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RISK-INFORMED INSPECTION OF MARINE VESSELS

SHIP STRUCTURE COMMITTEE
2002

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The study developed and demonstrated a practical methodology and procedures for using a risk approach in the decision making process for structural inspection. A systems approach has been developed for risk-based optimal inspection management of ship structures. This approach consists of the synergistic combination of decision models, advanced probabilistic reliability analysis and risk algorithms, and conventional mechanistic residual strength assessment methodologies that have been employed in the marine vessel industry for structural integrity evaluation. This approach realistically accounts for the various types/sources of uncertainties involved in the decision-making process including uncertainties in the defect data gathered from inspections, material types, loads, parameters of the repair method, as well as the engineering strength models that are employed. Furthermore, the probabilistic approach is capable of taking direct advantage of previously verified residual strength assessment models and engineering experience that has been compiled over the years from the operation of these vessel systems.

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16. Abstract

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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			
$inches^2$ $feet^2$	$centimeters^2$ $meters^2$	multiply by	1.9665
$inches^2$ $feet^2$	$centimeters^3$	multiply by	196.6448
$inches^4$	$centimeters^3$	multiply by	16.3871
MOMENT OF INERTIA			
$inches^2$ $feet^2$	$centimeters^2$ meters	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/$inch^2$ $inch^{½}$(ksi√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

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ABSTRACT

This report documents the results of a study conducted by a team comprised of Proteus Engineering Division of Anteon Corporation (Prime), BMA Engineering, Inc., and Martec Limited, working for the Ship Structure Committee under United States Coast Guard Research and Development Center Contract DTCG32-01-F-100017. The study focused on ship's structure risk-informed inspection, which is a probabilistic approach for making maintenance decisions on systems with inherent uncertainties. Although probabilistic based tools have been used for structural integrity analysis of ship structures, probabilistic risk-based methods have not been applied for inspection scheduling of ship structural systems.

The study developed and demonstrated a practical methodology and procedures for using a risk approach in the decision making process for structural inspection. A systems approach has been developed for risk-based optimal inspection management of ship structures. This approach consists of the synergistic combination of decision models, advanced probabilistic reliability analysis and risk algorithms, and conventional mechanistic residual strength assessment methodologies that have been employed in the marine vessel industry for structural integrity evaluation. This approach realistically accounts for the various types/sources of uncertainties involved in the decision-making process including uncertainties in the defect data gathered from inspections, material types, loads, parameters of the repair method, as well as the engineering strength models that are employed. Furthermore, the probabilistic approach is capable of taking direct advantage of previously verified residual strength assessment models and engineering experience that has been compiled over the years from the operation of these vessel systems. The proposed methodology could lead to the provision of a capability for quantitatively assessing reliability and risk levels to ensure the safe operation of existing vessels. The capability could also provide a rational framework and basis for extending the life of current vessels, as well as the re-qualification of such vessels using quantitative risk-based methodologies. The application of such a capability could lead to improved reliability levels, and significantly reduce incidents/accidents that cause damage to property, personnel and the environment. The application of the technology is also believed to have substantial potential to realize cost savings in the inspection, maintenance, and repair of aging vessel systems.

The guidelines are provided herein in seven chapters. Chapter 1 provides background information, problem definition, objectives, scope, and report structure. Chapter 2 provides background information on current inspection methods and degradation mechanisms of ship structures. Chapter 3 provides the proposed methodology and the guidelines. Chapter 4 demonstrates the guidelines and the methodology using a case study and examples. Chapter 5 provides a software development plan. Chapter 6 provides conclusions and recommendations. A bibliography is provided in Chapter 7 is a bibliography that includes all the cited references along with other sources providing background information on risk methods and their applications.

The innovative aspects of the study include: (i) the development and application of probabilistic based qualitative and quantitative risk measures, and ranking and screening schemes for optimizing the inspection/maintenance of ship structures; and (ii) the use of a decision framework that incorporates risk and comparative cost models for optimal selection of inspection scheduling. The scope of the study includes: (i) the development and testing of a prototype risk informed methodology for performing marine inspections; (ii) the preparation of a long-term plan to evolve the prototype into a fully mature capability; and (iii) the creation of the infrastructure needed to support the development, use and dissemination of the new technology.

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1. INTRODUCTION

1.1. Background

This report documents the results of a study conducted by a team comprised of Proteus Engineering Division of Anteon Corporation (Prime), BMA Engineering, Inc., and Martec Limited, working for Ship Structure Committee under United States Coast Guard Research and Development Center Contract DTCG32-01-F-100017. The study focused on ship's structure risk-informed inspection, which is a probabilistic approach for making maintenance decisions on systems with inherent uncertainties. Although probabilistic based tools have been used for structural integrity analysis of ship structures, probabilistic risk-based methods have not been applied for inspection scheduling of ship structural systems.

The innovative aspects of the study include: (i) the development and application of probabilistic based qualitative and quantitative risk measures, and ranking and screening schemes for optimizing the inspection/maintenance of ship structures; and (ii) the use of a decision tree framework that incorporates risk and comparative cost models for optimal selection of inspection scheduling. The scope of the study includes (i) the development and testing of a prototype risk informed methodology for performing marine inspections; (ii) the preparation of a long-term plan to evolve the prototype into a fully mature capability; and (iii) the creation of the infrastructure needed to support the development, use and dissemination of the new technology.

1.2. Risk-Based Methods

Inspection practices of marine vessels including structural systems, that consists of subsystems, components and details, can be improved by utilizing risk-based methods and tools. These methods and tools can be used to assess existing practices, and develop inspection strategies that optimize use of resources. In an environment of increasingly complex engineering systems, the concern about the safety of these systems continues to play a major role in both their design and operation. Failure consequences of vessels can include human injuries and/or loss, economic losses due to unavailability of the system, and environmental damages such as pollution, for example, in the case of oil tankers. Systematic, quantitative or qualitative or semi-quantitative approaches for inspection planning, management and execution for these systems by assessing their failure probabilities and consequences and managing associated risks are needed. A systematic approach allows an engineer to evaluate and manage the inspection of complex engineering systems for safety and risk under different operational conditions. A risk-based framework is compatible with decision analysis methods that are based on cost-benefit tradeoffs.

Ayyub, et al. (1997, 1998a and 2002) recently discussed the marine-industry needs in these areas. Appendix A provides the needed background information on risk-based technology methods.

When assessing and evaluating uncertainties associated with an event, risk is defined as the potential for loss as a result of a system failure, and can be measured as a pair of factors, one being the probability of occurrence of an event, also called a failure scenario, and the other being the potential outcome or consequence associated with the event's occurrence. This pairing can be represented by the equation:

$$Risk \equiv [(p_1, c_1), (p_2, c_2), \ldots, (p_x, c_x)] \quad (1\text{-}1)$$

where p_x is the probability that event x will occur, and c_x is the consequence or outcome of the event's occurrence. Risk is commonly evaluated as the product of the likelihood of an event's occurrence and the impact of the event:

$$RISK\left(\frac{Consequence}{Time}\right) = LIKELIHOOD\left(\frac{Event}{Time}\right) \times IMPACT\left(\frac{Consequence}{Event}\right) \quad (1\text{-}2)$$

In Eq. 2, likelihood may also be expressed as a probability. Occurrence probabilities (which can be annual) and consequences can be plotted as a Farmer curve (Ayyub et al. 1999).

Risks to a system may result from its interaction with natural hazards, its aging and degradation, or from human and organizational factors. Consequently, risk can be classified as either voluntary or involuntary, depending on whether or not the events leading to the risk are under the control of the persons at risk. Society generally accepts a higher level of voluntary risk than involuntary. The losses associated with events may be classified as either reversible or irreversible, depending whether the loss is of property or of human life, respectively.

Risk studies should consider the population-size effect because society responds differently to risks associated with large populations than it does to those associated with small populations. For example, a risk of fatality at the rate of 1 person in 100,000 per event for an affected population of 10 results can be viewed as a *tolerable* expected fatality of 10^{-4}; whereas the same fatality rate per event for an affected population of 10,000,000 results in an *intolerable* expected fatality of 100 per event. While the numerical impact of the two scenarios is the same on society, the size of the population at risk should be considered as a factor in setting an acceptable risk level.

Risk methods may be classified as either risk management, which includes risk assessment and risk control, or risk communication, as shown in Figure 1-1.

Risk assessment is a technical and scientific process by which the risks of given situations for a system are modeled and quantified. Risk assessment provides qualitative and quantitative data to decision-makers for later use in risk management.

Risk assessment includes risk analysis and risk evaluation, where risk analysis consists of hazard identification, event-probability assessment, and consequence assessment, and risk evaluation requires the definition of acceptable risk and a comparative evaluation of options and/or alternatives. Risk control is achieved through monitoring and decision analysis. Risk communication is classified according to its target audience: either the media and the public or the engineering community.

The reliability of a system can be improved or decreased by the combination of individual elements in a system; therefore, occurrence probability and consequence are used to determine the risk associated with the system. When applying risk-based technology methods to system safety analysis, the following interdependent primary activities are considered: (1) risk assessment, (2) risk management, and (3) risk communication. These activities, when applied consistently provide a useful means for developing safety guidelines and requirements to the point where hazards are controlled at predetermined levels.

A risk assessment answers three questions: (a) What can go wrong? (b)What is the likelihood that it will go wrong? (c) What are the consequences if it does go wrong? In order to perform risk assessment several methods have been created including:

- Safety and Review Audits,
- Check list,
- What-if,
- Hazard and Operability Study (HAZOP),
- Probabilistic Risk Analysis (PRA),
- Preliminary Hazard Analysis (PrHA),
- Failure Modes and Effects Analysis (FMEA),
- Failure Modes Effects and Criticality Analysis (FMECA),
- Fault Tree Analysis (FTA), and
- Event Tree Analysis (ETA).

Each method is suitable in certain stages of a system's life cycle.

The characteristics of commonly used methods are shown in Table 1-1. Each method is discussed thoroughly in subsequent sections. Other methods for reliability and consequence analysis and assessment are described by Kumamoto and Henley (1996).

Risk assessment methods can also be categorized according to whether the risk is determined by quantitative or qualitative analysis. Qualitative risk analysis uses expert opinion to identify and evaluate the probability and consequence of a hazard; quantitative analysis relies on statistical methods and databases. Safety Review/Audit, Checklist, What-If, Preliminary Hazard Analysis, and HAZOP are normally considered qualitative techniques. Probabilistic Risk Analysis, Failure Modes and Effects Analysis, Fault Tree, and Event Tree are generally considered quantitative risk assessment techniques. Whether to select a quantitative or a qualitative risk assessment method depends upon the availability of data for evaluating the hazard and the level of comfort of those performing the risk assessments.

Risk management incorporates all the processes by which system operators, managers, and owners make safety decisions and regulatory changes, and choose system configurations based on the data generated in the risk assessment; risk management involves using information from risk assessment stage to make educated decisions about different configurations and operational parameters of a system. Its aim is to maintain the safety of the system and to control the risks involved in operating the system.

Risk management facilitates the making of decisions based on risk assessment and other factors including economic, political, environmental, legal, reliability, producibility, and safety.

Despite society's attempt to prevent accidents, government agencies can be reactive in the development of regulations. The answer to the question "How safe is safe enough?" is difficult to reach because of changing perceptions and understandings of risk. Unfortunately, it often takes a disaster to stimulate action for safety issues. Although communication is necessary, it is important that risk management be separated from risk assessment to lend credibility to the risk assessment without biasing the evaluation in consideration of other factors. Especially in a qualitative assessment of risk, where "expert judgment" plays a role in decisions, it is important to allow the risk assessors to be free of the political pressures that managers encounter; however, there must be communication linking the risk assessors and risk managers. The risk assessors need to assist the risk managers in making decisions. While the managers should not be involved in making risk assessments, they should be involved in presenting the assessors with questions that need to be answered.

Several steps that should be considered in order to determine acceptable risk (Ayyub et al. 1999): (1) define alternatives, (2) specify the objectives and measures for effectiveness, (3) identify consequences of alternative, (4) quantify values for consequences, and (5) analyze alternatives to select the best choice. Risk managers need to weigh various other factors for example, a manager might make a decision based on cost and risk using decision trees (Ayyub and McCuen 1997).

Risk communication can be defined as an exchange of information and opinion among individuals, groups, and institutions. This definition of risk communication contrasts it to risk-message transmittal from experts to non-experts. Risk communication should be interactive (NRC 1989); however, simply constructing a process as two-way does not make it an easy process. Technical information about controversial issues needs to be skillfully related by risk managers and communicators who may be viewed by the public as adversaries. Risk communication between risk assessors and risk managers is necessary to fully understand and effectively apply risk assessments in decision-making. Risk managers must participate in determining the criteria for determining acceptable and unacceptable risks.

While risk communication vitally links risk assessors, risk managers, and the public, it does not necessarily lead to harmony among the parties. Risk communication is a complex, dynamic process that must be handled with extreme care by experts, especially after disasters. Risk managers must establish contingency plans for risk communication about disasters. Added pressure by the media and the public, following a disaster, can create miscommunication that might be difficult to undo or remedy.

Reliability of a system can be defined as the system's ability to fulfill its design functions for a specified time. This ability is commonly measured using probabilities. Reliability is, therefore, the probability that the complementary event will occur to failure, resulting in

$$\text{Reliability} = 1 - \text{Failure Probability} \tag{1-3}$$

Based on this definition, reliability is one of the components of risk. Safety can be defined as the judgment of a risk's acceptability for the system safety, making to a component of risk management.

After risk and safety analyses are performed, system improvement in terms of risk can be achieved in one or more ways: (1) consequence reduction in magnitude or uncertainty, (2) failure-probability reduction in magnitude or uncertainty, and (3) reexamination of acceptable risk. Commonly in engineering, attention is given to failure-probability reduction in magnitude or uncertainty because it offers more system variables that can be controlled by analysts than the other two cases. As a result, it is common to perform a reliability-based design of systems. However, the other two cases should be examined for possible solution because they might offer some innovative options for system improvement.

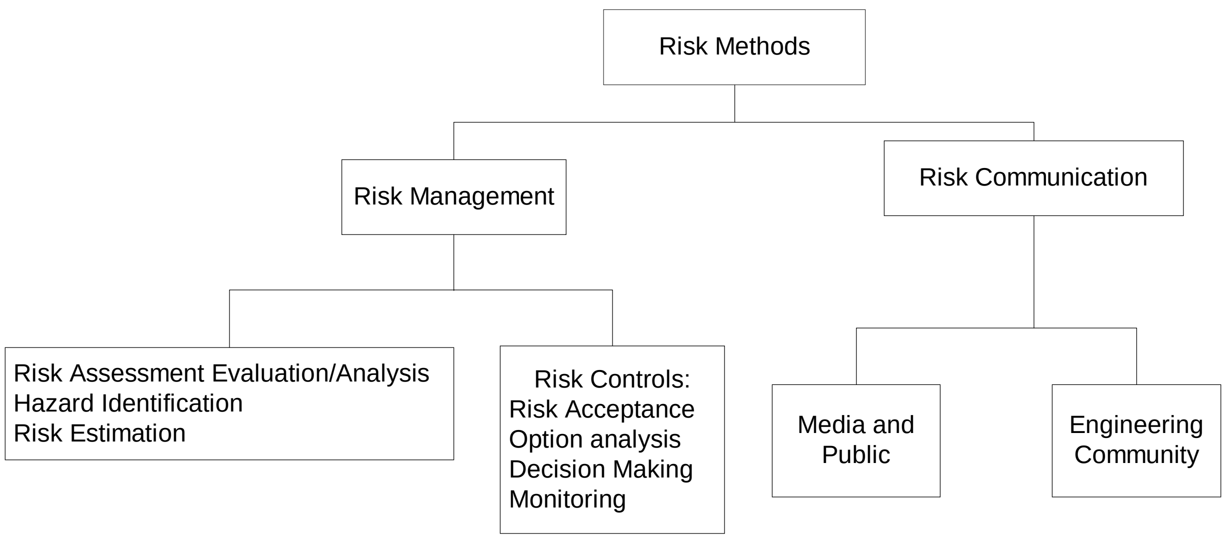

Figure 1-1. A Classification of Risk Methods

Table 1-1. Risk Assessment Methods

Method	Scope	Type of Analysis
Safety/Review Audit	Identify equipment conditions or operating procedures that could lead to a casualty or result in property damage or environmental impacts.	Qualitative
Checklist	Ensure that organizations are complying with standard practices.	Qualitative
What-If	Identify hazards, hazardous situations, or specific accident events that could result in undesirable consequences.	Qualitative
Hazard and Operability Study (HAZOP)	Identify system deviations and their causes that can lead to undesirable consequences and determine recommended actions to reduce the frequency and/or consequences of the deviations.	Qualitative
Probabilistic Risk Analysis (PRA)	Methodology for quantitative risk assessment developed by the nuclear engineering community for risk assessment. This comprehensive process may use a combination of risk assessment methods.	Quantitative
Preliminary Hazard Analysis (PrHA)	Identify and prioritize hazards leading to undesirable consequences early in the life of a system. Determine recommended actions to reduce the frequency and/or consequences of the prioritized hazards. This is an inductive modeling approach.	Qualitative
Failure Modes and Effects Analysis (FMEA)	Identifies the components (equipment) failure modes and the impacts on the surrounding components and the system. This is an inductive modeling approach.	Quantitative
Failure Modes Effects and Criticality Analysis (FMECA),	Identifies the components (equipment) failure modes and the impacts on the surrounding components and the system. This is an inductive modeling approach.	Quantitative
Fault Tree Analysis (FTA)	Identify combinations of equipment failures and human errors that can result in an accident. This is a deductive modeling approach.	Quantitative
Event Tree Analysis (ETA)	Identify various sequences of events, both failures and successes that can lead to an accident. This is an inductive modeling approach.	Quantitative

1.3. Degradation Mechanisms

The most invasive types of structural damage encountered by ship structures include corrosion and cracking, either of which, if neglected, may lead to unnecessary expense, with potentially dire consequences. Corrosion may reveal itself in a variety of forms, including general corrosion, corrosive pitting, and corrosion-assisted fatigue cracking. The rate at which corrosive degradation occurs is highly dependent on environmental conditions, such as moisture, acidity, and oxygen content. Cracking, fatigue-induced or otherwise, is a very serious problem for ship structural components. Whether brittle or ductile in nature, crack development and subsequent growth depends on a number of material-, load-, and environment-related parameters. Excessive deformation such as denting, buckling or distortion of structural components also contributes significantly to damage in ship structures. Structural components may also be damaged over time as a result of erosion, which is particularly common in areas where a fluid's direction of flow is altered. Some sort of protective coating is often applied to components as a first line of defense against structural damage. However, this coating may deteriorate over time, thereby opening a window of opportunity for other damage mechanisms. A more extensive review of the damage mechanisms and maintenance requirements for ship structures is provided in Chapter 2.

1.4. Inspection and Maintenance Practices

Inspection and maintenance practices have been developed and are documented by a number of maritime organizations, including ship owners, the Navy, and classification societies. Ongoing trends in this area include increased standardization of inspection and maintenance practices among organizations, a drive to decrease cost while improving reliability, and the increased use of technology. The most important inspection practice continues to be visual inspection. Maintenance practices are turning more to condition-based instead of run-to-failure or periodic maintenance.

1.5. Objectives, Scope and Report Structure

The primary objective of the work is the development and demonstration of a practical methodology and procedures for using a risk approach in the decision making process for structural inspection. A systems approach has been developed for risk-based optimal inspection management of ship structures. This approach consists of the synergistic combination of decision models, advanced probabilistic reliability analysis and risk algorithms, and conventional mechanistic residual strength assessment methodologies that have been employed in the marine vessels industry for structural integrity evaluation. This approach realistically accounts for the various types/sources of uncertainties involved in the decision-making process including the defect data gathered from inspections, material types, loads, parameters of the repair method, as well as the engineering strength models that are employed. Furthermore, the probabilistic approach is capable of taking direct advantage of previously verified residual strength assessment models and engineering experience that has been compiled over the years form the operation of these vessel systems. The proposed methodology could lead to the provision of a capability for quantitatively assessing reliability and risk levels to ensure the safe operation of existing vessels. The capability could also provide a rational framework and basis for extending the life of current vessels, as well as the re-qualification of such vessels using quantitative risk-based methodologies. The application of such a capability could lead to improved reliability levels, and significantly reduce incidents/accidents that cause damage to property, personnel and the environment. The application of the technology is also believed to have substantial potential to realize cost savings in the inspection, maintenance, and repair of aging vessel systems.

This study provides risk-based guidelines for managing inspection needs for maintaining structural integrity of ships in a lifecycle framework. The guidelines provide risk measures that can help focus a vessel condition manager's attention on the most risk-significant degradation modes and sites.

The guidelines are provided herein in seven chapters. Chapter 1 provides background information, problem definition, objectives, scope, and report structure. Chapter 2 provides background information on current inspection methods and degradation mechanisms of ship structures. Chapter 3 provides the proposed methodology and the guidelines by presenting the technical approach in the form of a risk-based methodology for maintaining and managing the structural integrity of ship systems through inspection. Chapter 4 demonstrates the guidelines and the methodology using a case study and examples. Chapter 5 provides a software development plan. Chapter 6 provides conclusions and recommendations. A bibliography is provided in Chapter 7, at the end report that include all the cited references along with other sources that provide background information on risk methods and their applications.

2. OVERVIEW OF CURRENT INSPECTION AND MAINTENANCE PRACTICES

2.1. Introduction

Ship structural maintenance is the term used to describe a collection of actions that are taken to prevent unwarranted degradations in the strength and serviceability of a ship structure. Such actions typically include some form of monitoring, inspection and repair. The ultimate goal of ship structural maintenance is to preserve the integrity of a ship's structural system through judicious renewal of steel and repair of damaged elements

Currently, steel is the primary material used in ship construction. This common use of steel can be attributed to the material properties, in particular, strength, durability and stiffness, required to meet the needs of ship structures at a reasonable cost. However, steel structures degrade with time due to the continuous environmental loading imposed on the ship, the corrosive nature of the environment in which ships operate, and general wear and tear. This degradation manifests itself in several forms, including corrosion and cracking.

Cracks and corrosion are the most pervasive types of structural damage experienced by ship structures. Each problem, if not properly repaired or rectified, can potentially lead to catastrophic failure or unanticipated out-of-service downtime. Several studies have been undertaken to investigate the nature of degradation in commercial and naval ship structures (Ship Structure Committee reports SSC-365, SSC-386, SSC-312, and SSC-372, for example). Most of the studies indicate that the nature of the defect found in a ship structure depends on a large number of variables, including the quality of construction, inspection, and repair practices, and also quality control and assurance.

This chapter provides a summary of various degradation mechanisms and maintenance practices that are commonly executed in ship structures throughout their lives.

2.2. Degradation Mechanisms

2.2.1. Protective Coating Breakdown

Protective coating is a component of the structure that performs a very important task. As noted by Naval Sea System Command (1997), "*Annual corrosion control costs have led the Navy maintenance community to institutionalized state of the art surface preparation, coating and inspection procedures for seawater ballast, potable water and other critical tanks and void spaces. This new direction will double or triple the current service life of tank corrosion.*"

Protective coating encompasses any coating, lining, or other material designed to protect the ship from wear and corrosion. Protective coatings typically include galvanizing, paint, deck linings/deck compositions (excluding carpet), anodizing, and metal spray. The importance of a protective coating and the level of priority for its repair are directly related to the structure that it protects. A protective coating can break down through blistering or some other mechanism, and subsequently expose the bare steel surface of the structure. In this sense, a defect is essentially a failure of the protective coating as opposed to corrosion, in that corrosion is deemed to have occurred after there has been an appreciable loss of protective coating and the metal surface has been exposed for some time. Repairs for protective coating failures are closely linked to the required performance and maintainability of the coating.

The range in coating lives can be related to the component location and environment. For example, the coating life normal distribution statistics outlined in Table 2-1 can be used (SSC SR 1396).

Table 2-1. Coating Life Statistics (SSC SR 1396)

Locations	Coating Life (years)	
	Mean	Coefficient of Variation
Living Space	10	0.2
Exterior Deck	9	0.2
Interior Deck	10	0.2
Dry Cargo Space	1	0.3
Ballast Tank	5	0.3
Liquid Cargo Space	7	0.3

2.2.2. Corrosion

Corrosion is the electro-chemical attack of metal and is one of the most prevalent and pervasive damage mechanisms encountered by ship structures. Corrosion, both internal and external, manifests itself in several forms, including general corrosion, pitting and grooving. Corrosion in uncoated steel is a process of continuous degradation, whereas corrosion of coated steel usually begins after the protective coating has broken down. Corrosion in steel takes the form of common rust. Rusting occurs on unprotected metal that is exposed to both oxygen and moisture, and is therefore a constant problem in ship structures. The rate of corrosive attack depends on a number of factors, including heat, acidity, salinity, and the presence of oxygen.

Although steel surfaces are generally protected with paint systems, these systems can fail due to improper application, aging, cracking, or chipping. Once exposed, the steel can corrode rather quickly via the mechanisms of pitting, where effects are localized and damage progresses through the metal thickness rather than over its surface.

Occasionally during welding, changes in the grain structure of the metal in the heat-affected zone (HAZ) can lead to preferential degradation known as grooving. Corrosion will gradually reduce the ability of a structure to bear the loads for which it was constructed. A summary of the various types of corrosion is given in Table 2-2 below.

Corrosion is most likely to occur in the following areas:

1. Locations that are inaccessible for the most part (the use of mirrors, endoscopes, and so forth should be maximized);
2. Areas that are always wet or oily, such as bilges;
3. Areas where dissimilar metals are in close proximity or in contact with each other;
4. Areas where the paint appears to be raised, uneven, or flaky;
5. Pitting near non-ferrous metals;
6. The underside of frames, seating areas, and so forth;
7. Weather-deck scuppers, beneath lockers and so forth;
8. The lower edges of bulkheads that bound frequently-washed areas (e.g., passageways);
9. Representative areas under deck coatings or insulation such that a professional judgment regarding the underlying structure can be made; and
10. Plate butt and seam welds.

A Tanker Structure Cooperative Forum (TSCF) publication entitled “Condition Evaluation and Maintenance of Tanker Structures” provides detailed descriptions on corrosion suspect areas in tankers (TSCF 1992). It notes that the corrosion problems are different for each vessel. Even among sister ships there can be significant differences in findings. However, a number of common problems that are found on many ships are summarized in terms of three general areas: tank bottom structures, side shell and bulkheads, and deckhead structures. This reference can be consulted for more information on corrosion in existing tankers. Table 2-3 gives typical corrosion rates for uncoated steel of longitudinal primary members in cargo oil tanks (TSCF 1997).

Corrosion reduces the section modulus of the hull of a tanker by thinning the thickness of primary structural members. It reduces the ability of the structure to resist externally induced bending moment. Several models of general corrosion growth have been suggested (Orisamolu et al. 1999a, 1999b, 1999c; Paik et al. 1998). The most commonly used model is

$$r(t) = C_1(t - t_0)^{c_2} \tag{2-1}$$

where $r(t)$ is the thickness reduction; t_0 is the life of coating (years); t is the age of the vessel (years); C_1, C_2 are random variable coefficients; C_1 represents annual corrosion rate and C_2 is taken as 1. The life of coating varies for different vessels and depends on the coating type. For the purpose of demonstration, it is assumed to be 5 years after new construction. Thus, in the presence of corrosion the moment capacity is given by

$$M_u(t) = \phi\sigma_u \begin{cases} Z(r(t_0)) & t \le t_0; \quad r(t_0) = 0 \\ Z(r(t)) & t > t_0; \quad r(t) > 0 \end{cases} \tag{2-2}$$

Formula for calculating midship section modulus $Z(r(t))$ can be found in any standard monograph on ship structures such as Hughes (1983).

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. 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 does not influence the structural integrity of the vessel but should tracked as an independent degradation mode. Example pitting corrosion rate data are shown in Table 2-4 (SSC SR 1396).

Table 2-2. Classification of Various Types of Corrosion

Category of Corrosion	Defining Characteristics
General Corrosion	Exposed surface subject to uniform metal loss; readily detectable.
Pitting	Randomly distributed, localized, non-uniform metal loss; HS Al alloys and stainless steels particularly susceptible.
Intergranular Corrosion	Preferential corrosion along grain boundaries; characterized by leaf-like bulging.
Crevice Corrosion	Due to presence of a crevice or debris deposit; lap joints typically prone; severity usually increases with time due to increasing acidity.
Galvanic Corrosion	Due to coupling of dissimilar metals.
Corrosion Fatigue	Fatigue resulting from cyclic loading in a corrosive environment; accelerated by the presence of pitting corrosion; compromises fatigue and endurance limit of a non-corroded material.
Stress-Corrosion Cracking (SCC)	Results from static tensile stresses being superimposed on actively corroding metals; high-strength alloys (e.g., aluminum, steels, titanium) are susceptible to SCC.

Table 2-3. Typical Corrosion Rates for Tanker Members (TSCF 1997)

Corrosion Rates						
	Mean		Min		Max	
Location	mm/yr	in/yr	mm/yr	in/yr	mm/yr	in/yr
Deck Plating	0.065	2.5591E-03	0.03	1.1811E-03	0.10	3.9370E-03
Deck Longitudinals (Web)	0.065	2.5591E-03	0.03	1.1811E-03	0.10	3.9370E-03
Side Shell Plating	0.030	1.1811E-03	0.03	1.1811E-03	0.03	1.1811E-03
Side Shell Longitudinals (Web)	0.030	1.1811E-03	0.03	1.1811E-03	0.03	1.1811E-03
Bottom Shell Plating	0.170	6.6929E-03	0.04	1.5748E-03	0.30	1.1811E-02
Bottom Shell Longitudinals (Web)	0.065	2.5591E-03	0.03	1.1811E-03	0.10	3.9370E-03
Longitudinal Bulkhead Plating	0.065	2.5591E-03	0.03	1.1811E-03	0.10	3.9370E-03
Longitudinal Bulkhead Longs. (Web)	0.065	2.5591E-03	0.03	1.1811E-03	0.10	3.9370E-03

Table 2-4. Proposed Pitting Corrosion Rate Data (SSC SR 1396)

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

COV = Coefficient of Variation

2.2.3. Cracks

Cracks are very serious defects that can rapidly grow in size, leaving the affected structure unable to bear the loads for which it was constructed. As a result, the surrounding structure must accept a greater loading, which can in turn lead to its failure. Cracking may be brittle or ductile in nature. Operation in cold conditions can render normally ductile steel brittle. Under such circumstances, any minor structural discontinuity can initiate a crack, which may grow extremely quickly unless arrested by a material with greater notch toughness.

Ductile cracks are generally caused by fatigue. Fatigue is a process in which the repeated application of a stress cycle gradually weakens the granular structure of a metal, eventually leading to a surface crack, and may ultimately induce overall material failure. The time required for a fatigue crack to develop greatly depends on the material properties and stress levels. In general, higher stresses will lead to faster crack initiation and subsequent growth.

Since fatigue cracking is promoted by high stresses, it is most likely to occur in areas of stress concentration. Areas near the middle third of the ship are most vulnerable to fatigue cracking, due to the increased hull bending stresses there. However, items continually slamming against compartment walls can also produce high-stress, low-cycle fatigue. Other areas of concern include:

1. Deck and bulkhead openings, especially if not rounded and smooth;
2. Abrupt changes in cross section;
3. Stiff connection points such as the intersection of longitudinal and transverse stiffeners;
4. The ends of superstructure blocks; and
5. Weld defects.

Ship structures need to be continually examined and repaired to safeguard against the development of critical cracks. Examinations for cracks could be carried out visually. A visual examination can allow determination of the type of crack present, and assess whether it is likely to propagate.

Brittle cracks are usually characterized by bright, granular, flat surfaces, which generally exhibit a chevron pattern on the face. Ductile cracks, on the other hand, appear dull and non-granular, and will typically show obvious signs of stretching or tearing. Fatigue cracks are usually flat and smooth, and exhibit small parallel lines on the face (fatigue striations), which occur in groups running parallel to the direction of crack growth. The lines are generally curved and point in the direction of crack growth. The origin of a brittle crack may be located by following the characteristic chevron patterns in the direction they point until they either stop or change direction, which would indicate that the crack has propagated in two directions. Fatigue cracks are generally initiated by surface flaws, the origin of which can be identified by an increase in the density of the lines on the face, and also by their pattern, which will tend to surround the origin with small semicircles. More details on the determination of crack type, origin, and possible growth path, along with methodologies for obtaining samples of cracked material, are provided in SSC-337 (Part 2).

Various studies (Ayyub and Assakkaf 1999a and 1999b; Ayyub, et al. 2002; Jordan and Cochran, 1978; Bea et al., 1995; DNV, 1991; Yonega, 1993; Ma and Bea, 1992; Dexter and Pilarski, 2000) have been undertaken to identify critical structural details to fatigue cracking. The two main approaches for assessing fatigue strength are

1. *S-N* for crack initiation assessment, and
2. Fracture mechanics for crack propagation assessment.

The *S-N* approach predicts the strength based on crack initiation of a critical structural detail as a function of the number of stress cycles. The fracture mechanics approach can be used in risk analysis based on crack propagation assessment.

