or maintenance lasts longer due to the slower general corrosion rate compared to pitting.

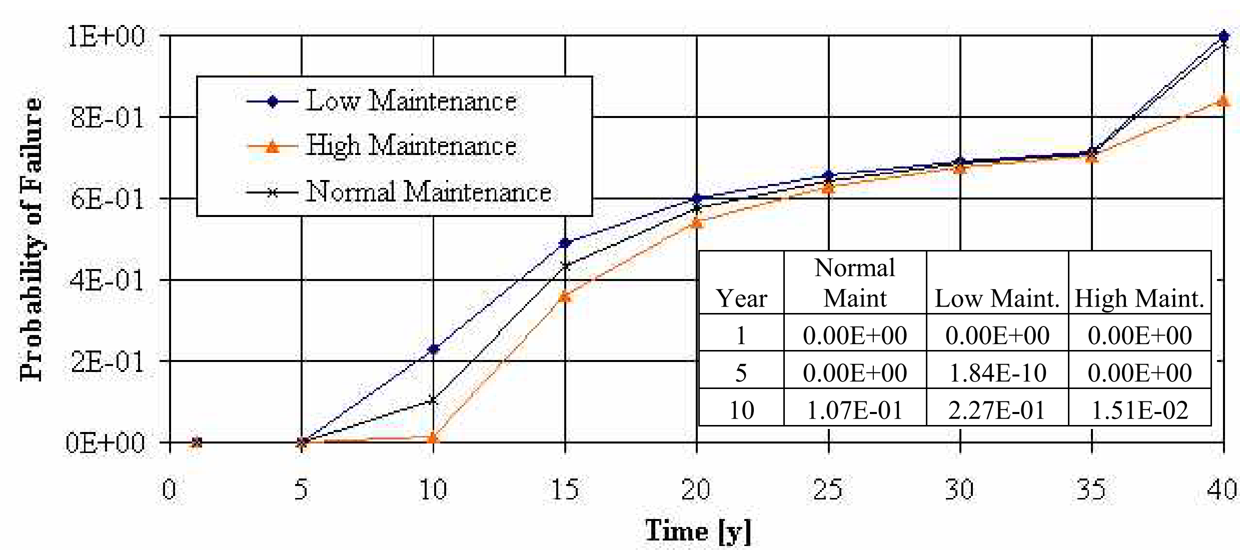



| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 10 | 1.12E-07 | 6.71E-05 | 6.66E-15 |
| 15 | 1.28E-02 | 3.31E-02 | 2.96E-03 |
| 20 | 1.16E-01 | 1.58E-01 | 7.63E-02 |

**Figure 4.29: Bulk Carrier Frame Component Corrosion Diminution Failure Probability**

*4.6.1.2 Tanker Corrosion Diminution System Reliability*

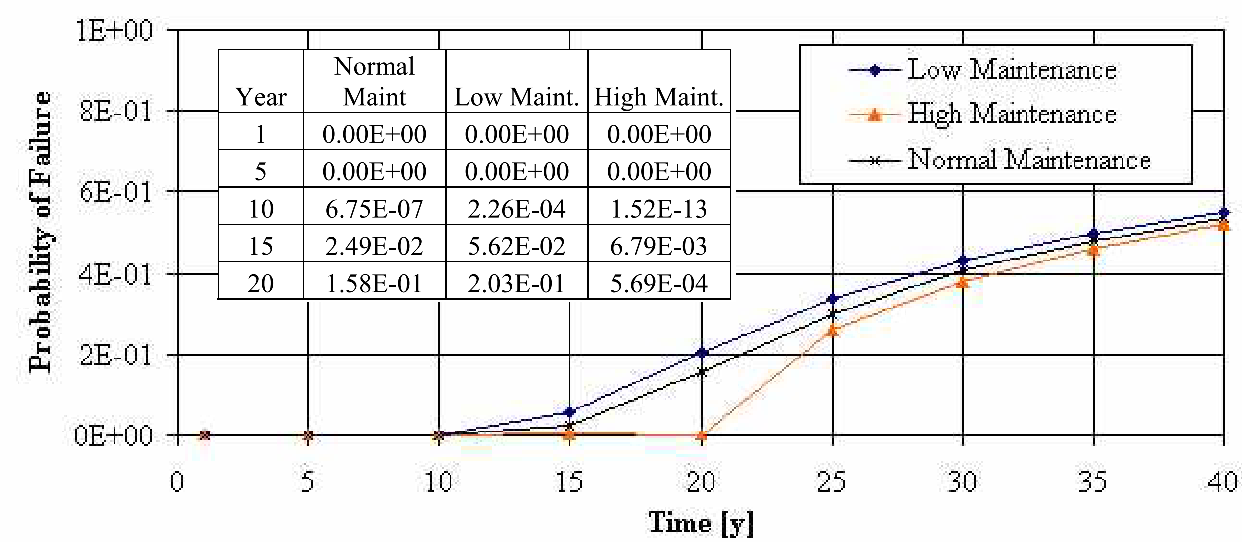
For the tanker, only one frame type was defined, with respect to pitting corrosion, therefore the probability of frame failure shown in Figure 4.30 is the same as the probability of segment failure and thus vessel failure. The results illustrate that during the initial stages of the vessel's life the quality of the paint or coating maintenance has a significant effect on the probability of failure, however, without paint renewal the long term probability of pitting corrosion is not affected by paint quality or maintenance level.




| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 1.84E-10 | 0.00E+00 |
| 10 | 1.07E-01 | 2.27E-01 | 1.51E-02 |

**Figure 4.30: Tanker Frame Pitting Corrosion Diminution Failure Probability**

Paint quality or coating maintenance has the same effect on the component corrosion failure mode as is had on pitting as shown in Figure 4.31. The only difference is that the beneficial effects of higher quality paint or maintenance lasts longer due to the slower general corrosion rate compared to pitting.




| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 10 | 6.75E-07 | 2.26E-04 | 1.52E-13 |
| 15 | 2.49E-02 | 5.62E-02 | 6.79E-03 |
| 20 | 1.58E-01 | 2.03E-01 | 5.69E-04 |

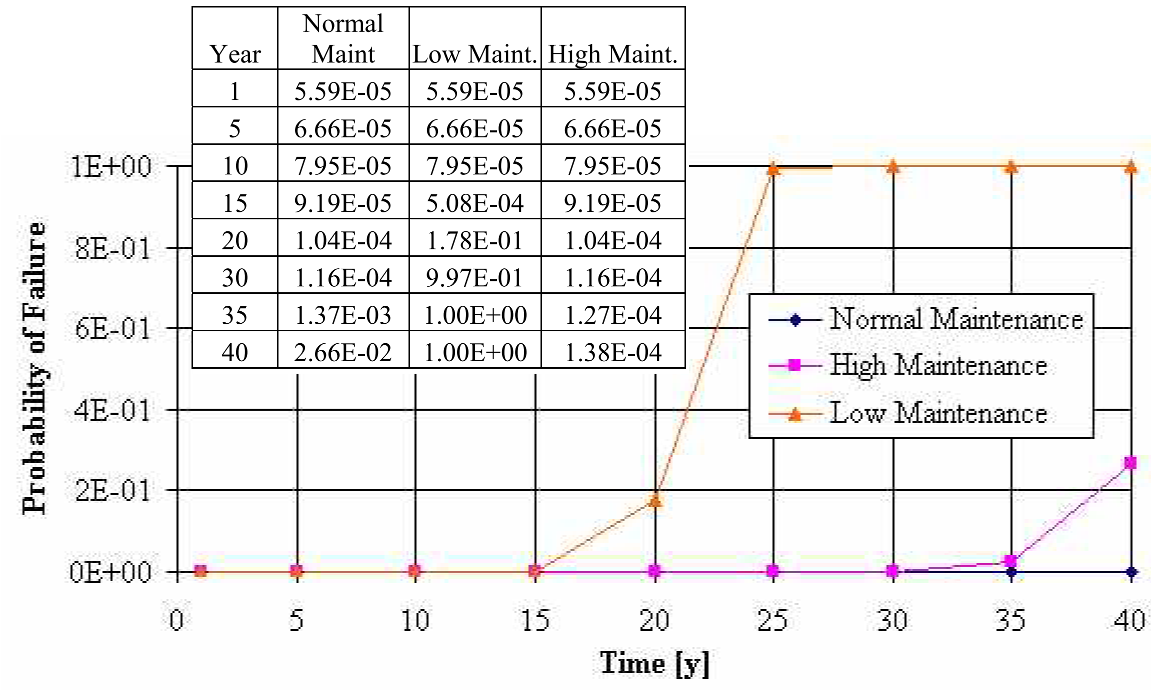
**Figure 4.31: Tanker Frame Component Corrosion Diminution Failure Probability**

As observed in the component corrosion time dependant reliability analyses, the tanker structure exhibits higher probabilities of failure due to the more corrosive environment assumed to exist in its holds. If a more complex system reliability frame failure criteria were considered, such as a multiple pass criteria in which N component failures are required to denote frame failure, the tanker would exhibit a higher failure rate because it includes a greater number of components in each frame.

## 4.6.2 Buckling and Ultimate Strength System Reliability

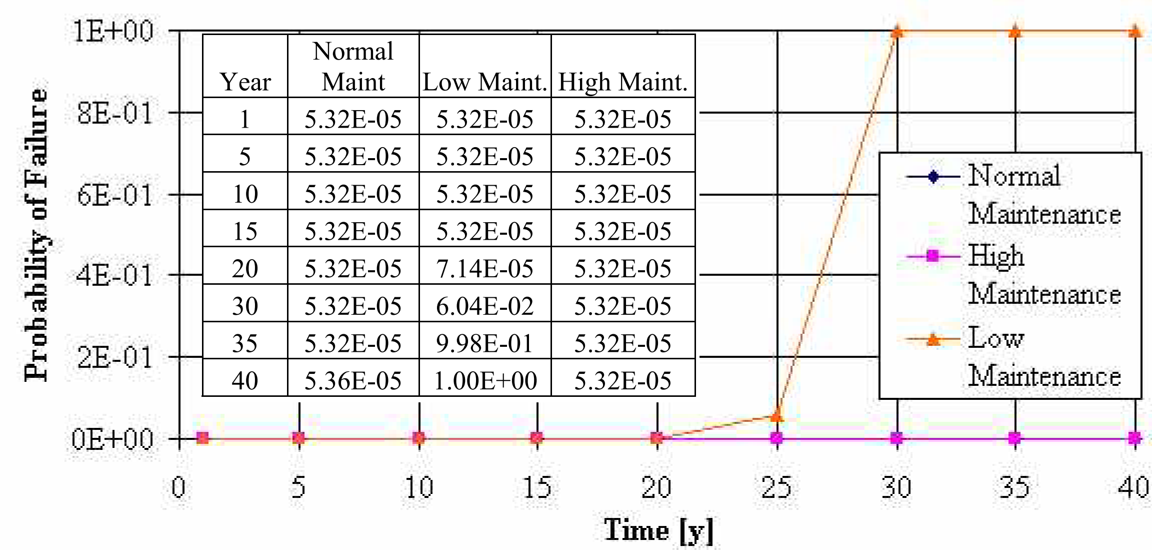
### *4.6.2.1 Bulk Carrier Buckling and Ultimate Strength System Reliability*

In the bulk carrier sample application, only one frame type is defined as far as component buckling and first yield failure criteria are concerned, however, the applied load varies along the length of the vessel. The sample problem was developed to only consider two loading types, mid ship and fwd and aft segments. Figure 4.32 and 4.33 present the probabilities of frame failure due to buckling or first yield for the midship and fwd/aft segments of the vessel, respectively. The difference in failure probabilities lies in the lower bending moments estimated to occur in the fwd or aft segments of the vessel. The lower loads permits corrosion diminution to continue to reduce scantlings before the extreme loading is possible and thus failure occurs.




| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 5.59E-05 | 5.59E-05 | 5.59E-05 |
| 5 | 6.66E-05 | 6.66E-05 | 6.66E-05 |
| 10 | 7.95E-05 | 7.95E-05 | 7.95E-05 |
| 15 | 9.19E-05 | 5.08E-04 | 9.19E-05 |
| 20 | 1.04E-04 | 1.78E-01 | 1.04E-04 |
| 30 | 1.16E-04 | 9.97E-01 | 1.16E-04 |
| 35 | 1.37E-03 | 1.00E+00 | 1.27E-04 |
| 40 | 2.66E-02 | 1.00E+00 | 1.38E-04 |

**Figure 4.32: Bulk Carrier Midship Frame Buckling and Ultimate Strength Failure Probability**

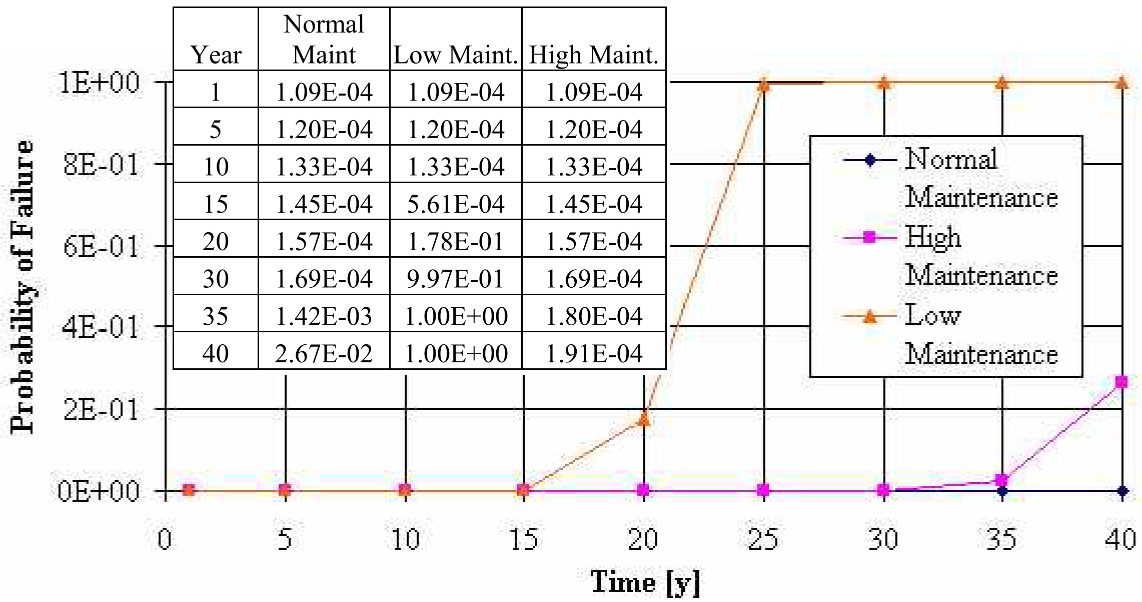



| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 5.32E-05 | 5.32E-05 | 5.32E-05 |
| 5 | 5.32E-05 | 5.32E-05 | 5.32E-05 |
| 10 | 5.32E-05 | 5.32E-05 | 5.32E-05 |
| 15 | 5.32E-05 | 5.32E-05 | 5.32E-05 |
| 20 | 5.32E-05 | 7.14E-05 | 5.32E-05 |
| 30 | 5.32E-05 | 6.04E-02 | 5.32E-05 |
| 35 | 5.32E-05 | 9.98E-01 | 5.32E-05 |
| 40 | 5.36E-05 | 1.00E+00 | 5.32E-05 |