The fracture mechanics approach uses crack growth equations to predict the size of a crack as a function of time. Two formulations for predicting the size of a crack, namely, mechanistic (and non-mechanistic (Yang and Manning 1990) have been reported. The mechanistic model relates the crack growth to the stress intensity factor, stress range, material and environmental properties. Implementation of a mechanistic model requires a detailed knowledge of all the factors that affect crack growth. The most commonly used mechanistic model is the Paris-Erdegen formula given by (de Souza and Ayyub 2001)

$$\frac{da}{dN} = C\Delta K^{m} \tag{2-3}$$

$$\Delta K = \Delta\sigma Y(a)\sqrt{\pi a} \tag{2-4}$$

where a is the crack size; N is the number of load cycles; $\Delta\sigma$ is the stress range; ΔK is the stress intensity factor; and $Y(a)$ is a geometric factor. Assuming $Y(a) = Y$ is constant, then integration of Eq. 2-3 gives

$$a(N) = [a_0^{1-m/2} + (1-\frac{m}{2})C\Delta\sigma^{m}Y^{m}\pi^{\frac{m}{2}}N] \qquad m \neq 2 \tag{2-5}$$

$$a(N) = a_0 \exp(C\Delta\sigma^{2}Y^{2}\pi \;\; N] \qquad m = 2 \tag{2-6}$$

where a_o is the initial crack size; m and C are constants. In order to use Eqs. 2-5 and 2-6 for analysis, the stress range at the various details and joints must be known and practical estimation of these quantities could be very difficult. Most of the reported studies on fatigue of ship structural details have used *S-N* approach. A study by Dobson et al. 1983 (SSC 315) used measured load spectra to calibrate the fatigue crack growth parameters, C and m for two steel materials, HY-80 and CS.

2.2.4. Deformation

Deformation is the term applied to dents, buckling or general distortion found in plating or stiffeners. Deformation can occur as a result of poor design, or from external forces arising from collisions or wave action. Although deformation can occur anywhere in a ship structure, it is particularly common on:

1. Flightdecks;
2. Bow plating and nearby internal structures (as a result of slamming);
3. Hull plating at the quarter points in the form of diagonal wrinkling; and
4. The waterline and bottom (due to minor impacts or groundings).

Although minor deformation may not be serious, only small allowances to the load-carrying capacity are made for imperfections in the design process. Excessive levels of distortion can therefore unacceptably reduce buckling strength, leading to premature structural failure. All visible distortions to the structure should be noted and repaired.

2.2.5. Erosion

Erosion is the wearing-away of material over time by the action of a fluid. The process is accelerated in the event that the fluid contains gas bubbles or small particles. Areas where changes in the direction of flow occur, such as bends in pipes and areas of the hull near inlets, discharges, and appendages are especially susceptible to erosion. Propellers may experience erosion as a result of cavitations. Erosion can be repaired using the same repair techniques employed for corrosion.

2.3. Inspection Practices

Ship structural inspections are carried out in order to assess the capability of the ship to remain safe and meet its functional requirements until the next inspection and to alert the ship's owners to the need to accomplish any necessary corrective measures to maintain the ship's integrity and functionality. Inspections can be performed visually or using sensors and data acquisition systems. A primary function of inspection is to verify the existing conditions, identify, record and document any defects and/or damage, and monitor the overall structural performance. However, several practical difficulties are associated with the inspection process, including the associated costs, and also the physical size of the structure being inspected. It is well known that the cost of inspection for corrosion and fatigue cracking represents an enormous financial burden for ship owners and operators. Special surveys, for example, require dry-docking and the cleaning of tanks and holds. In addition to the cost of labor and material, such surveys require the vessel to be out of service for some time, often referred to as 'downtime'. In cases where permanent access facilities are not installed, the inspection costs becomes even larger due to the high cost of providing temporary access facilities.

Ship structural inspection objectives comprise one or more of the following (Ma 1998):

- Detecting defects including fatigue cracks, buckling, corrosion and pitting;
- Reporting present condition of steel plate thickness reduction due to corrosion;
- Reporting present condition of coating and other corrosion protection systems; and/or

- Detecting any other problems such as structural deformation and leakage.

Inspections may be categorized as owner's voluntary inspections or mandatory inspections. The owner's mandatory inspections are carried out by owners to satisfy their private standards. Mandatory inspections are carried out by regulatory organizations such as classification societies. Mandatory inspections are typically of the following types (Ma 1998):

- Annual surveys are carried out each year to ensure that the hull structure and piping are maintained in satisfactory condition and typically take one to two days. Usually, the survey includes the external accessible hull and piping surfaces.
- Intermediate surveys are carried out at the mid-point of the five-year special survey/certificate cycle, and comprise the same inspection of external hull and piping surfaces as the annual surveys plus an examination of ballast tanks and cargo tanks. The aim of the intermediate surveys is to verify that conditions have not deteriorated at a rate greater than that assumed during the preceding special survey. For vessels that are older than ten years, the extent of survey is increased. Thickness measurements may be required. Intermediate surveys take about three to four days to complete.
- Special surveys are carried out each five years in order to provide an in-depth examination of the structural condition of the vessel. All compartments are subjected to survey and the vessel is dry-docked. Special surveys take about one to two weeks, and their extent increases with the age of the ship.

Although inspection requirements do vary among classification societies, a set of common minimum standards has been developed by the International Association of Classification Societies (IACS) Unified Requirements and form the basis for International Maritime Organization (IMO) Resolution A744, "Guidelines on the Enhanced Program of Inspections During Survey of Oil Tankers and Bulk Carriers." The Requirements cover the three types of surveys described above, as well as thickness measurements, tank testing, survey planning and reporting. As can be seen in the following sections on the American Bureau of Shipping the Det Norske Veritas, there are a great many similarities among the rules of major classification societies.

The International Association of Classification Societies (IACS) is an organization made up of classification societies within whose registries are more than 90% of the world's cargo carrying tonnage. The IACS is dedicated to safe ships and clean seas, and provides technical support, compliance verification and research and development. The IACS comprises the following member organizations (IACS Website 2002):

- American Bureau of Shipping,
- Bureau Veritas,
- China Classification Society,
- Det Norske Veritas,
- Korean Register of Shipping,
- Lloyds Register,
- Nippon Kaiji Kyokai (ClassNK), and
- Registro Italiano Navale Group.

IACS Associates comprise the following:

- Croatian Register of Shipping, and
- Indian Registry of Shipping.

The large size of modern ships makes total inspections impractical, as do designs that limit surveyor access. Thus, an approach called priority assessment has been developed to quantitatively prioritize structural components and locations for inspection. Priority assessment is based on the concept that structural details with high failure rates and serious failure consequences should receive a high priority for inspection. This concept has not been formally applied to practice, but is used informally by today's surveyors, which inspect ship structure in light of their structural experience and histories of past or typical failures.

Inspection planning includes gathering relevant documentation (e.g., main structural plans, description of coating and corrosion protection systems, previous maintenance and repair history, cargo and ballast loading history, and trading route history), and preparation of areas to be inspected (e.g., cleaning tanks, providing ventilation and lighting, and providing access for the inspector). During inspections, surveyors record their findings by means of written notes or tape recorders. Following the inspection, the surveyors develop formal reports of their findings, which may include data analysis, e.g., of thickness measurements.

Numerous advances in the field of ship structural inspection have been achieved in areas such as inspection guides, procedures, programs, probability of detection, and industry-wide databases (Basar 1985; Shinozuka 1990; Reynolds 1992; Ma 1992; Bea 1991; Dry 1995; Demsetz 1996a; Daidola 1997; Reeve 1998; also, see Bibliography).

So far, the discussion has been limited to ship inspections; however, structural inspections are carried out in other industrial fields as well, for example (Ma 1998):

- In the nuclear power industry, the American Society of Mechanical Engineers Center for Research and Technology Development set up a task force in 1988 to develop risk-based inspection guidelines for nuclear structural systems and components.
- In the aerospace industry, inspection programs and requirements are largely driven by the specifications of the Aircraft Structural Integrity Program (AISP) introduced by the U.S. Air Force (USAF 1973). The AISP is used worldwide by many commercial and military organizations for maintaining aircraft structural integrity. The AISP is predominantly focused on fatigue crack damage and has no corrosion component.
- In the offshore industry, probabilistic inspection strategies are being successfully employed in the field, especially by the Norwegians on North Sea platforms.

The following sections discuss present inspection practices of several important safety-related maritime organizations. Each section presents general observations, frequency of inspections, areas of focus, and methodology guidelines. For up-to-date, detailed, and authoritative information, the reader is invited to contact the respective organization. There are additional sections which summarize inspection practices in non-marine industries, and which describe non-destructive testing (NDT) technology.

2.3.1. United States Coast Guard

General
The United States Coast Guard (USCG) is a military, multi-mission, maritime service. Operating within the Department of Transportation during peacetime, the Service falls under the direction for the Secretary of the Navy upon declaration of war or when the President directs. Along with its defense role, the USCG is charged with a broad scope of regulatory, law-enforcement, humanitarian, and emergency response duties (USCG 2001a). Within the scope of the USCG Marine Safety and Environmental Protection services is the preparation and maintenance of documents entitled Navigation and Vessel Inspection Circulars (NVICs) (USCG 2001b). Several NVICs provide guidance in the area of the inspection of steel merchant vessel hulls, as described below.

In 1991, the Goast Guard implemented a detailed inspection program of problematic, critical fracture areas, and new reporting requirements for vessels experiencing a high frequency of structural cracking (NVIC 15-91a, NVIC 15-91b). The purpose of these Circulars is to establish the procedures and to provide guidance to the marine industry for the development, use, and implementation of CAIPs. Both the procedures and the guidance for implementation have been given in Navigation and Vessel Inspection Circular (NVIC 15 –91a, b). While it has shown a great success of CAIP since 1991, the cost associated with the implementation of CAIP is high, An effective repair procedure based on a fracture mechanics methodology has been developed for oil tankers to justify relaxation from NVIC 15-91 vessel specific requirements after a period of good performance (Rolfe et at. 1991).

Frequency of Inspections
The frequency of hull structural inspection is tailored to each vessel or vessel class as deemed necessary by the cognizant Officer in Charge, Marine Inspection (OCMI), district commander, or Commandant (USCG 1991).

Areas of Focus
In general, the inspector looks for structural deficiencies that may affect the strength of integrity of the hull to an extent that would make it unseaworthy (USCG 2001c). Deficiencies are divided into the following categories:

- Deterioration, general or local;
- Hull Defects, fractures, buckling or other deformation, cracking or tearing, weakening or failure of fastenings; and
- Hull Damage, such as that caused by grounding, collision, or the employment of the vessel.
- Particular areas of focus include the following (each of which is addressed in more detail in the following sub-section):
    - Special Coatings;
    - High Strength Steels;
    - Deck Plating;
    - Deck Longitudinals;
    - Keel Plating;

  - Bottom Plating;
  - Side Plating;
  - Longitudinal and Transverse Bulkheads; and
  - Frames, Beams and Stiffeners.

Methodology Guidelines

In order to determine whether deficiencies will compromise a vessel's seaworthiness, the inspector is to consider the following factors (USCG 2001c):

- The extent and degree of deterioration.
- The period of time involved before the next scheduled inspection of the area in question. Certain areas are accessible to inspection at every dry-docking, while others are exposed only during the surveys required by the classification societies. A progressing condition may be acceptable if it is in a visible area and available for frequent monitoring.
- Whether the repair work contemplated is necessary to restore seaworthiness or is a maintenance measure to ensure prolonged utilization of the vessel. In the first case, the repair must be carried out, but in the second case, it may be reconsidered at a future inspection.
- Once a decision has been reached by the inspector that repair work is necessary, the specific requirement should be documented. The general guideline is to "renew as original;" however, in cases where the deficiency resulted from faulty design or construction, the repair should correct the problem through an appropriate change.
- In some instances, the owner may desire to reduce the structural work by an alternate means of repair. In view of the cost of complicated repairs, less expensive alternatives should be considered, as long as they comply with approved repair guidelines.
- If the vessel is in class, and/or is assigned a load line, the nature and extent of repairs as determined by the classification society surveyor is to be given full consideration. If there is a difference of opinion, the inspector should refer the matter to his superior officer.

Notes regarding inspections include the following (USCG 2001c):

- Deterioration – Gauging is the only practical way of determining the degree of deterioration, and is undertaken if there is reasonable doubt as to the adequacy of the present scantlings. The present thickness of the member in question is compared with the original thickness, and used as a basis for determining the need for repair. Gauging may be for a local or over a large area, depending on the situation.
- Corrosion – In general, a local thickness deterioration of up to about 25 percent may be accepted before replacement is necessary for most portions of a vessel. Localized wastage of some portions of plates or structural members in excess of 25 percent may be accepted in many cases, if the condition of the adjacent material is sufficient to maintain an adequate margin of strength. Conversely, general or localized wastages of less than 25 percent could necessitate material replacement.
- Oversize or Undersize Scantlings – Some vessels are built with scantlings different from those stipulated by the classification society. In evaluating the need for replacing deteriorated structure in such vessels, consideration must be made for this difference, and corresponding adjustments made to the allowable percentage of deterioration.

- Special Coatings – Recent advances in protective coating technology have the potential for vastly limiting corrosion. As a result, scantlings in some cases have been reduced. For example, ships constructed since 1965 have been permitted to have scantlings 10 percent below those stipulated in the American Bureau of Shipping provided acceptable special coatings have been applied. Normally, painting of hull structure has not been the subject of USCG requirements. However, in the case of these reduced-scantling vessels, coatings can be a valid concern of the inspector.
- High Strength Steels – The use of high strength steels introduces new problems that must be considered with regard to renewals and repairs. These steels offer significant advantages in weight reduction, and may be built with thinner sections. However, this thinner structure is not as forgiving as the heavier sections of mild steel. Special attention must be paid to the possibility of buckling. Also, special procedures are required for welding.
- Deck Plating – Deck plating comprises a highly stressed portion of the hull girder and is of critical importance to the longitudinal strength of the vessel. Accelerated corrosion may be expected in the deck because it is subject to mechanical abuse from deck cargo, hatch beams, and repeated scaling. Also, it is always exposed to the elements and frequently awash. Deck plating, especially in the midships half-length, should be carefully examined for cracks, leaks, or signs of excessive wear.
- Deck Longitudinals – In tank vessels, the corrosive deterioration of deck longitudinals may be much more rapid than that of deck plating. These longitudinals are necessary to support the deck plating so that it can carry local hydrostatic loading, provide hull girder panel stiffness, and contribute to hull girder strength. Permitted wastage of up to 40 percent may be acceptable in local areas. However, this varies by profile shape and specific ship design, and must be considered on a case basis.
- Keel Plating – In recognition of local strength factors and also the additional corrosion to which keel plates are subject as a result of being unavailable for painting when sitting on keel blocks in dry-dock, keel plating is normally of greater thickness than other bottom plating. A large part of this extra thickness may be regarded as extra corrosion allowance.
- Bottom Plating, Inner Bottom Plating and Bottom Internals – As well as sustaining a major portion of the hull bending moment, bottom plating is subject to increased stress due to water pressure. Its strength may be reduced either by general or localized corrosion and by buckling. The maximum average reduction in thickness permitted about the midships half-length is about 20 percent. Tank tops are considered in the computation of scantlings for load line assignment and must be maintained in good condition. A moderate amount of buckling of tank tops is acceptable provided the buckling is confined to the plating between transverse and longitudinal girders.
- Side Plating –The strake between wind and water is highly susceptible to corrosion. The maximum general wastage is to be expected in this area. Also, serious localized corrosion may often be encountered in way of overboard discharges and scupper openings.
- Longitudinal and Transverse Bulkheads – Cargo hold bulkheads are usually not troubled by excessive corrosion except along the lower boundaries and in way of bilge wells.

Such corrosion is a local condition. Wastage of up to about 35 percent may be accepted provided there is no evidence of deformation when subjected to a hydrostatic test.

- Frames, Beams and Stiffeners – Generally, the flanges and portions of the webs next to the flanges are more highly stressed, more subject to mechanical damage, and corrode faster than the balance of the member.

A management tool has been developed by the USCG to track the historical performance of a vessel, identify problem areas, and provide greater focus to periodic structural examinations. This tool is called a Critical Areas Inspection Plan (CIAP) (USCG 1991). The decision to require a CIAP may be based on the vessel's history, its service, or the climatologic characteristics of the trade route, and is in keeping with the USCG's authority to require the necessary inspections and documents to ensure vessel and environmental safety. Developing and maintaining a CIAP results in the vessel's management becoming more closely involved in the process of finding a solution to identified structural and/or maintenance problems. The ultimate goal of the CIAP is to address the cause of the problems, not merely the symptoms. The CIAP is developed by the vessel's owner when required in writing from the appropriate USCG authority. Surveys are an integral part of CIAPs. CIAP structural failures are classified into two types:

- Class 1 – a fracture that occurs during normal operating conditions (i.e., not as the result of a grounding, collision, or other damage) that is a fracture or buckle of the oil/watertight envelope, or a fracture 10 feet or longer that involves an internal strength member; and
- Class 2 – a fracture less than 10 feet in length or a buckle that involves an internal strength member and that occurred during normal operating conditions.

2.3.2. American Bureau of Shipping

General

The American Bureau of Shipping (ABS) was incorporated by Act of Legislature of the State of New York 1n 1862 and is one of the world's leading ship classification societies. The primary purpose of ABS is to determine the structural and mechanical fitness of ships and other marine structures for their intended purpose. It does this through a procedure known as classification. ABS establishes and administers standards, known as Rules, for the design, construction, and operational maintenance of marine vessels and structures. ABS is a not-for-profit, non-governmental, and self-regulating agency serving the international marine industry (ABS 2001a).

Ships that are classed by ABS receive an annual survey that includes weather decks, hull plating and its closing appliances together with watertight penetrations. The scope of inspection varies by type of vessel, with certain elements common to all types. Vessel types include the following (ABS 2001b):

- Accommodation/Hotel Barges,
- Barges,
- Bulk Carriers,
- High Speed Craft,
- Passenger Vessels, and
- Tankers and Tank Barges.

Frequency of Inspections

Annual surveys comprise inspection of representative structure. For ships over certain ages (five, ten, 15 years), the inspection is more comprehensive. Each five years, a Special Periodical Survey is carried out. The Special Periodical Survey is more comprehensive than the Annual Survey (ABS 200b).

Areas of Focus

Annual Surveys typically include the following structural areas (ABS 200b):

- Weather decks;
- Hull plating and its closing appliances;
- Watertight penetrations: Thickness measurements may be required;
- Barges: Tank tops, underside of main deck and side shell plating, framing and attachments;
- Bulk carriers: Hatch covers and cargo holds;
- High speed craft: Dry-docking;
- Passenger vessels: All shell connections below bulkhead deck, all openings and their closures in watertight bulkheads below the bulkhead deck; and
- Tankers and tank barges: Cargo tanks, cargo pump room, salt water ballast spaces.

Special Periodic Surveys typically include the following structural areas (ABS 200b):

- Dry-docking survey,
- Rudder,
- Anchor and chain cable,
- Shell openings,
- Decks,
- Bulkheads, and
- Shell plating.

While the Annual Survey typically addresses portions of various types of structure, the Special Periodic Survey stipulates examination of all decks, watertight bulkheads, and internal and external surfaces of shell plating. Likewise, an overall survey of spaces is to be carried out, including holds and their between decks where fitted; double bottom, deep ballast, peak and cargo tanks; pump rooms, pipe tunnels, duct keels, machinery spaces, dry spaces, cofferdams and voids including the plating and framing, bilges and drain wells, sounding, venting, pumping and drainage arrangements. In addition, thickness measurements are required. As before, there are special requirements for each vessel type, e.g., engine foundations and their attachments to the hull are to be examined for high speed craft of fiber reinforced plastic.

Methodology Guidelines

The ABS Surveyor is to make formal preparations prior to conducting the survey, with special planning for vessels over 15 years of age (ABS 200b).

- Documentation is to be available to and consulted by the Surveyor, including the following:
  - Survey status and basic ship information,
  - Documentation on board the ship,
  - Main structural plans,

  - Relevant previous survey and inspection reports,
  - Information regarding the use of the ship's holds, tanks, and cargo,
  - Information regarding corrosion protection level on the new building, and
  - Information regarding the relevant maintenance level during operation.
- Planning, as appropriate, is to be carried out for the following:
  - Tank testing,
  - Close-up survey, and
  - Thickness measurements.

The owner is to provide necessary facilities for the safe execution of the survey, including the following:

- Tanks and spaces are safe for access;
- Tanks and spaces are sufficiently clean and free from water, scale, dirt, oil residues, etc., to reveal significant corrosion, deformation, fractures, etc.;
- Sufficient illumination is to be provided; and
- Access is to be provided (e.g., by staging, lifts, and boats).

ABS guidelines are provided to the Surveyor for examining key structural areas, such as the following (ABS 200c):

- Cuts in structural members,
- Cuts in shell decks, watertight bulkheads and compartment subdivisions,
- Unauthorized cuts in structure,
- Pipe penetrations,
- Cuts in stiffening members, and
- Indents in barges, tugs and other small vessels.

In addition to the classic manual inspection by a Surveyor, ABS has instituted a computer-aided approach for ships to maintain their classification. This approach is presently valid for bulk carriers and tanker, which are modeled using the ABS SafeHull. In this approach, the condition of the structure is assessed, based on visual survey and thickness measurements, and rated on a range from 1 (highest: "very good") to 5 (lowest: "unexamined"). Provision is made to consider structural wastage and the condition of coating systems. The Surveyor completes a detailed form as documentation of the survey (ABS 1999).

Surveys are documented and reported in accordance with ABS procedures and formats.

2.3.3. United States Navy

General

The United States Navy is a military, multi-mission, maritime service. Operating within the Department of Defense, the Service falls under the direction for the Secretary of the Navy. The Navy expects high levels of individual ship readiness, including the ability to withstand battle damage and to protect equipment from shock damage. Navy ships can be divided into three broad categories: surface ships, thin-hulled surface ships, and submarines. Recent design and building practices for thin-hulled ships have resulted in some ship classes with very limited excess strength. United States Navy ships are exempt from federal regulations governing inspections of commercial vessels and operate under their own inspection and maintenance programs. The programs are specified in the Naval Ships Technical Manual and executed under the Planned Maintenance System and Integrated Class Maintenance Program (Fox 2002).

Frequency of Inspections

The frequency of hull structural inspection is tailored to each ship class and is made up of a series of waterborne underwater hull, drydocked underwater hull, tank, and internal structural assessments. Ideal or specified inspection frequencies are modified as a result of varying maintenance strategies and funding priorities of the individual Type Commanders, with major differences occurring between the East (Commander, Naval Surface Force, U. S. Atlantic Fleet - CNSL) and West (Commander, Naval Surface Force, U. S. Pacific Fleet – CNSP) Coast surface type commanders.

Generally speaking, waterborne hull assessments are conducted during the regularly scheduled hull cleanings. These occur between two and four times per year. CNSL also statistically monitors external hull coatings on a biannual basis. Tanks are inspected internally on a schedule that is determined by the product contained in the tank. CNSL also takes into account the type of coating applied to the tank surface and the observed rate of coating degradation in determining the frequency of tank inspections. Assessment of internal structure other than tanks is conducted on an annual basis by the ship's crew and is also assessed by shipyard personnel when the ship is in dry dock. In dry dock external inspections and air testing of inaccessible voids and keels are conducted in conjunction with the ship's normal drydocking availabilities which are scheduled approximately every five to six years.

Generally speaking, because of a more severe operating environment, submarines are inspected more frequently and in greater detail than surface ships. For example, submarine structural inspections include removal of insulation or tile covering structural surfaces, whereas surface ship assessments generally rely on detection of secondary indications of problems in hidden areas.

Areas of Focus

As in the USCG inspections, USN inspectors look for structural deficiencies that may adversely affect the strength of the hull to an extent that would make it unseaworthy. Generally speaking, any cracking, buckling (deformation), or corrosion/erosion that reduces the original thickness of the plating or other structural member to 75% of its original thickness is recorded and forwarded for engineering analysis and repair recommendation. Ideally, in every case where corrosion is present, immediate action is taken to arrest the corrosion, even if the effect of the corrosion has not reached the 75% trigger point.

Although the entire hull is inspected, special attention is paid to Critical Inspection Areas (CIAs). CIAs are any areas that have been documented through maintenance data to be "prone to failure." In the absence of maintenance data, generic CIAs are defined by the Naval Ships Technical Manual and Joint Fleet Maintenance Manual as areas:

- Under boilers and turbines,

- Around boiler feed-water tanks,
- That are continuously wet from condensation or “sweating”,
- Around the overboard intakes and discharges where external turbulence often produces erosion,
- Around the interior of the side shell along the exterior waterline (where the design thickness of the shell plating is thinnest and exterior erosion from wave action is always present),
- Around “wet” equipment (e.g., pumps, condensers, evaporators), which continuously operate with steam/water emission, and
- Areas of the bottom shell which are subject to the corrosive action of bilge water.

As CIAs are identified using maintenance data, efforts are made to eliminate the CIA by removing the cause of the corrosion/cracking. Alternatively, actions can be taken to protect the CIA from the cause.

<u>Methodology Guidelines</u>
The USN inspection strategy seeks to minimize cost while ensuring operability and extending hull service life. This is achieved by:

- Identification and repair of existing structural defects before they become severe enough to interfere with unrestricted operations, and
- Identification and repair of coating and structural degradation before they are classified as defects and result in costly metal replacement.

Assessment and repair strategies also seek to:

- Optimize the ship’s operational schedule and minimize repair overhead costs by packaging repairs into scheduled repair availabilities whenever such action is safe and feasible;
- Minimize operational impact by integrating the assessment and repair process with the Inter Deployment Training Cycle and availability planning process;
- Achieve improved work planning; and
- Minimize risks associated with extending drydocking cycles toward ten years, which in turn results in reduced maintenance costs.

In order to achieve the above, it is frequently necessary to defer necessary repairs to a future date or availability. Prior to deferral, careful consideration must be given to:

- Severity and nature of the defect,
- Overall condition of the hull and effect of other defects (cumulative effect of all defects),
- Residual strength in the hull,
- Expected operating environment,
- Likelihood of a structural failure resulting from the defect, and
- Consequences of the structural failure.

Consequently, an engineering analysis and risk assessment is required if a repair is deferred. Additionally, deferred repairs must be tracked to ensure future repair and to ensure that they are taken into account if additional defects are found at a later date.

Structural assessment and repair program implementation success varies throughout the United States Navy. Program failures, when they do occur, are seldom severe. However, when they are severe, they result in untimely emergent drydocking availabilities and impact on operational schedules. When the program fails, lack of success is usually attributed to poor knowledge of requirements and failure to enforce coherent, detailed and standardized assessment and repair procedures.

Recent high profile process failures along with an emphasis on condition based maintenance within the United States Navy and a desire to increase time between drydocking availabilities have resulted in some efforts to improve processes related to hull structure maintenance. Consequently, CNSL commissioned a study related to structural maintenance. The study resulted in significant changes in CNSL hull assessment and repair processes. These changes include biannual structural assessment by structural technicians/engineers, use of moisture detectors and infrared detectors to identify corrosion behind insulation, tracking of defects to identify critical inspection areas, and a formal engineering review of the assessment results to ensure that appropriate repairs are made after the assessment is complete. If repair deferral is contemplated, an engineering risk assessment is conducted to make sure that potential risks are identified and appropriate mitigating strategies are applied to ensure that risk remains at an acceptable level until repairs are completed. Results of the study are being applied to east coast FFG class ships. Use of the improved processes will be extended to other ship classes after they have been proven effective on the FFG class (USN 2001).

2.3.4. Det Norske Veritas

General

Det Norske Veritas (DNV) is an independent, autonomous foundation established in 1864 with the objective of safeguarding life, property and the environment. As one of the world's leading maritime classification societies, DNV establishes rules for ship and mobile offshore unit construction and inspection, and carries out inspections. DNV has extensive research and development facilities, with laboratories in Norway, the Netherlands, Singapore, Fujairah, and the U.S. (DNV 2002)

Vessel types include the following (DNV 2001):

- Cargo Ships (e.g., oil, chemical, liquefied gas, fishing, tugs),
- Passenger Ships, and
- Mobile Offshore Units.

Frequency of Inspections

All DNV-classed ships are subjected to periodic surveys to ascertain the condition of structure, with the surveys generally in the following categories (DNV 2001):

- Annual surveys;

- Intermediate surveys - carried out in order to ascertain that the vessel remains in compliance with the rules, and take place at the second or third annual survey after the renewal survey;
- Renewal surveys - major surveys of hull structures in order to confirm that the ship complies with the relevant rule requirements and is satisfactorily maintained, and take place in three or five years intervals, depending on the ship class; and
- Other complete periodical surveys – carried out for additional class notations at one, two and a half, or five year intervals.

<u>Areas of Focus</u>

Annual surveys typically include the following structural areas (DNV 2001):

- Hull plating as far as can be seen;
- Watertight bulkheads with watertight doors and penetrations;
- Ballast tanks internally, as a consequence of no protective coating, soft coating or poor protective coating from previous intermediate or renewal survey;
- Suspect areas identified at previous intermediate or renewal survey; and
- Areas with substantial corrosion are to have thickness measurements taken.

Intermediate surveys typically include the following structural areas (DNV 2001):

- Visual examinations of hull structures;
- With regard to ballast tanks, the following apply:
    - Thickness measurements are taken if considered necessary by the surveyor,
    - If overall examination reveals no structural defects, the survey may be limited to verification of effectiveness of the corrosion protection system,
    - Ballast tanks with no protective coating, soft coating, or poor condition of coating must be inspected annually.
- Ships up to five years old are surveyed as per annual survey;
- Ships between five and ten years of age are surveyed as per annual survey, and also:
    - Overall examination of representative ballast tanks,
    - Examination of ballast tanks with no protective coating, or with soft or poor-condition coating.
- Ships more than ten years of age are surveyed as per annual survey, and also:
    - Overall examination of all ballast tanks,
    - For dry cargo ships more than 15 years of age, selected cargo compartments are to be examined.

Renewal Surveys typically include the following structural areas (DNV 2001):

- Examination of underwater parts
    - Hull plating and sternframe;
    - Openings;
    - Steering fins, shaft brackets and other appendages;
    - Rudder with attachments.
- All spaces, including holds and their ‘tween decks where fitted, ballast and cargo tanks, pump rooms, pipe tunnels, duct keels, etc..
- All engine room structure, with particular attention being giving to tank tops, shell platin in way of tank tops, brackets connecting side shell frames and tank tops, and engine room

bulkheads in way of tank top and bilge wells. Where wastage is evident or suspect, thickness measurements are to be carried out;
- Internal survey of tanks;
- Close-up examinations as necessary;
- Thickness measurements as specified; and
- Pressure testing of boundaries of double bottom tanks, deep tanks, ballast tanks, peak tanks and other tanks, including holds that carry ballast water.

Continuous surveys may be carried out as an alternative to the renewal surveys, on the condition that the items are normally surveys at intervals not exceeding five years or three years, depending on the ship class. An Integrated Survey Programme (ISP) is an alternative survey scheme which allows the owner's shipboard and shore side; personnel to partly conduct inspections and tests. These inspections and tests are verified by DNV at regular intervals.

<u>Methodology Guidelines</u>
DNV and the owner work out and document in writing a specific survey program in advance of the hull renewal survey or complete periodical survey. The following structure-related documentation is collected and consulted (2001):
- Survey status and basic ship information;
- Documentation on board the ship;
- Main structural plans;
- Relevant previous survey or inspection reports from DNV and the owner;
- Information regarding the use of the ship's tanks and holds with particular emphasis on typical cargoes;
- Information regarding relevant level of maintenance during operation;
- Relevant information in areas such as:
    - Basic ship information and particulars,
    - Main structural plans including information on the use of high strength steel, stainless steel and clad steel,
    - Plan of thanks and holds,
    - List of tanks and holds with information on use, corrosion protection and condition of corrosion protection,
    - Provisions and methods for access to structures,
    - Equipment for survey,
    - Nomination of tanks, holds, and areas for close-up examination,
    - Nomination of sections for thickness measurements,
    - Nomination of tanks to be tested, and
    - Damage experience related to the ship in question and, as applicable, for similar ships.

Planning to account for and comply with requirements for:
- Close-up examination,
- Thickness measurements, and
- Tank testing.

The owner is to provide the necessary facilities for a safe execution of the survey, including (DNV 2001):

- Tanks and spaces are to be safe for access (e.g., gas free and ventilated);
- Tanks and spaces are to be sufficiently clean and free from water, scale, dirt, oil residues, etc., to reveal significant problems;
- Sufficient illumination is to be provided to reveal potential problems; and
- Means are to be provided to enable the surveyor to examine the structure in a safe and practical way.

In addition to the manual inspection by a surveyor, DNV has instituted a computer-aided approach named Nauticus (DNV 2002). Nauticus is an integrated product model, which manages the information flow related to ship classification and the lifecycle of a vessel (Computas 2002).

DNV also maintains an information access capability for owners named DNV Exchange, with capabilities for accessing:

- Survey schedule aids,
- Important reference information, and
- Certificates and survey status.

2.3.5. Inspection Practices in Non-Marine Industries

General

A number of industries depend on structural integrity, and in certain of these industries the consequence of failure can be catastrophic, involving significant loss of life. Included are bridges in the civil structural industry, and airframes in the air transportation industry. The following sections present an overview of metal structural inspection practices for bridges and airframes.

Bridge Inspection Practices

Bridge inspection practices encompass all structural elements of bridges, including pilings, concrete decks, support cables, fittings, and steel profile and plate structure. The following paragraphs address those practices dealing with steel profile and plate structure, which are those most relevant to ships.

To support the maintenance of the 470,000 highway bridges (not counting culverts and tunnels) in the U.S., the Federal Highway Administration (FHWA) sponsors a large program of research and development in new technologies for nondestructive evaluation (NDE) (Chase 1997). One of the highest priorities in the program is developing technologies for steel bridge inspection of 110,000 structurally deficient highway bridges, about 60 percent are of steel construction. Today, most of the data on bridge condition is gathered by visual inspection with condition evaluation determined by visible indications of deterioration and distress. Among the inspection-oriented research and development initiatives with prototypes under evaluation, as of 1997, are the following:

- Portable coherent laser radar scanning system that is deployed under a highway bridge. Using the computer controllable scanning system, bridge engineers are able to measure deflections of a bridge with sub-millimeter accuracy at hundreds of individual points in a few minutes. This device also measures bridge vibration.
- Global bridge monitoring with wireless transponders consist of off-the-shelf components from the cellular phone and automotive industries fabricated into a number of sensor-transponder modules that communicate via spread-spectrum radio to a local controller. This device measures strain and rotation.
- The New Ultrasonic and Magnetic Analyzer for Cracks (NUMAC) combines ultrasonic and magnetic inspection capabilities into a single instrument for detecting fatigue cracks. The system consists of a backpack computer and a heads-up display and operates even if the steel is covered with paint.
- Thermographic imaging to detect and quantify fatigue cracks is based on the use of commercially available high-resolution thermographic imaging systems to detect surface-breaking fatigue cracks. The method, called forced diffusion thermography, uses active heating of the bridge surface with high-wattage light to detect cracks. A special pattern of hot and cold regions is created on the steel bridge, and the thermographic imaging system presents the operator with an image of heat flow patterns. If a crack is present, a characteristic pattern is observed.
- Acoustic emission monitor for bridges was specifically engineered and packaged to meet the need to monitor a fatigue crack on an in-service highway bridge. The system will be small, rugged, and battery-powered, and can be left in place unattended for up to a week.
- Wireless strain measurement system is portable, rugged, yet accurate for measuring strains at inaccessible locations. Each radio transponder module accepts up to four standard resistive strain gauges with all power and signal conditioning provided by the transponder. Up to ten transponders can be used simultaneously in local radio telemetry networks.

Airframe Inspection Practices

Regular and periodic NDE is carried out on all commercial airframes. Most of the inspection is carried out manually with limited area coverage using NDE techniques such as eddy current, ultrasonic, and X-rays. This manual inspection has drawbacks, including unreliability of results caused by the tiredness of an inspector charged with inspecting every structural element of the airframe. Just as with ship inspections, there is a tradeoff between speed and accuracy of the inspection. The use of X-rays can result in the coverage of a large area of the aircraft, but they pose a radiation hazard to personnel and are expensive because wings must be removed for the X-ray inspection process. Research being conducted in the areas of automated and robotic systems which can operate on large areas of an aircraft structure and automatically collect and interpret data to identify all structural defects (Khalid 2000; Melloy 2000).

With regard to inspection frequency, one idea is to schedule inspections closer to when damage is expected to occur. Since aircraft utilization and loading environments differ among aircraft, a closer to damage inspection schedule must account for these differences. The inspection program must be tailored to the individual aircraft, and monitoring and tracking systems must be put in place (Meyer 1992).

2.3.6. Inspection Technology

Selected commercially available technologies appropriate for nondestructive testing (NDT) of steel hulled ships and their relative costs are summarized in Table 2-5. Numerous other methods exist, with local as well as remote recording, and data transmission via wire, fiber optics, or wireless means, and many manual and computer-aided means of data recording, reduction, presentation, and reporting.

Table 2-5. Selected Nondestructive Test Methods Applicable to Ship Inspections (Fox 2002, Baumeister 1978)

Test Method	Items Measured or Detected	Relative Cost
Visual inspection	• Surface deformities, corrosion, cracks, breaks • Staining or leaking liquids • Standing moisture and water • Surface coating breakdown	Low
Eddy current	• Surface and subsurface cracks and seams • Heat-treatment variations • Wall thickness, coating thickness • Crack depth	Medium
Leak testing	• Leaks of gases and liquids	Medium
Magnetic particle	• Surface and slightly subsurface defects; cracks, seams, porosity, inclusions • Extremely sensitive for locating small, tight cracks	Medium
Penetrants	• Defects open to surface of parts; cracks, porosity, seams, laps, etc. • Through-wall leaks	Low
Radiometry (X-ray)	• Wall thickness • Plating thickness • Variations in density or composition • Inclusions or voids	High
Ultrasonic	• Internal defects and variations; cracks, lack of fusion, porosity, inclusions • Thickness • Poisson’s ratio, elastic modulus	Medium
Deep ultrasonic	• Hull plating defects from diver-held instrument on outside of waterborne hull	High
Moisture detection	• Indication of corrosion	Low

2.4. Maintenance and Repairs

2.4.1. Types of Maintenance Actions

Traditional maintenance actions can be broadly divided into four types: corrective maintenance, preventive maintenance, predictive maintenance, and proactive maintenance.

Corrective Maintenance

Corrective Maintenance (CM) refers to the performance of maintenance tasks aimed at restoring the functional capabilities of an operating system or one of its components that has unexpectedly failed or malfunctioned in some manner. This maintenance can be planned, that is, a part of a scheduled maintenance activity which is deferred until the impact of failure is minimal; or it can be unplanned, such that the repair is mandatory and must be carried out immediately to return the system to operation.

Preventive Maintenance

Preventive maintenance (PM) is the performance of inspection and maintenance actions that have been preplanned, that is, scheduled for accomplishment at specific time, to reduce the probability of the occurrence of a particular failure mode. It is the most widely employed of the maintenance strategies. It has the benefit of providing the first level of control of maintenance cost beyond reactive maintenance modes. Four basic maintenance categories associated with PM tasks:

1. Periodic Time-Directed Maintenance: The maintenance tasks are designed to directly prevent or retard failure modes of the component or system.
2. Periodic Condition-Directed or Condition-Based Maintenance: The maintenance tasks are based on identifying condition or performance attributes that could provide indications of immanent potential failure.
3. Periodic Failure-Finding Maintenance: Inspections or tests are used to identify functional failures that are not always apparent to operators and maintenance actions are provided prior to these functions actually being needed.
4. Run-to-Failure (No Maintenance).

Predictive Maintenance

Predictive Maintenance (PdM) relies on gather system or equipment data, and analytical tools to determine and trend machinery condition rather than open and inspect. For example, · vibration analysis, thermography, thermal imaging, spectra-analysis of cooling and lubricating fluids, etc. are used as condition indicator data.

Proactive Maintenance (PaM)

Proactive Maintenance (PaM) uses proven and emerging technologies into an integrated corrective and preventive maintenance task strategy, capable of identifying and solving specific maintenance problems, and promotes reengineering individual equipment/system maintenance processes.

2.4.2. Maintenance Philosophies in Practice

Several philosophies on structural integrity maintenance management for ship structures are currently being employed or explored by maintenance officers and practitioners. These philosophies include Reliability, Availability, Maintainability and Supportability (RAMS), Reliability-Centered Maintenance (RCM), and Risk Management (RM) technique (Bea 1991, and Kirkhope et al. 1994). The two key differences between these three maintenance management approaches (RAMS, RCM and RM) involve the method in which the vessel or component condition is represented, and the flag used to trigger vessel maintenance actions. These philosophies are described in subsequent sections.

Reliability, Availability, Maintainability and Supportability (RAMS)

A RAMS approach relies on a database of historical performance data to infer structural failure or degradation rates. The statistical significance and/or validity of this trend information are a function of the amount of relevant experience or data accumulated for the vessel being investigated. With a structural maintenance management system based strictly on a RAMS approach, maintenance actions would be requested when the structural degradation mean time between failures indicates that preventive actions are required.

Reliability-Centered Maintenance (RCM)

RCM employs current vessel structural condition information and vessel operational profile descriptions to estimate a notional probability of component failure (1 – component reliability). Quantification of failure probabilities in this fashion requires an in-depth understanding of vessel behavior and the mechanics of its potential failure modes, expressed algebraically, in conjunction with statistical descriptions of the key load and material resistance parameters. By setting maximum acceptable or threshold failure probability levels, the RCM approach identifies the need for a maintenance action when the estimated structural failure probabilities reach these limits due to degradation. The U. S. Navy is currently implementing such maintenance philosophies.

Risk Management (RM) Technique

A RM technique employs structural risk as a yardstick to assess the relative urgency of structural degradation. Risk is defined as an aggregate measure of the failure consequences (cost, operational ramifications, damage potential) and likelihood (probability, frequency, uncertainty). Both historically inferred and theoretical estimates of failure probability are used to define the likelihood of component risk, while the most appropriate measure of the consequence of failure is estimated based on economic and/or management principles. In a RM technique maintenance actions are initiated when structural risk reaches an unacceptable level due to an increase in the probability of failure and/or the consequences of the failure. The consequences of failure may change over time due to remedial actions, costs and the future operational needs for the vessel.

Many of the complex probabilistic structural analysis techniques that are desirable for either of the RCM approaches may be too expensive to be practically implemented by vessel operators. In addition, statistically significant amounts of relevant component degradation data required for a RAMS approach and used to differing degrees by the other life cycle management techniques is not available for all vessels. A successful maintenance management system should therefore be developed around philosophies that embrace the desirable features of these approaches. The U. S. Navy is currently exploring such maintenance philosophies.

SEMAT Proactive Maintenance Strategy

A maintenance philosophy that has practical appeal, known as Proactive Maintenance (PaM), has been developed and is currently being implemented by the U. S. Navy (COMNAVSURFLANT 2000). The PaM strategy focuses on using corrective and preventive maintenance technologies toward identifying and solving specific maintenance problems. It is an 8-step process that employs the RCM philosophy as shown in Figure 2-1. The steps include system selection, definition of system boundary, equipment verification, functional description and failure definition, failure mode analysis, and root-cause analysis. The strategy relies on maintenance history and the use of Subject Matter Experts (SME) and Original Equipment Strategy to establish an initial maintenance strategy. This approach is currently at the implementation stage, and Measures of Effectiveness (MOE's) need to be developed to assess its performance over time and can be used to enhance the overall maintenance strategy as it matures.

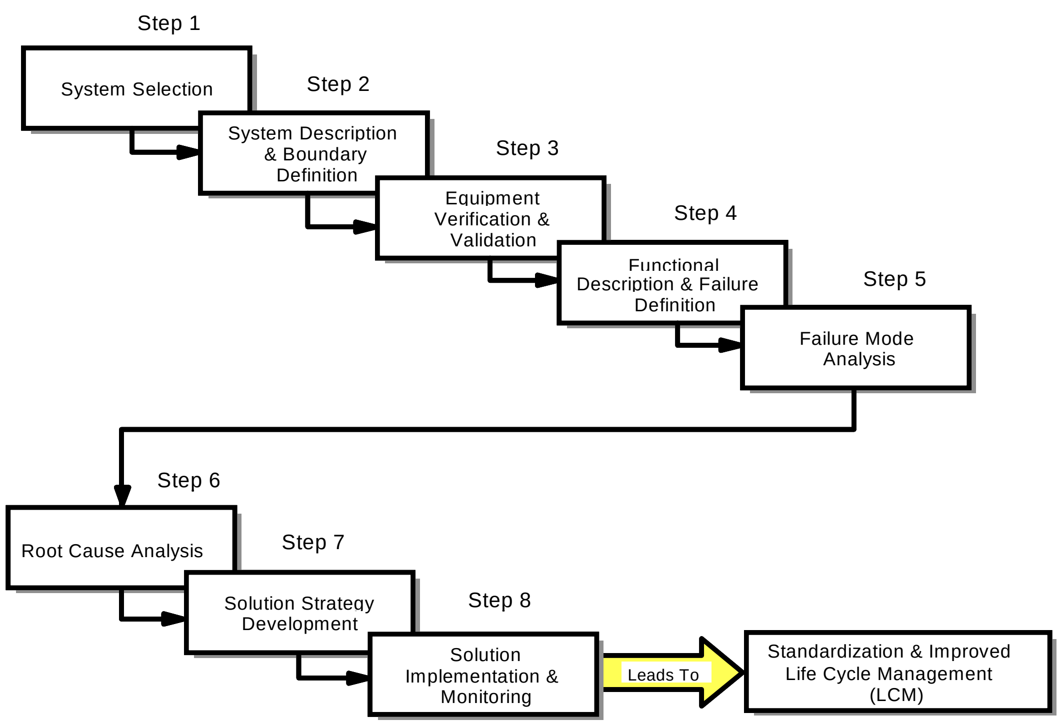

Figure 2-1. SEMAT Proactive Maintenance Strategy (COMNAVSURFLANT 2000)

2.4.3. Repair Methods

The repair of a ship structural system is both a difficult and demanding task for ship owners. There is no reasonable consensus on what, how and when to repair. The general lack of readily retrievable and analyzable information on maintenance and repairs makes tracking such activities very difficult.

Several repair methods are available for corrosion problems, as outlined in SSC-312. These methods are summarized in Table 2-5. The amount of new material used should be sufficient to maintain a structure's continuity and avoid any potential discontinuities (SSC-395). Replacing entire panels of an affected structure could also help repair corrosion damage. This may prove cost-effective and ultimately more reliable than merely renewing individual members, especially if the projected life span for the vessel may be extended as a result. For instance, in the case of the removal and re-welding of bulkhead stiffening to bulkhead plating, the possibility of the remaining corroded plating penetrating the newly-replaced plating is usually very high, and the future watertight integrity of the division remains questionable. Also, the combination of steel renewal and protective coating application could be the most cost-effective method to achieve a longer life span.

In some cases, excessive corrosion may lead to section moduli below the minimum required. In such instances, it may be possible, at the discretion of the relevant Classification Society, to install additional steelworks in conjunction with an effective corrosion protection system (e.g., painting), rather than carry out extensive steel renewals. This form of repair endeavours to re-establish the minimum required section moduli of the overall defective areas, while dealing directly with local defects or fractures as deemed necessary. Regular re-inspection of this alternative reinforcement should be carried out to ensure its continued effectiveness in maintaining the overall structure integrity of the vessel (TSCF, 1992).

Pitting corrosion can be found on the internal horizontal surface, particularly in the bottom plate of the cargo or ballast tanks. If widely scattered, they may not affect the general strength of the vessel. However, due to their depth and quick deterioration rate, they may quickly lead to a through-thickness penetration, which poses significant danger of subsequent pollution. A minimum thickness should be established for pitting repair (Ma and Bea, 1992). Pitting repairs can be classified according to the remaining plate thickness. When the remaining plate thickness is greater than the specified minimum thickness, pitting repair can be carried out by means of grit blasting and brush coating with the affected area with coal tar epoxy. Alternatively, the region may be vacuum blasted and filled with pourable pit filler. When the remaining thickness has been reduced to somewhere between the specified minimum thickness and 6 mm, pitting repair can be carried out by filling any pits with weld metal. Finally, when the pitting is so severe that the remaining thickness is less than 6 mm, the affected area or component should be cropped and replaced by a new one.

Strategies employed for crack repair vary widely. A summary of possible crack repair methods is presented in Tables 2-6 and 2-7. Repairs of cracks can range from temporary cold patches (to stop leaks) to the complete re-design of the structural detail and replacement of any adjacent steel. Welding of cracks is a popular repair technique, but such repairs often fail again within a short time. Drilling of crack tips is another frequently used temporary repair measure that may delay more extensive repairs until the ship can be taken into drydock. Repairs of these cracks can range from simple welding to addition of reinforcing elements such as doubler plates. Experience indicates that many of these repairs must be redone during subsequent dry-docking (Bea, 1992).

Selection of a suitable crack repair method also depends on the location of the crack. Cracks in primary structures require more serious repair actions than those in secondary structures. A primary structure is simply one that contributes significantly to the main structural strength of the ship. Examples of primary structures include hull plates, stiffeners, principal decks, and main transverse members. A secondary structure is a structure that neither contributes to the structural strength nor the watertight integrity of the vessel. Examples include partition bulkheads and platforms.

Fitting doubler plates or removing the affected material around the crack and filling in the area with weld metal may temporarily repair cracks in a primary structure. Material removal and re-welding is a relatively simple and commonly used repair technique. However, the strength of re-welded cracks is almost invariably worse than that of the original material. The repaired area may induce new cracks, and thus fail earlier than expected. Such repairs are sometimes considered in attempting to get the ship to a facility where more extensive repairs can be made. Better repair methods include cropping the affected area and replacing it with new material or plating, or modifying the local geometry to reduce stress concentrations responsible for cracking. If the life of the ship needs to be extended beyond that originally planned, a more robust repair, such as geometry modification, should be considered. On the other hand, cracks in secondary structures may be arrested temporarily simply by drilling a hole at the crack tips. The hole should be of a diameter equal to the plate thickness, and should be placed at a distance of twice the plate thickness in front of the visible crack tip and in line with the direction of anticipated crack propagation (Ma, 1992). It is difficult to decide which repair method is most reliable and cost effective for a particular crack. The selection of different repair alternatives is usually dependent on the location of the crack and the expected life span of the ship.

Table 2-6. Summary of Corrosion Repair Methods

Severity of Corrosion	Type of Corrosion	Corrosion Repair Options
Minor Coating Breakdown	General corrosion	1. No repair and monitor 2. Spot blast and patch coat 3. Add/maintain anodes
	Pitting corrosion: small shallow pits with a depth of less than 50% of the plate thickness	1. No repair and monitor 2. Spot blast, epoxy pit fill and patch coat 3. Add/maintain anodes
Major Coating Breakdown	General corrosion	1. No repair and monitor 2. Spot blast and patch coat 3. Reblast and recoat 4. Add/maintain anodes
	Pitting corrosion: large, deep pits with a depth greater than 50% of the plate thickness, few in number	1. No repair and monitor 2. Spot blast, weld fill, patch coat 3. Add/maintain anodes
	Pitting corrosion: large, Deep pits with a depth of greater than 50% of the Plate thickness, numerous	1. No repair and monitor 2. Spot blast, weld cover plate, patch coat (temporary repair) 3. Cut out, weld new plate, blast, coat (permanent repair) 4. Add/maintain anodes

Table 2-7. Summary of Crack Repair Options

Crack Repair Option	Notes
No repair and monitor	
Temporary fix and monitor	1. Drill hole at crack tip 2. Drill hole at crack tip, insert bolt and tighten lug to impose compressive stresses at crack front 3. Add doubler plate 4. Cover crack with cold patch
Permanent fix, keep same design	1. Gouge out crack and re-weld 2. Cut out affected section and butt weld new section 3. Impose post-weld improvement techniques
Permanent fix, modify design	1. Gouge out crack, re-weld, add/remove/ modify scantlings, brackets, stiffeners, lugs or collar plates 2. Cut out section, re-weld, add/remove/ modify scantlings, brackets, stiffeners, lugs or collar plates 3. Impose post-weld improvement techniques

2.5. Reliability-based Inspection Planning

Pre- and in-service inspections and repair of detected defects can reduce the probability of failure and the cost of operating the component. Costs of inspection and repair may be a significant part of the overall lifetime cost of a ship structure. These costs should be balanced by the benefits to be gained, both in economic and reliability terms. There are tradeoffs between the extent and accuracy of inspection, required level of reliability, and cost. One could envision two alternatives: relatively frequent but cursory inspections or infrequent, comprehensive inspections. Reliability-based condition assessment and life prediction methodologies should provide guidance to schedule the routine inspection/maintenance, if necessary, to keep the failure probability of the structure at or below an established target probability during its service life. Inspection /maintenance strategies should be determined by minimizing the expected total future cost, while keeping the failure probability at or below an established target failure probability during the service life of an aging structure. The American Society of Mechanical Engineers (ASME 1991) provided procedures for risk-based inspection planning.

The reliability-based inspection planning has been implemented recently for various aging structures such as prestressed concrete containment structures (Pandey 1997), offshore structures (Soerensen et al. 1999; Hoersholm et al. 1999; Shetty et al. 1998; and Garbatove and Soares 2001), pipes (Nessim and Pandey 1997; Hellevik and Langen 2000; and Hellevik et al. 1999), and bridges (Thoft-Christensen 1999). Various models have been developed to quantify the effect of different maintenance activities on the structural reliability and to demonstrate how the results of these models can be used in a reliability-based framework for implementing optimal integrity maintenance plans. The structural reliability method coupled with the Bayesian statistics has been developed by Hellevik and Langen (2000) to determine the time for the next inspection and the inspection method to be used. In the lifecycle cost design of these deteriorating structures, an optimization problem is formulated based on minimizing the expected total lifecycle cost while maintaining an allowable lifetime reliability level for the structure. Most of these methods incorporate: (1) the quality of inspection techniques with different detection capabilities; (2) the effects of aging, deterioration, and subsequent repair on structural reliability; and (3) the time value of money. The overall cost to be minimized includes the initial cost and the cost and the costs of preventive maintenance, inspection, repair, and failure. Since some uncertainties in the risk-based inspection planning cannot be fully described within the probabilistic concepts, a fuzzy reliability concept has been introduced recently by Kanegaonkar (2001) to characterize the cognitive uncertainties associated with the initial flaw size, crack length at failure, and the constants in the fatigue crack growth law. The final optimal inspection interval is determined by using fuzzy reliability index as a function of time and target fuzzy reliability index.

In order to design an inspection/maintenance strategy, it is necessary to evaluate the effectiveness of periodic inspection and maintenance on the failure probability of a component. In studies to evaluate the failure probability of metallic structures subjected to fatigue, it has been assumed that a fatigued component is replaced if the intensity of detected damage exceeds a critical value. However, a component may not even be replaced or repaired during maintenance unless damage is detected and is larger than a certain threshold. In this case, the effect of damage overlooked at an inspection or detected but not repaired also should be considered. To accomplish this task, it is necessary to consider the probability of detecting damage of a given size or extent and to introduce models of damage initiation and intensity. The number of damage zones and the damage intensity before and after maintenance are random variables. Tang and Halim (1988) developed a procedure for updating the distribution function of damage intensity immediately following maintenance through such modeling.

The imperfect nature of nondestructive examination (NDE) methods is random and can be described in statistical terms. It is important that the NDE method be able to distinguish between different defects with a high level of reliability so that needless repairs can be avoided. Inspections for the purpose of reliability-based condition assessment and evaluation of suitability for continued service of ship structures and components will require a greater detection reliability and more quantitative assessment of defects and accumulated damage than traditional in-service inspection of concrete structures (House 1987).

There are tradeoffs between the extent and accuracy of inspection, required level of reliability, and cost. One can perform this tradeoff by defining an objective function that take into account the cost of failure, cost of inspection, and costs of repair. An optimal inspection strategy for highway steel girder bridges has been developed by Sommer at al. (1991) using the minimization of the total cost. The inspections are performed at constant time intervals that are calculated by the optimization. An inspection strategy has been formulated where the girders with largest failure probability are inspected more frequently than others. The inspection intervals are chosen optimally so that the expected costs of inspection, repair and failure are minimized.

To design an optimum inspection /maintenance program, the failure probability of a component during its service life, $P(t)$, provides one of several constraints on the optimization. The resulting risk-based inspection planning can be formulated by solving

$$\begin{array}{c}\text{Minimize } C_T \\ \text{Subject to } P(t_L) \le P_{fT}\end{array} \tag{2-1}$$

where P_{fT} is an established target probability during the service life, t_L, of a component/structure and C_T is the total cost of inspection/repair plus expected losses due to failure of a structure. Additional constraints can be included such as the minimum and maximum time intervals between inspections, and the minimum threshold value of detection of the NDE method which is available. The total cost function can be expressed as

$$C_T = C_{ins} + C_{rep} + C_f\, P(t_L) \tag{2-2}$$

in which C_{ins} is expected inspection cost, C_{rep} is expected repair cost, and C_f is the loss due to structural failure.

Thoft-Christensen and Sorensen (1982) assumed that a component is replaced if the intensity of detected damage exceeds a critical value. The cost of repair was assumed to be constant. In many cases, however, a component may not be replaced; instead, only detected damage might be repaired. In this case, the cost of repair would be a function of damage intensities to be repaired. This aspect should be considered in designing an optimum strategy.

Two inspection strategies can be implemented by solving the optimization problem defined by Eq. 2-1, namely, the full inspection strategy and partial inspection strategy. In the full inspection strategy, the decision variables are the times at which inspections/repairs are carried out, $t_R=\{t_{R1}, t_{R2}, \ldots, t_{Rm}\}$, and the threshold value of detection for inspections, $x_{th1}=x_{th2}\ldots.=x_{thm}=x_{th}$. The number of inspections, m, during the service life of a structure is given in advance. The influence of m can be explored by solving the optimization problem for a number of different values of m and comparing the optimal total cost C_T.

Different from the full inspection strategy, a small part of a structure or a component is inspected to assess its condition based on the partial inspection strategy because of the cost of inspection. Inherent in this procedure is assumption that any part of the component is representative of the component as whole, and the rest of the component is amenable to a statistical representation. At each time when a partial inspection is carried out we gain some information about the strength and degradation of the component and make a decision whether or not to repair the component, depending on the result of the inspection. A decision policy can be implemented at each inspection (Thoft-Christensen and Sorensen 1982). A typical policy can be described by

1. Inspect α% of the component (Stage I).
2. If the maximum intensity of damage detected at Stage I, $X_{maxI}(t_R)$, is less than the predetermined critical value x_{cr}, then perform no further inspection until the next scheduled inspection.
3. If $X_{maxI}(t_R) \geq x_{cr}$, then inspect another α% of the component (Stage II).
4. If the maximum intensity of damage detected at Stage II, $X_{maxII}(t_R)$, is less than x_{cr}, then perform no further inspection until the next scheduled inspection.
5. If $X_{maxxII}(t_R) \geq x_{cr}$, then inspect the entire component and repair all detected damage (Stage III).
6. If a Stage III inspection is carried out at t_{Rj}, then during the rest of its service life the component will be fully inspected and all detected damages will be repaired.
7. The parameters of the degradation model are updated after each partial inspection (Stage I and Stage II) but the component is not repaired. Since the portion of a component partially inspected is generally small, the impact of repairing the detected damage on the degradation function and thus on the failure probability of the component is small.

For a given decision policy, the optimization problem of a partial inspection strategy can be solved using a number of decision variables, such as the number of partial inspections to be scheduled, m_P, critical value of decision at the i^{th} partial inspection x_{cri}, times at which the i^{th} partial inspection is carried out, t_{Pi}, the number of full inspections after Stage III inspections is performed at t_{Pi} (Branch i) m_i, the threshold value of the j^{th} inspection/repair in Branch I, x_{thij}, and the time at which full inspection/repair is carried out in Branch I, t_{Rij}. In comparison with the full inspection strategy, an extensive list of decision variables is involved in the optimization problem.

2.6. Limitations of Current Inspection Strategies

Although advances have been made in the development of modern maintenance philosophies, these approaches do have inherent limitations. The limitations include the following:

1. Traditional maintenance strategies are driven mainly by subjective experience of experts. An objective evaluation of optimal maintenance strategies involves the translation of these expert opinions into objective measures or numbers using the Expert Elicitation Process (Ayyub, 2002). These numbers can then be manipulated to arrive at the most efficient maintenance policy in terms of cost and life extension. To the best of our knowledge, there is no known existing maintenance software for ship structures that has attempted to accomplish this goal, thus making improvement in ship structures maintenance practices an elusive exercise.
2. Current ship maintenance strategies do not encourage systematic gathering of information required for the evaluation of the costs of performing all relevant activities. Therefore, it is rather difficult to objectively assess the cost effectiveness of the strategies employed.
3. Most maintenance philosophies are driven by the need to maintain operational requirements within a dwindling budget. That is, there is a desire to reduce maintenance costs without jeopardizing the structural integrity of a vessel. However, these strategies do not have systematic frameworks in place for incorporating maintenance cost models and alternative maintenance actions for similar maintenance needs. It is therefore difficult to access their effectiveness with regards to cost reduction and maintenance action selection.
4. Advances in structural reliability techniques and global numerical response models have been made for ship structures. Although some of the modern strategies acknowledge these advances, they do not provide a framework for their incorporation into maintenance scheduling and execution.
5. The risk-based management strategy, which combines probability of failure with consequence of failure, within the framework of financial engineering and economics is quite likely the most advanced maintenance management philosophy available. However, there exists no known practical model that implements this strategy for ship structures. Thus, its benefits have remained largely untapped.
6. Most software available to support a risk-based management approach is not tailored to the particular requirements of ship structure, or is not a complete inspection-through-analysis package.

3. RISK-BASED INSPECTION METHODOLOGY

3.1. Methodology Requirements and Definition

This chapter develops the strategy employed for risk-based inspection of marine vessels. The methodology utilizes a combination of risk methods, life cycle modeling and probabilistic reliability modeling for ship structures. The underlying methodology is developed in a systematic framework that provides managers with risk-based guidance on significant failure locations by first assessing failure modes, failure probabilities and consequences, and then feeding the results into decision models.

The basic philosophy of the proposed methodology assembles a catalogue of experience gathered from databases, ship personnel (including managers), risks assessment models, and other industries and experts, and incorporates this information into tools used in ship structural analysis and damage assessment/prediction. The methodology consists of the synergistic combination of decision models, advanced probabilistic reliability analysis algorithms, failure consequence assessment methods, and conventional mechanistic residual strength assessment methodologies that have been employed in the marine industry for structural integrity evaluation and management. The approach realistically accounts for the various sources and types of uncertainty involved in the decision-making process, including defect data gathered from inspections, material types, loads, and repair method parameters, as well as the engineering strength models that are employed. Furthermore, the probabilistic approach proposed is capable of taking direct advantage of previously verified residual strength assessment models and engineering experience that has been compiled over time from the operation of vessel systems.

The essential requirements imposed on the proposed risk based methodology are to optimize the inspection process by addressing the following:

- What and where to inspect, i.e., critical inspection areas.
- When to inspect, i.e., inspection intervals.
- How to inspect, i.e., decision analysis to select a cost effective inspection method.
- What to use as an optimal inspection strategy at the system level.

The overall methodology, which seeks to answer the aforementioned questions, is described using a flow chart or block diagram. Figure 3-1 provides an overall description of the proposed methodology for risk-based inspection of marine vessels. The sections of this chapter are structured to address these questions of what and where to inspect, when to inspect, how to inspect, and what to use as an optimal inspection strategy at the system level.

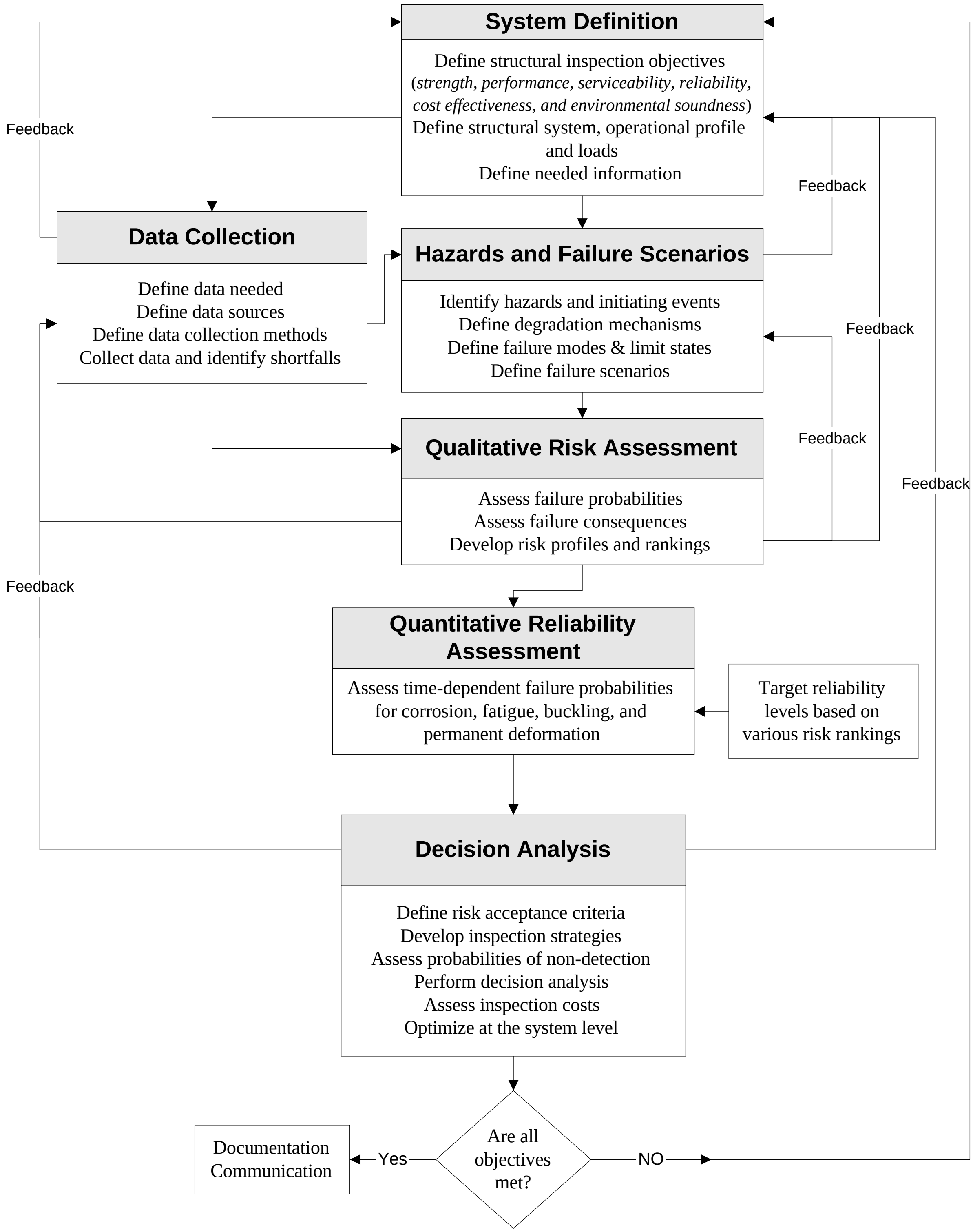

Figure 3-1. Methodology for Risk-Based Inspection of Structural Systems

3.2. Steps Needed to Define Critical Areas for Inspection

As mentioned in the previous section, the first fundamental requirement of the proposed methodology is help inspectors identify structural elements and/or regions that must be inspected and prioritize these elements and/or regions. The basic steps that have to be undertaken in answering the question what and where to inspect have been highlighted in Figure 3-1 and include the following:

- System definition and its boundaries;
- Definition of analysis objectives and systems, and data collection;
- Hazards and failure scenario definition;
- Qualitative risk assessment;
- Quantitative reliability assessment; and
- Definition of an optimal inspection strategy based on decision analysis.