**Figure 4.33: Bulk Carrier Fwd/Aft Frame Buckling and Ultimate Strength Failure Probability**

Figure 4.34 presents the probability of component buckling or first yield failure for the entire vessel. The results shown in this figure are essentially the same as those for the midship segment since it has the lower level of reliability. The probability of vessel failure is estimated as follows:

$$Pf_{vessel} = 1 - (1 - Pf_{mid}) * (1 - Pf_{fwd/aft})$$

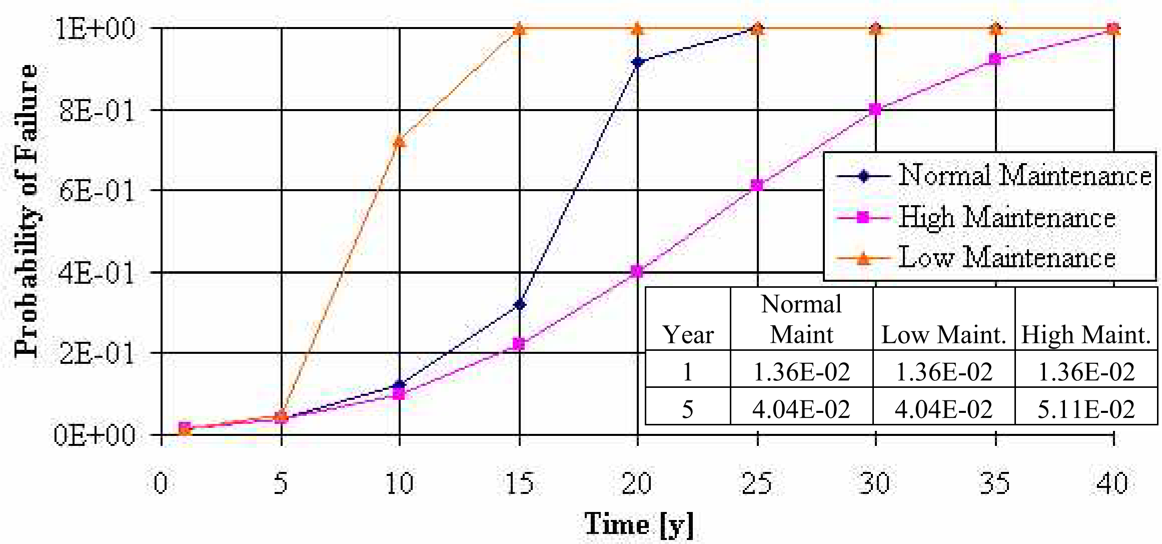



| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 1.09E-04 | 1.09E-04 | 1.09E-04 |
| 5 | 1.20E-04 | 1.20E-04 | 1.20E-04 |
| 10 | 1.33E-04 | 1.33E-04 | 1.33E-04 |
| 15 | 1.45E-04 | 5.61E-04 | 1.45E-04 |
| 20 | 1.57E-04 | 1.78E-01 | 1.57E-04 |
| 30 | 1.69E-04 | 9.97E-01 | 1.69E-04 |
| 35 | 1.42E-03 | 1.00E+00 | 1.80E-04 |
| 40 | 2.67E-02 | 1.00E+00 | 1.91E-04 |

**Figure 4.34: Bulk Carrier Vessel Buckling and Ultimate Strength Failure Probability**

*4.6.2.2 Tanker Buckling and Ultimate Strength System Reliability*

In the tanker sample application, only one frame type is defined as far as component buckling and first yield failure criteria are concerned, however, the applied load varies along the length of the vessel. The sample problem was developed to only consider two loading types, mid ship and fwd and aft segments. Figure 4.35 presents the probability of frame failure due to buckling or first yield for the midship segment of the vessel, respectively. The difference in failure probabilities lies in the lower bending moments estimated to occur in the fwd or aft segments of the vessel. The lower loads permit corrosion diminution to continue to reduce scantlings before the extreme loading is possible and thus failure occurs. It is noted that the scantlings are assumed to be the same over the entire length of the vessel and thus the probability of failure in the forward and after segments of the vessel are insignificant.




| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 1.36E-02 | 1.36E-02 | 1.36E-02 |
| 5 | 4.04E-02 | 4.04E-02 | 5.11E-02 |

**Figure 4.35: Tanker Midship Frame Buckling and Ultimate Strength Failure Probability**

The probability of component buckling or first yield failure for the entire vessel is essentially the same as the probability of a midship segment failure (Figure 4.35). The results are the same since the midship segment has a significantly lower level of reliability than the forward and aft segments, and the probability of vessel failure is estimated as follows:

$$Pf_{vessel} = 1 - (1 - Pf_{mid}) * (1 - Pf_{fwd/aft})$$

4.6.3 Fatigue Crack Initiation System Reliability

*4.6.3.1 Bulk Carrier Fatigue Crack Initiation System Reliability*

In the bulk carrier sample application, two frame types are defined as far as component fatigue initiation are concerned. These include frame types 2 and 1 with and without the cargo hatch openings, respectively. In addition, the effect of the applied load that varies along the length of the vessel needs to be considered, therefore, forward and aft segments are assessed independently of the midship segments.

Figures 4.36 and 4.37 present the probabilities of frame failure due to fatigue crack initiation the midship and fwd/aft segments of the vessel, respectively. The difference in failure probabilities lies in the lower bending moments estimated to occur in the fwd or aft segments of the vessel.

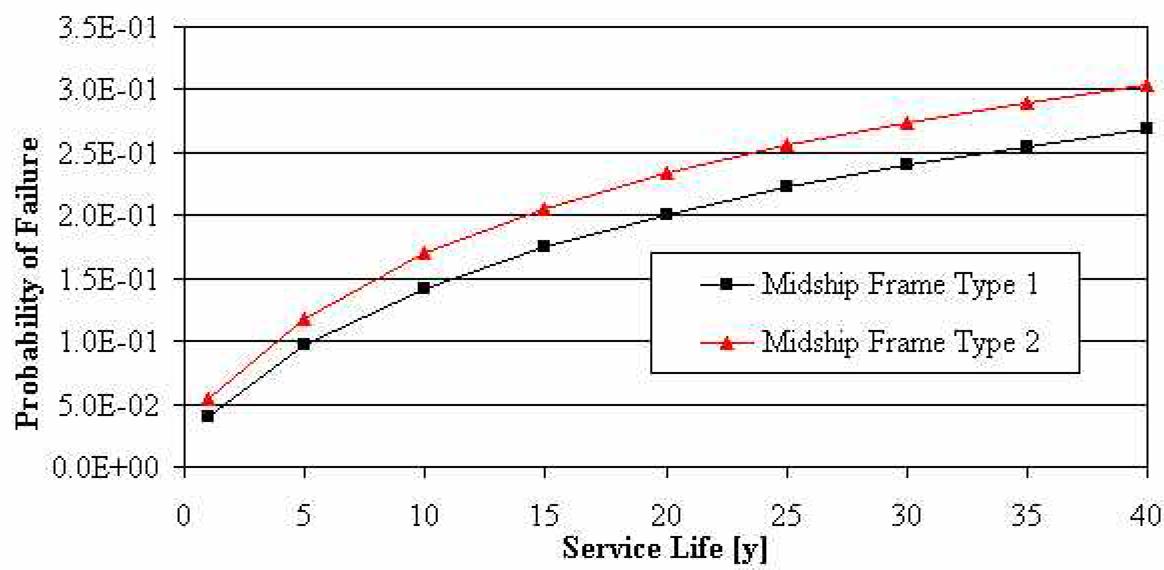



**Figure 4.36: Bulk Carrier Midship Frame Fatigue Initiation Failure Probability**

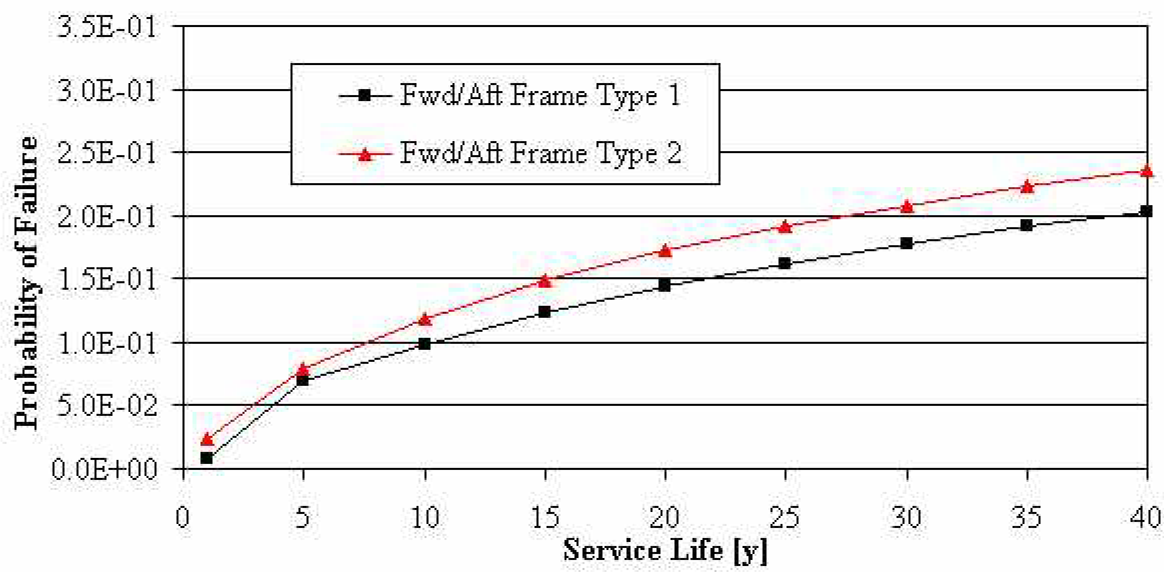



**Figure 4.37: Bulk Carrier Fwd/Aft Frame Fatigue Initiation Failure Probability**

Figure 4.38 presents the probability of component fatigue initiation for the entire vessel. The results shown in this figure are a combination of those developed for the midship and forward and after segments of the vessel since they have comparable failure probabilities. The probability of vessel failure is estimated as follows:

$$Pf_{vessel} = 1 - (1 - Max(Pf_{midship\ Frame\ 1}\ \&\ Pf_{midship\ Frame\ 2}))\ *\ (1 - Max(Pf_{fwd/aft\ Frame\ 1}\ \&\ Pf_{fwd/aft\ Frame\ 2}))$$

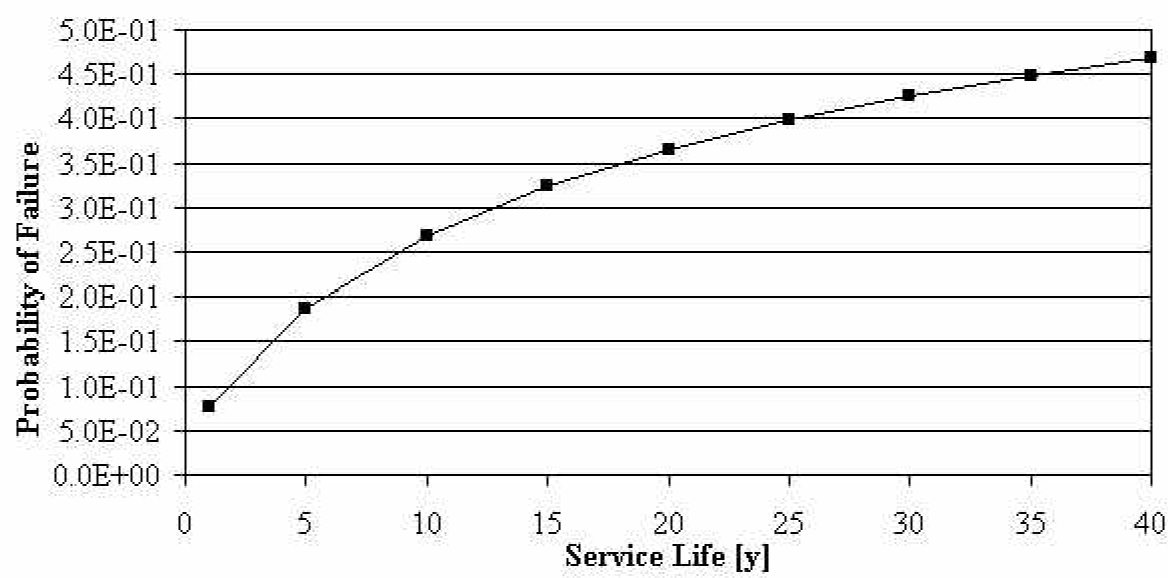



**Figure 4.38: Bulk Carrier Vessel Fatigue Initiation Failure Probability**

*4.6.3.2 Tanker Fatigue Crack Initiation System Reliability*

In the tanker sample application, two frame types are defined as far as component fatigue initiation are concerned. These frame types include web frames and bulkhead frames. In addition, the effect of the applied load that varies along the length of the vessel needs to be considered, therefore, forward and aft segments are assessed independently of the midship segments.

Figures 4.39 and 4.40 present the probabilities of frame failure due to fatigue crack initiation the midship and fwd/aft segments of the vessel, respectively. The difference in failure probabilities lies in the lower bending moments estimated to occur in the fwd or aft segments of the vessel.

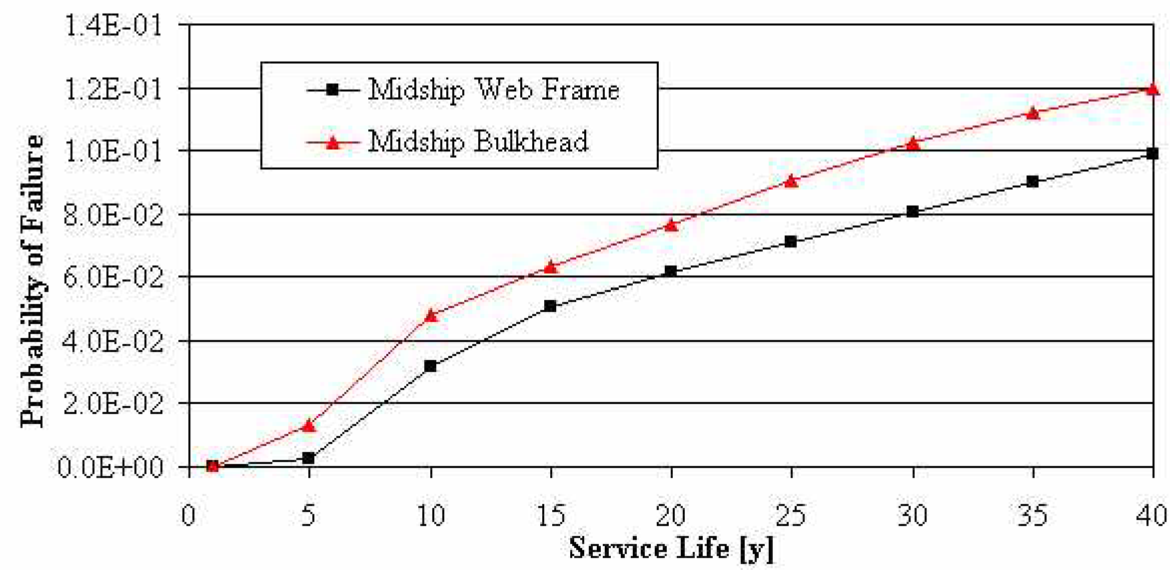
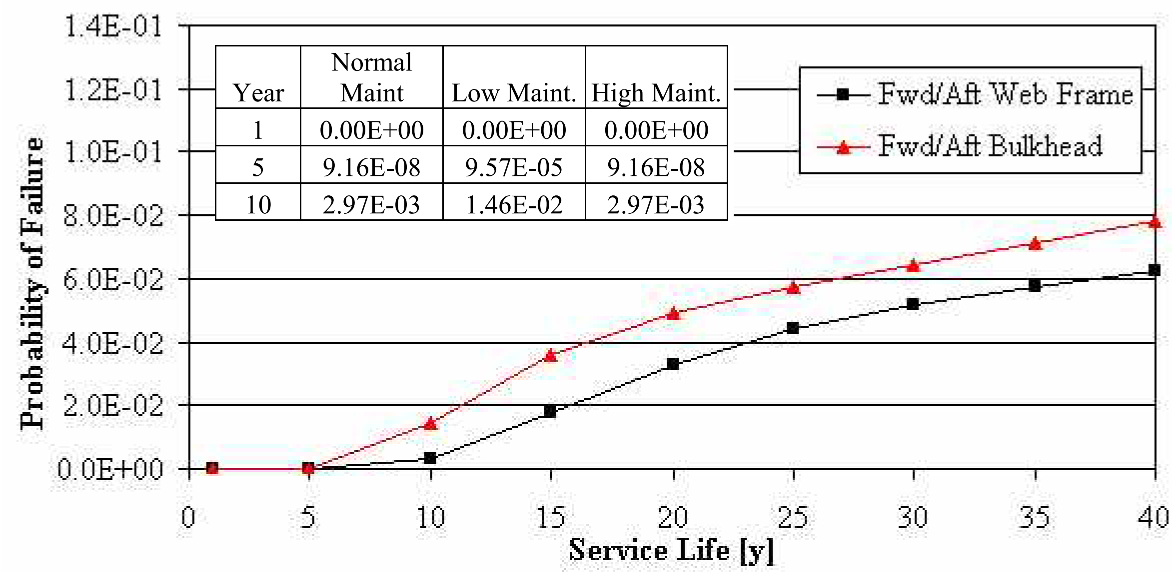



**Figure 4.39: Tanker Midship Frame Fatigue Initiation Failure Probability**




| Year | Normal Maint | Low Maint. | High Maint. |
|---|---|---|---|
| 1 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 5 | 9.16E-08 | 9.57E-05 | 9.16E-08 |
| 10 | 2.97E-03 | 1.46E-02 | 2.97E-03 |

**Figure 4.40: Tanker Fwd/Aft Frame Fatigue Initiation Failure Probability**

Figure 4.41 presents the probability of component fatigue initiation for the entire vessel. The results shown in this figure are a combination of those developed for the midship and forward and after segments of the vessel since they have comparable failure probabilities. The probability of vessel failure is estimated as follows:

$$Pf_{vessel} = 1 - (1 - Max(Pf_{midship\ Frame\ 1}\ \&\ Pf_{midship\ Frame\ 2}))\ *\ (1 - Max(Pf_{fwd/aft\ Frame\ 1}\ \&\ Pf_{fwd/aft\ Frame\ 2}))$$

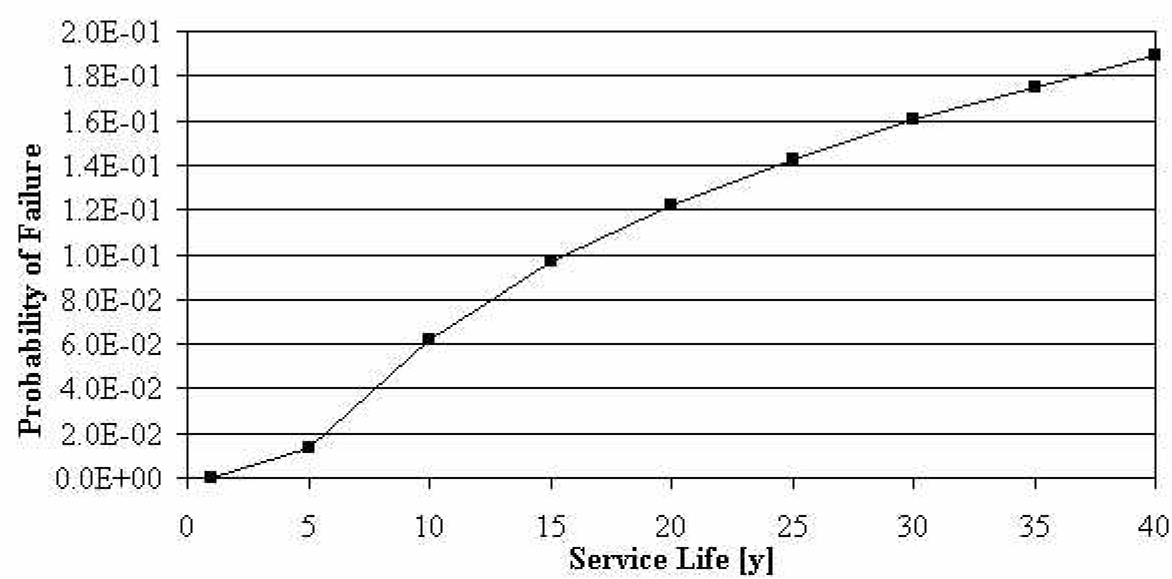



**Figure 4.41: Tanker Vessel Fatigue Initiation Failure Probability**

The results of the fatigue analysis indicate that the bulk carrier is more than twice as likely to experience fatigue crack initiation than the tanker. This result is due to the higher stresses experienced by the bulk carrier structure that appears to have been designed with a lower margin of safety.

## 4.7 Application of the Results

The results developed from a reliability based life expectancy assessment such as those performed in the sample applications can be used to improve design and maintenance techniques. Some applications could include:

<u>Inspection Focusing:</u>
The time dependant reliability analysis results indicate those components or frames most likely to fail. Since a typical inspection cannot realistically include every component in a vessel, the results of analyses such as those described in this report could be used to prioritise or direct inspection efforts on the areas which are most prone to failure or degradation. By highlighting areas of concern, more resources can be spent inspecting these areas and less on those which are more reliable.

Repair Prioritization
The sensitivity of failure probability to degradation rate or structural conditions could be used to prioritise repairs so that those areas of degradation which pose the greatest threat to vessel structural integrity in the short term are dealt with first. This information could be used to develop proactive maintenance prioritisation techniques based upon maintenance needs.

Identification of Critical Details
Details which are most prone to failure could be redesigned or strengthened. The results of an approach such as the one presented in this project could be used as part of a vessel preliminary design to identify details which pose problems and suggest modifications to improve thier performance.

Failure Mode Significance
The results demonstrate the significance of each failure mode on the reliability of the vessel. These results, along with estimated repair costs, could be used to determine the relative economic importance of each mode of failure. The techniques oulined in this project could be applied to develop a better understanding of the relative significance of each mode of failure and thus indiate appropriate levels of resouces should be applied in developing techniques to either better understand them or prevent them.

Vessel Managment Support
The rate at which degradation is accumulating and thus repairs are becoming necessary could be used to support major expenditure decisions by vessel owners and operators. Vessel replacement or repair decisions ideally should consider that the current and future maintenance requirements of a vessel. The results of a reliability based vessel life expectancy assessment could be used to compare the expected maintnence requirements of an existing vessel with those of an alternative new or replacement vessel. The same type of comparison could also be used to compre alternative vessels when deciding which vessel to sell, purchase or retire from service.

The sections that follow provide some ideas of specific applications of the analysis results produced in the previous sections. Additional applications of the results are possible including those that consider the economics of decision-making and maintenance programs could be considered, however, these elements of the maintenance management process are considered beyond the scope of this project.

### 4.7.1 Application of Tanker Buckling and Ultimate Strength Time Dependant Reliability Results

The results of the tanker buckling and ultimate strength time dependant reliability analysis (see Section 4.5.3.2) may be used to either direct in-service inspection and maintenance or initial design modifications. Figure 4.42 presents the probability of failure of individual components as a function of their duration of service (5, 20 and 40 years). This data may be used to direct inspection or plan maintenance to target resources to those components that pose the greatest risk. Risk being defined as the probability of failure multiplied by the consequence of failure. If the consequence of any individual component failure is assumed to be equal then component risk reduces to its failure probability. Alternatively, components of higher significance to the survival of the vessel or pollution prevention might be given a higher consequence of failure.

The tanker analysis results, in Figure 4.42, indicate that seven component types pose a significant risk or have significant probabilities of failure. By focusing maintenance resources (coating preservation and renewal) on these components, a greater return in terms of vessel safety or life expectancy per maintenance dollar would be realized than by treating all structural components equally.

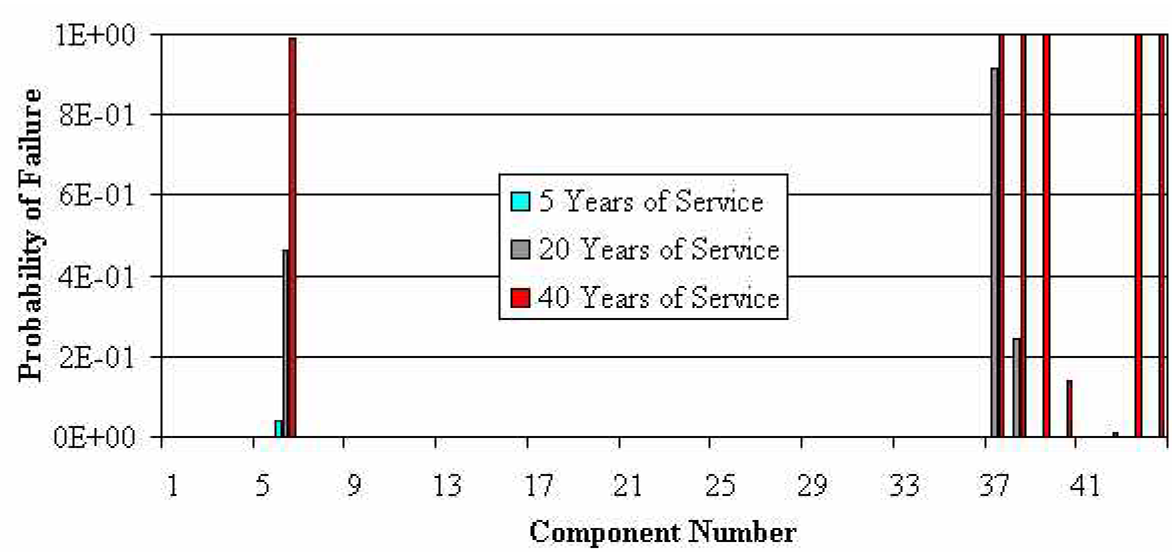



**Figure 4.42: Time History of Tanker Yield and Buckling Component Failure Probability**

The results of Figure 4.42 may also be used to review the initial vessel design. It appears that component type 6 of the vessel has a significant probability of failure early on in the vessel's service life. This indicates that its initial scantlings could promote premature failure and perhaps it should be redesigned to increase its design margin of safety. If the design probability of failure of component 6 were reduced it is suggested that it would not pose a significant through life risk.

### 4.7.2 Application of Bulk Carrier Fatigue Crack Initiation Time Dependant Reliability

The results of the bulk carrier fatigue crack initiation time dependent reliability analysis (see Section 4.5.4.1) may be used to either direct in-service inspection and maintenance or initial design modifications. Figure 4.43 illustrates the time history of fatigue reliability for all Midship frame type 1 components in the bulk carrier. This result simply illustrates that fatigue damage accumulates with service life and that this accumulation is non-linear due to the statistical nature of the loading. In addition, these results demonstrate, as expected, that damage accumulates faster in components that experience higher stress ranges due to their distance from the hull girder neutral axis.

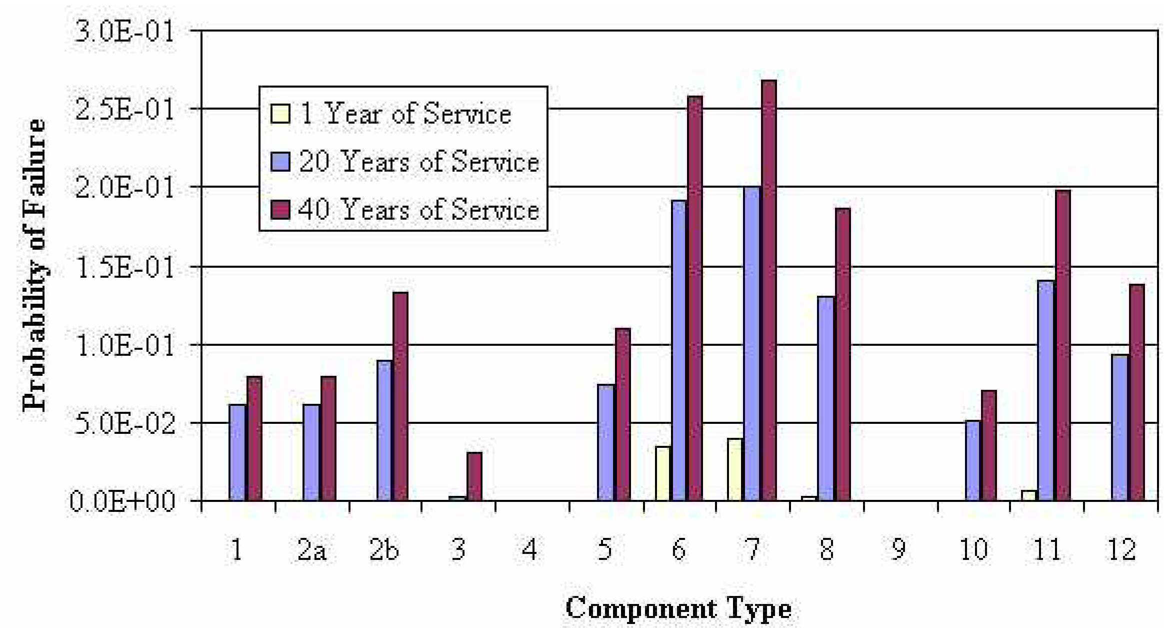



**Figure 4.43: Bulk Carrier Midship Type 1 Frame Component Failure Probability History**

The results shown in Figure 4.43 are idealized since they do not consider the effects of either local or global stress concentrations nor do they consider all of the different types of connections with different fatigue performance characteristics. If each connection detail on the ship were assigned individual fatigue performance categories and all of the local and global stress concentration effects at each detail were considered, results of the type shown in Figure 4.43 could be used to identify the most likely sites for fatigue crack initiation and rough estimates for the time at which crack initiation should be expected to be come significant. Based upon this information, inspection and maintenance effort could be focused on high risk (crack initiation probability) components or redesign efforts could be applied to those components with high probabilities of failure early in their service lives.