These steps are briefly described in subsequent sections.

3.2.1. System and Objectives Definition, and Data Collection

The first step of the methodology requires definition of the inspection objectives and structural system. This definition should be based on an overall goal that is broken down into a set of analysis objectives. A system can be defined as an assemblage or combination of elements of various levels and/or details that act together for a specific purpose. Defining the system provides the risk-based methodology with the information it needs to achieve the analysis objectives. The system definition phase of the proposed methodology has four main activities. The activities are highlighted in Figure 3-2, and include:

(i) Define the goal and objectives of the analysis;
(ii) Define the system boundaries;
(iii) Define the success criteria in terms of measurable performances;
(iv) Collect information for assessing failure likelihood; and
(v) Collect information for assessing failure consequences.

The inspection goal can include objectives stated in terms of strength, performance, serviceability, reliability, cost effectiveness, and environmental soundness requirements. The objectives can be broken down further to include other structural integrity attributes such as alignment and watertightness. A system can be defined based on a stated set of objectives. The same system can be defined differently depending on these stated objectives. A vessel's structural system can be considered to contain individual structural elements such as plates, stiffened panels, stiffeners, longitudinals, etc. These elements could be further subdivided into individual components and/or details. Identifying all of the elements, components and details allows an analysis team to collect the necessary operational, maintenance and repair information throughout the life cycle of each item such that failure rates, inspection and repair frequencies, and failure consequences can be estimated. The system definition might also need to include non-structural subsystems and components that would be affected in case of failure. The subsystem and component information is needed to more accurately assess the consequences of failure.

Although the risk-based methodology advanced in this study is quite general, and can be applied to the inspection of any system within a ship structure, emphasis herein is placed on inspection of the hull structural system. This system includes longitudinals, stringers, frames, beams, bulkheads, plates, coatings, foundations, and tanks. The hull structural system delineates the internal and external shape of the hull, maintains watertight integrity, ensures environmental safety, and provides protection against physical damage. The boundaries of a hull structural system include the hull, its appendages from (and including) the boot topping down to the keel for the exterior surfaces of the ship, the structural coating, and insulation for the interior and exterior surfaces.

In order to understand failure and its consequences, the various states of success need to be defined. For a system to be successful, it must be able to perform its designed functions by meeting measurable performance requirements. However, a system may be capable of various levels of performance, all of which might not be considered a successful performance. Consider, for example, a vessel which, although capable of traveling from point A to point B, must do so at a reduced speed for fear of potential fatigue failure that may result from excessive vibration in the engine room. The performance of this vessel would probably not be considered successful. The same concept can be applied to individual elements, components and details. It is clear from this example that the impact of a vessel's success and failure should be based on overall vessel performance, which, in turn, can easily extend beyond the structural systems.

With the development of the definition of success, one can begin to assess the occurrences and causes of failures. Most of the information required to develop an estimate of the likelihood of failure exists within the inspection, maintenance and operating histories of the systems and equipment. Such an estimate may be based on sound engineering judgment and expert opinion. However, this information might not be readily accessible, and extraction from its current source may prove difficult. Also, assembling the information in a manner suitable for the risk-based methodology may be challenging.

Operation, inspection, maintenance, engineering and corporate information on failure history must be collected and analyzed for the purpose of assessing failure consequences. Failure consequence information might not be available from the same sources as those containing information regarding the failure itself. Typically, documentation exists outlining repair costs, re-inspection or re-certification costs, lost man-hours of labor, and possibly even lost opportunity costs due to system failure. Much more difficult to find and assess are costs associated with the effects of failure on other systems, the cost of shifting resources to cover lost production, and also environmental, safety-loss or public-relations costs. Such information may be attained through carefully organized discussions and interviews with cognizant personnel, including the use of expert-opinion elicitation.

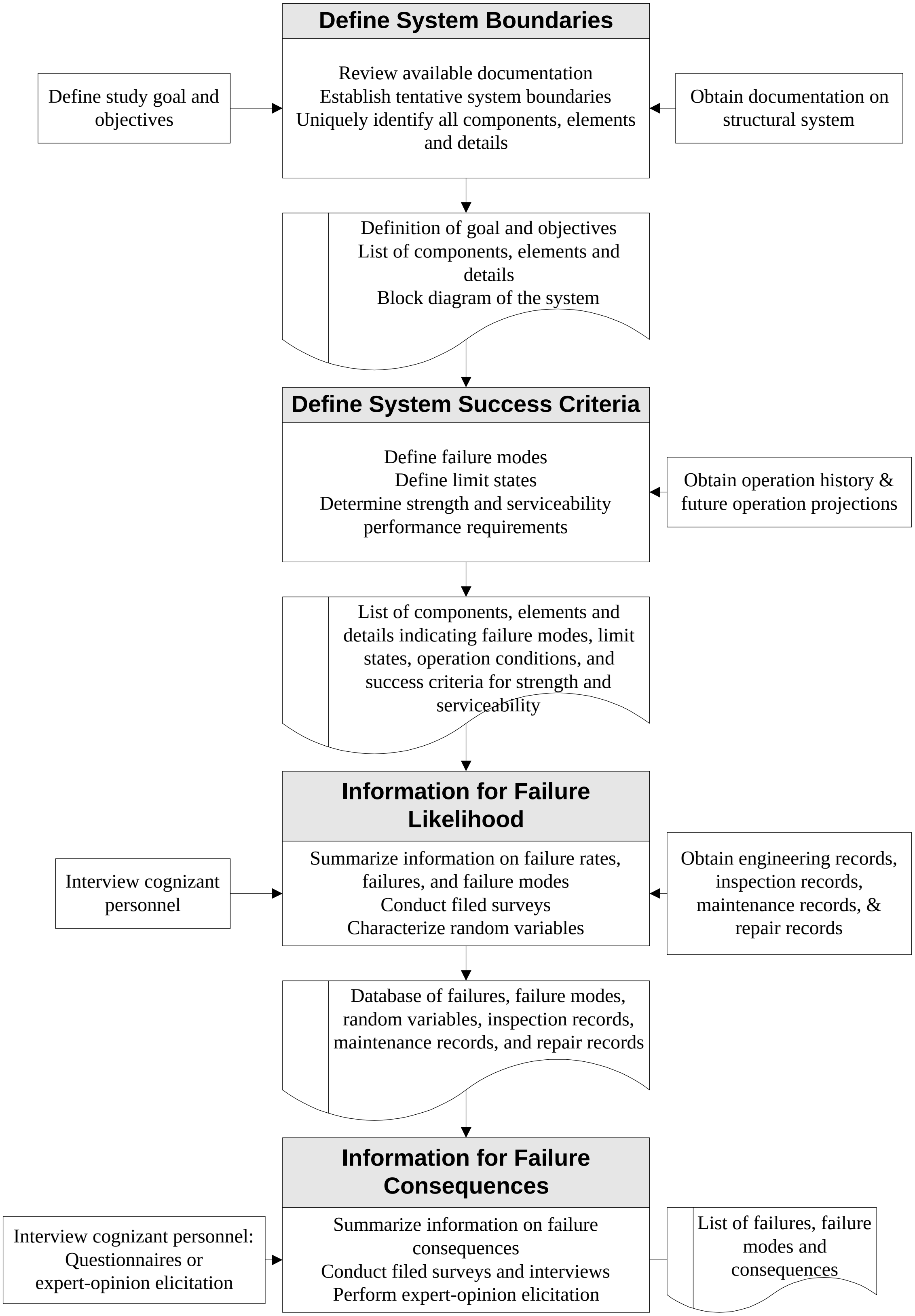

Figure 3-2. System Definition

3.2.2. Hazard Analysis

A hazard is an act or phenomenon posing potential harm to some person(s) or thing(s), (i.e., a source of harm), and its potential consequences. For example, uncontrolled fire is a hazard, water can be a hazard, and strong wind may also be a hazard. The methodology requires the performance of preliminary hazard analysis, which should produce a list of hazards that are suitable for system analysis and which may effect assessment due to such hazards. A Preliminary Hazard Analysis (PHA) identifies and prioritizes hazards leading to undesirable consequences early in the life of a system. Such an analysis also recommends actions aimed at reducing the frequency and/or consequences of the prioritized hazards. For ship structures, the hazards might include several damage inducing sources, such as, corrosion environments, wave loads, and water pressure.

Preliminary Hazard Analysis

Preliminary Hazard Analysis (PHA) is a common risk-based technology (RBT) tool with many applications (Ayyub, et al 2000). In PHA, hazards are defined as initiating events coupled with consequences. Hazards may be categorized into a number of classes, ranging from Class I for 'Negligible Effect' to Class IV for 'Catastrophic Effects'. The initiating events are typically ranked into five groups, ranging from frequent (of about E-1 to E10, where 'E' denotes the exponent or power, therefore the 'frequent' range is from approximately 10^{-1} to 10^{10}) to infrequent (of about E-6 or 10^{-6}). The consequence groups can be also categorized into five groups, ranging from trivial consequences to non-repairable with fatalities or health-related consequences. This technique requires that experts first identify and then rank the possible accident scenarios that may occur. It is frequently used as a preliminary attempt to identify and reduce the risks associated with major hazards of a system.

The PHA uses an interdisciplinary team in a creative, systematic approach to identify hazards resulting from deviations in original design intent. It employs a list of hazards and generic hazardous situations, which are applied to various segments or 'nodes' of the system. The analysis then develops recommendations for those consequences for which the current safeguards are deemed inadequate by the PHA team. The method requires, if available, codes and standards; previous safety studies; current drawings and flow diagrams; operating procedures; incident history; maintenance, inspection and test records; and material properties. It also requires a team leader trained in PHA methods, and team members with sound knowledge of both the design and operation of the particular system being evaluated.

The PHA can produce findings (recorded in the form of hazard scenarios), recommendations for changes in design, operating procedures, etc., and recommendations for areas needing further evaluation. The PHA can also produce prioritized lists of recommendations based on risk rankings estimated by the PHA team, who use predetermined guidelines for assigning likelihood and severity of consequences from various scenarios.

Figure 3-3 provides a PHA definition specifically developed for use with the suggested methodology be covering selected steps or portions of Figure 3-1. The figure illustrates the detailed steps required to effectively achieve the goals of PHA. The PHA process and its results are commonly provided in tables, under the following column headings:

1. Subsystem or function;
2. Mode (or phase of operation);
3. Hazardous element (gas, steam);
4. Event causing hazardous condition (error, malfunction);
5. Hazardous condition;
6. Event causing potential accident;
7. Potential;
8. Effects;
9. Hazard class;
10. Accident prevention measures (hardware, procedures & personnel); and
11. Validation.

The PHA has a number of advantages, including:

1. It can be used at the concept/design stage by relying on team expertise;
2. It produces lists of risk-ranked hazardous scenarios;
3. It is a creative process for identifying hazardous scenarios that can be readily used in quantitative risk analysis; and
4. It can address both potential safety and productivity losses.

However, it also has a number of limitations, which include:

1. It requires an interdisciplinary team of at least four persons, including a scribe and leader trained in PHA;
2. It is less systematic than some other qualitative methods (e.g., FMEA or HAZOP analysis), and therefore relies more heavily on team knowledge and commitment to quality analysis;
3. If properly applied, can require a level of effort approaching a significant fraction of that required to perform a HAZOP analysis, FMEA, or PRA.

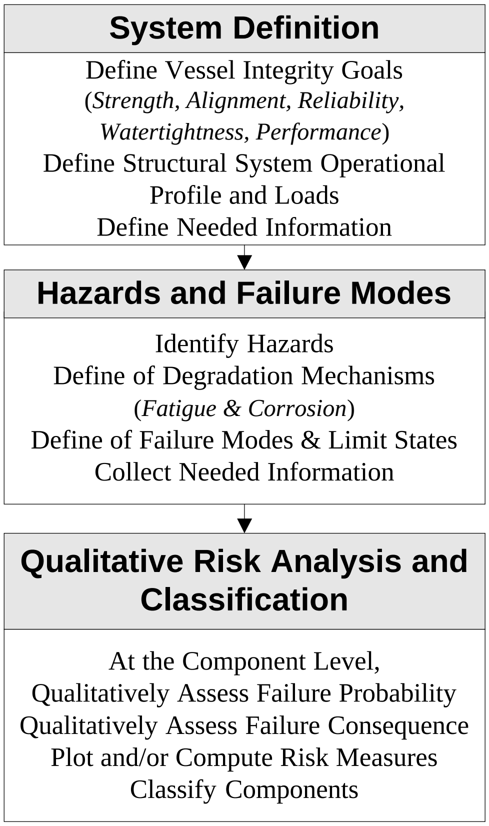

Figure 3-3. Preliminary Hazard Analysis (PHA)

3.2.3. Definition of Failure Scenarios

Once identified, potential hazards form the basis for defining the initiating events. Initiating events are considered bad beginnings, accident initiators, or failures. The suggested methodology transforms these initiating events into risk measures or profiles. After identifying the initiating events, all possible outcomes for the system as a result of these initiating events must be evaluated. The outcomes are defined based on scenarios that consider a given hazard as an initiating event, and describe the event propagation in the system, defining all the possible outcomes associated with that hazard.

The description of the hazard propagation in the system can be executed using cause-consequence diagrams. For example, a simple diagram is shown in Figure 3-4 as a marriage of event trees and fault trees. The cause part of the analysis uses the fault tree technique to define the likelihood of occurrence of the basic or initiating event. In the cause analysis, possible causes of each initiating event are identified to the extent necessary to estimate a particular likelihood of occurrence. The consequence part of the analysis utilizes event trees to propagate the failure initiation. The consequence tracing part of the diagram involves taking the initiating event and following the resulting chain of events through the system. At various steps, the chains may branch into multiple paths. The consequence analysis results in a description of all relevant accident scenarios, given the occurrence of a particular initiating event, and is used to calculate both the likelihood of occurrence and corresponding consequences of each potential accident scenario. The occurrence likelihood for each event presented in the cause-consequence diagram can be determined by breaking down the event with using a fault tree analysis.

The procedure for constructing a consequence scenario is first to take the initiating event, and then select each subsequent event by asking the following questions:

(i) Under what conditions does the event lead to further events?
(ii) What alternative conditions lead to different events?
(iii) What other components or sub-systems are affected by the event?
(iv) What subsequent events are caused by this event?

In cases where such in an depth cause-consequence analysis cannot be executed due to lack of expertise or limited financial resources, a simplified procedure based on engineering judgment and experience should be employed, which might be more feasible for the practicing community.

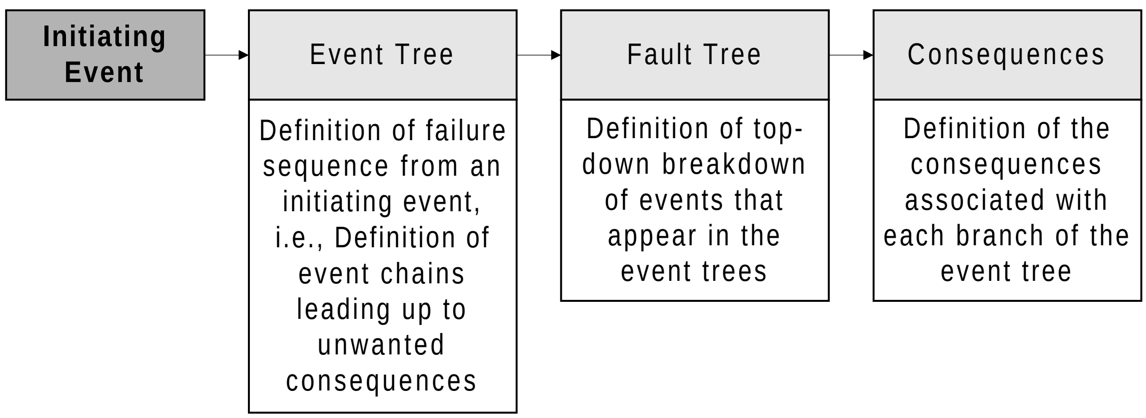

Figure 3-4. Basic Steps for Performing a Cause-Consequence Analysis

3.2.4. Qualitative Risk Assessment

Components of a typical ship vessel include the main hull form (part of which is below the waterline), single or multiple decks, an engine room, an equipment room, fuel tanks, freshwater tanks, ballast tanks, super-structures, and a storage area. These components experience structural deterioration due to loads from a variety of sources, both environmental and otherwise. The type, rate, and extent of structural damage are each dependent on the physical location of a component and may be different for different regions of a vessel. Furthermore, the inspection requirements of various components of a ship structure may differ in terms of frequency, type, and cost, even for components within the same region.

Components or systems prone to various hazard categories should be identified during the hazard analysis phase. The identification process should utilize previous studies and reports, as well as elicitation from subject matter experts (SME's). Qualitative risk assessment can then be performed for the purpose of ranking the risk levels of the various components or subsystems.

Qualitative risk assessment requires approximate estimates of the failure likelihood at the identified levels of decision-making. The failure likelihood can be estimated in the form of lifetime failure likelihood, annual failure likelihood, mean time between failures, or failure rate. The estimates can be in either numeric or non-numeric form. An example numeric form for an annual failure probability may be 0.00015, and for a mean time between failures one might determine 10 years. An example non-numeric form for an annual failure likelihood may be simply *large*, and for the mean time between failures, simply *medium*. In the latter non-numeric form, guidance must be provided regarding the meaning of terms such as *very large, large, medium, small, very small*, etc. The selection of form (numeric versus non-numeric) should be based on the availability of information, the ability of the personnel providing the required information to express it in one form or another, and the importance of having numeric versus non-numeric information available with which to formulate final decisions.

The types of failure consequences that should be considered in the study also need to be selected. They may manifest themselves in the form of production loss, property damage, environmental damage, and safety loss leading to human injury or death. Moreover, approximate estimates of failure consequences at the identified levels of decision-making need to be determined. The estimates can be in numeric or non-numeric form. An example numeric form for production loss may be 1000 units, whereas a non-numeric example for production loss may be simply *large*. In the latter non-numeric form, guidance must be provided regarding the meaning of terms such as *very large, large, medium, small, very small*, etc. As was the case for qualitative failure likelihood estimation, the selection of form (numeric or non-numeric) should be based on the availability of information, the expressive ability of the personnel providing the information, and the importance of having numeric versus non-numeric information in formulating the final decisions.

For the element, component or detail levels, risk estimates need to be evaluated. The estimated failure likelihood and consequences obtained in the previous activities are used for this task. Risk estimates can be determined as a pair of the likelihood and consequences of failure, and may be computed as the arithmetic multiplication of the respective failure likelihood and consequences for the equipment, components and details. Alternatively, for all cases, plots of failure likelihood versus consequences may be developed. Then, the information in each plot may be grouped and ranked approximately according to risk estimates, failure likelihood, and/or failure consequences.

The computation of a risk profile involves combining an event's failure probability and its corresponding consequence. The event's risk can be expressed by multiplying these two measures, producing an expected loss or a measure of loss potential. Such an approach, however, fails to account for risk aversion. Risk may be shown either figuratively or numerically. In either case, the resulting risks are grouped into a handful of risk categories ranging from extremely low risk to high-risk situations. In most cases, it is desirable to maximize the number of events that occur in the lowest one or two risk categories, depending on the situation. Events that fall into the high-risk category may be the result of high consequences, high probabilities of occurrence, or both. Events falling into the high-risk categories should be examined further to find ways in which the risk may be reduced to an acceptable level, or managed more effectively.

Based on the cause-consequence analysis presented in previous sections, a risk profile analysis can be performed to define the critical scenarios for a vessel's safety based on a structural failure as an initiating event. The probability of occurrence of a given failure scenario can be determined by multiplying all the conditional probabilities of the events along a branch of the resulting tree which define the scenario. A consequence rating can then be developed and provided for each scenario or branch. The probability of occurrence and consequence rating associated with each scenario can then be used to define the Farmer curve or risk profile resulting from a given initiating event. Figure 3-5 provides an example risk profile associated with the occurrence of a fatigue crack in the main engine foundation stiffener. The figure also depicts four risk quadrants that correspond to four levels of differing implication and mitigation requirements.

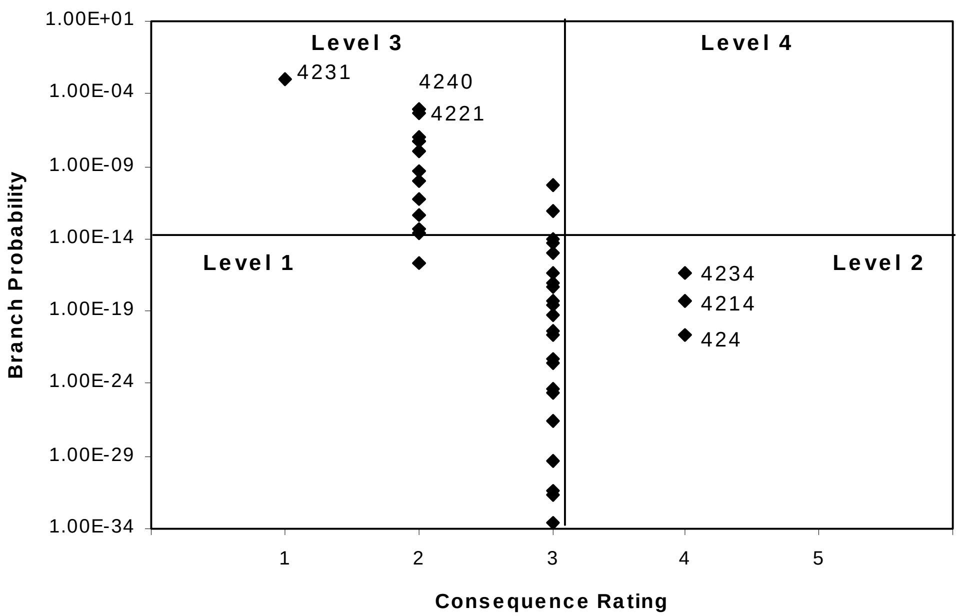

Figure 3-5. Risk Profile Associated with the Occurrence of Fatigue in a Main Engine Foundation Stiffener (Ayyub, et al. 2000)

3.3. Steps Needed to Compute Inspection Intervals

This section constitutes the phase of risk-based inspection for computing inspection intervals, and should be guided by the results of the qualitative and quantitative risk/reliability assessments presented in the previous section and subsequent sections. Computation and selection of inspection intervals requires the following:

1. Computing time-dependent failure probabilities; and
2. Selecting target reliability levels as thresholds below which inspections become necessary.

3.3.1. Quantitative Reliability Assessment

The primary objective of this activity is to assess in a quantitative fashion the failure likelihood for various components, segments or regions with high-risk profiles. The failure likelihood must be based on identified failure modes. In its final form, quantitative failure likelihood should be expressed in terms of either a lifetime or annual failure probability. A time dependent reliability strategy, which accounts for continuous growth of identified damage within a given region, can be employed. In gathering the information needed to predict time dependent failure probability due to structure deterioration, either the mean time between failures or the failure rate itself may be utilized. The information required to establish an annual failure probability can be obtained from the following sources:

1. In-house or industry failure databases,
2. Failure information from other vessels or studies performed on them,
3. Published results based on literature reviews,
4. Probabilistic analysis, and/or
5. Expert elicitation.

Figure 3-6 shows factors that significantly contribute to reliability assessment of ship structures. Figure 3-7 outlines a procedure for assessing the reliability of a ship structural system subjected operational, seaway and other loads. Analysts and designers are faced with numerous sources of uncertainty and product variability during ship design and fabrication. Reliability-based design uses probabilistic methods to account for uncertainties and maximizes structural performance for an acceptable level of structural safety and reliability. Reliability-based ship structural design can provide an optimal solution in light of the available knowledge, tools and consequent uncertainty. As shown in Figure 3-7, critical elements associated with the reliability assessment of a ship structure are: (1) accurate quantification of statistical distribution of ship response subjected to various loads and load combinations; and (2) accurate quantification of statistical distribution of structural capacity via material/ structural/ virtual testing. A limit state function can then be formulated based on a given failure mode such as yielding, buckling, creep, corrosion, fatigue, or fracture. The resulting reliability model can be either time dependent or time independent. Based on the available information and the nature of the system, various solution methods such as level I, II, III or a combination of these (hybrid) can be employed to quantify the structural reliability for a given target reliability level (Ayyub and McCuen 1997). To meet the target reliability level, an iterative design procedure has to be performed by changing the most important design variables determined from the sensitivity analysis.

In order to perform the probabilistic vulnerability assessment of surface ships under extreme dynamic loads, a stochastic finite element tool, SIMLAB has been developed by integrating the nonlinear finite element code, DYNA3D, into a simulation based probabilistic analysis framework. SIMLAB can provide probabilistic failure prediction of a structural system characterized by both random variables and random processes (Lua 2000; Lua and Hess 2001). The time dependent reliability analysis has been performed based on the first-excursion probability.

To assist the U.S. Navy in assessing reliability levels of existing ships and developing reliability-based guidelines for the design of advanced double hull ship structures, the Probabilistic

ULltimate STRength (PULSTR) tool has been developed by integrating the ULTSTR program into a probabilistic analysis framework (Lua 2001). Both the MCS and the FORM analysis modules have been implemented in PULSTR. A hybrid approach based on the combination of the Monte Carlo Simulation (MCS) technique and the First Order Reliability Method (FORM) has also been developed and numerically implemented in PULSTR to quantify the small probability of failure of a hull-girder under longitudinal bending (Lua and Hess 2002). The predicted probability of failure associated with either the single or the advanced double hull of a Navy combatant is on the order of 10^{-7}. Such a small failure probability can never been validated from the past performance or the failure records of the entire Navy fleet. It is a notional rather than the actual failure probability of the hull girder. Therefore, it is quite often that the computed reliabilities can be used only as reflectors or gages of the true reliabilities.

Unlike a time independent reliability analysis where both the structural capacity and the structural response are independent of time, a time dependent reliability model has to be implemented if material aging has been involved. Under structural degradation, the capacity of a structural element degrades with time; hence the need for time dependent reliability assessment. Computing the time dependent reliability requires the instantaneous failure probability at any time *t* and is based on conditional probability theory. The hazard rate or failure function strategy is used in this study. The progressive or time dependant reliability, $\gamma_p(t)$, of a degrading ship structure is given by

$$\gamma_p(t) = \exp\left(-\int_0^t \lambda(\tau) d\tau \right) \tag{3-1}$$

where τ = variable of integration, and $\lambda(t)$ is a conditional probability function called the hazard rate (Akpan and Luo 2000, Heller and Thanjitham 1993, Soares and Ivanov 1989, Ellingwood and Mori, 1993, de Souza and Ayyub 2000) and is defined by $\lambda(t)$ = *Prob*[*Failure between time t and t+dt | no failure up to time t*]. For continuous systems, the hazard rate is defined by Ang and Tang (1984) as

$$h(t) = \frac{f(t)}{1 - F(t)} \tag{3-2}$$

where *f*(t) represents the joint probability density function and *F*(t) is the joint cumulative density function. For discrete space with a fixed time increment of for example one year, the hazard function becomes

$$h(t_i) = \frac{P_f(t_i)}{1 - \sum_{j=1}^{i-1} P_f(t_i - 1)} \tag{3-3}$$

Substituting Eq. 3-3 into Eq. 3-1 gives the time dependent reliability. The time-dependent failure probability is given by

$$P_{ft}(t) = 1 - \gamma_p(t) \tag{3-4}$$

where the subscript *ft* is for time dependent failure probability. Equation 3-4 is used to estimate the progressive or time dependant reliability. It should be emphasized that $P_{ft}(t) = 1 - \gamma_p(t)$ is not equivalent to $P[R(t) < L(t)]$, the latter being just an instantaneous failure at time, t, without regard to previous or future performance. This is a very important point that is lacking in much of the literature.

Ellingwood and Mori (1993) have an alternative formula for estimating the time dependent reliability. It can be computed as

$$RL(t) = \int_0^\infty \exp\left[-\lambda t \left(1 - \frac{1}{t} \int_0^t F_L(g(t)r)dt] \right) \right] f_R(r)dr \tag{3-5}$$

where RL = reliability, $f_R(r)$, denotes the probability density function of initial strength, R, and $g(t)$ represents the time-dependent degradation in strength. Ellingwood and Mori (1993) express the reliability in terms of the conditional failure rate or hazard function, $h(t)$, as

$$h(t) = -\frac{d}{dt} \ln RL(t) \tag{3-6}$$

which can be expressed as

$$RL(t) = \exp[-\int_0^t h(\xi)d\xi \tag{3-7}$$

Ellingwood (1995) later notes that both the time-dependent reliability, $RL(t)$, and the corresponding probability of failure, $P_{ft}(t)$, are cumulative, that is, they should be used to define the probability of successful performance during a service life interval $(0,t)$. Ellingwood (1995) further emphasizes that the $P_{ft}(t) = 1 - RL(t)$ is not equivalent to $P[R(t) < L(t)]$, the latter being just an instantaneous failure at time, t, without regard to previous or future performance.

Figure 3-8 provides example time-dependent reliability results.