### 4.7.3 Application of Tanker Fatigue Crack Initiation Time Dependant Reliability

In a fashion similar to the results in the previous section, the results of the tanker carrier fatigue crack initiation time dependent reliability analysis (see Section 4.5.4.2) may be used to either direct in-service inspection and maintenance or initial design modifications. Figure 4.44 illustrates the time history of fatigue reliability for all midship bulkhead frame components. This result simply illustrates that fatigue damage accumulates with service life and that this accumulation is non-linear due to the statistical nature of the loading. In addition, these results demonstrate, as expected, that damage accumulates faster in components that experience higher stress ranges due to their distance from the hull girder neutral axis. As before, for the bulk carrier, it is noted that this assessment is idealized since it does not consider the effects of either local or global stress concentrations nor does it consider all of the different types of connections with different fatigue performance characteristics.

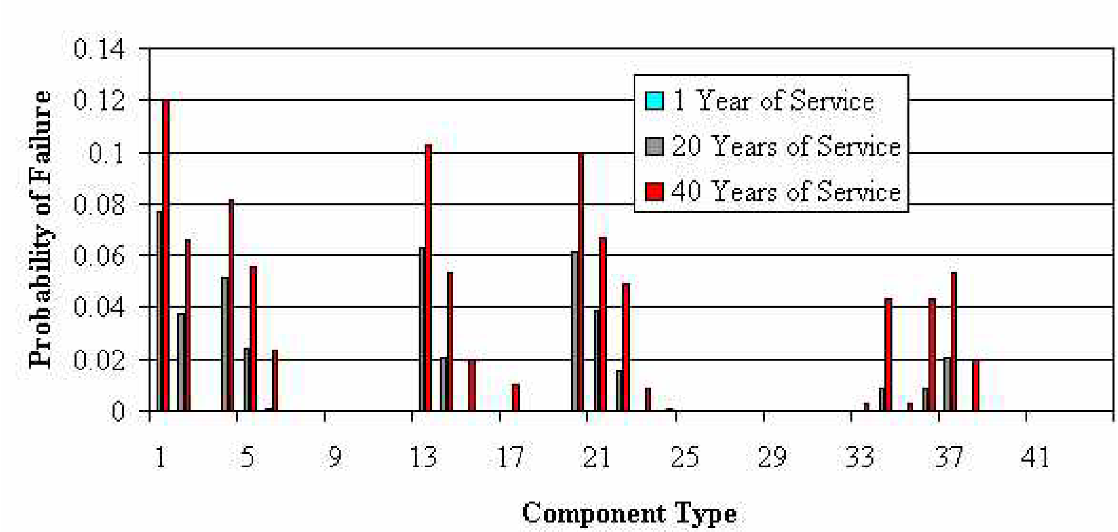



**Figure 4.44: Tanker Midship Bulkhead Frame Component Failure Probability History**

The fatigue crack initiation failure probabilities may be modified using a consequence factor, as mentioned earlier, to develop a cargo leakage risk measure that would promote inspection or maintenance at details that provide a barrier between the cargo and ballast or cargo and the ocean (e.g., a single hull tanker). A lower consequence factor could be applied to locations separating ballast tanks from the ocean or ballast tanks to the air.

# 5. CRITICAL REVIEW OF THE ANALYSIS APPROACH LIMITATIONS

The analysis approach developed in this project was assembled to demonstrate conceptually the techniques needed to perform a reliability based vessel life expectancy assessment. In assembling this approach, it was noted that a number of assumptions and short cuts had to be taken to avoid over-complicating the analysis. Further, the completion of this project identified a number of challenges that could not be dealt with in this project. Therefore, this section of the report presents a listing of the limitations of the current approach and, where possible, discusses some improvements or modifications required to overcome these limitations.

This discussion of limitations is presented in terms of the seven step process including:

- Vessel Particular Identification,
- Structural Section and Component Definition,
- Load Assessment,
- Definition of Local Detail Characteristics,
- Time Dependant Reliability Assessment,
- System Reliability Analysis, and
- Application of the Results.

The sections that follow, describe the perceived limitations of the analysis approach associated with each of these steps.

## 5.1 Vessel Particular Identification

The first step in the analysis is a data collection effort. The data being collected includes:

- Structural configuration and scantlings,
- Materials, and
- Hull form and weight distribution.

The limitations of the approach taken that could be remedied include:

- considering the development of a GUI to define standard ship structural systems. This development could both make the data assembly more efficient as well as reduce errors in the data.
- development of a material property database to support this assessment. The statistical variability of material properties for commonly used steels and weld metals should be explored. The current analysis treated material properties as deterministic values based upon nominal minimum specified mill properties. The nominal properties are in general under estimates of the actual values and thus introduce bias into the calculated reliability. Not considering the variation of material properties will also affect the outcome of the analysis.
- The definition of the hull form and weight distribution through the use of a GUI. Standard GUI's exist and were used in the sample applications.

## 5.2 Structural Section and Component Definition

The second step involves breaking down the structural system into segments, frames and components. This subdivision of the structure in future applications of the proposed approach should consider:

- the development of a database to track the base structural data and thus facilitate the definition of components, frame and segments. In the sample application, a spreadsheet was developed, however, in a useful example a great deal more data is required and this would likely overwhelm a spreadsheet.
- future applications should use a higher degree of structural division to better represent changes in loads and structural behavior. In the current application only two segment types were defined (midship and fwd/aft) for which loads were defined.
- more detail in the assignment of connection detail types to better differentiate between the performances of different details. In the sample application only the cruciform connection details at web frames and bulkheads were considered. In a more useful application all connections including lap joint, butts and corner joints would be considered along with openings and changes in dimension.
- additional structural assessment parameters need to be assigned to consider local and global stress concentrating effects. The current approach only considered global hull girder bending. A useful application of this approach should, as a minimum, define global and local stress concentration factors. Alternatively, finite element modeling could be used, adding significant effort.

## 5.3 Load Assessment

The third step in the analysis involves the definition of the loads applied to the vessel and thus its structure. This is accomplished through a statistical analysis of the loads generated based on a defined operational profile to estimate load distributions for fatigue and ultimate strength calculations. In addition, still water load distribution is estimated for the vessel. The limitations of the current analysis that should be considered in future applications include:

- consideration of all of the applied load components. The sample application completed in this project considered only the vertical wave bending moment. While the vertical wave bending moment is the most significant element of the applied loading, the other components (e.g., horizontal bending, shear, local pressure and torsion) could be significant depending on the vessel type and load/ballast condition. Future applications need to consider means of applying all components of the wave-induced loads.
- the consideration of non-linear load effects. The analysis completed made use of linear strip theory to estimate vessel moments. Since ultimate strength limit states are being considered, non-linear effects need to be considered such as slamming.
- the effect of wave statistics needs to be considered. The sample application made use of BMT's Global Wave Statistics whose accuracy for rare events has been questioned. While the accuracy of different wave statistical databases has been dealt with elsewhere, this matter should be explored.

## 5.4 Definition of Local Detail Characteristics

The fourth step in the process involves the definition of the characteristics of individual structural components. The characteristics of interest to this investigation include:

- nominal stress transfer functions,
- cross-section geometry,
- stress concentration effects, and
- corrosion rate and coating quality information.

In future applications it is suggested that the following issues be addressed:

- linear elastic hull girder bending theory was used to estimate the relationship between hull girder applied loads and structural stresses. Non-linear analysis might be more useful to evaluate extreme load events for ultimate strength limit states. This could be accomplished through the use of non-linear beam theory or non-linear FEA, however, the latter would add significantly to the computational complexity of the analysis.
- the cross-sectional geometry of components was defined in terms of individual stiffened plates with plate and flange dimensions. In future, an automated means of describing these sections would be worth investigating.
- in the examples, only one material type was used for each vessel. In reality, a range of materials could be used and separately assigned to each component.
- the current approach to defining structural components did not facilitate the identification of transverse structure (e.g., bulkheads) and their loading. This limitation could be addressed if 3-dimensional FE modeling were used.
- in defining structural components and their environments to define corrosion rates, most components form the boundary between two spaces with different environments. In the sample applications the most severe environmental conditions were applied to all surfaces of the component. This treatment would over-estimate corrosion rate, thus a means of better estimating the exposed surface weighted average effect should be implemented.
- the quality of paint application, weld quality and construction tolerances needs to be considered in the analysis. In the current example, these effects were treated as deterministic values. Paint quality was dealt with in terms of coating life (high medium and low quality/coating maintenance), while weld quality and construction tolerances were suggested to be nominally those used in the definition of the mean S-N data. In future applications, these parameters could be randomly assigned to components to better represent the variability in coating, welding and fabrication quality.
- in the future, it would likely be beneficial to increase the level of detail of the structural component description to explicitly include the stiffener flanges and other bracketing attachments. This improvement in the level of detail will allow more accurate consideration of component failure modes and the consideration of other load effects such as lateral bending, local pressures or torsion. Ultimately, it would be possible to consider the application of finite element analysis techniques, however, this step requires a significant increase in the data preparation process.

- it is also suggested that while the current model has been developed based on a nominal stress S-N analysis for fatigue initiation, it can be improved. The modular approach envisaged for the development of software would allow for the replacement of the nominal stress approach with a hot-spot stress approach that would allow the explicit consideration of construction quality in terms of residual stresses, eccentricity and weld quality. This improvement, however, only refines the crack initiation analysis and does not consider propagation. It would be possible to incorporate a fracture mechanics based crack growth algorithm to consider the growth of cracks and ultimately failure in a fracture mode.

## 5.5 Time Dependant Reliability Assessment

The fifth step in this analysis process is the time dependant reliability analysis. This step in the analysis process includes:

- definition of the limit states of interest
- assembly of the reliability assessment techniques
- collection and review of the analysis results.

In future applications of the reliability analysis approach, it is proposed that the following limitations of the demonstrated assessment be dealt with:

- Only a few limit state equations were used to demonstrate the reliability assessment approach. It is suggested that in a practical application a wider range of limit state equations be applied. The potential for fatigue crack growth or fracture, deformation limits, additional buckling modes, etc., could be considered.
- It is suggested that the application of limit states be carefully reviewed in terms of their applicability with respect to the structural discretization. For example, the pitting limit states were assigned to all components to evaluate the probability of the loss of water tightness. This limit state was inappropriately applied to stiffening elements in which pitting did not lead to a loss of water tightness.
- The reliability analysis techniques were developed to include a mix of first order approximations and simulated results. The level of convergence or accuracy of these techniques should be reviewed.
- The reliability analysis included wave induced loads and corrosion rate as the only sources of uncertainty. In the future, it is recommended that other sources of uncertainty (weld quality, paint quality, fabrication quality, material properties, etc.) could be considered.
- The current analysis made use of very simple structural analysis techniques. Perhaps in the future finite element analysis techniques could be applied, however, this would require the development of a set of guidelines to assess the potential for structural component failure based upon the FE stress distributions.

- The current analysis approach did not consider repair or maintenance (e.g., coating or steel renewals) strategies. Further development of the life expectancy assessment approach could extend the scope of the analysis to include in-service repair strategies. This improvement would involve the establishment of simple repair strategies (renewal/ repair) for cracks or corrosion given a threshold remaining thickness or crack size at which repairs are completed. The maintenance rules used for corrosion, for example, could include:
  - Sand blasting and painting for a range of residual thickness for which the reduction in thickness associated with the sand blasting is considered along with the coating reapplication
  - Replacement of plating for thickness reductions below a given value.
- In the event that either crack growth limit states or repair techniques are applied, it would be desirable to consider the probability of detection of the degradation. This would permit the simulation to allow continued degradation until the damage is detected.

## 5.6 System Reliability Analysis

The objective of the sixth step is to estimate time dependant probabilities of failure of ship structures from the simulated component and section probabilities of failure. In this analysis a first passage approach was applied to determine the time dependant probability of the first failure at the frame, segment, and vessel levels. Improvements on the approach used in the analysis include:

- Replacing the weakest link (first passage) approach with a more realistic systems reliability approach. For example, corrosion on a single component does not constitute failure; perhaps failure could be considered to occur when a given number, say four, components on a frame reach the allowable diminution limit.
- Ideally, the user would be able to define the systems reliability failure criteria (Nth passage) and these criteria would be limit state dependant (i.e., different criteria for different failure mechanisms).
- To facilitate the definition of systems reliability failure criteria, a GUI system could be developed to guide the user through the criteria development and assignment process.
- In the future, a life expectancy assessment software could be configured to estimate the optimal time between maintenance actions. This approach could define work areas and identify the accumulation of sufficient degradation within a work area to trigger a work action in a similar fashion as reliability centered maintenance.

## 5.7 Application of the Results

The final step is the application of the results. The scope of the project did not include the development of this step, however, some suggestions are given in the report to indicate how the results could be used. These uses included inspection focusing, repair prioritization, critical detail identification, and illustration of failure mode relative significance. It is suggested that in future applications of the analysis:

- the most important improvement that could be made in the analysis process is the solicitation of potential user input to identify the types of information of interest and the most usable format for the information.
- repair or maintenance cost data be considered to allow the user to consider the time dependant costs of delayed repairs versus more proactive maintenance.
- economic criteria could be incorporated to allow weighing the cost of continued operation and maintenance versus the revenues a vessel could generate. This information could be used to make vessel retirement or repair decisions.
- the probabilities of failure could be used to further consider the risk of operation with various maintenance strategies.

# 6 CONCLUSIONS AND RECOMMENDATIONS

A number of lessons were learned in the development, application and documentation of the reliability based vessel life expectancy assessment approach in this project. A number of shortcomings and limitations of the approach were identified and these are discussed in the previous section. The sections that follow make some general comments regarding the analysis approach and results by way of concluding statements and recommendations for future work.

## 6.1 Conclusions

The work completed in this project has reviewed vessel life expectancy assessment tools, described potential analysis approaches and presented two worked sample applications. In addition, potential improvements for these techniques have been discussed to support continued work in this area. Based upon the findings, it is possible to make the following general conclusions:

- The tools to perform reliability based vessel life expectancy assessment as described and demonstrated in this project are available and their use in vessel life expectancy assessment is possible.
- The data to validate the results was not available and therefore it is suggested that an analysis of the type proposed herein be used to draw conclusions on a relative basis.
- The sample applications considered the time dependant reliability of two vessels, a bulk carrier and tanker, by estimating the probability of corrosion diminution, fatigue, buckling and first yield limit states.
- The results of the sample applications indicated that the analysis techniques are capable of identifying critical structure and thus focusing inspection, maintenance or repair efforts. In addition, if completed at the design stage the analysis approach could be used to identify high risk structural element and identify the relative significance of each failure mode.
- While sample applications demonstrated the required techniques and identified the data required for the analysis, the volume of data and complexity of the analysis techniques suggests that database systems and automated software would need to be developed before more complex cases could be analyzed.

## 6.2 Recommendations

While the work completed in this project has provided a great deal of information regarding the application and performance of reliability based vessel life expectancy assessment, a number of issues remain unresolved or require further attention. The comments that follow provide recommendations for future development or investigations for vessel life expectancy assessment.

- While the sample applications demonstrated the concepts of interest, it is suggested more detailed sample application should be completed to better demonstrate the potential of the approaches developed in this project. The additional detail would include, for example:
  - a greater number and variety of limit states,
  - a higher degree of structural discretization,
  - additional sources of statistical variability (e.g., material, weld quality, coating life, etc.)

  - consideration of other applied loading components (not just vertical bending), and
  - more detailed treatment of systems reliability.

- Perhaps a future application of these techniques could also consider repair or renewal rules to better simulate the maintenance of a vessel and thus illustrate through life reliability.
- Future applications of the approaches presented in this project would require the development of software tools (databases and GUI's) to facilitate their implementation.
- Future development or implementation of reliability analysis techniques is dependant on the availability of basic statistical data. It is suggested that data describing uncertain quantities be collected to statistically describe factors such as weld quality, fabrication tolerances, and material properties.
- Additional work be completed to demonstrate how this work could be used to focus inspection, prioritize repairs, identify critical details and compare the relative significance of failure modes.

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# APPENDIX A - PROJECT LITERATURE REVIEW

The objective of the literature review task was to review and summarize collected literature and identify applicable approaches and data for use in the reliability-based structural life assessment. This task sought to collect data in the following subject areas:

1) Structural Data: This category of information captured data and techniques useful in statistically describing material degradation rates and the factors that influence them.

2) Limit State Modeling: This information will provide the basis for the development of structural component limit state equations, that is, engineering models for estimating structural resistance.

3) Load Estimation: In order to evaluate the integrity of a structure it is necessary to compare its load carrying capacity against expected loads. Techniques useful in assessing both typical "service" loads and extreme "ultimate" loads were outlined.

4) Reliability Evaluation Techniques: This category of information outlines techniques developed for time dependant reliability assessment.

While the end objective of this information collection task was to develop a reliability based methodology for the estimation of the life expectancy of ship structures, it should be noted that a great deal of related material exists for a variety of marine structures amongst other structure types (e.g., aircraft and pipelines). This information was not ignored even though the degradation modes or failure modes differ from those exhibited by ship structures, the life expectancy estimation techniques they employ were considered.

The sections that follow presented the information collected in four sections associated with the subject areas of interest. Each section includes a brief narrative relating the references that follow to the understanding of the subject matter. These brief remarks should give an overview of the types of information being collected for each topic.

## A.1 Structural Data / Degradation Mechanisms

### A.1.1. Fatigue

#### *A.1.1.1 S-N Approach*

Traditionally, the design of marine and offshore structures has considered in-service fatigue damage accumulation based on an *S-N* curve approach. For this reason, the approaches for the reliability-based fatigue assessment of ships and offshore structures employing *S-N* curves and a Miner damage accumulation rule are presented first. This approach focuses on the fatigue crack initiation life and thus does not provide information on crack growth rates.

The books published by Fuchs and Stephens (1980), Suresh (1991) and Maddox (1991) present good reviews of the metal fatigue process, which can be used as the basis for the fatigue analysis of any metallic structure. According to these authors, the fatigue behavior of a structural detail is a function of a variety of factors, including: (1) the general configuration and local geometry of the member, (2) the material from which the members are made, and (3) the loading conditions to which the detail is subjected.

The ship structure presents another important feature that influences the fatigue process which is the use of welding process for the assembly of the structural parts. According to many authors, such as Morgan (1986); Mansour et al. (1995), Kihl and Sarkami (1996); Petenov and Thayambali (1998); Moan and Berge (1997), and Xu (1997), the weld can induce stress concentrations due to the weld geometry that influence crack growth behavior. Furthermore, according to Petenov and Thayambali (1998), and Xu (1997), the presence of residual stresses, induced by welding process, can affect the crack growth behavior, usually increasing the crack growth rate.

Therefore, for welded structures, the weld geometry that produces stress concentrations must be considered as an additional local structural geometry effect that may be incorporated in nominal stress S-N curves or considered explicitly in hot-spot SN curves. In addition, the residual stress field developed in the weld solidification (contraction) process is inherently included in the test results used to develop the S-N curves.

The Ship Structure Committee has sponsored a great number of research projects to study the fatigue process of ship structures. Most of them were executed to characterize high-cycle fatigue, based on an *S-N* curve approach, although some studies related to low-cycle fatigue were developed.

The technical report SSC-7 presented the experimental results of fatigue tests executed with large welded test specimens that were used to characterize the fatigue resistance of structural components. To provide data on the performance of structural details, the Ship Structure Committee sponsored two projects (SSC-272 and SSC-294) to identify fatigue susceptible ship structural details.

The technical report SSC-318 not only presented a catalog of ship structural details and assemblies but also established the mean fatigue strength of these details based on the *S-N* fatigue model. The ship details included in the investigation were representative of current ship design and shipyard practice. This report also presented a reliability-based design model for fatigue applicable to ship structures. The report SSC-346 provided a fatigue design procedure for evaluating the fatigue damage accumulation process in ship structural details. It also presented the results of fatigue tests carried on structural details in order to compare the theoretical prediction with test results.

Results of additional tests of structural details are provided by Berge and Eide (1982), Maddox (1982), Lawrence Jr. et al (1982), Fricke and Muller-Schmerl (1995), Sarkani et al (1995), Kihl and Sarkani (1996) and Martinez et al (1998). The technical report SSC-370 presented experimental analysis developed to evaluate the fatigue performance of underwater welds.

In the report SSC-396 tensile, fatigue and fracture toughness data for high strength TMCP steels and their weldments were compiled and analyzed, and recommendations made for utilizing these steels in ship design.

The report SSC-338 presented examples of the use of deterministic and probabilistic fatigue life assessments for a container ship hatch corner.

The reports SSC-140, SSC-367 and SSC-379 provided a review and summary of fatigue design strategy for welded ship structures. The report SSC-356 presented a summary of methodologies used to predict the fatigue performance of structural details under multi-axial loading condition.

The report SSC-405 (Fatigue Resistant Detail Design Guide) presented a design guide for practicing designers on the methods for assessing the fatigue strength of ship structural details.

The technical reports SSC-137 and SSC-151 analyzed the low-cycle fatigue behavior of metals, presenting experimental studies of this process for small coupon-type specimens.

In the fatigue analysis of ship structural details, the uncertainties associated with the following analysis variables may be considered: (1) Miner's fatigue damage ratio, (2) the fatigue life prediction related to S-N curve model, (3) the applied stress range, and the (4) theoretical stress analysis procedure (Wirsching 1984).

Over the years, there have been numerous articles and some books written on the topic of statistical analysis of fatigue data, such as the one written by Little and Jebe (1975). This book discusses the statistical analysis of *S-N* fatigue tests results, including regression analysis and application of analysis of variance techniques, in order to define *S-N* curves and their confidence levels.

An ASTM conference was devoted to explaining and assessing the variability of *S-N* fatigue test data (Little and Eckvall, 1981). The two majors area considered in this publication were: (1) maximum likelihood analysis used as a tool in statistical analysis of fatigue data and in the study of alternative fatigue models and (2) assessment of fatigue variability using statistically planned test programs with appropriate replication. The standard practice ASTM E739-91 (ASTM, 1999) provides a guideline for statistical analysis of fatigue data related to *S-N* fatigue tests.

The quantification of S-N analysis uncertainties was reviewed by Munse (1983) in the report SSC-318 and by Wirsching and Chen (1988). The statistical bases for characterizing Miner's fatigue damage ratio and stress analysis uncertainty factor are presented by Wirsching and Chen (1988) and White (1992). These variables are modeled as lognormally distributed.

Fatigue reliability of ship structures can be assessed using the models presented in SSC-405 or those proposed by Ang (1977), Munse (1983), which was presented in the report SSC-318, Wirsching (1984) and Mansour et al (1995). Hansen and Thayamballi (1995) also discussed the fatigue damage of ship structures considering whipping arising from slamming.

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#### *A.1.1.3 Fracture Mechanics Approach*

The second approach to fatigue damage accumulation is based on a fracture mechanics crack growth modeling. This approach only considers the growth of preexisting cracks (does not consider the crack initiation life).

The fatigue failure of a mechanical or structural element under dynamic loading can be considered as the dominant time to a crack length grows up to a critical magnitude, which may be decided by serviceability requirement or final fracture criterion.

The book written by Rolfe and Barsom (1987) presented the basic concepts related to the linear elastic fracture mechanics theory, which is the base for the fatigue fracture mechanics analysis.

The first attempts to describe fatigue crack growth in offshore structures using fracture mechanics were made in the early 90's by Wirsching and Torng (1990), Wirsching and Kung (1993), Skjong and Torkaug (1991), and Madsen et al. (1991). All of these approaches employed the Paris law with random variables, discussed in Section 3.1.1.1, and applying the First Order Second Moment to define the failure probability related to the structure.

The effects of inspection and repairs of defects on the structure reliability were also discussed by Madsen et al. (1991).

The fracture mechanics approach has been used to evaluate the fatigue process of offshore structures, mainly those operating in harsh environment. Many authors such as Sorensen et al (1992), Sigurdson and Torhaug (1993) and Hagan and Sigurdson (1994) applied the probabilistic crack growth approach to study the fatigue reliability of structural joints of jackets operating in North Sea. Moan and Hovde (1994 and 1997) and Dalane and Haver (1995) analyzed the fatigue fracture of TLP platform tethers. The same approach was used by Lanning and Shen (1996) to analyze the reliability of welded structures.

Although probabilistic fracture mechanics approaches have been studied and used to analyze offshore structure fatigue damage accumulation since the beginning of the 90's, this technique was only applied to ship structures in 1992 (Pegg et al 1992 and Sire et al 1992).

In 1995, Kaminski and Krekel (1995) applied the probabilistic fatigue fracture mechanics approach in the analysis of the possible operational life extension of a tanker in order to be used as a storage ship in a FSPO offshore system.

Since this date, Soares and Garbatov (1996, 1997, 1998) have published some studies related to the probabilistic fracture analysis of ship structures. Fricke and Muller-Schmerl (1998) applied the probabilistic fracture analysis to define the operational life of some ship structural details, considering the propagation of cracks emanating from holes used for lightening weight in ship structures.

Random factors entering into the reliability analysis against fatigue damage accumulation in this approach can be divided into three groups. The first one is composed of random material mechanical properties, the second one of random defects and imperfections of structural components, and the third one of random loads, actions and environmental conditions.

The statistical distribution of the material properties is still not well studied, although the Paris Law is based only on experimental data analysis (Ramsamooj and Shugar, 1998). There are a few studies that present the statistical analysis of the crack growth curve for the structural materials.

Virkler at al (1978) presented a statistical analysis of crack growth test results for 2024-T3 aluminum alloy test specimens. An attempt was made to use a probability density function to describe the variation of Paris law material constants *C* and *m*, respectively the crack growth propagation rate and crack growth exponent. Despite using a great number of probability density functions, the authors did not conclude what function could be used to represent the coefficients variation.

The ASTM promoted a conference dedicated to discuss the measurement and data analysis related to fatigue crack growth tests, Hudak Jr and Bucci (1979). This publication presented some papers related to the statistical analysis and representation of crack growth data, mainly analyzing the application of regression analysis to fatigue crack growth rate data and the application of analysis of variance for reproducibility within a laboratory and repeatability between laboratories.

Johnston (1983) reviewed data on fatigue crack growth rates for steel specimens used in nuclear reactor pressure vessels, and a statistical analysis of data had enabled a distribution for parameter *C* to be derived assuming a linear *lnC* versus *m* relationship, considering *m* constant and *lnC* normally distributed.

Ichikawa (1987) conducted crack growth tests on 30 specimens of 2024-T3 aluminum alloy, usually used on aeronautical structures, under identical conditions. Paris law was applied to each specimen and the scatter of *C* and *m* among specimens was studied. The authors concluded that *logC* and *m* show approximately normal distribution.

Studies in marine structures fatigue reliability have typically used a lognormal distribution to describe the variation of *C* and a normal distribution to describe the variation of *m*. This same approach was adopted by Fisher (1984), Zhao and Haldar (1994, 1997) and Agerkov and Nielsen (1999) in the study of bridge structure fatigue.

For steels used in construction of pressure vessels structures, the variation of the parameter *C* is modeled as a lognormal distribution, according to Newby (1998) and Hong et al (1999), and the parameter *m* is considered fixed.

Finally, the initial crack size distribution is a parameter that has great influence on the fatigue crack growth period, but its statistical distribution is dependent on the non-destructive inspection methodology used during the structure construction. The nuclear and aerospace industry studied the initial crack size distribution issue and Becker and Pedersen (1974) and Newman Jr. (1998) were able to define typical crack size distributions for welded structures. The offshore and naval industry (Shinozuka (1990) and Moan et al. (1997)) has also performed some studies in this field, which indicated the initial crack size distribution is best represented by an exponential or a lognormal distribution.

The Ship Structure Committee also performed a series of studies related to the application of the fracture mechanics approach to the analysis of ship structural fatigue.

Just after the end of the Second World War, the Ship Structure Committee performed some research related to the characterization of the fracture toughness of steels used in shipbuilding activities. The results of these experimental programs are presented in the technical reports SSC-1, SSC-148 and SSC-303.

Additionally, some work was performed to characterize the effect of cyclic loading on the fracture resistance of ship steels (technical reports SSC-31, SSC-143, SSC-188 and SSC-358). In the project SR-1384, the experimental determination of ship structure weldment toughness is being examined. The objective is to investigate the potential for restricting crack growth in the HAZ.

The technical report SSC-315 presented the results of an experimental study that represented the first attempt of the Ship Structure Committee to analyze the crack growth process under random loading in ship steels based on the fracture mechanics concepts. The report SSC-386a presented a procedure for fatigue analysis of ship structures based on fracture mechanics.

The report SSC-402 reviewed the essential elements of damage tolerance analysis, and pulled together a practical guide for the use of naval architects on the use of failure assessment diagrams, cyclic loads and linear elastic fracture mechanics.

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### A.1.2 Corrosion

In the literature survey, many 10 papers describing the effects of corrosion rates on the reliability of ship hull. The papers include work on Tanker Structure Co-operative Forum-TSCF (1992), Shi, (1992) Loseth et al. (1994), Weber (1996), Guedes Soares and Garbatov (1996), Yamamoto and Ikegami (1996), Paik, et al. (1997), Wirsching et al. (1997), Paik et al. (1998a), Paik et al. (1998b).

Corrosion is typically considered in design or analysis in two ways: 1) reducing scantlings by a fixed corrosion allowance or 2) assuming a uniform corrosion rate at which the structural scantlings are gradually reduced over time. In applying either of these approaches in a probabilistic fashion requires statistical distributions of annual corrosion rates.

Guidelines for the inspection of corroded hulls developed by (IACS) are presented and recommendations for repair of corroded areas are given. Nominal design corrosion values (NDCV) for different parts of structures and vessel types have been developed (ABS, 1995).

Corrosion in tankers in particular has been extensively studied by the TSCF (1992,1997). Due to the contributions from all of TSCF's members, the guidance on corrosion susceptibility and rates provided is a very valuable reference in the evaluation of the corrosion rate of ship hulls.

Weber's paper [4] it is reported that the Exxon Corporation has conducted a comprehensive program of structural surveys for all 46 owned V/ULCCs, to obtain a comprehensive assessment of their structural condition. Corrosion rates were given in three zones; ullage, splash, and immersed zones for each tank space.

Based in part on the TSCF data, Loseth et al. [1] provided estimates of corrosion rate (mm/yr) for primary members of tanker structural elements. Based on data for existing vessels, they provided mean value and COV (coefficient of variation) data for corrosion rates for various types of primary members of single- and double-hull tankers. Differences due to location and corrosion severity of the space were taken into account.

In Paik et al.'s paper, a corrosion rates models are developed in terms of the life of coatings which are assumed to follow a normal distribution and the reduction of the plate thickness due to corrosion, expressed as a function of the time.