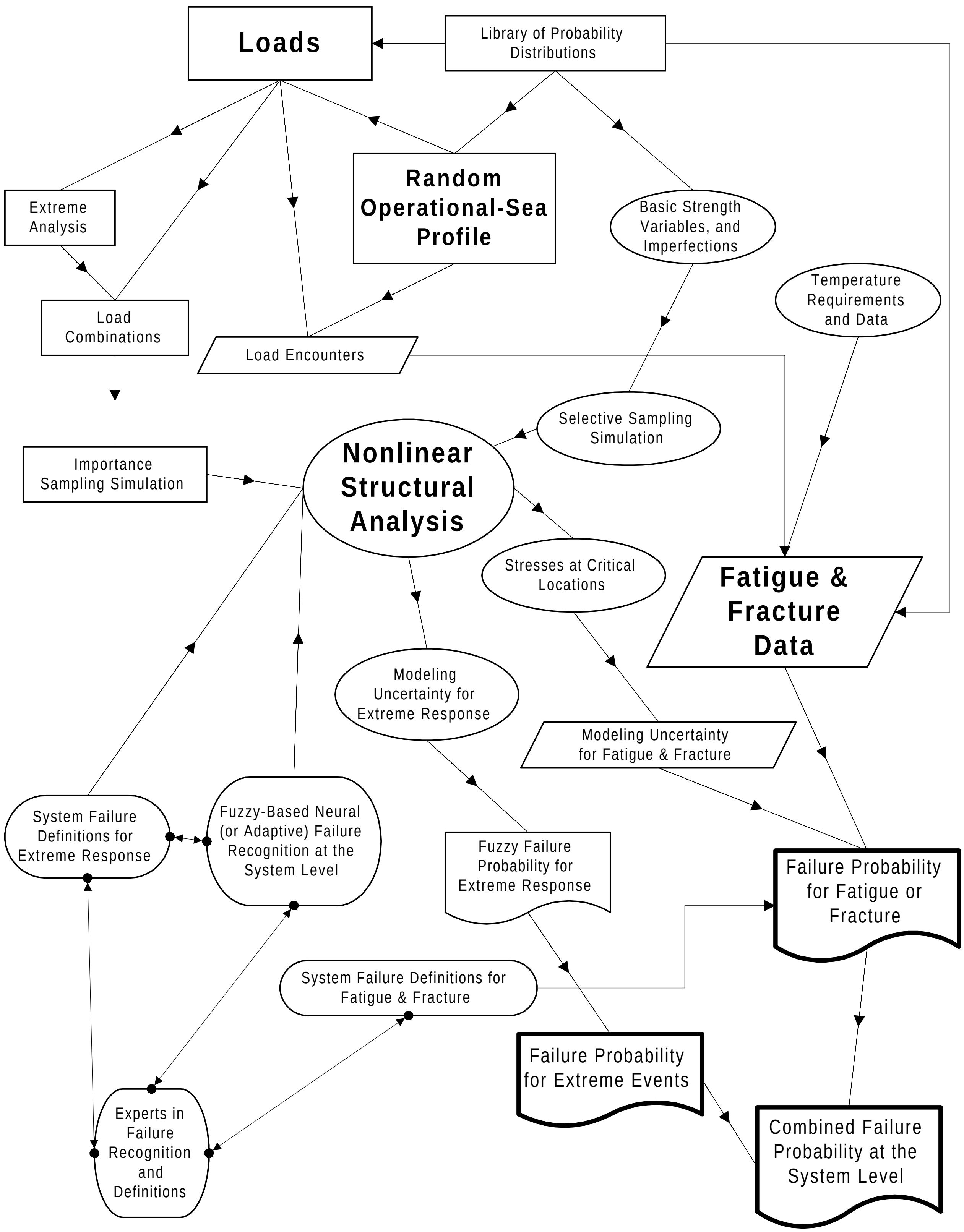

Figure 3-6. Contributing Factors to Reliability Assessment for Ship Structures

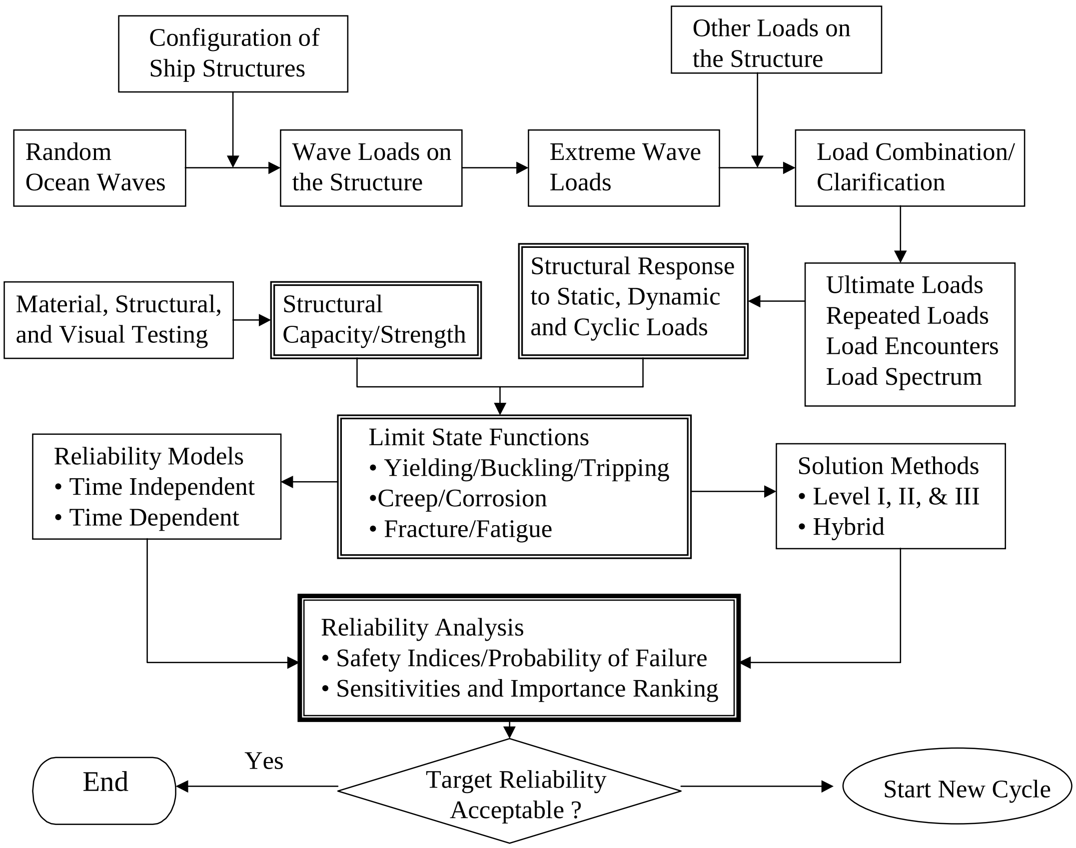

Figure 3-7. Reliability Assessment of Ship Structures

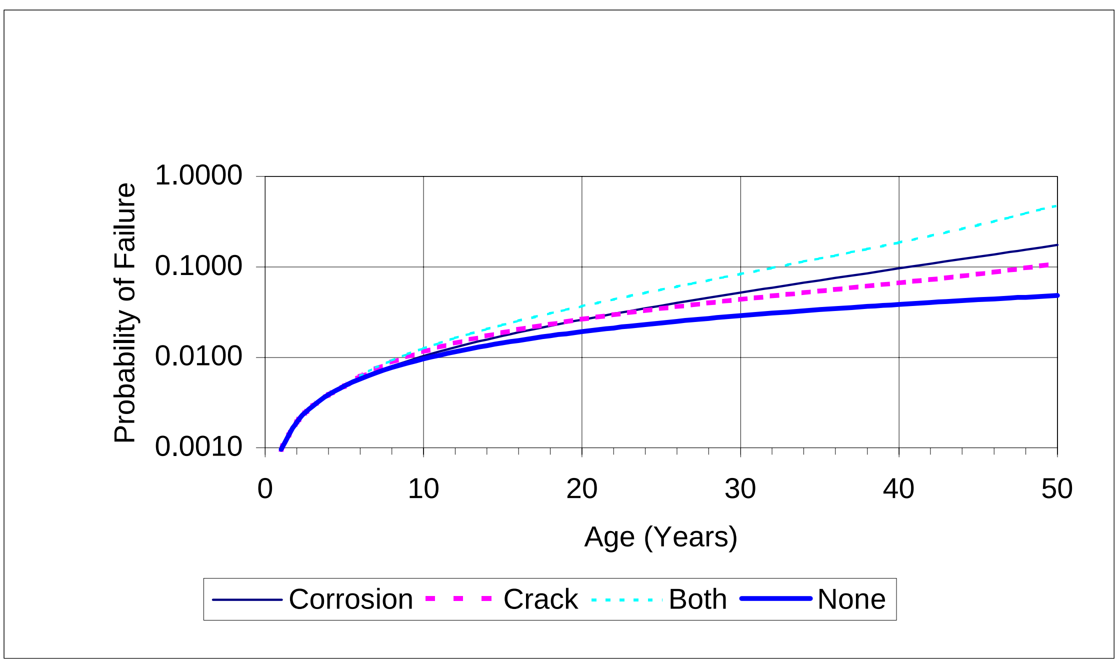

Figure 3-8. Time-Dependent Reliability of a Ship Structure at Mid-Ship

3.3.2. Target Reliability Levels

Risk acceptance constitutes a definition of safety and is therefore, considered a complex topic that is often subject to controversial debate (Modarres 1993). The determination of acceptable levels of risk is important to determine the risk performance a system needs to achieve to be considered safe. If a system has a risk value above the risk acceptance level, actions should be taken to address safety concerns and improve the system through risk reduction measures. One difficulty with this process is defining acceptable safety levels for activities, industries, structures, etc. Since the acceptance of risk depends upon society perceptions, the acceptance criteria do not depend on the risk value alone. This section describes several methods that have been developed to assist in determining acceptable risk values as summarized in Table 3-1.

Target risk or reliability levels are required for developing procedures and rules for ship structures. For example, the selected reliability levels determine the probability of failure of structural components. The following three methods were used to select target reliability values:

1. Expert Opinion: Agreeing upon a reasonable value in cases of novel structures without prior history.
2. Code calibration: Calibrating reliability levels implied in currently successfully used design codes.
3. Economic Model: Choosing target reliability level that minimizes total expected costs over the service life of the structure for dealing with design for which failure results in only economic losses and consequences.

The first approach relies on judgment, and can be based on expert-opinion elicitation (Ayyub 2001). The second approach called code calibration is the most commonly used approach as it provides the means to build on previous experiences. For example, rules provided by classification societies can be used to determine the implied reliability and risk levels in these rules, then target levels can be set in a consistent manner, and new procedures and rules can be developed to produce future designs and vessels that are of similar levels that offer reliability and/or risk consistency. The third approach is based on developing an economic model that minimizes total expected costs over the service life of the structure.

Some reported work has been done on target reliability levels for ship structure (Mansour et al, 1997). The approach adopted by Mansour relied on review of target reliability levels for other industries such as those provided by ANS (American National Standard-A58), Nordic Building Committee, National Building Code of Canada, Canadian Standard Association (CSA), American Petroleum Institute, and A. S. Veritas research for Offshore Structures and ASSHTO Specifications for Bridges. The target reliability levels developed by Mansour considers primary (example hull girder), secondary (example stiffened panel) and tertiary (example unstiffened plate) components of ship structures. The recommended target safety indices (Mansour, 1997), along with the corresponding notional probabilities of failures based on professional judgment are given in Table 3.2. The recommended safety levels presented in Table 3.2 do not consider structural damage.

Mansour et al, (1997) have also recommended safety levels for fatigue. These values, which are presented in Table 3.3, are considered lifetime values and are based on professional judgment and rely on expert opinion. There are no reported recommended safety levels for corrosion or other damage categories; however, the values suggested for fatigue cracking may be used as benchmark for corrosion and other similar damage categories.

Table 3-1. Methods for Determining Risk Acceptance

Risk Acceptance Method	Summary
Risk Conversion Factors	This method addresses the attitudes of the public about risk through comparisons of risk categories. It also provides an estimate for converting risk acceptance values between different risk categories.
Farmers Curve	It provides an estimated curve for cumulative probability risk profile for certain consequences (e.g., deaths). Demonstrates graphical regions of risk acceptance/non-acceptance.
Revealed Preferences	Through comparisons of risk and benefit for different activities, this method categorizes society preferences for voluntary and involuntary exposure to risk.
Evaluate Magnitude of Consequences	This technique compares the probability of risks to the consequence magnitude for different industries to determine acceptable risk levels based on consequence.
Risk Effectiveness	It provides a ratio for the comparison of cost to the magnitude of risk reduction. Using cost-benefit decision criteria, a risk reduction effort should not be pursued if the costs outweigh the benefits. This may not coincide with society values about safety.
Risk Comparison	The risk acceptance method provides a comparison between various activities, industries, etc., and is best suited to comparing risks of the same type.

Table 3-2. Recommended target Safety Indices (probabilities of Failure for Ultimate Strength (Mansour et al, 1997)

Failure Mode	Commercial Ships	Naval Ships
Primary (Initial Yield)	5.0 (2.9×10^{-7})	6.0 (1.0×10^{-9})
Primary (Ultimate)	3.5 (2.3×10^{-4})	4.0 (3.2×10^{-5})
Secondary	2.5 (6.2×10^{-3})	3.0 (1.4×10^{-3})
Tertiary	2.0 (2.3×10^{-2})	2.5 (6.2×10^{-3})

Table 3-3. Recommended target Safety Indices (Probabilities of Failure) for Fatigue Design (Mansour et al, 1997)

	Description	Commercial Ships	Naval Combatants
Category 1	A significant fatigue crack is not considered to be dangerous to the crew, will not compromise the integrity of the ship structure, and will not result in pollution; repairs should be relatively inexpensive	1.0 ($1.6x10^{-1}$)	1.5 ($6.7x10^{-2}$)
Category 2	A significant fatigue crack is not considered to be immediately dangerous to the crew, will not immediately compromise the integrity of the ship; and will not result in pollution; repairs will be relatively expensive	2.5 ($6.2x10^{-3}$)	3.0 ($1.4x10^{-3}$)
Category 3	A significant fatigue crack is considered to compromise the integrity of the ship and put the crew at risk and/or will result in pollution. Severe economic and political consequences will result from significant growth of the crack	3.0 ($1.4x10^{-3}$)	3.5 ($2.3x10^{-4}$)

3.4. Decision Analysis to Select an Inspection Method

The cost of inspection is highly affected by inspection scheduling. In developing a risk based optimal policy for inspection, a time dependent risk profile of the component or region in question should be considered. Furthermore, Flag Administration Officer or Classification Society requirements, elicitation of subject matter experts (SME's), engineering experience, and current practice must all be considered throughout the decision-making process. Using a combination of Flag Administration Officer and Classification Society requirements, SME elicitation, and previous experience, acceptable risk thresholds may be set for major structural components. Alternative inspection implementation schedules may then be compared, considering factors such as cost savings, risk reduction, and condition state deterioration, as well as any effects that 'delayed inspection' may have on these factors. After combining this information with specific budgetary resources and risk tolerance levels of individual owners/operators, optimal risk informed inspection schedules for the marine vessel may be estimated and recommended for implementation.

Decision analysis provides a means for systematically dealing with complex problems to arrive at a decision. Information is gathered in a structured way to provide the best answer to the problem. A decision generally deals with three elements: alternatives, consequences, and preferences (ASME 1993). The alternatives are the possible choices for consideration. The consequences are the potential outcomes of a decision. Decision analysis provides methods for quantifying preference tradeoffs for performance along multiple decision attributes while taking into account risk objectives. Decision attributes are the performance scales that measure the degree to which objectives are satisfied (ASME 1993). For example, one possible attribute is reducing lives lost for the objective of increasing safety. Additional examples of objectives may include minimize the cost, maximize utility, maximize reliability, and maximize profit. The decision outcomes may be affected by uncertainty; however, the goal is to choose the best alternative with the proper consideration of uncertainty. The depth of calculation for decision analysis depends on the desired detail in making the decision. Cost-benefit analysis, decision trees, influence diagrams and the analytic hierarchy process are some of the tools to assist in decision analysis. Also, decision analysis should consider constraints such as availability of vessel for inspection, availability of inspectors, preference of certain inspectors, and availability of inspection equipment (Demsetz et al. 1996, and Ma, et al. 1998).

The elements of a decision model need to be considered in a systematic form to make decisions that meet the objectives of the decision-making process. One graphical tool for performing an organized decision analysis is the decision tree. A decision tree is constructed by showing the elements of alternatives for decisions and the uncertainties. The result of choosing a path (alternative) is the consequences of the decision(s). The presentation of decision analysis as shown herein was adopted from Ayyub and McCuen (1997).

The construction of a decision model requires the definition of the following elements: objectives of decision analysis, decision variables, decision outcomes, and associated probabilities and consequences. The objective of the decision analysis identifies the scope of the decisions to be considered. The boundaries for the problem can be determined from first understanding the objective.

The decision variables are the feasible options or alternatives available to the decision maker at any stage of the decision-making process. The decision variables for the decision model need to be defined.

Ranges of values that can be taken by the decision variables should be defined. Decision variables can include: what and when to inspect components or equipment, which inspection methods to use, assessing the significance of detected damage, and repair/replace decisions. Therefore, assigning a value to a decision variable means making a decision at a specific point within the process. These points within the decision-making process are called decision nodes. The decision nodes are identified in the model by a square.

The decision outcomes for the decision model need also to be defined. The decision outcomes are the events that can happen as a result of a decision. They are random in nature, and their occurrence cannot be fully controlled by the decision maker. Decision outcomes can include: the outcomes of an inspection (detection or non-detection of a damage), and the outcomes of a repair (satisfactory or non-satisfactory repair). Therefore, the decision outcomes with the associated occurrence probabilities need to be defined. The decision outcomes can occur after making a decision at points within the decision-making process called chance nodes. The chance nodes are identified in the model using the “circle.”

The decision outcomes take values that can have associated probabilities and consequences. The probabilities are needed due to the random (chance) nature of these outcomes. The consequences can include, for example, the cost of failure due to damage that was not detected by an inspection method.

Decision trees are commonly used to examine the available information for the purpose of decision making. The decision tree includes the decision and chance nodes. The decision nodes, that are represented by squares in a decision tree, are followed by possible actions (or alternatives, A_i) that can be selected by a decision maker. The chance nodes, that are represented by circles in a decision tree, are followed by outcomes (or chances) that can occur without the complete control of the decision maker. The outcomes have both probabilities (P) and consequences (C). Here the consequence is cost. Each segment followed from the beginning (left end) of the tree to the end (right end) of the tree is called a branch. Each branch represents a possible scenario of decisions and possible outcomes. The total expected consequence (cost) for each branch could be computed. Then the most suitable decisions can be selected to obtain the best utility value. In general, utility values can be used instead of cost values.

An example is used herein to illustrate decision analysis for selection of an inspection strategy. The objective herein is to develop an inspection strategy for the testing of welds using a decision tree. This study is for illustration purposes, and is based on hypothetical probabilities, costs, and consequences.

The first step is to select a system with a safety concern, based on risk assessment techniques. After performing the risk assessment, managers must examine the best alternatives. For example, the welds of a ship's hull plating could be selected as a ship's hull subsystem having risk. If the welds are failing due to poor weld quality, an inspection program may correct the problem. Next, the selection and definition of candidate inspection strategies, based on previous experience and knowledge of the system needs to be conducted. For the purpose of illustration, only four candidate inspection strategies are considered. They are visual inspection, dye penetrant inspection, magnetic particle inspection, and ultrasonic testing as shown in Figure 3-9. These inspection methods were selected for demonstrative purposes and do not necessarily include all methods for inspecting ship welds. For example, X-ray inspection is a most effective method to detect flaws in butt welds, although it is the most expensive method. Some classification rules have requirements of minimal x-ray inspection of hull welds. The magnetic particle inspection method is of a limited capability as it cannot penetrate more than ¾ inch plate thickness.

The outcome of an inspection strategy is either detection or non-detection of a defect, which are identified by P(.). These outcomes originate from a chance node. The costs of these outcomes are identified with the symbol C(.). The probability and cost estimates were assumed for each inspection strategy on its portion of the decision tree.

The total expected cost for each branch was computed by summing up the product of the pairs of cost and probability along the branch. Then total expected cost for the inspection strategy was obtained by adding up the total expected costs of the branches on its portion of the decision tree.

Assuming that the decision objective is to minimize the total expected cost, then the "magnetic particle test" alternative should be selected as the optimal strategy. Although this is not the most inexpensive testing method, its total branch cost is the least. Decision making on choosing a inspection method cannot be based on cost only as the objectives of inspection include find the flaws, therefore effectiveness is important and is accounted for by the probability of non-detection. Certainly, if two different inspection methods can provide the same effectiveness, the least-cost one is to be chosen.

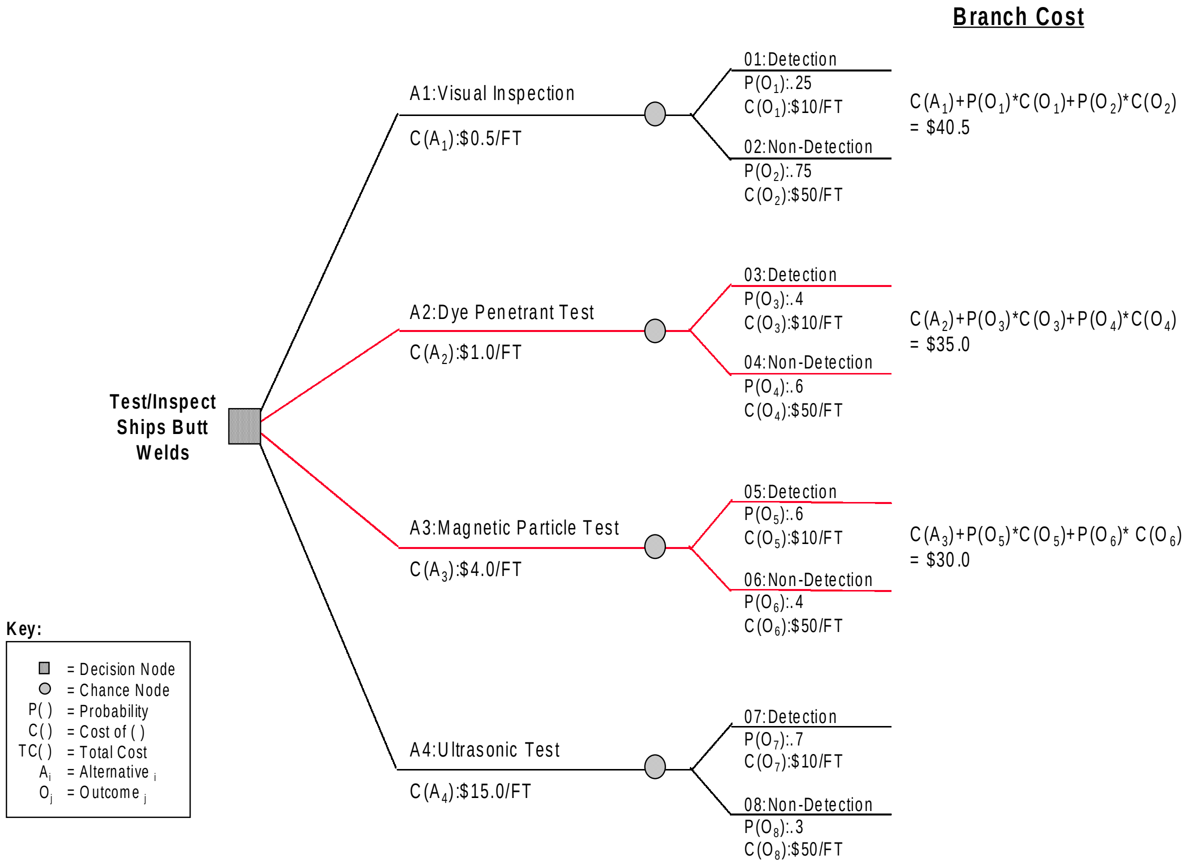

Figure 3-9. Decision Tree for Weld Inspection Strategy

3.5. Optimal Inspection Strategies at the System Level

Defining optimal inspection strategies at the system level requires integrating risk and cost information gathered according to the methodology provided in Figure 3-1 according to the steps provided in Figure 3-10. The ultimate goal of the proposed methodology is to achieve a reduction in a vessel’s life cycle inspection costs, while at the same time maintaining its structural integrity. The flow chart also highlights the strategy that will ultimately lead to cost reduction. The two factors having the most significant influence on overall cost of inspection include inspection scheduling and the extent to which an inspection is carried out. The review of inspection practices presented in Chapter 2 has highlighted three main inspection strategies, all approved by IACS that are periodically executed by the maritime industry. These include annual surveys, intermediate surveys, and special surveys. Annual surveys, which typically require one or two days, are carried out each year to ensure that hull structures and piping networks are maintained in satisfactory condition. Intermediate surveys are generally performed every 30 months and may require from three to four days to complete. Lastly, special surveys are usually conducted every five years and typically require dry-docking of the ship structure. These special surveys are generally very extensive, involving all compartments, and may require up to two weeks or more.

Thus, in general, it can be concluded that a periodic inspection by means of a ‘special survey’ every five years is the most extensive (as it involves inspection of all components), and generally the most expensive (as it may involve dry-docking for extended periods). The overall strategy for reduction of inspection costs endeavors to maintain an acceptable level of structural integrity through a combination of retaining both annual and intermediate survey scheduling and exercising some flexibility in the scheduling of special surveys.

A two-fold strategy is adopted for cost reduction, requiring the following components:

1. Streamlining the scope of inspection by focusing on high-risk areas; and
2. A non-periodic inspection strategy for special surveys that considers the vessel’s age.

A degree of inspection cost reduction may be achieved by focusing time and inspection resources on high-risk areas during the annual, intermediate, and special surveys. Such a concentration of resources is made possible due to the risk-based procedure outlined in the previous section, which has laid the groundwork for the ranking of ship structural component criticality via a qualitative assessment of risk level. The methodology has also advanced time dependent reliability strategies for projecting the temporal failure probability levels of high-risk components.

Currently, the suggested interval for special surveys is five years. Although the surveys are extensive, such an interval does not reflect the time-varying nature of the risk that a vessel experiences with age. It is well known that a vessel’s risk profile will increase with age, and is greatly dependent on the risk levels associated with the high-risk structural components. For example, the risk levels of a relatively new vessel may dictate that a special survey be performed every six to seven years, whereas for an aging vessel, increasing risk levels for critical components may require special surveys on a more frequent basis, say every four years. These temporal risk levels can be projected, by means of a time dependent reliability analysis, and subsequently compared with acceptable threshold levels that reflect vessel age. Thus, a non-periodic time frame may be selected for special surveys, which not only recognizes the growth of risk with age, but also focuses on high-risk components.

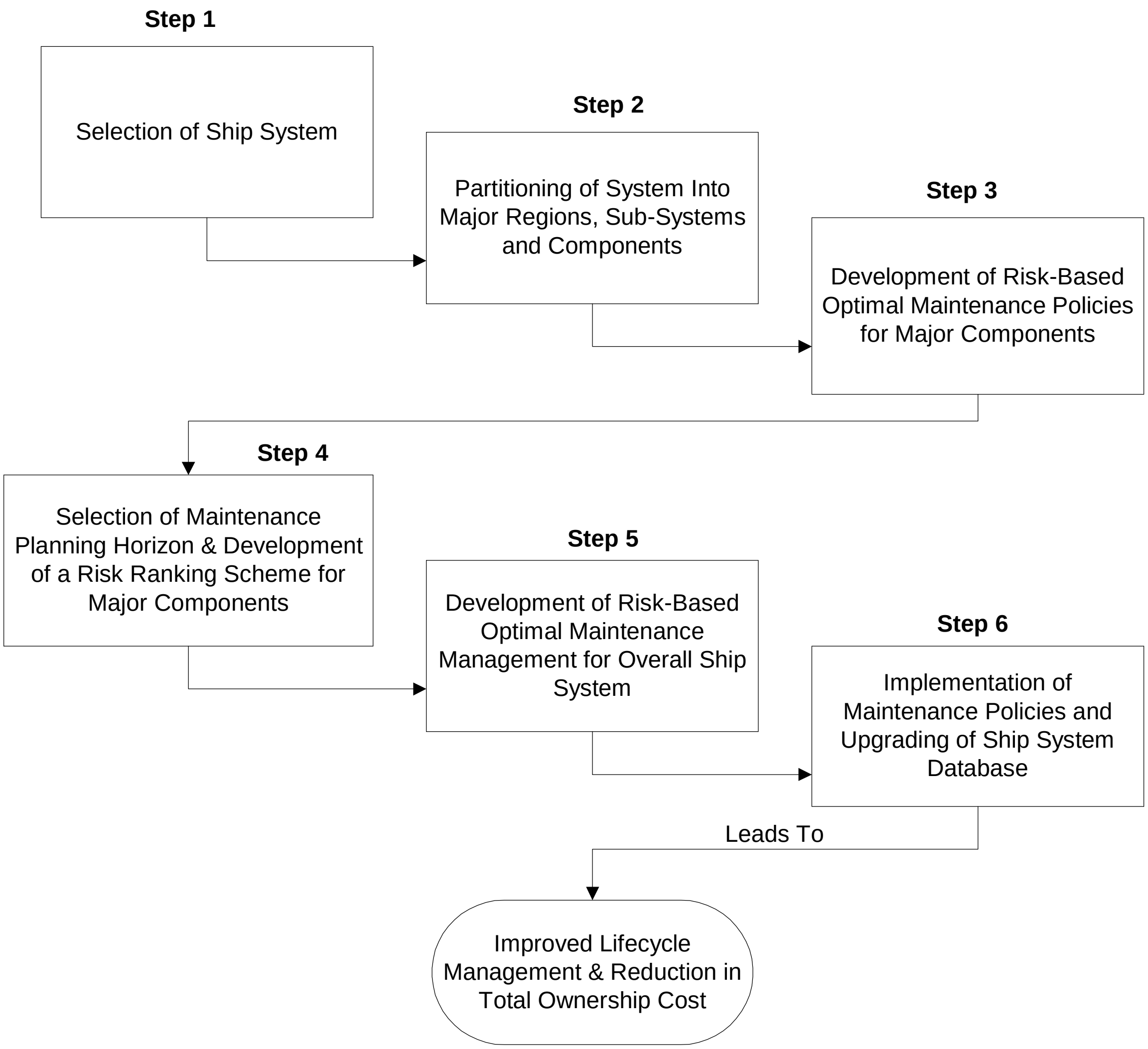

Figure 3-10. Summary of Risk-Based Methodology for Reduction of Inspection Costs

4. DEMONSTRATION OF RISK-BASED INSPECTION METHODOLOGY

4.1. System Definition

The methodology demonstration focuses on the inspection of a large tanker ship structure, more specifically the hull and structural details. The discussion in this chapter is general and may be applied to either a single- or double-hull tanker. Typical midship configurations for single- and double-hull tanker structures are shown in Figures 4-1 and 4-2, respectively. For clarity of presentation, common structural nomenclature and typical midship section nomenclatures for a double-hull tanker structure are presented in Figures 4-3 and 4-4, respectively. The nomenclature in these two figures have been adopted from TSCF (1997). Structural components for tanker structures can be grouped into one of four major categories, including (TSCF 1997):

1. Longitudinal Elements,
2. Transverse Web Frames,
3. Transverse Bulkheads, and
4. Swash Bulkheads.

The essential components of each of these four elements are summarized in Table 4-1.

A typical tanker structure has a number of tanks for transporting specific cargo. The overall risk posed to a tanker structure might depend on the type of tank that is damaged. Typical tank categories include (TSCF 1997):

1. Segregated ballast tanks, used to carry permanent water ballast only;
2. Cargo/arrival ballast tanks, used to transport cargo and arrival clean water ballast;
3. Cargo/departure ballast tanks, which, in addition to cargo, transport departure dirty water ballast;
4. Cargo/heavy ballast tanks, used for transporting cargo and dirty water ballast in heavy weather only; and
5. Cargo-only tanks, which are used specifically for transporting only cargo oil.

These tanks might have some or all of the structural components listed in Table 4-1. The importance of damage to these structural components will depend on both the contents of the tank and the tank's location within the overall ship's structure. A typical tanker arrangement is shown in the upper portion of Figure 4-5. For the purposes of inspection, a tanker vessel could be partitioned into a number of identifiable principal components, each possessing, in turn, a number of sub-components. An example of a potential partitioning scheme is demonstrated in Figure 4-5, in which the vessel is first partitioned into fore-, mid-, and aft-regions. The major mid-ship structural sub-systems and their components are shown in Figure 4-6. It is important to emphasize that there is no unique breakdown scheme to be used for a given tanker vessel. Alternative partitioning methods could be employed, although it is highly recommended that any such scheme adopted for an existing vessel should reflect current practice wherever possible. A breakdown of the structure into its major components must be performed in order to rank the components according to their relative risk levels. The objective of a risk-based inspection of a tanker structure is to achieve a reduction in the vessel's life cycle inspection, maintenance, and failure costs, while at the same time maintaining its structural integrity and environmental soundness above specified thresholds. In order to estimate the risk costs associated with tanker structures, a combination of common failure modes and their consequences must be identified. It should be noted that failure consequences associated with tanker structures are not only dependent on potential damage categories, but are also a function of the location and nature (i.e., usage) of its numerous tanks.

Table 4-1. Categorization of Structural Components for Tanker Structures

Category	Structural Component	Component Description
(i) Longitudinal Elements	Deck	Plating, web, and face plate of longitudinals and vertical girder
	Side Shell	Plating, web, and face plate of longitudinals and horizontal girder
	Bottom Shell	Plating, web, and face plate of longitudinals, vertical girder, and bottom centerline girder
	Longitudinal Bulkhead	Plating, web, and face plate of longitudinals and horizontal girder
	Centerline Bulkhead	Plating, web, and face plate of longitudinals and horizontal girder
	Inner Bottom	Plating, web, and face plate of longitudinals
(ii) Transverse Web Frames	Deck Transverse	Web plating, stiffener and bracket, and ring face plate
	Horizontal Tie Beam	Web plating, stiffener and bracket, and ring face plate
	Bottom Transverse	Web plating, stiffener and bracket, and ring face plate
	Side Shell Transverse	Web plating, stiffener and bracket, and ring face plate
	Longitudinal Bulkhead Transverse	Web plating, stiffener and bracket, and face plate
	Centerline Bulkhead Transverse	Web plating, stiffener and bracket, and face plate
(iii) Transverse Bulkheads	Plating	Web and face plate of stiffener and bracket
	Horizontal Stringer	Web plating, stiffener and bracket, and face plate
	Vertical Girder	Web plating, stiffener and bracket, and face plate
(iv) Swash Bulkheads	Plating	Web and face plate of stiffener and bracket, and ring face plate
	Horizontal Stringer	Web plating, stiffener and bracket, and face plate
	Vertical Girder	Web plating, stiffener and bracket, and face plate

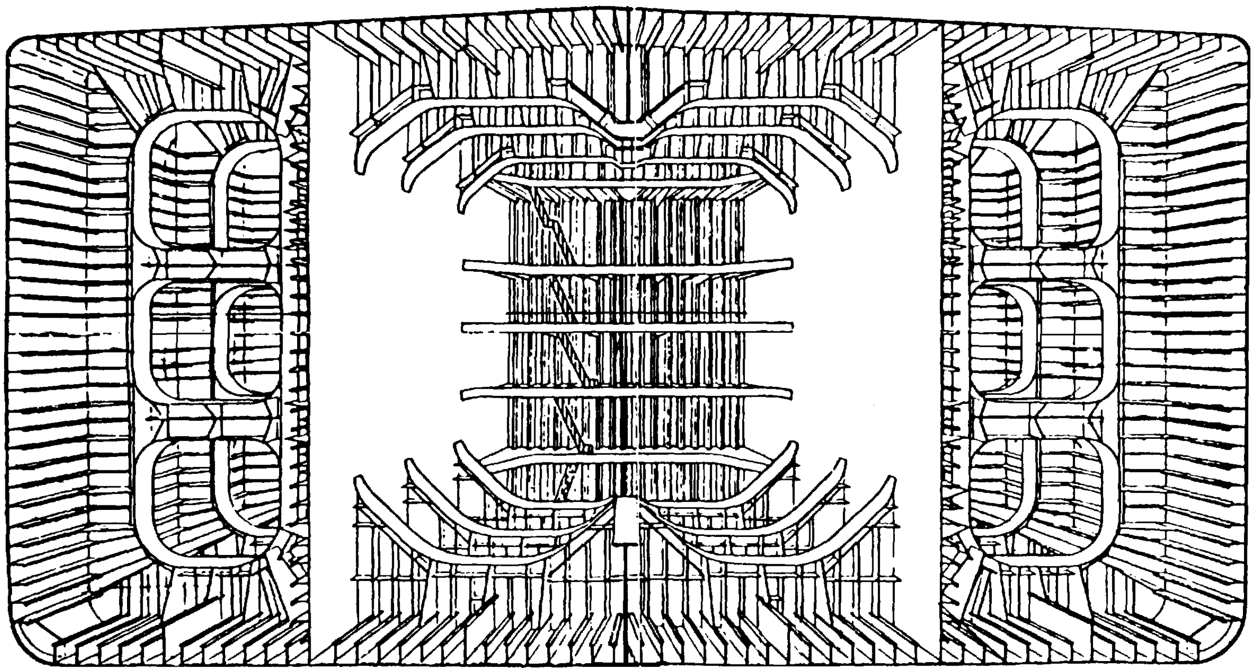

Figure 4-1. Typical Mid-Ship Structural Configuration for a Single-Hull Tanker (TSCF 1997)

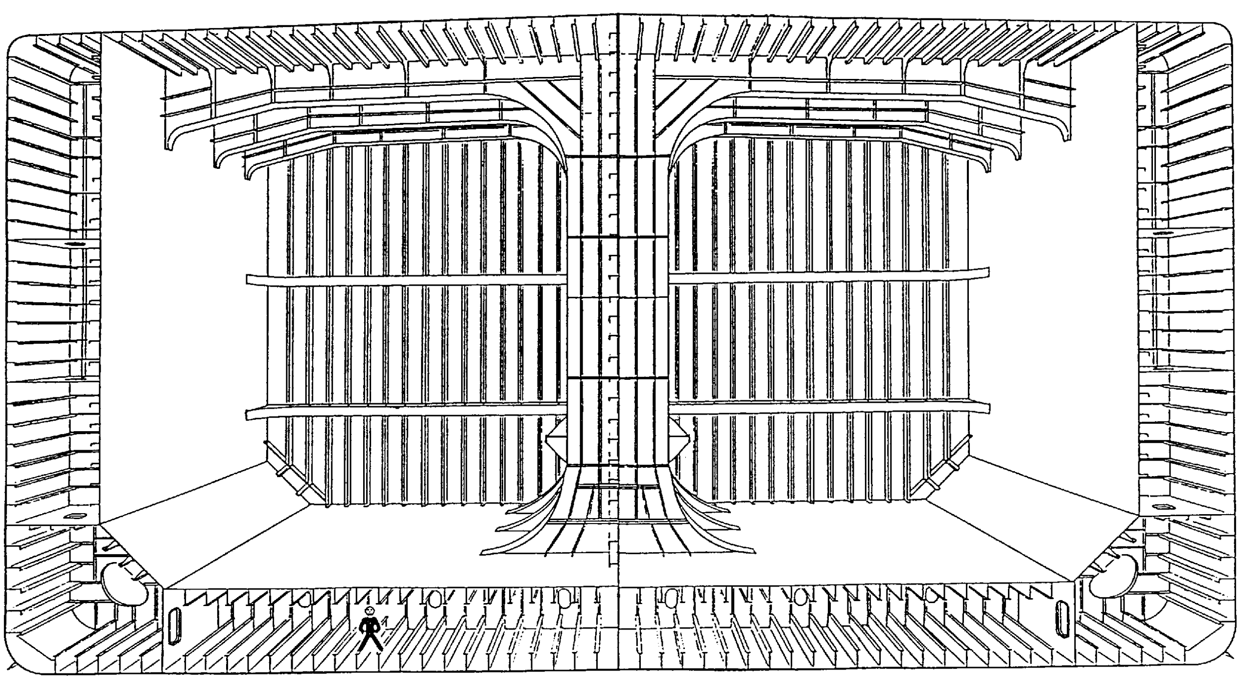

Figure 4-2. Typical Mid-Ship Structural Configuration for a Double-Hull Tanker (TSCF 1997)

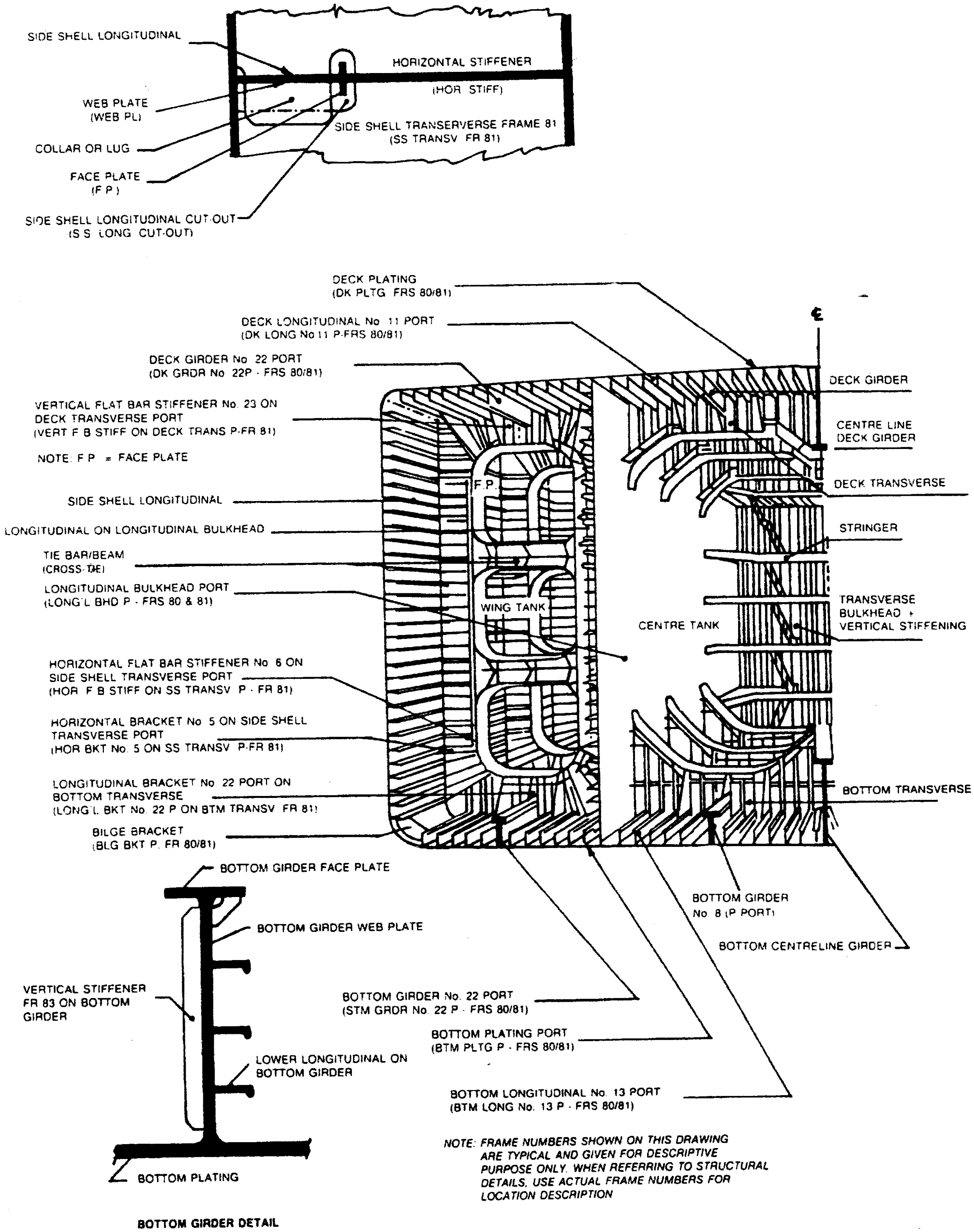

Figure 4-3. Common Structural Nomenclature (TSCF 1997)

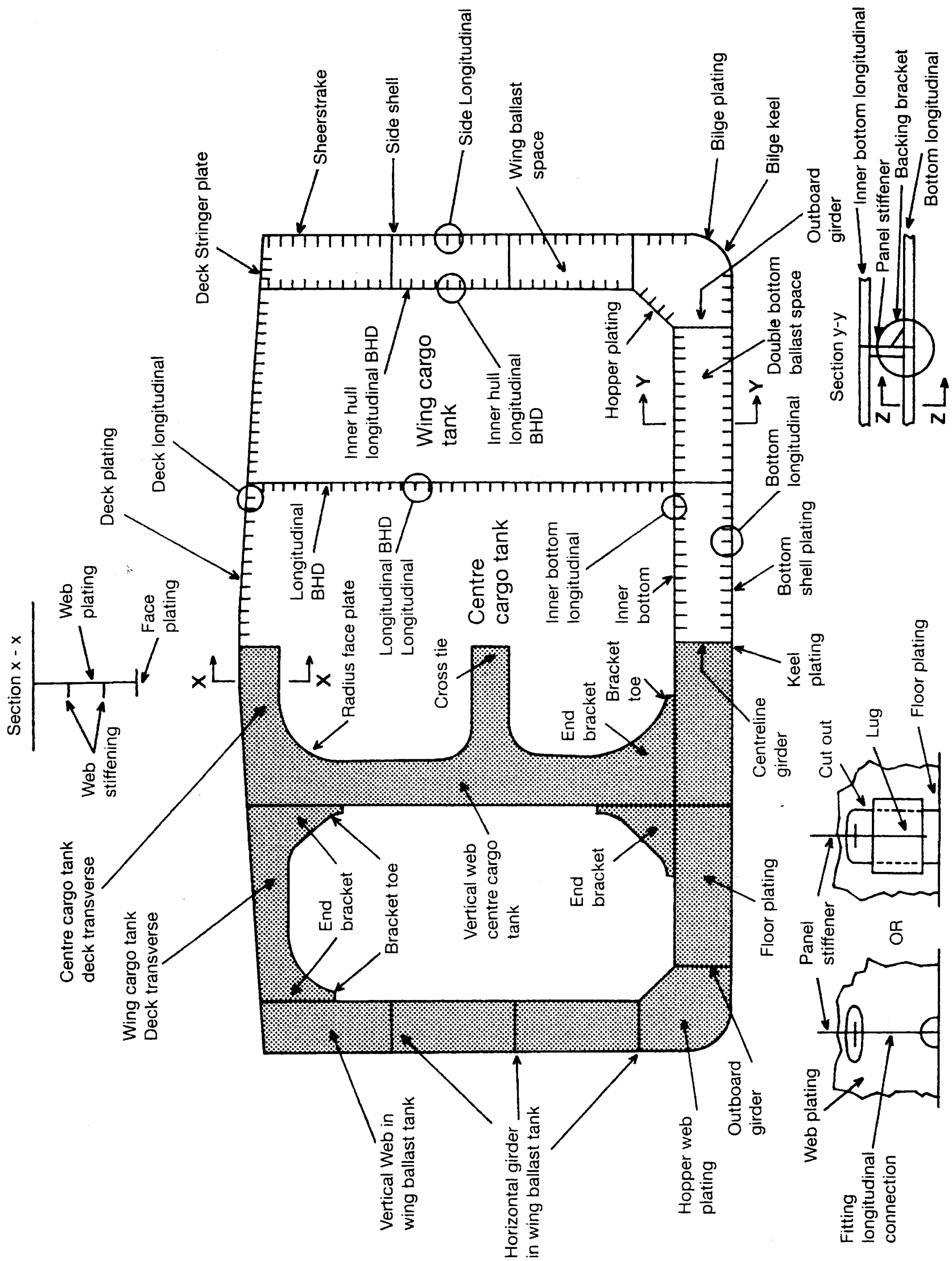

Figure 4-4. Mid-Ship Section Nomenclature for a Double-Hull Tanker (TSCF 1997)

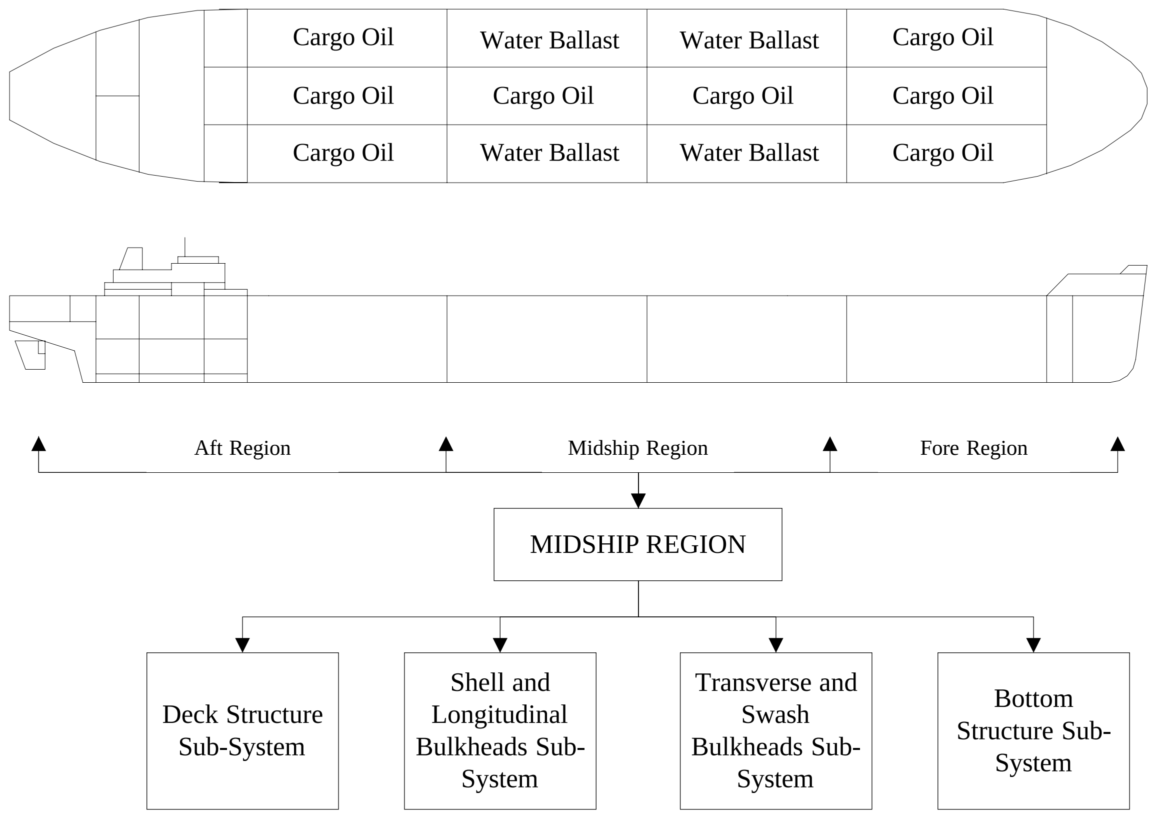

Figure 4-5. Demonstration of a Potential Partitioning Scheme for a Tanker Structure

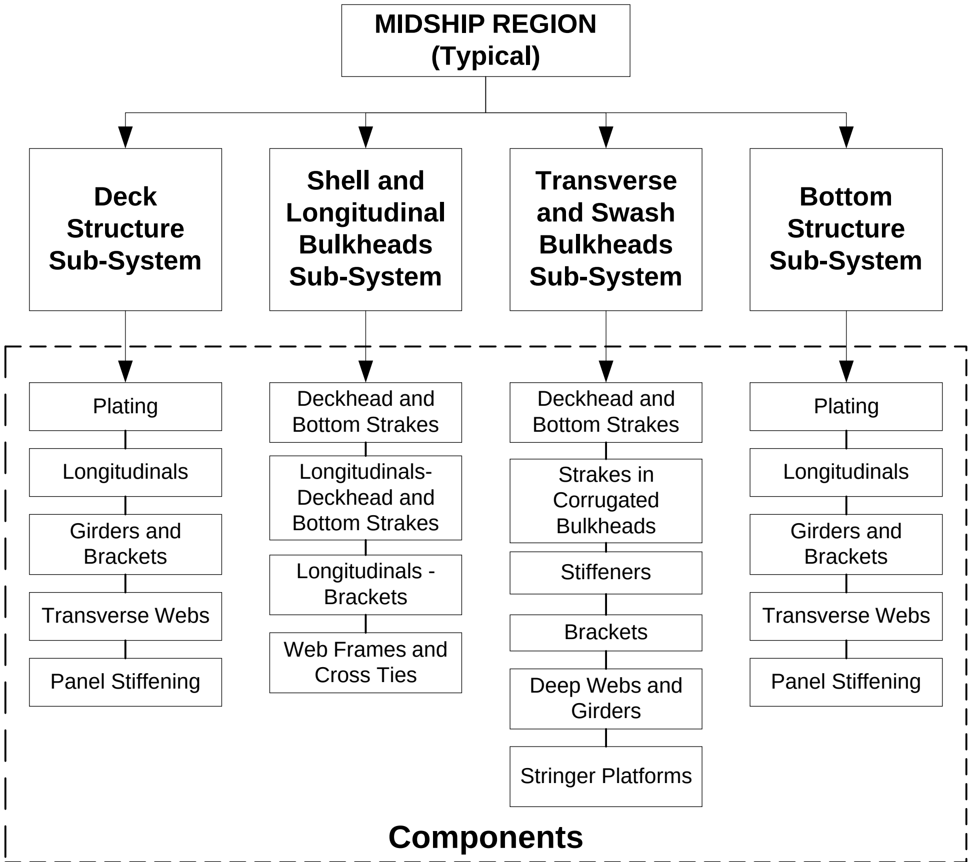

Figure 4-6. Typical Tanker Mid-Ship Sub-Systems and Their Components

4.2. Hazard and Failure Scenarios

Most hulls and structural details of existing tanker ships are made from steel. This is owing to the many desirable propeties of steel, including durability, stiffness, and strength. However, tanker structures are exposed to various hazards that contribute to the degradation of steel properties, in turn increasing the potential for structural failure. Typical hazards experienced by tankers include extreme sea waves, strong winds, continuous loading and unloading of vessels, coating breakdown, buckling, corrosion, and fatigue cracking. Other, less common hazards include accidental loads such as vessel grounding, fire, and blast. A cursory look at these hazards suggests that corrosion, fatigue cracking, and buckling are the three hazards that can most easily be controlled through a combination of effective inspection, maintenace, and repair practices. Such hazards may therefore be considered managable hazards. Furthermore, these three hazards constitute the most prominent hazards experienced by tankers, and if left unchecked, the situation may become critical. For example, hull cracking or penetration may lead to structural collapse, or may result in environmental damage from cargo spillage. Thus, a risk-based inspection strategy for tanker structures must give priority to miminizing the risk associated with buckling-, fatigue-, and corrosion-related hazards. To this end, identification of structural details that are prone to such hazarads represents the first step in the vessel hazard management process. An overview of the literature pertaining to corrosion and fatigue in tankers structures has been undertaken by Ayyub et al (2001). Those tanker structural details, tank types, and components that are prone to buckling-, corrosion-, and fatigue-induced damage are identified in the next section.. Furthermore, a brief identification and discussion of potential failure consequences encountered in tanker structures is presented. This information is required for qualitative risk assessment purposes. Since some of the high-risk components of tanker structures might be subjected to quantitative reliability estimates and projection, time variant limit state functions that incorporate fatigue, corrosion, or a combination of both, are also presented for primary, secondary and tertiary components.

4.2.1. Identification of Tanker Components Prone to Corrosion Damage

Corrosion represents the most prevalent damage hazard encountered by tanker structures. Corrosion manifests itself in several forms, including general corrosion, pitting, and grooving. Corrosion measurement and inspection techniques for tanker structures are geared toward thickness gauging for general corrosion, and pit size (depth and width) gauging for pitting corrosion and grooving. Locations requiring inspection, maintenance, and/or repair can be selected based on prior experience with a particular ship class. Based on past observations, a number of studies have identified the most common corrosion-susceptible areas to be inspected (Ma and Orisamolu 1997, and Ma and Bea 1995). The following list includes a summary of corrosion damage indicators and common areas that should be inspected for localized corrosion in oil tankers:

1. Top and bottom of ballast tanks;
2. Bottom of cargo tanks;
3. Any horizontal surface that may entrap water, such as horizontal stringers or transverse bulkheads;
4. Welds, sharp edges, and any areas in which protective coating would be difficult to apply;
5. Local stiffening members which may become the sites of grooving corrosion;
6. Structures located adjacent to heating devices;
7. Locations that are inaccessible for the most part (the use of mirrors, endoscopes, and so forth should be maximized);
8. Areas that are always wet or oily, such as bilges;
9. Areas where dissimilar metals are either in close proximity or in contact with each other;
10. Areas where the paint appears to be raised, uneven, or flaky;
11. Pitting, especially near non-ferrous metals;
12. The underside of frames, seating areas, and so forth;
13. Weather-deck scuppers, beneath lockers, and so forth;
14. The lower edges of bulkheads that bound frequently-washed areas (e.g., passageways);
15. Representative areas under deck coatings or insulation such that a professional judgment regarding the underlying structure can be made;
16. Plate butt and seam welds; and
17. Junctions of longitudinal bulkhead plating and longitudinals.

These areas could occur at the fore-, aft- or mid-ship regions of the tanker, which will affect the risk levels associated with corrosion development. Furthermore, the location of the corroded area might be on a primary, secondary or tertiary structure, as defined for a particular tanker class. The application and subsequent maintenance of a protective coating will significantly affect a vessel's structural performance and safety. While the coating system remains intact, no corrosion will occur. However, most coating systems will only be guaranteed for a specific period, after which a slow breakdown of the coating can be expected. Coatings normally last between 7 and 15 years, depending upon whether zinc- or epoxy-based coatings are used (Sipes 1990). Many paint manufacturers claim their hard coatings have a life span of approximately 10 years, provided they are properly applied and maintained. However, it should be noted that localized coating breakdown usually occurs much earlier. This implies that starting from the second special survey, which typically occurs around the 10-year mark in a vessel's service life, coating integrity becomes very important, and should be carefully monitored. Corrosion and pitting susceptibility of the various tank types is presented in Table 4.2, which has been adapted from TSCF (1997).

Table 4-2. Vessel Tank Susceptibility to Corrosion and Pitting Based on Coating Coverage (TSCF 1997)

TANK CATEGORY	**COATING COVERAGE**				
	Fully Coated	***Upper Part Coated***	***Upper & Lower Parts Coated***	***Anodes Coated***	***No Coating Applied***
Segregated Ballast	L	H^+	H^+	M – H	H^{++}
Cargo/Clean Ballast (Arrival Ballast)	Lp	H	Hp	M	H^+
Cargo/Dirty Ballast (Departure Ballast)	Lp	M	Mp	M – L	M – H
Cargo/Heavy Ballast	(L)	L	L	X	L – M
Cargo Only	X	L^-	L^-	X	L
Legend:	H = High Risk L = Low Risk X = Not Considered	H^+ = Higher Risk L^- = Lower Risk p = Risk of Pitting	M = Medium Risk ( ) = Negligible Risk		

It is seen that those tanks used to transport cargo only are consistently least susceptible to corrosion-induced damage, regardless of coating application type. Failure to apply a protective coating becomes a real issue for exposed regions such as horizontal stringers, longitudinals, upper bulkhead plating, bottom plating, and cross ties. Moreover, the risk of corrosion in a tanker structure may be amplified by a number of additional factors, including heating of neighboring tanks, localized coating defects due to poor workmanship, details for which coating application may be difficult, areas of localized high stress and cargo flow rate, and even the drip location of a cleaning gun. Figure 4-7 illustrates common areas subject to corrosion-induced material loss and pitting across the bottom structure of a typical tanker vessel. The corrosion rates for various structural components are dependent on the type of tank in which they are located. A summary of corrosion rates for individual structural components in different tanks may be found in Section 4.2.2. It is seen that most of these rates are presented in terms of a range of possible values.

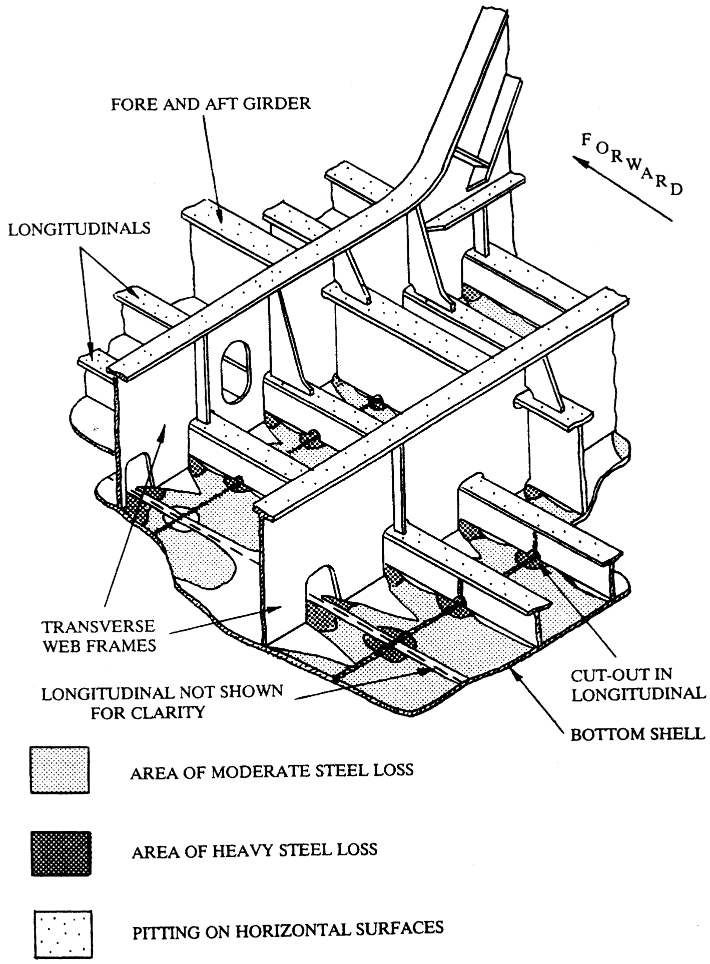

Figure 4-7. Material Wastage on Bottom Structure of a Tanker Vessel (TSCF 1997)

4.2.2. Identification of Tanker Locations Prone to Fatigue Cracking

Fatigue cracking is also a common damage category that often plagues tanker structures. A number of studies and reports have been presented on tanker strutural details that are susceptible to fatigue cracking (e.g., Jordan and Cochran 1978, Bea et al. 1995, and Ma et al. 1997). The results of a study into fatigue cracking in typical vessels (Bea et al. 1995) suggested that most cracks occur at junctions where the side shell longitudinals are connected to transverse bulkheads or web frames. Cracks were also found to occur in the bottom longitudinal end-connections and horizontal stringers. Figure 4-8 illustrates the crack distribution for a typical tanker ship structure along the vessel's length. It can be seen that for this class of vessel, there is a tendency for more cracks to occur near the mid-body region. Moreover, all factors being equal, the figure suggests that smaller tanks should have fewer cracks than larger tanks. Most of the studies found that the majority of side shell and longitudinal bulkhead cracks tend to occur within the middle third of the vessel height (see Figure 4-9 and Figure 4-10). Thus, in summary, the principal areas of a tanker structure that are prone to fatigue cracking include:

1. Intersections of longitudinal stiffeners (particularly side shell longitudinals) with transverse bulkheads or transverse web frames, especially within the region between full load and ballast waterlines;
2. Bracketed end-connections of primary and secondary supporting components;
3. Discontinuities in highly-stressed face plates, stiffeners, and longitudinal members;
4. Openings and cut-outs in primary structures;
5. Deck and bulkhead openings, especially if not rounded and smooth;
6. Abrupt changes in cross section;
7. Stiff connection points such as the intersection of longitudinals and transverse stiffeners;
8. The ends of superstructure blocks; and
9. Weld defects.

It should be noted that fatigue cracking is promoted by high stresses and is most likely to occur in areas of stress concentration. Areas near the middle third of the ship are most vulnerable to fatigue cracking, due to the increased hull bending induced stresses there. However, cases involving cargo and other items continually slamming against compartment walls can also produce high-stress, low-cycle fatigue cracking.

Figure 4-11 shows a distribution of fatigue cracks in a typical ship structural component. The basic mechanics by which these cracks develop can be explained by considering the overall load transmission path. The cyclic load acting on the side shell plates is transmitted into the longitudinals, where it is then transmitted to the web frames and transverse bulkheads through the small footage of flat bar stiffeners and lugs (collar rings). In some designs, the longitudinal cutout is left open without a lug attachment. Load transfer to flat bar stiffeners often produces a region of high stresses that may lead to crack initiation in the heel or toe weld at the flat bar-to-longitudinal connection. The resulting crack (type B in Figure 4-11) will then propagate along the connection weld until such time as the flat bar stiffener is completely cracked through and detached from the longitudinal. At this time, a progressive redistribution of loading takes place, which normally leads to additional fatigue cracks (type D in Figure 4-11) originating at the longitudinal cutout corner of the web frame. If such cracks are left unrepaired, the web frame crack may grow into the shell plate, or new cracks may initiate at the web frame-to-shell plate connection weld (type C and C1 in Figure 4-11). Such progressive fatigue cracking may eventually lead to shell plate collapse and/or cargo spill. This crack sequence, however, is more favorable, because the more serious longitudinal stiffener crack (type A in Figure 4-11) does not occur until later in the sequence. This type of crack starts from the toe or heel of a flat bar stiffener or bracket, and propagates into the web of the adjacent longitudinal.

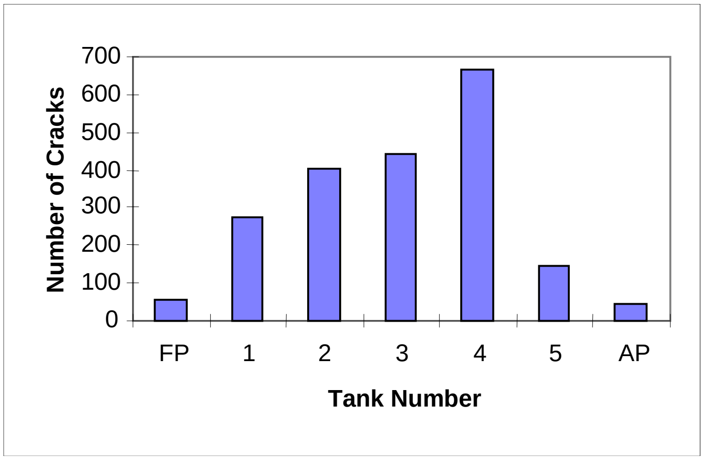

Figure 4-8. Crack Distribution Along the Vessel Length in Four Tankers of the Same Class (Schulte-Strathaus 1991)

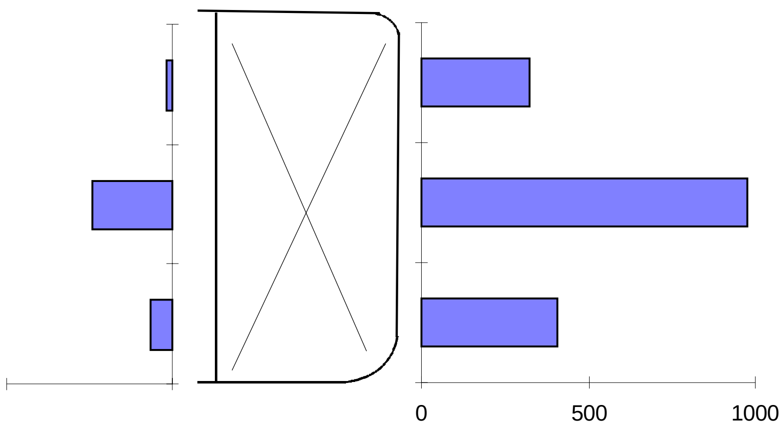

Figure 4-9. Crack Distribution with Height Along the Longitudinal Bulkheads (Left) and Side Shells (Right) of 10 Typical Tanker Structures (Schulte-Strathaus 1991)

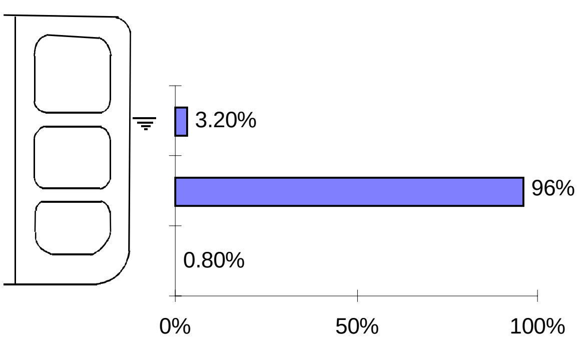

Figure4-10. Crack Distributions along the Side Longitudinals of 2nd-Generation VLCCS (Yoneya 1993)

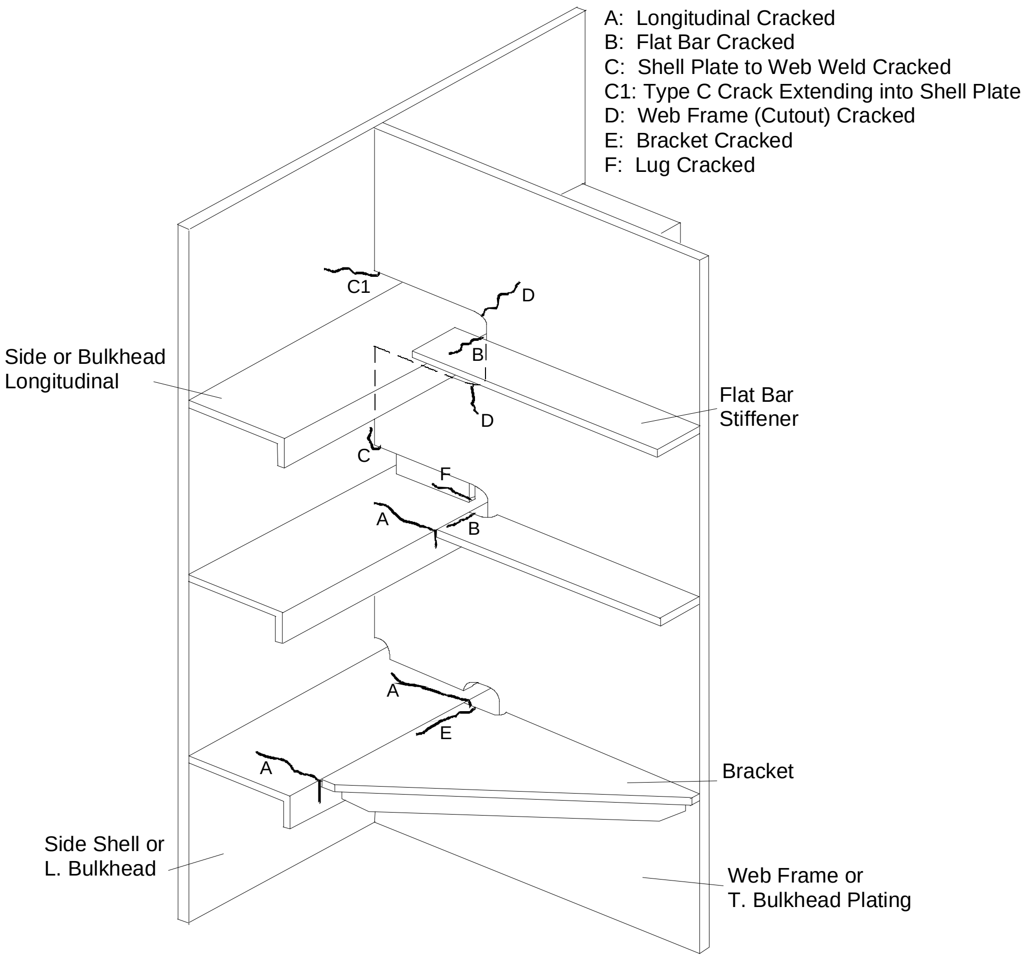

Figure 4-11. Typical Cracks in Side Shells or Longitudinal Bulkheads (TSCF 1992)

4.2.3. Identification of Tanker Locations Prone to Buckling

Tanker structures may also experience buckling, which, if left unchecked, may lead to collapse of the structure. The hull girder compressive flange (i.e., deck and bottom), shell plating, and stiffening are the components most susceptible to buckling. Web frames may also experience shear bucking. A summary of tanker structural elements and their components that are prone to all the above mentioned damage categories is presented in Table 4-3.