Yamamoto et al found that the probability density function for corrosion rate can be assumed to follow a Weibull distribution. In Yamamoto' paper [5], corrosion survey results tare used to develop a ship structural corrosion model including: 1) loss of an effectiveness of anti-corrosion coating, 2) generation of pitting point and 3) progress of pitting corrosion. The variability of coating life characterized in terms of a normal distribution, the transition time between an effective coating and the establishment of a pitting point is governed by an exponential distribution, and the progress of pitting corrosion is characterized in terms of a lognormal distribution

Paik et al. [7], [8] performed comprehensive studies regarding the effect of corrosion on ship hull girder ultimate strength for tankers. In this work, the probability density function of the corrosion rate is assumed to follow the Weibull distribution.

In Shi's paper, corrosion rates have been found to vary linearly with time for younger ships and to increase sharply due to the deterioration of protective coatings. Among different types of ships, lumber carriers, bulk carriers and oil tankers are most susceptible to high corrosion wastage. Mean corrosion rates range from 0.08 to 0.1 mm per year with very large coefficients of variation reported

In Wirsching et al.'s paper the probability of hull girder ultimate strength failure is estimated considering the effects of corrosion. The effect of corrosion is applied to discrete longitudinal section in which the corrosion rate, $C_i$, of the ith component is a random variable and is assumed to be constant over time; all $C_i$s are taken to be independent and identically distributed.

In Guedes Soares and Garbatov's paper (1996) investigating hull girder collapse probabilities, the structural corrosion rate is considered to be time invariant but uncertain.

SSC-395 (15) reports provide a table of table of the corrosion rates for VLCC midship structure.

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## A.2 Structural Limit States

In order to examine the safety of ship structures, it is important to identify the major modes of hull failure. In general, these modes can be grouped as follows:

a) Failure due to yielding or plastic flow of deck or bottom,

b) Failure due to elastic-plastic buckling of deck or bottom panels, and

c) Failure in a fatigue and fracture mode.

When considering the primary hull structure, reference is usually made to the midship section, and checks on the capability of secondary structures were only made in some studies. Basically the ship hull is considered to behave globally as a beam under transverse load subjected to the still water and wave induced load effects. In general the governing variable is the vertical bending moment that will induce the bending of the hull. The resulting stresses are distributed linearly across depth of the hull and their intensity at the bottom and deck is the ratio of the applied moments by the respective section modulus.

The moment to cause first yield of the midship section either in the deck or in the bottom is a common limit state. This moment is equal to the product of the minimum section modulus by the material yield stress. It tends to be conservative in that typical ship structural steels have reserve strength after initial yielding in terms of their ductility and related work hardening capabilities. In addition, when first yield is reached at one hull girder extreme fiber, the other likely has not yielded and the hull girder will remain in this partially plastic state until plastic collapse.

Another limit is the plastic collapse moment, which is reached when the entire section becomes fully plastic. This moment is calculated considering that all the material is at yield stress. Thus, the plastic neutral axis is in a position that the total areas of material above and below the neutral axis are equal. This limit state is generally unconservative because some of the plates that are subjected to compression may buckle locally decreasing their contribution to the overall moment. The ultimate moment will in general be between the first yield and the plastic collapse moments.

The study of the ultimate resistance of midship section has been subject of study in many papers, such as those presented by Casella et al (1996), Ren et al (1996) and Mansour (1972).

The buckling failure of bottom or deck structures is more complex. Bottom and deck structures are generally grillages stiffened longitudinally, but still presenting transverse structures, named frames, so that different buckling modes can occur: failure of plates between stiffeners, interframe flexural buckling of the stiffeners, interframe tripping of the stiffeners, interframe buckling of the panel and overall grillage failure, usually between bulkheads, involving deflection of both longitudinal and transverse stiffeners. The elastic-plastic buckling strength of this type of structural elements is the objective of active research, and there are various adequate expressions to quantify their strength. Among these the methods proposed by Faulkner (1975), Adamchak (1975) and Hughes (1988) are oriented to marine structures.

The failure of deck or bottom panels structures under compressive loads can affect such a large portion of the cross-section that it is sometimes considered equivalent to a hull failure mode, Mansour (1972), and can represent the loss of ship safety.

The failure due to yielding, plastic flow or buckling of deck or bottom is associated with the failure of the ship under an extreme sea load to be faced during the operational life of the ship. So for the failure analysis it is often necessary to known the maximum of the combined value of still water and wave-induced loads effects. There is some correlation between the two-load process in that significant changes of deadweight may imply some changes in the wave-induced load effects.

Although many reliability studies are related to the analysis of midship section, the ship transverse frame can also present yielding, plastic flow or buckling collapse. These failure processes were analyzed by Wang (1996) in a similar fashion as that used for midship section analysis.

Fatigue damage accumulation is associated to the total history of the cyclic wave bending moment rather than just the extreme value of the moment per se, thus the random nature of this history needs to be considered.

Failure by fatigue is a progressive cracking and unless it is detected this cracking can lead to a catastrophic rupture. When a repeated load is large enough to cause a fatigue crack, the crack starts at the point of maximum stress. This maximum stress is usually associated with a stress concentration (stress raiser). After a fatigue crack is initiated at some microscopic or macroscopic level of stress concentration, the crack itself can act as an additional stress raiser causing crack propagation. The crack grows with each repetition of the load until the effective cross section is reduced to such an extent that the remaining portion fails with the next application of the load (fracture). For a fatigue crack to grow to such an extent to cause rupture, it usually takes thousands or even millions applications of the stress, depending on the magnitude of the load, type of the material used, and on other related factors.

Usually, the fatigue life of a structural component, subjected to the action of cyclic stress, is defined as the total number of stress cycles required to initiate a dominant fatigue crack added to the number of stress cycles required to propagate this crack until the final failure. This total life, in a simplified view, is a function of the geometry of the structure (local and global), applied stress range, the mean stress and the environment where the structure is located.

The stress-based fatigue analysis methodologies, represented by the classical *S-N* diagram, embody the damage evolution, crack nucleation and crack growth stages of fatigue into a single, experimentally characterized continuum formulation. However, it should be noted that the S-N curves are developed experimentally based on relatively small structures and their failure does not necessarily correspond to ship structural failure that is based on the behavior of very large highly redundant structure.

A detailed evaluation of engineering structures and their construction processes shows these processes can induce the presence of small flaws, despite structural inspection for quality assurance purposes. Therefore, a modern defect-tolerant design approach to fatigue are based on the premise that engineering structures are inherently flawed, and the useful fatigue life then is determined by the time or number of cycles to propagate a dominant flaw of an assumed or measured initial size to a critical dimension.

Because of the limitation on the control of the properties of steel and other materials used in shipbuilding and because of limitations on production and fabrication of ship components, the strength of apparently identical ships will not be, in general identical. In addition, uncertainties associated with residual stresses arising from welding, the presence of small holes, etc may also affect the strength of the ship. These limitations and uncertainties indicate that variability in strength about some mean value will result. This will, in turn, introduce an element of uncertainty as to what is the actual strength of the ship that should be compared with the loads and their uncertainties in order to define the reliability index associated with the structure. The report SSC-322 presented the different uncertainties associated with ship structural strength and external loading considering probabilistic analysis and design.

The foregoing brief discussion indicates that it is convenient to split the analysis of failure into: 1) ultimate failures that will represent the loss of the ship, and 2) serviceability failures that will decrease the operational performance the ship structure, perhaps making it unsuitable for service.

The table below suggests a possible classification of ultimate and serviceability failures as for reliability analysis:

| ***Failure*** | ***Failure Degree of Importance*** | | |
|---|---|---|---|
| | *Primary* | *Secondary* | *Tertiary* |
| *Ultimate* | 1) Midship cross section plastic flow<br>2) Buckling of panel structures<br>3) Fatigue fracture. | Stiffened panels buckling between frames. | Unstiffened panel buckling. |
| *Serviceability* | First yield of the midship cross-section. | 1) Cyclic load induced through thickness crack.<br>2) Stiffened panel permanent set | Unstiffened panel permanent set. |

According to this table, the ultimate failure modes include flexural strength and buckling, and the serviceability failure modes include permanent deformation and first yield. The fatigue failure is included in both modes, depending on the extent of fatigue damage.

The importance of a failure is classified according to the degree of deterioration of ship safety or extension of the ship structure affected by a given failure mode. For this proposal, the failure are classified as:

a) Primary: a failure mode that may affect great part of the structure and cause the loss or great major degradation of the structure performance,

b) Secondary: a failure mode that may affect a part of the structure and cause damage or degradation of the structure performance, and

c) Tertiary: a failure mode that may affect a small part of the structure and cause minor damage or degradation of the structure performance.

Finally, according to Spencer et al (1996) the ship classification societies are using reliability models to define the safety associated with a given structural design.

### A.2.1 Structural Limit States References

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## A.3 Loads and Load Combination

Two general approaches are outlined in previous SSC reports (i.e., SR-1337 and SR-1344) for the design and analysis of ships or marine structures, to incorporate the statistical nature of the environment or loads (Hogben et. al. 1986) over the short- and long-terms. The *short-term* analysis approach identifies an extreme design condition used to estimate the probability of vessel ultimate strength failure, whereas, the *long-term* analysis approach predicts the probability of structural failure due to a progressive damage accumulation (a fatigue failure mode) or a one time over load event (ultimate strength failure).

These approaches were applied to four vessels based on their operational profiles in SSC-406. This demonstration of the algorithms and subsequent application in the ship structure fatigue design guide (SSC-405) and damage tolerance manual (SSC-402), illustrated the practical application of these load estimation techniques in the design and analysis of ship structures.

In addition to these technically involved approaches, classification societies have presented (DNV 1998) simpler empirical formulations for estimating the long- and short-term load distributions.

Techniques for estimating the effects of slamming (Lacey et. al. 1993), and fluid cargo accelerations (ABS 1996) have been presented and outline practical means of estimating load effects other than those associated with hull girder bending.

### A.3.1 Loads and Load Combination References


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## A.4 Structural Reliability

### A.4.1 Instantaneous Reliability

Many methods have been proposed for structural reliability assessment purposes, such as the first-order second moment (FOSM) method, advanced second moment (ASM) method, computer-based Monte Carlo simulation (e.g., Ayyub and McCuen 1997, Ang and Tang 1990, Ayyub and Haldar 1984, White and Ayyub 1985, Madsen et al 1986), and conditional expectation simulation (e.g., Ayyub and McCuen 1997).

The FOSM and ASM method were developed considering that the random variables used in the reliability assessment are normally distributed. If a random variable is not normally distributed, then it needs to be transformed to an equivalent normally distributed random variable according to the procedure presented by Rackwitz and Fiessler 1978, and Ayyub and McCuen 1997.

Ayyub and Popescu (1998) developed a reliability assessment program with a user friendly, web interface. The reliability assessment methods used in this program are the advanced second moment method (ASM), computer-based Monte Carlo simulation (MC), and conditional expectation simulation (CE). Time-dependent reliability (TDR) was assessed using the CE methods.

Ayyub and McCuen (1996) presented some numerical methods that can be used to solve reliability problems.

Wen (1990) used the reliability concepts to model performance and safety of structures subjected to a variety of load conditions, and Dinovitzer (1992) applied the reliability concepts to execute structural optimization.

The Ship Structure Committee also developed some studies related to the reliability-based analysis and design of ship structures, including a symposium, SSS-87, where were presented eighteen papers related to the application of reliability methods in the design of marine structures.

The reports SSC-351 and SSC-368 provided, respectively, an introduction to structural reliability theory concepts directed specifically toward the marine industry and a demonstration on the use of probability based ship structural design, comparing its benefits versus those of traditional methods.

Considering the importance of the existence of a database for reliability analysis, the report SSC-371 proposed a material property gathering format with the objective that the database so developed is suitable for describing statistical measures.

The report SSC-375, as part of a SSC project directed to develop probabilistic design strategies for ship structures, presented and demonstrated a method for quantifying the bias and uncertainty in the structural strength algorithms.

As part of the uncertainty related to the structural performance of a given design is related to the human errors, the report SSC-378 established guidelines to consider the effect of human errors in the design and construction of marine structures.

In order to support researches about reliability-based design of ship structures, Ayyub and Chao (1994) analyzed some statistical distributions that could be used to model the uncertainties associated with variables that have great influence on ship structural design.

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### A.4.4 Life Expectancy Assessment (Time Dependant Reliability)

This summary outlines methods identified as viable methods for use in modeling uncertainties over time in structural systems.

Tung and Mays (1980) developed expressions for time-dependent reliability function, R(t) for random-fixed resistance (where randomness of resistance varies in time in a known manner) and random-independent loading (where the successive values assumed by random load are statistically independent). Tung and Mays (1989) proposed an equation for the time-dependent reliability for the random independent loading and random fixed resistance R.

Harrington and Melchers (1984 and 1985) chose the example of an idealized steel portal frame to study the time-dependent effect caused by non-linear crack growth for short duration and high intensity loading requiring the use of “low-cycle” fatigue analysis. Monte-Carlo simulation is used for the solution of the problem. From this, Wickham (1985) established the upper and lower bounds for probability of failure for any structural component.

Wen (1986) developed a method of modeling and analysis of inelastic structures under random excitation.

Guers and Rackwitz (1987) discussed a method for the reliability calculation of time-variant redundant systems subject to Gaussian load-process that includes the possibility of failure under fatigue-reduced resistances.

Wen and Chen (1987) given a realization of the resistance variable, proposed a method to reduce the time-variant reliability problem to that of a time-invariant reliability problem

Wen (1987) discusses a first order (linearization) method and second-order (asymptotic) methods based on the out-crossing rate analysis.

Geidel and Saunders (1987) developed a time-reliability equation, found to be useful for deriving the time-dependent reliabilities for engineering systems.

Nienstedt (1989) discussed the effect of corrosion as a function of the stress intensity factor, the frequency and the stress ratio of the loading process. The study discusses the effect of deterioration process of both corrosion and fatigue on time-variant structural reliability.

Wen and Chen (1989a and 1989b) proposed two methods for estimation of reliability using the ensemble out-crossing rate method and first- and second-order method.

Madsen and Tvedt (1988) discussed a method for computing failure probabilities for components and systems where the uncertainties are represented by a combination of random variables and a time-dependent process. Madsen and Tvedt (1990) described a procedure for calculation of time-dependent reliability by use of nested application of first-order reliability method (FORM).

Marley and Moan (1992) proposed a method for the time-variant reliability of a component with deteriorating resistance and subjected to a stochastic load process. The method used an out-crossing formulation.

Johnson and Ayyub (1992) presented a method to assess the time-dependent probability of bridge failure due to pier scour.

Li and Melchers (1992) discussed a method for computation of the probability of serviceability of failure of a reinforced concrete structure subjected to stochastic loadings. The resulting time-variant problem is formulated as an up-crossing problem in stochastic process theory. Melchers (1992) proposed a Monte Carlo simulation procedure for the estimation of reliability of a structural system subjected to multi-parameter time-varying loads.

Ressler and Daniels (1992) described the formulation of the system reliability simulation model. It mainly employs Monte Carlo simulation to compute system reliability.

Ellingwood and Mori (1993) developed a time-dependent methodology for the deterioration of concrete structures at nuclear power plants. This method models significant structural loads as a sequence of pulses described by a Poisson process. Ellingwood (1995) later noted that the reliability and limit state functions are cumulative, i.e., they should be used to define the probability of successful performance during a service life.