Table 4-3. Typical Defect Types for Tanker Structural Components (TSCF 1997)

Item	CATEGORY OF DAMAGE SUSCEPTIBILITY		
	Corrosion	**Fatigue Cracking**	**Buckling**
(i) Longitudinal Elements	• Upper deck plating and longitudinals • Welds between structural elements (especially deck longitudinals to deck plating) • Scallops & openings for drainage • Webs of longitudinals on longitudinal bulkheads (high rates & localized 'grooving') • Flanges of bottom longitudinals (pitting) • Bottom plating (pitting, erosion near suctions) • Longitudinal bulkhead plating (relatively thin)	• Discontinuities • Openings & notches • Connections with transverse elements	• Upper deck plating and longitudinals • Bottom plating and longitudinals • Longitudinal bulkhead plating (middle & upper) • Deck & bottom girders
(ii) Transverse Web Frames	• Upper part, connection to deck • Just below top coating • Flanges of bottom transverses	• Connections with longitudinal elements • Scallops in connection with longitudinals • Bracket toes • Holes & openings • Crossing face flats	• Web plate (shear buckling) • Brackets, flanges, and cross-ties
(iii) Transverse Bulkheads	• Upper part, connection to deck • Stringer webs • Close to openings in stringers • Highly-stressed regions (e.g., around bracket toes, etc.)	• Connections with longitudinal elements • Connections between girder systems • Bracket toes	• Horizontal stringers, web plate (shear) • Girder/stringer brackets • Vertical girders, web plate (shear buckling) • Corrugated bulkhead plating
(iv) Swash Bulkheads	• Upper part, connection to deck • Stringer webs • Close to openings in bulkhead plating • Highly-stressed regions (e.g., around bracket toes, etc.)	• Connections with longitudinal elements • Connections between girder systems • Bracket toes • Openings in bulkhead plating	• Horizontal stringers, web plate (shear) • Vertical girders, web plate (shear buckling) • Girder/stringer brackets • Openings in bulkhead plating

4.2.4. Identification of Possible Consequences Associated with Tanker Vessel Failures

Structural damage to and/or failure of a tanker structure could result in consequences that range from simple leaks to severe loss of lives, cargo, or the entire vessel. These failure consequences are functions of the vessel's age, the damaged element/component and its location, and the maintenance and repair history of the vessel. Failure consequences may be identified using a combination of information from previous studies, a database of accidents, and through elicitation of expert opinion from subject matter experts (SME's). The consequence of a particular failure is often measured in terms of a monetary value, which typically represents the sum of the costs induced either directly or indirectly as a result of the failure. The monetary costs of a severe failure will generally include expenses in addition to those associated with the repair of vessel damage. For a tanker structure, potential failure consequences that may be encountered include:

1. Loss of human lives, vessel cargo, or the vessel itself;
2. Environmental pollution;
3. Unscheduled maintenance and/or repair;
4. Effects on personnel health and safety;
5. Loss or reduction of serviceability; and
6. Declassification of the vessel.

Each of these will be discussed in the following paragraphs.

Loss of Vessel, Vessel Cargo, and Human Lives

Loss of human lives, a vessel, and/or its cargo is a rare occurrence for most types of ships, but is, nonetheless, a possibility. This category of failure consequence is quite likely the most serious. The cost of cargo loss is probably the easiest to compute precisely. However, as will be discussed later, the consequences of cargo loss may extend far outside those that can be quantified directly. The value of a typical tanker vessel may vary widely, ranging from $1 million to $100 million (US), depending on its age, size, and condition. A vessel's sinking, therefore, may mean the loss of millions of dollars. Finally, one of the most difficult aspects to consider involves the concept of placing a monetary value on a human life, a formidable task indeed. A number of factors must be considered in arriving at this value, including the victim's age, physical condition, and marital/dependant status. If the loss of lives, vessel, and cargo are considered in combination, the consequences arising from such a vessel failure could be enormous. Indirect consequences of such a failure must also be considered. For example, sizeable litigation costs may be incurred while assessing responsibility for the failure. Moreover, compensation costs may surface from personal injuries, deaths, or liability claims (e.g., vessel collisions). Consequences may also arise from the manner in which the incident is handled by the media. This so-called 'bad publicity' may be responsible for difficulties such as deterioration of public image, degradation if personal reputations, and loss of clientele.

Environmental Pollution

Environmental pollution from oil spills constitutes a second category of failure consequence, in which the costs incurred fall into three main categories (Liu and Thayamballi 1995): (i) clean-up expenses, (ii) environmental/wildlife restoration expenditures, and (iii) lost-use costs. Most major oil spill incidents are due to non-structural related causes such as collisions, grounding, fire, and explosions, which have little to do with structural inspections. Relatively few incidents are due to structural failures such as fatigue cracking in the outer shell of cargo tanks, or severe pitting corrosion causing penetration of the bottom shell plates. Such failures can often be prevented through detailed and comprehensive inspections. Moreover, such incidents are usually less severe, resulting in comparatively less oil spillage than from other causes. Regions of oil tankers are often given criticality ratings in terms of their relative consequences of leakage. For example, the side-shell plates and bottom plates that house cargo oil in single-hull tankers are considered as having *high* or *extreme* failure consequences. Longitudinal bulkheads separating cargo oil and ballast water often receive the same level of criticality. For double-hull tankers, inner bottoms and inner sides are the structures that enclose cargo oil. Failure within such compartments could result in oil leaking into the ballast tanks, whereupon pollution would occur during the de-ballasting process.

Failure consequences of an oil spill are not easy to estimate, as oil spills constitute an emotionally charged societal issue involving many environmental and wildlife-related concerns. Arriving at a consensus on the cost of their consequences is rather difficult. The manpower and resources required for cleaning up an oil spill may be phenomenal. As an example, the clean-up costs for the Exxon Valdez failure were reported in excess of $2 billion. By the time an oil spill has been thoroughly cleaned or even contained, the damage to the environment and native fish and wildlife may be devastating. Significant losses are often reported, which affects a number of wildlife-related industries. For those that survive, the effects of ingesting harmful chemicals may echo throughout the food-chain, possibly even reaching humans. Once again, litigation costs associated with assessing recovery and restoration liabilities are typically high. Legal proceedings may foster unfavorable media publicity, raising a number of company public relations issues. Loss of use of the vessel for a period of time (post-accident inspection and repairs, etc.) may greatly affect revenues. Oil spills may also depreciate the value and aesthetics of a once beautiful shoreline, thereby causing a potential reduction in tourism and real estate values for the affected area. One way to provide a context within which to consider the failure consequences of a spill is by comparison with legal claim payments made in the past. A study done by the National Research Council estimated typical payments of approximately $30,000 per ton of oil spilled, but notes that payments may be as large as $100,000 per ton (quoted by Liu and Thayamballi 1995). A review of insurance company data confirms that pollution represents one of the more expensive incidents involving claims. Their major pollution claims have an average claim amount of $1 million each. A reduced figure should be expected for the typically less severe oil spills due to structural failures.

<u>Unscheduled Maintenance and Repair</u>

Unscheduled maintenance and repair constitutes one of the most common consequences of failure. As many fatigue cracks tend to stop entirely, or grow at a relatively slow rate, their occurrence often requires only local repairs. A method of 'veeing and welding', one of the most common temporary crack repair methods, has relatively low cost. If a design modification or a plate insert is required, their costs may be higher, but still relatively low compared to the two previously mentioned consequences. The total cost of a repair should include material, labor, dry-dock charges, tank cleaning, staging, and down time costs. Some of the items, such as those associated with dry-docking, tank cleaning, and staging, may not be applicable to some repairs, depending on the location of the crack and other circumstances. Liu and Thayamballi (1995) have illustrated a sample of the charge rates:

1. Dry-dock charges: for vessels above 150,000 GRT: the minimum charge for the first two days is about $0.5 per GRT. The charge for each subsequent day is approximately $0.2 per GRT.
2. Tank cleaning: ranges from $2 to $12 per metric ton capacity, depending on type and location of tank, gas freeing and ventilation excluded.
3. Steel renewal: for mild steel, about $4000 to $5000 per ton of steel renewed.
4. Staging: about $5 per cubic meter of volume covered.

These rates are from a shipyard in the Far East, and they vary between yards. Nevertheless, they may be used to provide a relative ranking of the costs involved.

Effect on Personnel Health and Safety

Failure aboard a tanker vessel may have significant consequences relating to the safety and health of its personnel. For example, prolonged inhalation of harmful gases or noxious fumes may have drastic effects on the long-term health of crew and other personnel, possibly leading to litigation and compensation related expenses. Moreover, failure may alter the crew's perception of how safe their work environment really is, and they may harbor reluctance to perform their duties. Such reluctance may result in the loss of skilled employees, forcing the use of less experienced personnel.

Loss or Reduction of Serviceability

The loss or reduction of serviceability may result from a tanker vessel failure. Out of service costs may be significant. In some cases, client perception may be affected, possibly leading to reduction in usage once placed back in service.

Vessel Declassification

Damage to a vessel may be so extensive that even after judicious repair, the performance capacity of the vessel may have been permanently diminished, to the point that it is no longer suitable to execute the tasks for which it was originally designed. To satisfy the numerous regulatory and classification society requirements, and continue the service life beyond this failure, the vessel may have to be declassified, placing it in a lower operating class. As such, not only will the failure have induced reclassification expenditures, but it may also reduce future revenues from the vessel as a result of its declassification.

4.2.5. Procedures for Estimating Failure Probabilities of Tanker Systems

For the purpose of risk assessment, structural damage to tanker components must be quantified in terms of the associated failure probabilities. These failure probabilities are dependent on the loads to which a given component is subjected, the age of the component, the damage mode, and the maintenance and repair histories of individual components. Multiplication of these failure probabilities with their corresponding consequences allows quantification of a measure of the risk associated with failure of individual components, tanker subsystems, and the entire vessel. There are essentially two strategies which may be adopted in computing such failure probabilities, namely:

1. a qualitative approach, and

2. a quantitative approach.

The two strategies are discussed in more detail in the following sections.

4.2.6. Qualitative Estimates of Failure Probabilities

A qualitative evaluation of failure probability indicates a measure of the relative susceptibility of a structure to further damage based on its current condition. These qualitative measures must be quantified numerically for the purpose of risk assessment. However, the numerical values assigned do not have to be exact, and may be deduced using a combination of expert opinion elicitation, engineering judgment, classification society requirements, and historical data. Such measures should be developed for the various damage categories that affect tanker components and subsystems.

Past experience and in-service data are extremely valuable in estimating the likelihood of damage in structural details that are prone to several forms of damage. For example, experience indicates that tankers tend to develop fatigue cracks at the intersections of transverse webs and longitudinals in side shell areas between high and low water lines. In bulk carriers, fatigue cracks are often found in the corners of hold openings, side frames, welds of corrugated bulkheads, and stools. As such, these areas are considered to have a high likelihood of damage. Previous studies have compiled collections of structural details with high failure rates (IACS, 1994; TSCF, 1995; Jordan, 1978 and 1980) and may be used as guides in estimating likelihood of damage.

Classification societies have also developed guidelines which may be helpful. For example, DNV (1992) has defined acceptable annual failure probabilities for reliability analysis of marine structures. Acceptable failure probabilities range from 10^{-3} to 10^{-6}, depending on the consequence and class of failure. The class of failure depends on both the level of structural redundancy and the degree of warning provided by the failure mode under consideration. For redundant structures associated with less serious failure consequences, a failure probability lower than 10^{-3} (or a target reliability index greater than 3.09) is acceptable. On the other hand, for structures associated with more serious failure consequences, and which provide little or no failure warning, a probability of failure less than 10^{-6} (or a target reliability index greater than 4.75) is required. These values provide an approximate reference to the actual reliability of existing marine structures. In an effort to apply a probabilistic risk assessment to mechanical systems such as nuclear power plants, the American Society of Mechanical Engineers (ASME, 1991) has developed a strategy to convert qualitative statements to equivalent numerical failure probabilities. The strategy provides qualitative definitions for failure probabilities ranging from 10^{-1} to 10^{-8}. However, ASME (1991) notes that converting qualitative failure probability assessments based on expert opinion to a numerical equivalent is a process laden with potential pitfalls, and should thus be approached most carefully. Such conversions may be used as a guide in developing a likelihood of damage classification table such as Table 4-4 below.

Table 4-4. An Example of Structural Defect & Likelihood of Damage Classification Scheme

Classification	Annual Rating	Likelihood of Experiencing Damage
Extreme	10^{-2}	There is a very high likelihood the structure under consideration will experience this mode of damage (cracking, corrosion, or deformation) within the ship's maintenance cycle.
High	10^{-3}	This mode of damage may occur occasionally (several times during the ship's service life).
Moderate	10^{-4}	This mode of damage is quite rare, perhaps occurring once or twice during the ship's life.
Low	10^{-5}	It is extremely unlikely that the structure under consideration will experience this damage mode during the ship's life.

In order to develop qualitative estimates of failure probability, the various modes of damage affecting the components may be classified in terms of condition states. Examples of qualitative damage estimates for corrosion and fatigue cracking are provided in Tables 4-5, 4-6, and 4-7 below. It should be noted that the numbers are provided for demonstration purposes only, and are not intended as a guide.

Table 4-5. Condition States and Associated Failure Probabilities for Corrosion Damage (Visual Observation)

Condition State	Name	Description	Likelihood of Failure	Probability of Failure (P_f)
1	No Corrosion	Paint/Protection system is sound and functioning as intended.	Very Low	10^{-8} – 10^{-7}
2	Low Corrosion	Surface rust or freckled rust has either formed or is in the process of forming.	Low	10^{-7} – 10^{-6}
3	Medium Corrosion	Surface or freckled rust is prevalent and metal is exposed.	Moderate	10^{-6} – 10^{-4}
4	Active/High Corrosion	Corrosion is present and active, and a significant portion of metal is exposed.	High	10^{-4} – 10^{-3}
5	Section Loss	Corrosion has caused section loss sufficient to warrant structural analysis to ascertain the effect of the damage.	Very High	10^{-3} – 10^{-2}

Table 4-6. Condition States and Associated Failure Probabilities for Corrosion Damage (Measured Thickness Loss)

Condition State	Name	Description	Likelihood of Failure	Probability of Failure (P_f)
1	No Corrosion	Paint/Protection system is sound and functioning as intended.	Very Low	$10^{-8} – 10^{-7}$
2	Surface Corrosion	Less than 10% of metal thickness has been attacked by corrosion.	Low	$10^{-7} – 10^{-6}$
3	Moderate Corrosion	Metal thickness loss is between 10% and 35%.	Moderate	$10^{-6} – 10^{-4}$
4	Deep Corrosion	Metal thickness loss is between 35% and 55%.	High	$10^{-4} – 10^{-3}$
5	Excessive Corrosion	Metal thickness reduced to less than 55% of original thickness.	Very High	$10^{-3} – 10^{-2}$

Table 4.7. Likelihood of Failure Due To Fatigue Cracking

$\left(\mathbf{Crack\ Size}, \boldsymbol{a} \middle/ \mathbf{Critical}, \boldsymbol{a_c}\right)\%$	Description	Qualitative Likelihood of Failure	Probability of Failure (P_f)
$0\% < \boldsymbol{a}/\boldsymbol{a_c} \le 10\%$	Low Cracking	Low	$10^{-8} – 10^{-7}$
$10\% < \boldsymbol{a}/\boldsymbol{a_c} \le 35\%$	Moderate Cracking	Moderate	$10^{-7} – 10^{-4}$
$35\% < \boldsymbol{a}/\boldsymbol{a_c} \le 50\%$	High Cracking	High	$10^{-4} – 10^{-3}$
$\boldsymbol{a}/\boldsymbol{a_c} > 50\%$	Very High Cracking	Very High	$10^{-3} – 10^{-1}$

4.2.7. Quantitative Estimates of Failure Probabilities

Failure probability estimates based on the qualitative approach (presented in the previous section), although very subjective in nature, are generally sufficient for most risk-based inspection decisions. However, sometimes, in the case of high-risk components, and for the purpose of inspection budgeting and planning, it might be necessary to obtain quantitative estimates of failure probabilities. Input and tools required for such analyses include mathematical models for applicable component loads, strengths, and damage modes, computational engines and computer software for reliability analysis, and measures of component performance. In the following two sections, two critical components of this analysis input will be developed, namely:

1. formulation of performance functions for damaged components, and
2. development of formulas for calculating reliability of damaged components.

4.2.8. Formulation of Performance Functions for Damaged Components

Quantitative risk assessment of damaged high-risk components of tanker ships involves the computation of failure probability, which in turn requires identification of limit state or performance functions for such components. The performance functions employed in the analysis may range from simple to very complex. In this section, a library of performance functions applicable to the various damage categories are either developed or compiled from available literature. The general form of the performance function is given by

$$g(t) = C(t) - L(t) \tag{4-1}$$

where C(t) is the time varying capacity or resistance, and L(t) is the time dependent load.

Performance Functions for Corroded Components

Corrosion results in loss of cross sectional thickness and could, for example, lead to reduction in strength, water-tightness, or even cause oil leaks at various critical locations. Performance functions for corroded components should be defined based on allowable values. Such functions could be based on increased corroded depth, thickness reduction, or even area or volume reduction, especially for components where water-tightness is required. These functions must be developed on the basis of allowable wastage. The various performance functions applicable in these cases are as follows:

(1) Corroded Depth

$$g(t) = D_A - D_L(t)\,,\;\; D_L(t) = a(t - t_0)^b \tag{4-2}$$

(2) Area Reduction

$$g(t) = A_A - A_L(t)\,,\;\; A_L(t) = c(t - t_0)^d \tag{4-3}$$

(3) Volume Reduction

$$g(t) = V_A - V_L(t)\,,\; V_L(t) = e(t - t_0)^f \tag{4-4}$$

where D_A represents the allowable or tolerable depth reduction, D_L is the depth of corrosion due to pitting, A_A denotes the allowable or tolerable area reduction for the component, A_L is the effective corroded area due to pitting and general corrosion. V_A represents the allowable or tolerable volume reduction, V_L is the effective reduction in volume of component due to pitting and general corrosion, and t_0 denotes the coating life. The parameters *a, b, c, d, e, f* are random variables which depict the rate of material loss or wastage from a given component as a function of time *t*. In most cases, simple linear models will suffice in describing wastage growth, in which case the exponents *b, d,* and *f* assume values of 1. Results for TSCF for annual rate of corrosion in various tanker components are summarized in Section 4.4, and could be used as a guide in the estimation of coefficient *a*, *c* and *e*. The values of the random variables are highly dependent on the location of the components. Formulas for determining the effective thickness-, area-, and volume-loss of components can be found in Daidola et al (1997). The corresponding allowables are determined through elicitation of expert opinion from subject matter experts. Other alternative models could focus on reduction of local or global residual strengths of the components due to the presence of corrosion. Daidola et al (1997) have developed expressions and graphs for local yielding and plate buckling that could result from thickness loss due to corrosion. A performance function applicable to reduction in buckling strength of a plate due to thickness loss can be formulated (Daidola, et al, 1997) as

$$g(t) = \sigma_{cr} - \sigma_A \, , \; \sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{a}\right)^2 \left(1+\alpha^2\right)^2 \qquad (4\text{-}5)$$

Figure 4-12 illustrates an example of the reduction in critical buckling strength due to effective thickness loss in a component.

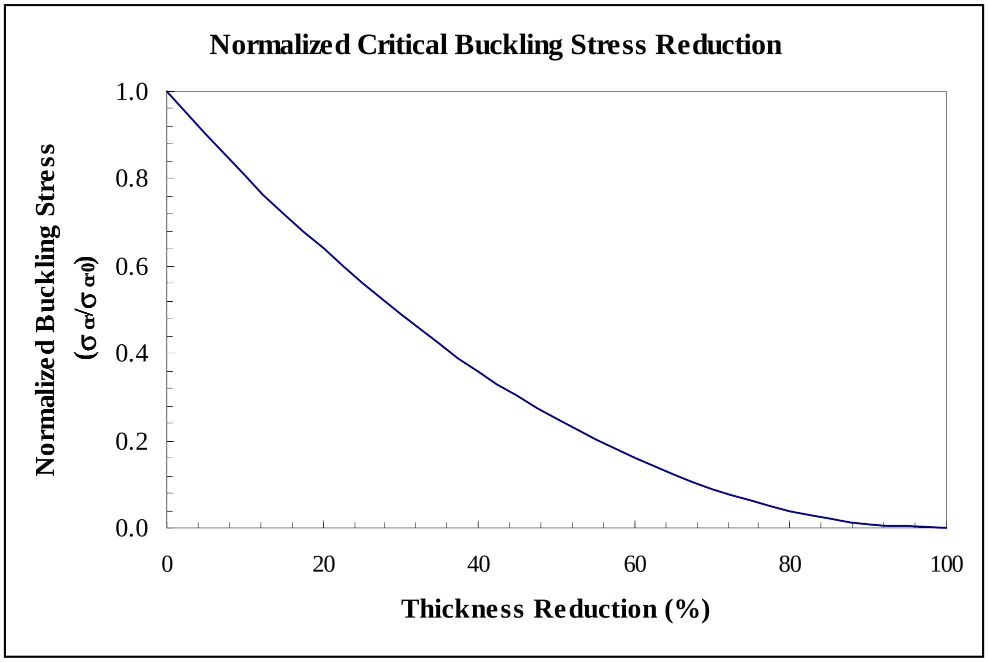

Figure 4-12. Reduction in Critical Buckling Strength Due to Effective Thickness Loss

<u>Performance Functions for Fatigue</u>

The presence of a fatigue crack can lead to loss of integrity of a structural element upon reaching a critical size. The reduction may be such as to increase nominal stress levels, which in turn increases the rate of crack growth. The two main approaches adopted in the assessment of a component's fatigue strength are:

1. The stress life (*S-N*) approach for crack initiation assessment, and
2. Fracture mechanics for crack propagation assessment.

The stress-life or '*S-N*' approach may be used to predict the fatigue strength of a component or structural detail as a function of the number of applied stress cycles. Although this approach is quite simple, most *S-N* curves have been developed for specific geometries, and may not be applied in a general sense. One of the major benefits of this approach lies in its ability to discretize total fatigue life into that component due to crack initiation and that consumed during crack propagation to failure.

Once crack initiation has taken place, the fracture mechanics approach is often more suitable for use in a risk analysis to assess subsequent crack growth to failure. This approach employs theories of fracture mechanics to predict the size of a propagating crack as a function of time (often expressed in terms of elapsed cycles, *N*). Data presented using this approach is independent of component geometry. The performance functions used in this case may be defined in terms of either crack size, *a*, or stress intensity factor, (*K*, as:

$$\boldsymbol{g(t) = a_c - a(t)} \tag{4-6}$$

$$\boldsymbol{g(t) = K_c - K(t)} \tag{4-7}$$

where a_c represents the critical crack size, $a(t)$ denotes the crack length at time *t*, K_c represents the critical stress intensity factor, known as the material fracture toughness, and $K(t)$ is the stress intensity factor at time *t*.

Two formulations, namely, mechanistic and non-mechanistic, have been reported for predicting the size of a crack as a function of time (Yang and Manning, 1990). The mechanistic model relates the crack growth to the stress intensity factor, stress range, material, and environmental-related properties. Implementation of a mechanistic model requires detailed knowledge regarding all factors that affect crack growth. The most commonly used mechanistic model is the Paris-Erdogen formula given by

$$\frac{da}{dN} = C\Delta K^m \tag{4-8}$$

$$\Delta K = \Delta\sigma Y(a)\sqrt{\pi a} \tag{4-9}$$

where *a* represents the crack size; *N* is the number of elapsed stress cycles; $\Delta\sigma$ denotes the applied stress range; ΔK is the stress intensity factor range, and $Y(a)$ is a geometric correction factor. Assuming that $Y(a) = Y$ is constant, then integration of Equation (4-8) gives

$$a(N) = [a_0^{1-m/2} + (1-\frac{m}{2})C\Delta\sigma^m Y^m \pi^{\frac{m}{2}} N] \qquad m \neq 2 \tag{4-10}$$

$$a(N) = a_0 \exp(C\Delta\sigma^2 Y^2 \pi \;\; N] \qquad m = 2 \tag{4-11}$$

where a_o represents the initial crack size, and *m* and *C* are constants. In order to use Equations (4-10) and (4-11) for analysis, the applied stress range at the various structural details and joints must be known. Unfortunately, practical estimation of these quantities may prove difficult. As a result, most of the reported studies on fatigue of ship structural details have used the much simpler *S-N* approach. A previous study by Dobson et al (1983) used measured load spectra to calibrate the fatigue crack growth parameters, *C* and *m*, for two steel materials, HY80 and CS. The study suggested that the crack length after *N* load cycles can be expressed by

$$a(N) = a_0 + \sum_{i=1}^{N}\frac{da}{dN}; \qquad \frac{da}{dN} = C\Delta K^m \tag{4-12}$$

The study also showed that $C = 1.77\text{x}10^{-9}$ and $m = 2.54$ for HY80, while $C = 2.54\text{x}10^{-9}$ and $m = 2.53$ for CS material. Threshold stress intensity factors ΔK required to achieve crack growth were set between the range of 5-6$ksi/\sqrt{in}$ in the study. In order to use Equation (4-12), the stress intensity factors at critical structural details have to be estimated, which is not a trivial task.

A non-mechanistic model for crack growth, which can be calibrated from measured cracks, and which has found wide application in the aerospace industry, is that developed by Yang and Manning (1990), given by

$$\frac{da}{dt} = Q[a(t)]^b \tag{4-13}$$

where b and Q are crack growth parameters. Integration of Equation (4-13) gives the crack size at time t as

$$a(t) = \begin{cases} [\exp(tQ) + In(a_0)] & b = 1 \\ [tQ(1-b) + a_0^{1-b}]^{1-b} & b \neq 1 \end{cases} \tag{4-14}$$

Equation (4-14) may be applied to an existing ship structure where crack sizes have been measured at critical joints and details. The crack growth parameters a_o, b and Q must be calibrated for each critical detail. The advantage of using Equation (4-13) is that it circumvents the need to mechanically model the complex mechanism of crack growth (i.e., Equations. (4-10) and (4-12)), especially at critical structural details, where the stress intensity factor under complex loading is not well understood. In the presence of fatigue cracking, the corrosion-enhanced fatigue crack growth can be modeled as

$$\frac{da}{dt} = C_{corr} Q[a(t)]^b \tag{4-15}$$

integration of which yields the time-dependent crack size $a(t)$ as

$$a(t) = \begin{cases} [\exp(tC_{corr}Q) + In(a_0)] & b = 1 \\ [tC_{corr}Q(1-b) + a_0^{1-b}]^{1-b} & b \neq 1 \end{cases} \tag{4-16}$$

where C_{corr} represents the corrosion-enhanced fatigue crack growth parameter, with a value greater than 1.

Performance Functions Relating the Impact of Crack Growth and Corrosion on the Primary Midship Section Structures

The governing limit state model for the ultimate strength of the vessel can be defined by

$$g(t) = U(t) - L(t) \tag{4-17}$$

where $U(t)$ represents a model describing the ultimate strength capacity of the vessel and $L(t)$ is a model of the effect of external load on the vessel. Degradation of the primary ship structure results in a time-varying reduction in ultimate strength capacity. Equation (4-17) can be defined in terms of the vertical bending moment that induces bending of the hull. For the ultimate collapse of a hull girder, the underlying random functions can be defined as

$$U(t) = M_u(t) \tag{4-18}$$

and

$$L(t) = M_{sw}(t) + M_w(t) \tag{4-19}$$

where $M_u(t)$ represents the ultimate hull girder bending moment capacity, and $M_{sw}(t)$ is the still-water bending moment and $M_w(t)$ denotes the wave bending moment, all of which may be functions of time. However, in this study, they are assumed to be independent of time in order to simplify the demonstration of the proposed methodology. In future use of the methodology, these moments, especially the wave bending and dynamic moments, should be treated using extreme value analysis, as provided by Ayyub et al. (1989).

Corrosion decreases the section modulus of the hull of a ship structure by reducing the thickness of primary structural members. It therefore reduces the ability of the structure to resist externally induced bending moments. Several models of general corrosion growth have been suggested (Orisamolu et al. 1999a, 1999b, 1999c; Paik et al, 1998). The most commonly used model is

$$r(t) = C_1(t - t_0)^{c_2} \tag{4-20}$$

where $r(t)$ is the thickness reduction, t_0 represents the life of the coating (in years), t is the age of the vessel (in years), and the parameters C_1 and C_2 are random variable coefficients. The coefficient C_1 represents the annual corrosion rate, and although C_2 may assume values ranging from 1/3 to 1, a value of 1 is used in the example problem. The life of the coating varies for different vessels and depends on the coating type. Thus, in the presence of corrosion, the ultimate moment capacity is given by

$$M_u(t) = \phi\sigma_u \begin{cases} Z(r(t_0)) & t \le t_0; \quad r(t_0) = 0 \\ Z(r(t)) & t > t_0; \quad r(t) > 0 \end{cases} \tag{4-21}$$

Formulas for calculating the midship section modulus, $\boldsymbol{Z(r(t))}$, can be found in any standard monograph on ship structures, such as that by Hughes (1983).

The stiffener is modeled as a flat bar with height h_{so} and thickness b_s. The variation in net sectional area with time depends on the crack size *a(t)*, which can be computed. Thus,

$$h_{si}(t) = h_{s0}(t) - a(t) \tag{4-22}$$

The area of stiffener *i* is given by

$$A_{si}(t) = b_{si} h_{si}(t) \tag{4-23}$$

The moment of inertia of the *i-th* stiffener with respect to its center of gravity is given by

$$i_{oi}(t) = \frac{b_{si} h_{si}^3(t)}{12} = \frac{b_{si}(h_{s0} - a(t))^3}{12} \tag{4-24}$$

The plate is of breadth b_{po} and thickness h_p. The variation in net sectional area of the plate is given by

$$A_{pi}(t) = h_{pi} b_{pi}(t) \tag{4-25}$$

$$b_{pi}(t) = b_{p0}(t) - a(t) \tag{4-26}$$

while the moment of inertia of the *i-th* plate element is given by

$$i_{oi}(t) = \frac{b_{pi} h_{pi}^3(t)}{12} = \frac{h_{pi}^3(b_{p0} - a(t))}{12} \tag{4-27}$$

Equations (4-24) and (4-27) are used to update the section modulus of the hull girder $Z((t))$. Thus, the ultimate bending moment capacity in the presence of cracks can be written as

$$M_u(t) = \phi\sigma_u \begin{cases} Z_0 & t < t_0 \\ Z(a(t) & t \geq t_0 \end{cases} \tag{4-28}$$

where Z_o represents the section modulus with no crack present, and t_o is the time required for crack initiation.

The load affecting the structure must also be considered in the analysis. The primary total bending moment on the hull can be decomposed into two components: (i) the still-water bending moment M_{sw}, and (ii) the wave-induced bending moment M_w. Strategies for modeling ship loads have been presented in Mansour et al (1997), where it is shown that M_{sw} and M_w are, in fact, correlated. In this study, the total bending moment is calculated as the linear summation of M_{sw} and M_w. The still water bending moment is calculated from the IACS design guidance formula (Nitta et al. 1992)

$$M_{sw}(t) = \begin{cases} +14.97CL^2B(8.167 - C_b)(lb - in) & hogging \\ -64.88CL^2B(0.7 + C_b)(lb - in) & sagging \end{cases} \tag{4-29}$$

where

$$C = \begin{cases} 2.917x10^7 L & L < 3540\, in \\ 1.559x10^{-3} - \left(\frac{11810-L}{1426575}\right)^{1.5} & 3540 < L < 11810\, in \\ 1.559x10^{-3} & 11810 < L < 13780\, in \\ 1.559x10^{-3} - \left(\frac{L-13780}{2139860}\right)^{1.5} & L > 13780\, in \end{cases} \tag{4-30}$$

The above formulae are typically used to provide estimates of the deterministic design still-water bending moments for a vessel. Hence, they are extreme, rather than average or point-in-time values. Procedures for estimating point-in-time values of still-water bending moment will have to be developed for time-dependent reliability analysis.

Two general loading conditions, namely short-term and long-term conditions, are used for the analysis of ship structures. The long-term condition is based on adequate knowledge of the ship routes over the duration of its service life, while the short-term condition assumes that these routes are not clearly defined or may change from time to time. In an analysis based on short-term loading conditions, either the routes that are considered most severe, or the waves considered most extreme are used in computing the wave-induced bending moment. In the demonstration example presented here, the short-term loading procedure is employed. A description of both short-term and long-term wave modeling strategies is given in Mansour et al (1997). The essential steps involved include: (i) identification of ship routes, (ii) computation of ocean wave statistics, (iii) calculation of extreme wave-induced bending moment using either linear or second-order strip theory (Jensen and Peterson, 1979), and (iv) application of the largest extreme wave bending moment in the analysis. For the current study, a simplified direct method, based on pre-calculated seakeeping tables, is used. In the proposed method developed by Loukakis and Chryssastomidis (1975), seakeeping tables are used, pre-computed based on parametric ship motion studies considering variation in ship size, operating speed, significant wave height and block coefficient. Among other response parameters, the tables are designed to efficiently determine the root-mean-square (RMS) value of the wave-induced bending moment, given the values of C_b, L/B, H_s/L, B/T, and F_n.