Li and Melchers (1993a) developed a formulation for the out-crossing rate for multiple Gaussian vector processes out of convex polyhedrons. This is then used in the evaluation of probability of failure. Li and Melchers (1993b) proposed a method for estimating time-dependent structural system reliability. Li (1994a) applied a method of calculating the reliability using the up-crossing rate formulation along the same lines reported in their earlier work.

Li (1994b) proposed a solution for time-dependent structural reliability problem by employing the concept of first passage probability in stochastic process theory. Li (1995) proposed a method for time-dependent reliability where reliability analysis of a deteriorating system is based on the reliability of structural members constituting the failure sequence for the structure. The procedure is very similar to the one proposed by Li and Melchers (1993b) briefly discussed previously in this proposal.

Li (1996) proposed a method for evaluation of time-dependent structural system reliability without the use of the global limit state functions for the structural system. This approach is similar to the approach proposed by the authors in their previous work (Li and Melchers 1993b; Li 1995). The approach for time-dependent reliability analysis of structural systems is based on the reliability of structural components constituting the failure sequence of the system.

Marley (1993) discussed an out-crossing formulation for fatigue degradation.

Chan and Melchers (1993a) proposed a one-dimensional simulation procedure to estimate structural reliability in multi-dimensional load and resistance space using the idea of "strips" of points parallel to each other and sampled on the limit state hyperplanes. Chan and Melchers (1993b) proposed a method for evaluation of structural system reliability using out-crossing formulation.

Holicky, Holicka and Kolisko (1994) discussed the time-dependent reliability of deteriorating structures considering the environmental impacts as well as structural capacity as random variables using a fuzzy probabilistic approach.

Mahadevan and Xiao (1995) proposed a failure path approach for time-variant system reliability estimation of brittle structures. The method essentially uses Markov chain assumption to model cumulative damage under time-varying loads.

Yao and Wen (1996) proposed a method for time-dependent reliability using the response surface methodology in conjunction with fast integration technique (Wen and Chen 1987). The authors claim that this provides a computationally simple limit-state solution based on a small number of response time histories.

Hong (1996) proposed a procedure using the point estimate method to discretize the uncertain distribution parameters in the time-invariant reliability analysis, and to discretize the time-independent random variables and uncertain distribution parameters in the time-variant reliability analysis.

Patev et al. (1996a and 1996b), and Putcha and Patev (1998) examined time-dependent corrosion effects for a non-built-in example W-section using the time-dependent methods of Ellingwood and Mori (1993) and Ellingwood (1995).

Specifically for marine structures, Ayyub, White, and Purcell (1989) discussed a methodology for the structural life assessment of a ship using the reliability concepts and the statistics of extremes. The structural life expectancy is basically established using the selected failure modes. Ayyub and White (1990a and 1990b) developed a methodology for assessment of structural life of marine structures using the basic concepts of probabilistic analysis, and statistics of extremes. As shown in Ayyub et al (1989), this work is also based on the identification of failure modes as a function of time (structural life). Ayyub, White, Bell-Wright and Purcell (1990c) reported a comparative analysis between two different patrol boats. The comparison is based on the identification of two critical failure modes, plastic plate deformation and fatigue. The results are based on the basic assumption of the increase of extreme load effect and decrease of structural strength as the service life of a structure increases. Most of these concepts were reviewed by Ayyub and White (1995) in order to generalize them for any structural system.

Also for marine structures, Soares and Ivanov (1989) discussed a model to quantify the time variation of the reliability of a primary ship structure. The variation of resistance is assumed to be a decreasing function due to the corrosion effect.

The Ship Structure Committee also supported a research related to the study of life expectancy of ship structures, and some of the results were summarized on SSC reports 386-c and 386-d. The latter presented a methodology to support repair decisions of ship structures. The former provided a comprehensive document on design and maintenance strategies to improve the durability of ship structures.

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# APPENDIX B - RELIABILITY BASED VESSEL LIFE EXPECTANCY ASSESSMENT SOFTWARE DEVELOPMENT PLAN

## B.1 Scope

### B.1.1 Identification

This Software Development Plan (SDP) applies to the development of all the Computer Software Configuration Items (CSCI's) for the Reliability-Based Vessel Life Expectancy Assessment Software, described by BMT Fleet Technology Limited and BMA Engineering in the SSC report 1396.

### B.1.2 System Overview

This SDP details the proposed plan of development for a computer program to be used in the advisement of ship owners as to the suitability of vessel retirement or continued operation considering time dependant degradation of structural integrity.

### B.1.3 Document Overview

This SDP addresses each function required for the software development effort; including project organization, risk management, security, software engineering, formal qualification testing, quality assurance and configuration management.

This SDP describes the software development schedule and milestones, and discusses the software development library, interface with associate contractors and, when applicable, software problem reporting, the corrective action process, the software engineering environment, software standards and procedures, and formal technical reviews.

### B.1.4 Relationship to Other Plans

This SDP bears no particular relationship to any other SDP.

## B.2 Proposed Software Technical Scope

This section outlines the general functionality and features proposed for the software. Functionality includes the technical issues, calculations and problems the software should solve, while, features relates to the facilities included to manage and present data.

### B.2.1 Software Functionality

In SSC report 1396, techniques were developed and presented to estimate the time dependant reliability of ship structures. The technical background and sample application demonstrated the feasibility of the approach, however, there were a number of limitations and the potential to apply it to real problems was restricted. The following list of features or capabilities is presented to describe software that could be used effectively to assess real problems.

Limit States - The software will include the limit states listed below, but will be developed such that additional limit states or alternative formulations may be considered as well.

- Fatigue crack initiation
- Corrosion diminution - frame average, local and pitting
- Component first yield
- Buckling - Panel and Tripping

Loading - The software will consider wave induced loads and structural effects that will magnify their significance.

- Vessel operational profile
- Vessel Route and loading condition
- Structural stress concentrations

Degradation Modes - The software will include the degradation listed below, but will be developed such that alternative damage accumulation rates can be considered.

- Corrosion - wastage and coating life
- Fatigue

Reliability Analysis - The software will estimate time dependant reliabilities for components, frames and segments of the vessel considering the uncertainties listed below.

- degradation rate
- loads
- material properties
- weld and paint quality

Maintenance Management - The software will allow time or reliability based maintenance or repair strategies to be considered including:

- Paint re-application
- Steel renewals
- Crack repair

B.2.2 Software Features

In general, the analysis was far too complex and had too much data to be practically performed by hand. For this reason a number of user interface modules for problem definition and reviewing the analysis results are recommended. In addition, a reasonably extensive vessel data base system was recommended to handle relatively large volume of data required by the problem. A preliminary software component design is shown below indicating the relative hierarchy of the components within the proposed system.

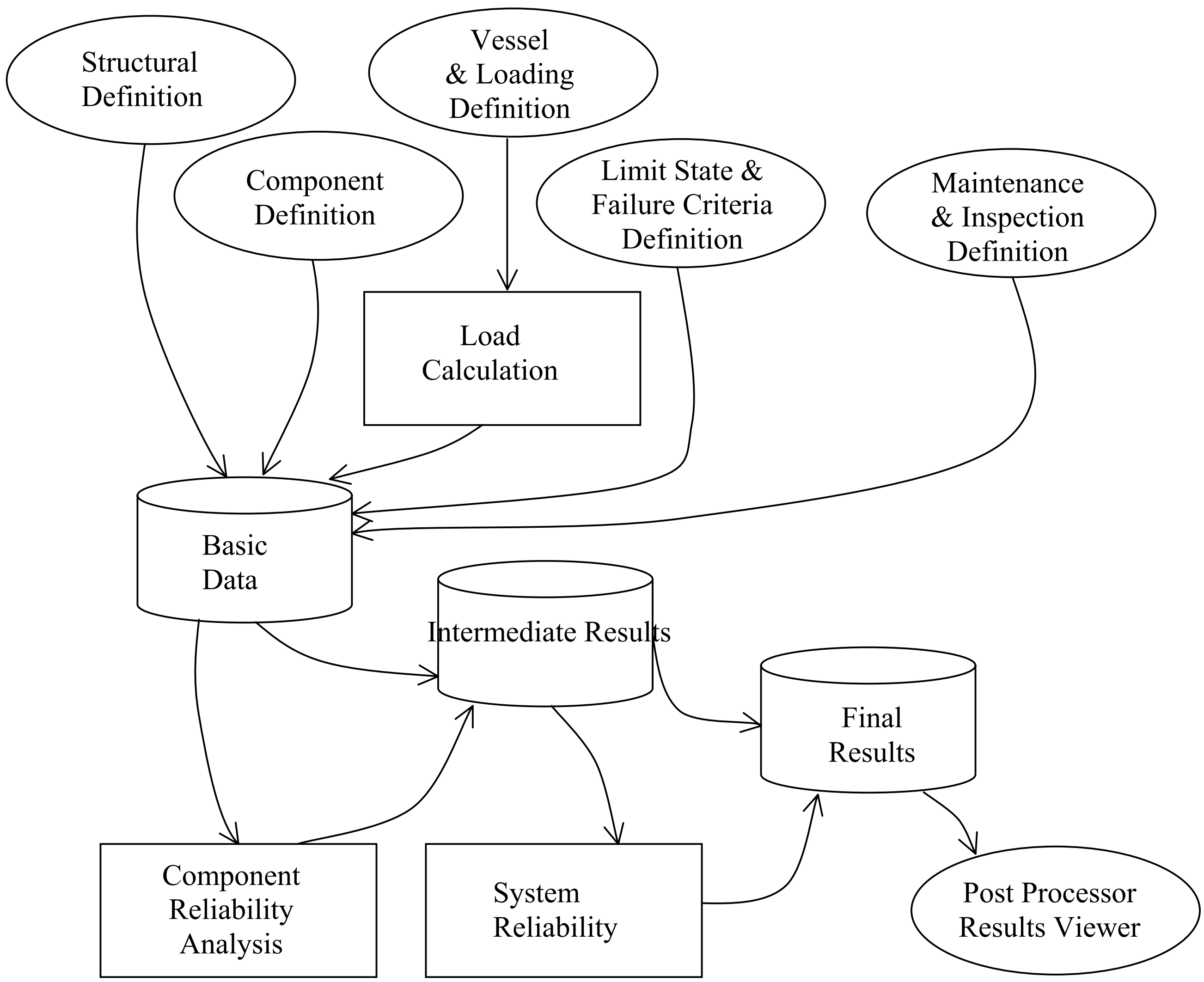


**Figure 2.1: Reliability-Based Vessel Life Expectancy Assessment Approach**

The software modules shown in Figure 2.1 include graphical user interfaces modules (oval), computational modules (rectangular) and databases (cans). The vertical position of the problem definition graphical user interfaces indicates their relative order in terms of data entry.

The key to the development of the proposed software is the development of user friendly and powerful graphical interfaces to collect data and the functionality of the data base systems. The remainder of the calculations and data processing are available in previously developed software and algorithms.

## B.3 Software Development Management

### B.3.1 Project Organization and Resources

#### *B.3.1.1 Supplier Facilities*

It is suggested that the development be carried our and directed from one primary engineering office since the complexity of the software requires a coordinated programming effort. All essential project resources, reference materials, hardware and software resources should be available at the primary engineering development location. There should not be any security aspects to this project requiring special secure areas or secure hardware.

#### *B.3.1.2 Client Furnished Equipment, Software and Services*

This project will ideally involve the use of pre-existing software developed by the coordinating engineering development company. No software or hardware will be required form the Client

The Client will be asked to support the project in terms of technical overview and input in terms of commentary on data availability and software ease of use.

#### *B.3.1.3 Organizational Structure*

The organizational structure of the project team should include:

- Project Manager - responsible for all administrative and managerial matters related to the project.
- Project Engineer - responsible for the analytical aspects of the program, coordination between the engineering and software portions of the contract, and in the conceptual design of the software. Also responsible for manual preparation, software quality assurance and testing.
- Consultant/Investigator - responsible for specific elements of the software technical content, as required.
- Software Engineer - responsible for all the programming, contributions to the user manual and concerned with all software development issues.

### B.3.2 Schedule and Milestones

#### *B.3.2.1 Activities*

The software development activities that are proposed for the development of the Reliability-Based Vessel Life Expectancy Assessment Software are as follows:

**Activity 1 - Software Kick-off Meeting**

An initial meeting between the development team and SSC to establish a working definition of goals and priority of desired program features. This meeting will comprise a segment of Progress Meeting #1.

Output from this meeting will be a written draft definition of the program objectives and user interface for the acceptance by the SSC representatives.

**Activity 2 - Formalization of Program Design and Production**

Based upon the acceptance of the draft definition of user interface, an initial version of the program will be produced. This version will include the user interface I/O modules envisioned necessary for all ship, degradation and limit state types, but will only contain data and calculation algorithms for corrosion diminution limit states. Output from this activity will be a functional program demonstrating the proposed input and output modules based upon the above ship, degradation and limit state types. Delivery and demonstration of this program will comprise a portion of the Progress Meeting #2.

**Activity 3 - Draft Final Program Design and Production**

Based upon feedback from the SSC representatives, the design and production of the complete program will be undertaken. The draft final version will contain data and calculation algorithms necessary for the remaining ship, degradation and limit state types outlined in the specified in the original software proposal, and any input/output module changes agreed upon after submitting the initial prototype. Output from this activity will be a functional draft final version of the program.

**Activity 4 - Final Program Production**

Based upon feedback from the SSC representatives, the production of the final version of the program incorporating any agreed upon minor changes from the submitted draft final will be produced. Output from this activity will be the final version of the program for contract purposes.

**Activity 5 - Program Testing**

Each working version of the program, from activities 2-4 above will be tested by a qualified user who has not been involved in the actual programming tasks. Internal company documentation will be produced listing any found program bugs complete with a description of the hardware platform and operating system software used for test purposes. A log of problem areas, known bugs and incomplete portions will be produced, which will be updated as each defect is corrected. Output from this activity is a dated log of program defects and omissions, and listing of when corrective measures were performed.

**Activity 6 - Production of a User Manual**

A user manual will be written which outlines the features and applications of the software. The user manual will be developed as an online help utility. The final version of the online manual, after SSC approval of content, will be published and used as the user manual.

*B.3.2.2 Activity Network*

**Activity 1** - The kick-off meeting will comprise a segment of Progress Meeting #1 which is scheduled to take place about two months after the beginning of the contract.

**Activity 2** - Formalization of the program design and production of the first working prototype will commence after completion of Activity 1, and will take place over a two-month period. Delivery and demonstration of the working prototype is scheduled to occur during Progress Meeting #3, about four months after the beginning of the contract.

**Activity 3** - Production of draft final program will commence after Activity 2, and will take place over a two six month period. Delivery and demonstration of the working draft final program is scheduled to occur about ten months after the beginning of the contract.

**Activity 4** - Production of the final delivered version of the program will be accomplished about 1 month after completion of Activity 3, or about eleven months after the beginning of the contract.

**Activity 5** - Program testing will be an ongoing process, beginning with the start of coding in Activity 2 and lasting until the final product is delivered.

**Activity 6** - Production of the user manual will begin as the coding commences and be completed upon final delivery of the software (Activity 4). Draft versions of the manual (in English) will be delivered along with the draft software versions from Activities 2 and 3.

B.3.3 Risk Management

Project risks are thought to be moderate. The completion of the previous concept demonstration project has demonstrated the feasibility of the approach and the technical aspects of the project are well understood.

Risks in terms of production of a working program containing acceptable input and output interfaces are very low. The programming skills needed to accomplish these requirements are readily available from a number of sources, should it become necessary to replace any existing personnel. Many of the required software modules should already be available to the project team as in-house resources.

Risks with regard to development of acceptable methodology to be used in the selection guide are of a more moderate nature. These skills are somewhat more difficult to replace if necessary, with a possible modest delay in delivery being the result.

Risks that the generalized algorithms developed for use for the production of the first prototype (corrosion diminution) are not applicable to remaining buoys are thought to be minimal. The consequences of this possibility are slight, with a modest increase in programming effort being the worst-case result.

#### B.3.4 Safety

There are no known safety considerations specific to this project alone.

#### B.3.5 Security

No information related to this project is of a classified nature.

#### B.3.6 Interface with Associate Contractors

There are no associate contractors to be involved in this project.

#### B.3.7 Interface with Software IV&V Agent(s)

An independent verification and validation (IV & V) agent could be used in this project. Alternatively, verification and validation could be provided by in-house personnel of the development company not involved with programming, as well as by SSC representatives themselves if they desire.

#### B.3.8 Formal Reviews

Due to the modest nature of the project formal reviews will not be held. Rather, informal reviews between the project team members will be held on an ongoing basis.

## B.4 Software Engineering

### B.4.1 Organizational Structure

The Project Engineer would be responsible for the software design, assisted by the Software Engineer, responsible for the software implementation. The organization of the project team is outlined below.

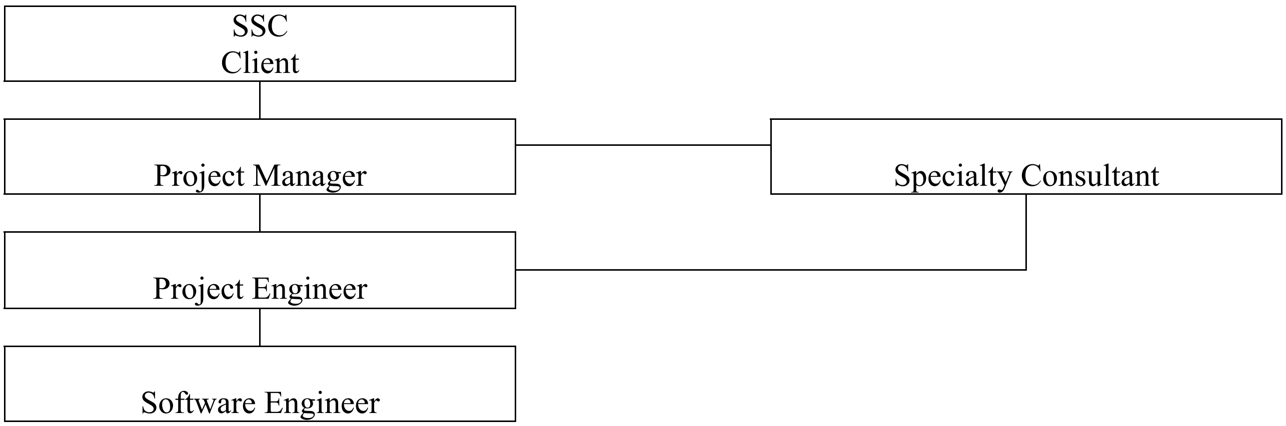


**Figure B.4.1: Software Development Team**

### B.4.2 Software Engineering Environment

#### *B.4.2.1 Software Items*

The software items that will be used to complete this project include:

- Visual Studio.net including (C++, C#, Fortran, Visual Basic)
- Microsoft Windows (version 2000 Professional)
- Microsoft Access (version Office XP)
- Microsoft Access Software Development Kit for Access (version Office XP)
- Map Info - GIS utility for vessel routing
- Visual Source Save - Software development configuration management tool
- ComponentOne - Plotting and graphing add in utility

Windows have become the de-facto operating system standards used throughout the world. Access was chosen as the primary programming tool because its database capability and Windows features were thought to provide an easily expandable, user friendly operating environment. The required software to run the program will be MS Windows. It will not be necessary to have Access to run the program, as the delivered program will contain a royalty-free run-time version of Access.

#### *B.4.2.2 Hardware and Firmware Items*

The program will be written to run on a minimum hardware platform of:

- Pentium III IBM compatible computer
- 128 MBytes Ram
- 100 MBytes hard disk space (database size dependant)
- VGA monitor and graphics card

#### *B.4.2.3 Source Identification*

The software resources identified in section 4.2.1 and the hardware resources listed in section 4.2.2 are commonly available resources that would need to be made available for project use throughout the duration of the contract.

#### *B.4.2.4 Proprietary Nature and SSC Rights*

SSC will have the right to use the software within their organizations while the rights to market, develop or distribute the software could be retained by the engineering development company. This point should be open for discussion and perhaps a royalty on sales could be provided to the SSC.

### B.4.3 Software Standards and Procedures

#### *B.4.3.1 Software Development, Techniques and Methodologies*

The techniques to be used to perform the design, coding and testing of the product will be ones that the development company has successfully employed in previous software development projects. Designs will be documented, discussed and finalized between the Project Engineer, the Software developer and the SSC Project Authorities. A preliminary framework of code will be written and critiqued. This preliminary program will become the working basis for the final product. Software testing will be performed by a person not intimately involved with the coding, and as problems are uncovered they will be corrected as necessary.

#### *B.4.3.2 Design Standards*

The program will conform to the normally found Windows interface standards. These interface standards are well known and are not discussed in this SDP. All charts and graphic elements will as well be standard Windows display elements. Naming conventions for data elements and software modules should conform to the internal practice of the development company and industry practice in being descriptive, easy to understand English names.

#### *B.4.3.3 Coding Standards*

The coding standards used for the project, while not formalized, are ones that follow the basic rule of readability. Indentation, spacing and capitalization are used throughout to improve the readability and logical grouping of code segments. Naming conventions used for variables, parameters, and code constructs are chosen to quickly impart an understanding of those items, using consistent prefixes and/or capitalization throughout.

### B.4.4 Non-Developmental Software

The Reliability-Based Vessel Life Expectancy Assessment Software should not incorporate any non-developmental (commercially available) software.

## B.5 Formal Qualification Testing

### B.5.1 Organizational Structure

Formal qualification testing should be performed by engineering development company personnel not involved in the software engineering.

### B.5.2 Test Approach/Philosophy

The qualification testing approach to be used will be to systematically vary the user selectable input parameters throughout the acceptable range to ensure operational integrity.

### B.5.3 Test Planning Assumptions and Constraints

No specific assumptions have been made with reference to test planning, and no constraints on formal qualification testing by SSC are envisioned.

## B.6 Software Configuration Management

### B.6.1 Organizational Structure

The software engineer will be responsible for configuration management for the project. In general, configuration management will follow the process outlined in Figure 6.1 to develop a documented trail of software modifications.

### B.6.2 Software Developmental Configuration

Standard practices will be used in identifying all Computer Software Configuration Items (CSCIs), Computer Software Components (CSCs), Computer Software Units (CSUs) and documents.

### B.6.3 Configuration Control

#### *B.6.3.1 Flow of Configuration Control*

Problems will be reviewed on an ongoing basis between project members. If the problems are sufficient to produce a change in approach or any significant change to the scope of the project they will be documented for team members and TDC/CCG authorities to review.

Visual Source Save will be used for software configuration management allowing more than one programmer to work on the project. The system controls software code and assures traceability and management of code modifications. The engineering development company project team should be well accustomed to working with a software configuration management system of this type.

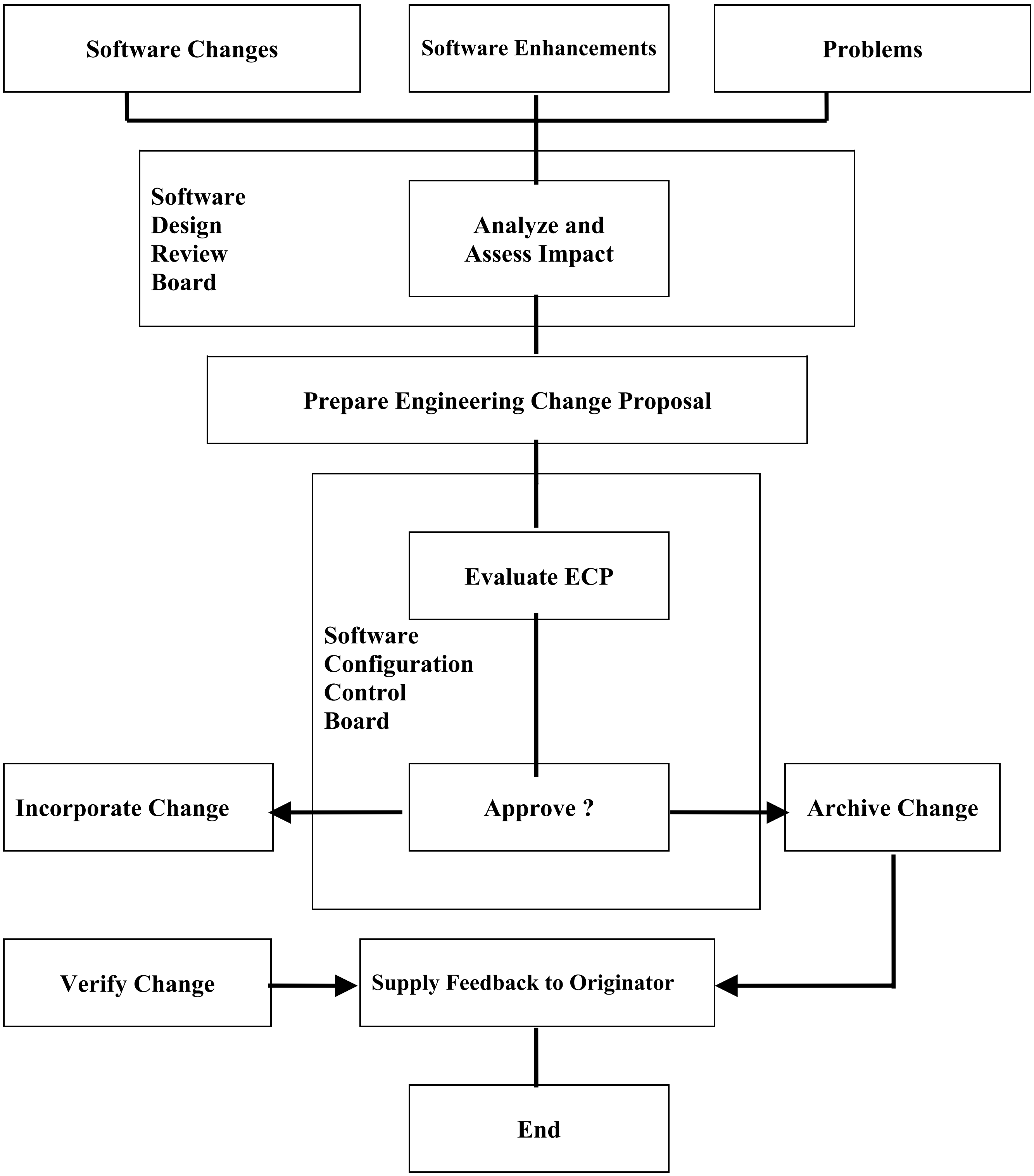


**Figure 6.1: Configuration Control Flow Chart**

*B.6.3.2 Problem/Change Report*

Internal company documentation will be produced listing any found program bugs complete with a description of the hardware platform and operating system software used for test purposes. A log of problem areas, known bugs and incomplete portions will be produced, which will be updated as each defect is corrected. Output from this activity is a dated log of program defects and omissions, and listing of when corrective measures were performed.

B.6.4 Preparation for Delivery

Software will be delivered on CDs with labels bearing the program name, version number and month/year of production. A similar name, version number and month/year of production designation will be used on printed documentation. A section of the delivered documentation will contain instructions pertaining to the installation and operation of the software.

## B.7 Software Quality Assurance

B.7.1 Organizational Structure

Software quality assurance will be performed by the project team members, primarily the Software Engineer and the Project Engineer. These personnel are organized as shown in section 4.1.

B.7.2 Schedule

Software quality assurance will occur concurrent with the production of the draft and final versions of the program as proposed in section 3.2.2.

B.7.3 Software Quality Assurance Procedures, Tools and Records

*B.7.3.1 Procedures*

Due to the modest nature of the programming project, formalized software quality assurance procedures will not be used. The program will be subject to continuing review by project team members to ensure it's overall quality is of a satisfactory nature.

*B.7.3.2Tools*

Specific quality assurance tools will not be used for this project.

*B.7.3.3Software Quality Records*

All quality assurance memos will be made available for review by the SSC Project Officers.

## B.8 Notes

### B.8.1 Glossary

**Computer Software Component (CSC) -** A distinct part of a Computer Software Configuration Item (CSCI). CSCs may be further decomposed into other CSCs and into Computer Software Units (CSUs).

**Computer Software Configuration Item (CSCI)** - An aggregate of software, or any of its discrete portions that satisfies an end-user function and is designated to be put under configuration control. CSCIs may vary greatly in complexity, size and type, from a database management system to a diagnostic function. Selecting too many CSCIs may decrease management visibility by making status reporting too burdensome, while selecting too few may increase development costs because changes in one function may require action on the entire CSCI.

**Computer Software Unit (CSU)** - An element specified in the design of a Computer Software Component (CSC) that is separately testable.

**Software Development Plan (SDP)** - A document outlining the methodology, control, and plan of a software program.

**SSC** US Ship Structures Committee.

### B.8.2 Software Development Report Forms

TABLE 1: Category Classifications for Problem Reporting

| SYMPTOM | | CATEGORY |
|---|---|---|
| | | |
| 1. | The software does not operate according to supporting documentation and:<br>a. the documentation is correct (Software Problem)<br>b. the documentation is incorrect but the software operation is correct (Documentation Problem) | <br>a<br>b |
| | | |
| 2. | The software operates according to supporting documentation, but a design deficiency exists (Design Problem) | c |
| | | |
| NOTE: | The design deficiency may not always result in a directly observable operational symptom but possess the potential for creating further problems. | |

TABLE II: Priority Classifications for Problem Reporting

| POTENTIAL IMPACT | | PRIORITY |
|---|---|---|
| | | |
| 1. | The problem affects the accomplishment of an operational or mission essential capability specified by baseline requirements and it: | |
| | | |
| | a. prevents accomplishments of the capability | 1 |
| | | |
| | b. prevents the operator's accomplishment of the capability | 1 |
| | | |
| | c. adversely affects accomplishments of the capability so as to degrade performance and; | |
| | | |
| | (1) no alternative work around solution is known | 2 |
| | (2) an alternative work around solution is known | 3 |
| | | |
| | d. adversely affects the operator's accomplishment of the capability so as to degrade performance and; | |
| | | |
| | (1) no alternative work-around solution is known | 2 |
| | (2) an alternative work-around solution is known | 3 |
| | | |
| 2. | the problem jeopardizes personnel safety | 1 |
| | | |
| 3. | the problem causes an operator inconvenience or annoyance but does not affect a required operational or mission essential capability | 4 |
| | | |
| 4. | the problem does not have one of the impacts described above | 5 |

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