4.2.9. Development of Formulas for Calculating Reliability of Damaged Components

The reliability of a ship structure can be defined as the likelihood of it maintaining its ability to fulfill its design purpose for a given time period. In this study, the goal is to calculate both instantaneous and time-dependent reliabilities for damaged high-risk component as well as the primary ship structure. The appropriate limit state functions have been formulated in the preceding sections.

Instantaneous Reliability

The instantaneous reliability of a ship structure may be obtained based on the limit state defined in Equation (4-17), where the failure domain is defined by $\Omega = [g(t) < 0]$ and its compliment $\Omega^{|} = [g(t) > 0]$ defines the safe domain. The instantaneous failure probability at time t is defined by

$$P_f(t) = \int_{\Omega} f(x(t))dx \tag{4-31}$$

where $f(x(t))$ represents the joint probability density function of the basic random variables at time t. In general, the joint probability density function is unknown, and evaluating the convolution integral is a formidable task. Several practical approaches have been developed, including First-Order Reliability Method (FORM), Second-Order Reliability Method (SORM), and Monte Carlo Simulation (MCS). SORM, available in the general-purpose reliability analysis software, COMPASS (Orisamolu et al, 1993), is used in the demonstration example. Theories of FORM, SORM, and MCS are well established and may be found in monographs such as that by Ayyub and McCuen (1997).

Time Dependent Reliability

In the presence of degradation mechanisms, the ultimate strength of the ship hull, $U(t)$, is a decreasing function of time. Therefore, the corresponding probability of failure is also a function of time. By varying the time period, t, from zero to an expected service life, the decreasing values of ultimate strength, $U(t)$, can be estimated. Furthermore, the instantaneous failure probability at any time t, defined by $P[U(t) < L(t)]$ without regard to survival of a vessel in the previous years, can be obtained using Equation (4-31) above.

Successive yearly loading and decreasing values of yearly ship ultimate strength are, however, dependant events, and must be accounted for according in reliability estimation. This is accomplished by using time-dependent or progressive reliability estimates, which are based on conditional probability theory. The concept of hazard rate or failure function strategy is used in this study. The progressive or time-dependant reliability of a degrading ship structure, $\gamma_p(t)$, is given by

$$\gamma_p(t) = \exp\left(-\int_0^t \lambda(\tau)d\tau\right) \tag{4-32}$$

where τ is the variable of integration, and $\lambda(t)$ is a conditional probability function called the hazard rate (Akpan et al, 2002). For continuous systems, the hazard rate is defined by

$$h(t) = \frac{f(t)}{1-F(t)} \tag{4-33}$$

where *f*(t) represents the joint probability density function and *F*(t) is the joint cumulative density function. For discrete space with a one-year increment, the hazard function becomes

$$h(t_i) = \frac{P_f(t_i)}{1-\sum_{j=1}^{i-1} P_f(t_i - 1)} \tag{4-34}$$

Substituting Equation (4-34) into Equation (4-32) gives the time-dependent reliability. The corresponding time-dependent failure probability is given by

$$P_{ft}(t) = 1-\gamma_p(t) \tag{4-35}$$

where the subscript *ft* denotes time-dependent failure probability. Equation (4-32) is used to estimate the progressive or time-dependant reliability.

4.3. Qualitative Risk Assessment and Decision Analysis

Deterioration or damage in structural components or subsystems of a tanker structure poses a potentially great risk to the operation of the vessel. The level of risk depends on both the severity or extent of damage and the consequences of failure. Qualitative risk assessment is concerned with evaluating the risk profile of components or subsystems based on qualitative estimates of its overall damage and associated failure consequences. This risk profile is then used to make risk-informed decisions with regard to inspection and maintenance of the vessel. Several tasks must be executed under qualitative risk assessment, including:

1. selection of components or subsystems;
2. development of a failure consequence profile for each subsystem;
3. estimation of component failure probabilities;
4. computation of risk cost, and
5. decision analysis using qualitative risk estimates.

4.3.1. Selection of Components or Subsystems

The process of qualitative risk assessment could prove quite involved and costly. In order to streamline the procedure, the first task involves selection of components or subsystems of the tanker structure. The selection process could be based on a partitioning scheme that has been adopted during major inspections of the vessel, or it could be based on components having similar damage profiles, such as components prone to a particular damage mode. There is no fixed rule for making such selections, but the importance of using engineering judgment and experience should be noted. In order to demonstrate the concept, it is assumed in this section that the partitioning scheme demonstrated in Figures 4-5 and 4-6 (in which the vessel has been subdivided into aft, fore, and mid-ship sections) can be used to represent subsystems of a tanker structure. Furthermore, components such as plating, longitudinals, girders, bulkheads, webs, and brackets, etc. will hereafter be referred to as simply ‘components’ in order to keep the discussion as general as possible. The components making up each subsystem should be ranked in terms of their unit replacement cost to determine their relative degree of importance. Consider the ten components of a subsystem shown in Table 4-8 below, with their individual replacement costs denoted by C_i. The relative degree of importance of each of these ten components, denoted by W_i, may be computed using the linear model given by

$$\boldsymbol{W_i} = \frac{\boldsymbol{C_i}}{\sum_{\boldsymbol{i}=1}^{10} \boldsymbol{C_i}} \tag{4-36}$$

In some cases, a nonlinear model may be more appropriate. Such information may be of great importance when calculating the risk posed by the failure of a given component.

Table 4-8. Computation of Weight Factors or Degree of Importance for Components of a Subsystem

Component No.	Approximate Cost of Replacement	Relative Degree of Importance (W_i)
1	$7,200	0.189
2	$500	0.013
3	$3,800	0.100
4	$5,600	0.147
5	$2,900	0.076
6	$2,100	0.055
7	$3,500	0.092
8	$4,500	0.118
9	$1,000	0.026
10	$7,000	0.184

4.3.2. Development of Failure Consequence Profile for a Subsystem

A subsystem is comprised of several components. The risk of operating a subsystem with damaged components will depend upon the extent of damage inflicted and the failure consequences for each component. The consequences of failure associated with each subsystem should first be identified and streamlined. A combination of experience, engineering judgement, and expert opinion should be employed in the process. Potential consequences of failure for a tanker structure could range from minor unplanned repairs and economic costs due to loss of serviceability, to litigation- and environmental pollution-related costs, and major dry-dock repairs. It should be noted that not all components contribute equally to these failure consequences. Therefore, cost measures should be assigned in some fashion to each incident associated with a failure consequence in order to rank the relative contribution of each component. An example of a possible failure consequence profile is given in Table 4-9. Additional consequence costs may be employed as the situation dictates.

Table 4-9. Example of a Possible Subsystem Failure Consequence Profile

Consequence of Failure	**Consequence Cost Per Incident ($)**
1. Minor Structural Failure	C_1=Cost of Minor Unplanned Repairs
2. Reduction or Loss of Serviceability	C_2=Economic Cost Due to Loss of Serviceability
3. Major Structural Failure	C_3=Substantial Unplanned Repair Cost/Economic Losses
4. Major Oil Spill or Leak, etc. : :	C_4=Costs of Litigation or Environmental Cleaning : :
j. Failure Consequence '*j*'	C_j=Costs Associated with Failure Consequence '*j*'

4.3.3. Estimation of Component Failure Probabilities

The estimation of component failure probabilities should be based on the results of vessel inspection. A qualitative approach, which relies on approximation of the physical/structural condition of individual components, should be used to assign failure probabilities. Since all components might not experience damage at the same level of severity, these estimates may be best obtained by combining the components into categories based on the different damage modes inflicted. Again, a combination of experience, engineering judgment, and expert opinion may be used in the process. Table 4-10 presents an example of failure probability estimates for the ten generic components considered earlier.

Table 4-10. Example of Failure Probability Estimation for Generic Components

Component	Measured Corrosion Damage		Fatigue Cracking		Buckling	
	Extent of Damage	Failure Probability P_f	Extent of Damage (a/a_c)	Failure Probability P_f	Extent of Damage	Failure Probability P_f
1	N/A	N/A	35%	$1x10^{-4}$	N/A	N/A
2	10%	$1x10^{-6}$	20%	$4x10^{-5}$	N/A	N/A
3	39.5%	$3x10^{-4}$	30%	$8x10^{-5}$	N/A	N/A
4	35%	$1x10^{-4}$	N/A	N/A	N/A	N/A
5	12%	$8x10^{-6}$	10%	$1x10^{-7}$	N/A	N/A
6	10%	$1x10^{-6}$	11.5%	$6x10^{-6}$	N/A	N/A
7	15%	$2x10^{-5}$	55%	$5x10^{-3}$	N/A	N/A
8	10.5%	$2x10^{-6}$	2%	$2x10^{-8}$	N/A	N/A
9	59%	$3x10^{-3}$	17.5%	$3x10^{-5}$	N/A	N/A
10	20%	$4x10^{-5}$	15%	$2x10^{-5}$	N/A	N/A

4.3.4. Computation of Failure Consequence Cost

The cost associated with failure of a component is dependent on a number of factors, including its relative degree of importance, its contribution to the cost of failure, and the level of damage experienced by the structure. A measure of the contribution of each component to the overall cost of failure must be determined. The potential contributions of any number of generic components (i=1,2,…,n) to the costs associated with a set of consequences, C_j (j=1,2,…,m), may be computed using Table 4-11, where the parameter α_{ij} denotes the contribution of component 'i' to the cost of failure consequence 'j'. Values of α_{ij} are typically determined based on a combination of experience, engineering judgment, and elicitation of expert opinion, and may range from 0 to1, with α_{ij}=0 implying that failure of component 'i' does not contribute to the cost of consequence 'j'. It should be noted that for a given consequence 'j', the sum $\sum_{i=1}^{n}\alpha_{ij} = 1$.

Similarly, comparison of the sum $\sum_{j=1}^{m}\alpha_{ij}$ for each component 'i' provides an indication of the relative importance of each component in terms of their combined contributions to all potential failure consequences. The expected failure consequence costs for each component are given by

$$FC_i = \sum_{i=1}^{n}\sum_{j=1}^{m}\alpha_{ij}C_j \tag{4-37}$$

Table 4-11. Component Contributions to Overall Cost of Failure

Component	Contribution to Failure Consequences	Expected Failure Cost
1	$\alpha_{1,1}$, $\alpha_{1,2}$, $\alpha_{1,3}$, $\alpha_{1,4}$,…, $\alpha_{1,j}$	$FC_1=\alpha_{1,1}C_1 + \alpha_{1,2}C_2 + \alpha_{1,3}C_3 +\ldots+ \alpha_{1,j}C_j$
2	$\alpha_{2,1}$, $\alpha_{2,2}$, $\alpha_{2,3}$, $\alpha_{2,4}$,…, $\alpha_{2,j}$	$FC_2=\alpha_{2,1}C_1 + \alpha_{2,2}C_2 + \alpha_{2,3}C_3 +\ldots+ \alpha_{2,j}C_j$
3	$\alpha_{3,1}$, $\alpha_{3,2}$, $\alpha_{3,3}$, $\alpha_{3,4}$,…, $\alpha_{3,j}$	$FC_3=\alpha_{3,1}C_1 + \alpha_{3,2}C_2 + \alpha_{3,3}C_3 +\ldots+ \alpha_{3,j}C_j$
4 : :	$\alpha_{4,1}$, $\alpha_{4,2}$, $\alpha_{4,3}$, $\alpha_{4,4}$,…, $\alpha_{4,j}$: :	$FC_4=\alpha_{4,1}C_1 + \alpha_{4,2}C_2 + \alpha_{4,3}C_3 +\ldots+ \alpha_{4,j}C_j$: :
n	$\alpha_{n,1}$, $\alpha_{n,2}$, $\alpha_{n,3}$, $\alpha_{n,4}$,…, $\alpha_{n,j}$	$FC_n=\alpha_{n,1}C_1 + \alpha_{n,2}C_2 + \alpha_{n,3}C_3 +\ldots+ \alpha_{n,j}C_j$

The failure costs for each component can then be used to rank the relative significance of a component failure, thereby lending assistance in making risk-informed decisions regarding prioritization of vessel inspection, maintenance, and repair. As an example, for the generic components considered in our example, the failure costs are summarized in Table 4-12.

Table 4-12. Summary of Failure Costs for Generic Subsystem Components

Component	Expected Failure Cost (FC_i)
1	$7,300
2	$7,075
3	$8,300
4	$6,750
5	$5,600
6	$3,250
7	$3,500
8	$1,900
9	$4,250
10	$4,925

Risk is defined as the pair of (failure consequence, failure probability). In the above discussion, we have given various weights to each component and associated a dollar amount with the failure of each according to a selected set of failure consequences and probabilities. Some components may be subjected to more than one failure mechanism, and in which cases a system reliability approach is more appropriate. In this study, a series system model is employed, wherein the system failure probability is estimated as the maximum failure probability for all failure modes. Implicit is the monetary value of the risk associated with failure of a component, which may be estimated in terms of the pair defined by Equation (4-38).

$$\boldsymbol{Risk_i} = \left(\boldsymbol{W_i FC_i}, \max\left(\boldsymbol{P_{fi}}\right)\right)_{\boldsymbol{i}=1,\ldots,\boldsymbol{n}} \tag{4-38}$$

For each of the ten generic components considered in our example, the expected costs induced as a result of individual failure consequences are summarized in Table 4-13, along with their corresponding maximum failure probabilities.

Table 4-13. Summary of Failure Consequence Induced Costs for Generic Subsystem Components

Component	Expected Failure Consequence Induced Cost (W_iFC_i)	Associated Maximum Failure Probability ($P_{fi,max}$)
1	$1,380	$1x10^{-4}$
2	$93	$4x10^{-5}$
3	$828	$3x10^{-4}$
4	$992	$1x10^{-4}$
5	$426	$8x10^{-6}$
6	$179	$6x10^{-6}$
7	$322	$5x10^{-3}$
8	$224	$2x10^{-6}$
9	$112	$3x10^{-3}$
10	$905	$4x10^{-5}$

4.3.5. Decision Analysis Using Qualitative Risk Estimates

The procedure outlined in the preceding tasks must be repeated for all subsystems of the structure. The risk associated with each component should be based on its relative damage condition. As noted in Chapter 3, there are three types of inspections for tanker ships, namely (i) an annual survey, (ii) an intermediate survey, and (iii) a major survey. The ultimate goal of a decision analysis is to use the risk associated with the respective damage states of the various components in making decisions regarding major inspections. This can be accomplished by ranking the components according to their individual risk levels. Acceptable risk levels for major components must be determined using expert opinion, engineering judgment, vessel cost, and classification society rules. In order to demonstrate the decision analysis procedure, the risk plot of Figure 4-13 illustrates the results of risk ranking for the generic components considered in this example (based on their current condition states). For the current analysis, it is assumed that the threshold risk level comprised of the pair (10^{-3}, $900) is used to differentiate between the various risk zones, as shown by the dashed lines in Figure 4-13. The lower left quadrant is referred to as the low risk zone, in which failure probabilities and consequences are relatively low. The upper left and lower right quadrants comprise the more moderate risk zones, where either the failure probabilities or consequence-induced costs are low. Finally, the upper right quadrant is known as the high-risk zone, where both failure probabilities and consequences are high. For the current state of the selected components, Figure 4-13 illustrates that the highest risk is associated with components 1, 4, 7 and 10, which lie in the two moderate risk zones. Similarly, it may be argued that component 3 is approaching the high-risk zone and may warrant further attention. In general, however, it is seen that component risk values lie within acceptable levels. These estimates should be updated using information gathered from annual and intermediate surveys, component costing reviews, and experts, and may also incorporate the effects of inflation. At this stage, there is no need for a quantitative reliability analysis. It is evident that additional effort (in terms of both time and personnel) should be devoted to the survey of components 1, 3, 4, 7 and10 during the annual and intermediate surveys. Major surveys should be delayed until such time as the risk coordinates for the individual components have begun to approach the boundaries defining the high-risk zone.

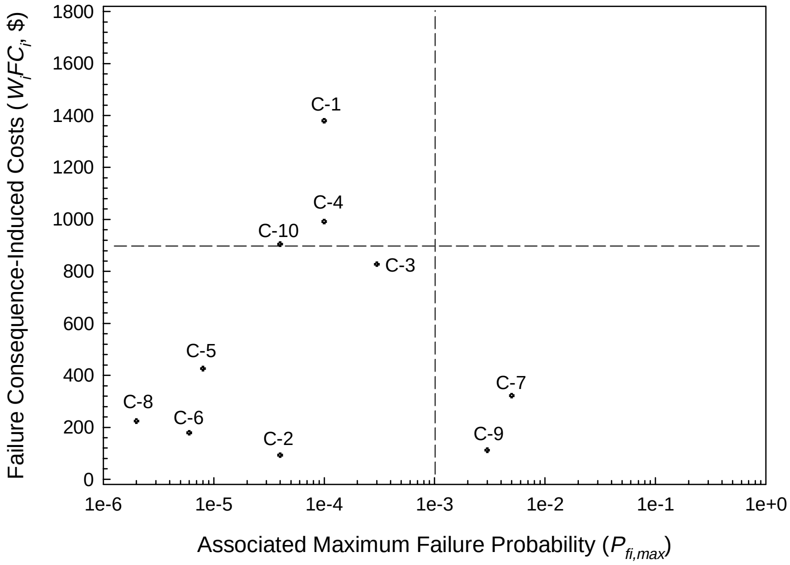

Figure 4-13. Risk Plot for Generic Subsystem Components

In order to demonstrate quantitative reliability estimates, it is assumed that the risk profile of each component (i.e., Table 4-13 values) has been updated using a combination of the results obtained during an intermediate (or annual) survey, inflation, a review of component costing, and expert solicitation. The revised values are shown in Table 4-14. It is also assumed that all components lie within the midship section.

Table 4-14. Updated Failure Consequence Induced Costs for Generic Subsystem Components

Component	Updated Failure Consequence Induced Costs (W_iFC_i)	Updated Maximum Failure Probabilities ($P_{fi,max}$)
1	$1,408	$3x10^{-3}$
2	$95	$2x10^{-3}$
3	$966	$8x10^{-3}$
4	$1018	$2x10^{-2}$
5	$870	$1x10^{-5}$
6	$184	$7x10^{-6}$
7	$336	$7x10^{-3}$
8	$241	$4x10^{-6}$
9	$119	$4x10^{-3}$
10	$931	$5x10^{-5}$

The corresponding (revised) risk plot is illustrated in Figure 4-14. It is seen that the risk levels of some components, namely components 1, 3, and 4, have crossed into the high-risk quadrant. As such, there is now a need to verify and refine the qualitative-based results through quantitative reliability analysis. Such an analysis facilitates refinement of the component failure probabilities and their impact on overall structural integrity, and also allows more accurate projection of the timeframe for scheduling major inspections.

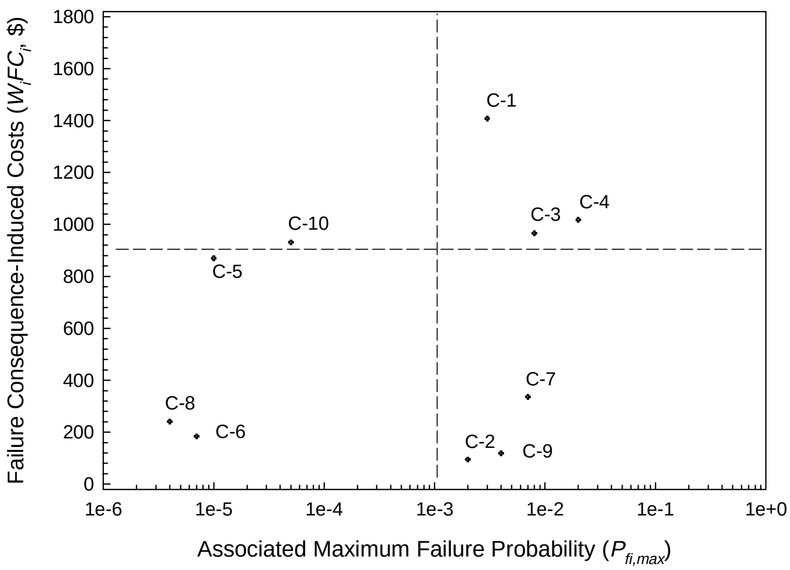

Figure 4-14. Updated Risk Plot for Generic Subsystem Components

To show the full range of results that may be obtained, it is assumed for demonstration purposes that the high-risk components mentioned above, as well as other similar components not included here, lie within the midship section of the vessel. This will allow for an overall assessment of the impact of damaged high-risk components on the integrity of the primary structure. Additional details regarding the midship section of a typical vessel, including sectional views, principal dimensions, scantlings, random variables of interest and applicable corrosion rates, will be provided in the next section.

4.4. Quantitative Risk Assessment and Decision Analysis

The risk-based inspection strategy developed in Chapter 3 demands that the failure probability for high-risk components be computed and their impact on overall structural integrity projected. This information is required in making risk-based decisions regarding the scheduling of major surveys and inspections. In this section, we demonstrate how the time-dependent reliability of multiple high-risk components afflicted by various damage modes can be used to project the risk levels of individual components, and how their damage levels can, in turn, affect the structural integrity of the primary structure of the tanker. For demonstration purposes, we will consider a number of tanker components afflicted by (i) corrosion, (ii) fatigue cracking, and (iii) a combination of corrosion and fatigue cracking, and then evaluate the impact of such damage modes on a major section of the vessel, such as the midship section.

4.4.1. Demonstration of Strategy for Major High-Risk Components

Damage modes to which vessel components are typically subjected include corrosion, fatigue cracking, and corrosion-enhanced fatigue damage. The performance functions corresponding to each damage mode have been presented in Section 4.2.8. Instantaneous and time-dependent reliability strategies have been reviewed previously in Section 4.2.9. The extent to which the components will be afflicted by such damage modes, as well as the level of risk posed by each, will most certainly be varied. The ultimate goal here is both to compute and project time-dependent failure probabilities for high-risk components during their lifetime. Such predictions can be compared to allowable threshold values in order to determine the best time for a major survey of the vessel. Examples of such components were presented in Section 4.3, in which the concept of qualitative reliability was advanced. It is assumed here when a major survey is suggested, the affected component will be repaired. Moreover, the quality of any repair is assumed to be such that the integrity of the repaired component is lower than that of the originally installed component (prior to the onset of corrosion and fatigue). Therefore, the repaired capacity can be seen to decrease with each subsequent repair. For the three damage modes considered herein, this repair efficiency is presented in terms of a percentage reduction in capacity from one repair to the next. The results of time-dependent component reliabilities in the presence of the aforementioned damage modes are presented in the following subsections.

Components Subjected to Corrosion Damage Only

Typical scenarios involving corrosion damage have been discussed in Section 4.2.8. High-risk components afflicted by corrosion may abound in different regions of a vessel, and the extent to which each is affected may vary significantly. Consider component (4) in the preceding example, a high-risk component affected only by corrosion. As shown in Figure 4-13, major surveys are recommended upon reaching a failure probability threshold of $P_{f,th}=10^{-3}$. Depending on the primary damage mechanism of interest (i.e., thickness reduction, area reduction, and volume reduction), any of the limit state functions developed in Section 4.2.8 may be applied. For demonstration purposes, it is assumed that the extent of depth reduction is of primary interest (Equation(4-2)), and that the parameters summarized in Table 4-15 are applicable to the damaged component.

Table 4-15. Probabilistic Characteristics of Principal Random Variables for Corrosion-Induced Component Damage

Random Variable	Mean Value	Coefficient of Variation	Distribution Type
Critical Corrosion Size	40	0.20	Normal
Coating Breakdown Time, t_0	3.0	-	Fixed
Corrosion Growth Coefficient (Intercept) a	2.1	0.01	Normal
Corrosion Growth Coefficient (Slope) b	1.0	-	Fixed
Reduction in Capacity Due to Repair (%)	4.2	-	Fixed

Assuming that no repairs are performed on the affected component during its lifetime, the time-dependent reliability projections are shown in Figure 4-15. Figure 4-16 illustrates the reliability profile for the same component, assuming that major inspections are scheduled upon reaching a threshold failure probability level of 10^{-3}. One can see the effect of the repair efficiency (95.8%) assumed for this case, depicted by the dashed line in Figure 4.16.

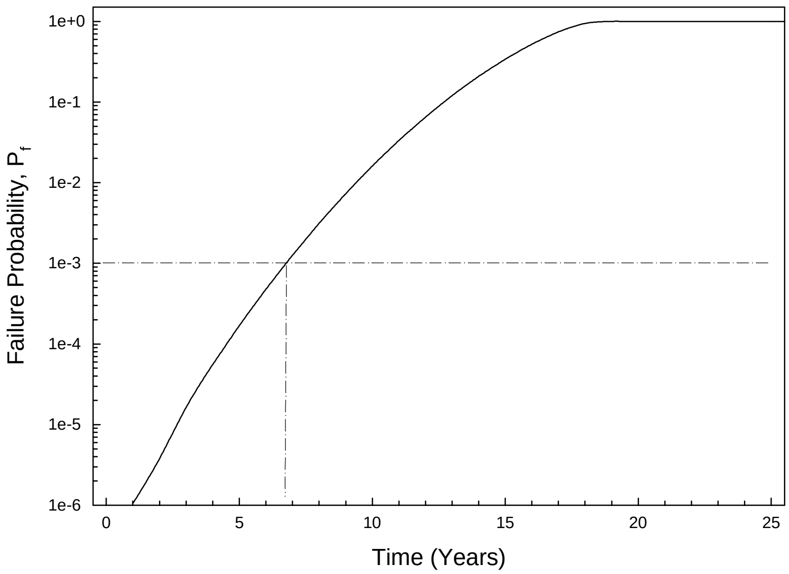

Figure 4-15. Time-Dependent Reliability for Component (4) Subjected to Corrosion Damage (Only) – No Repairs

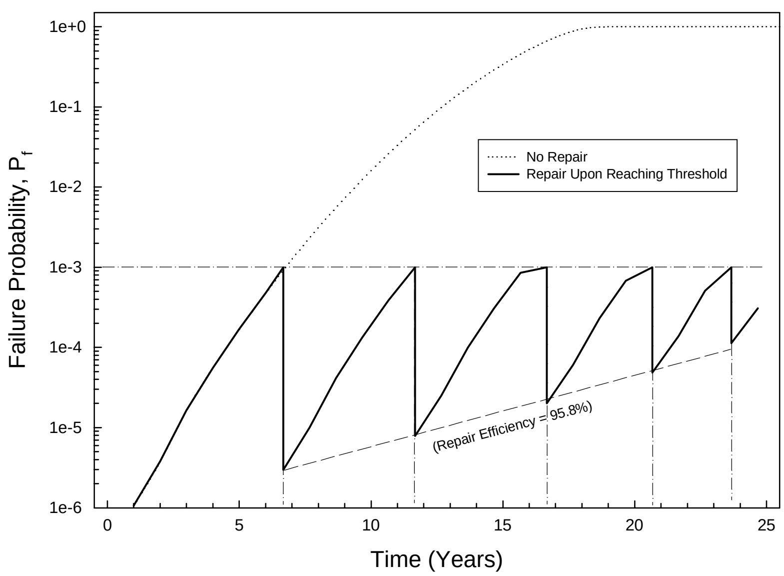

Figure 4-16. Time-Dependent Reliability for Component (4) Subjected to Corrosion Damage (Only) – With Repairs

Figure 4-15 suggests that the first major inspection of the component be done during year 6. When repairs are scheduled and performed as a result of these inspections, some degree of risk associated with the damaged component may be recovered, as illustrated in Figure 4-16. As previously mentioned, the extent of risk reduction is a function of both the repair technique selected and the quality of the repair. For example, the best repair method combined with a high-quality repair may improve the state of the damaged component to near-new condition. Following the initial inspection during year 6, Figure 4-16 suggests that based on the rate of post repair corrosion damage, a second major inspection of component (4) be carried out during year 11, a third be performed during year 16, a fourth performed during year 20, and a fifth major survey be performed during year 23. This, of course, assumes the use of similar repair techniques and qualities throughout its lifetime, as well as an equivalent failure probability threshold between major inspections. Should any of these variables change, the resulting failure probability profile will change accordingly. It is seen that the interval between major surveys decreases as the component ages. With age, the rate at which a component deteriorates following a repair may increase. However, high-quality repairs can significantly lower this rate. On the other hand, the improvements arising from lower quality repairs or inferior repair techniques could be significantly less. Moreover, such repairs may yield higher rates of subsequent deterioration.

Components Subjected to Fatigue Damage Only

Damage scenarios involving fatigue cracking are discussed previously in Section 4.2.8. Consider component (1) of the preceding example, a high-risk component affected by fatigue cracking only. Depending on the mechanism driving the fatigue damage, be it crack growth- or stress intensity factor-based, either of the two limit state functions developed in Section 4.2.8 may be applied. Assuming, for demonstration purposes, that exceedence of the critical crack length (a_C) is of primary interest, then the performance function defined by Equation 4-6 will be applied in conjunction with the crack growth relations given in Equations 4-13 and 4-14. The parameters summarized in Table 4-16 below are applicable to the damaged section.

Table 4-16. Probabilistic Characteristics of Principal Random Variables for Fatigue-Induced Component Damage

Random Variable	Mean Value	Coefficient of Variation	Distribution Type
Critical Crack Length, a_c	20	0.20	Lognormal
Initial Crack Length, a_0	0.60	-	Fixed
Crack Growth Coefficient (Intercept), Q	0.91	0.10	Normal
Crack Growth Coefficient (Slope), b	0.01	0.01	Normal
Reduction in Capacity Due to Repair (%)	6.6	-	Fixed

Assuming that no repairs are performed on the affected component during its lifetime, the time-dependent reliability projections are shown in Figure 4-17. Assuming that major inspections are scheduled upon reaching a threshold failure probability of $P_{f,th}=10^{-3}$, Figure 4-18 illustrates the reliability profile for the same component. The dashed line in Figure 4.18 shows the effect of the assumed repair efficiency (93.4%) for this case.

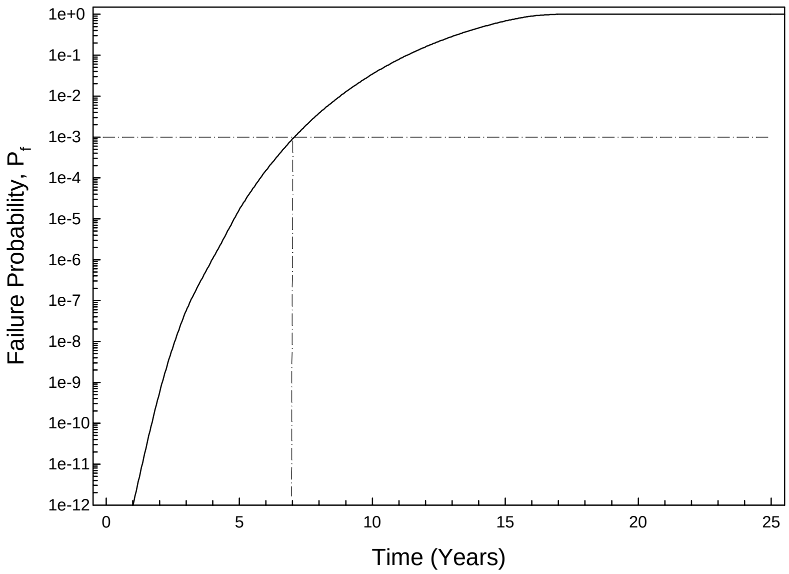

Figure 4-17. Time-Dependent Reliability for Component (1) Subjected to Fatigue-Induced Damage (Only) – No Repairs

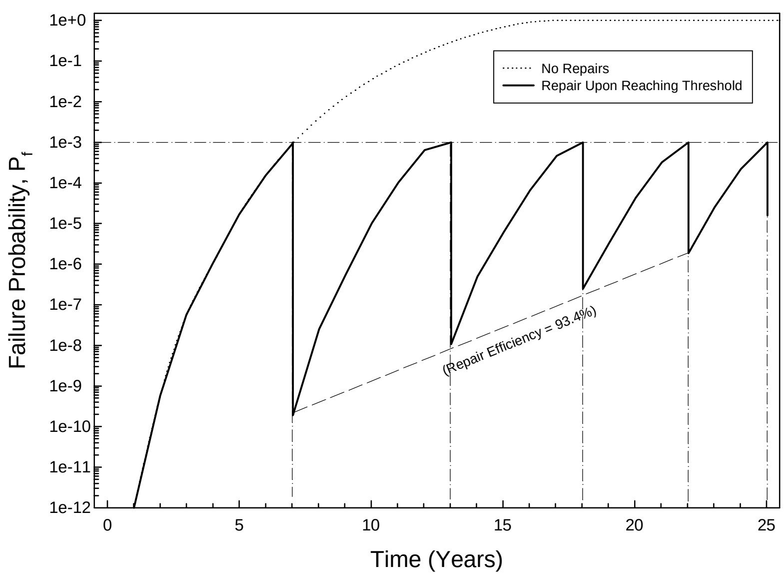

Figure 4-18. Time-Dependent Reliability for Component (1) Subjected to Fatigue-Induced Damage (Only) – With Repairs

Figure 4-17 implies that the first major survey of the component be done at just over 7 years. The extent to which failure probability is recovered as a result of repairs is illustrated in Figure 4-18. Following the initial major survey during year 7, Figure 4-18 suggests that based on the rate of fatigue damage following this repair, a second major inspection be carried out at approximately 13 years, a third be performed at just over 18 years, a fourth performed at approximately 22 years, and a fifth major survey be performed at 25 years. This again assumes that similar repair techniques/efficiencies are employed throughout its lifetime, as well as an equivalent failure probability threshold between major inspections. As was observed previously, it is seen that the duration between major inspections tends to decrease as the component ages, a result of the repair inefficiencies and limitations.

Components Subjected to Both Corrosion- and Fatigue-Induced Damage

Consider now component (3) of the example presented in Section 4.3, a high-risk component affected by both corrosion and fatigue cracking (i.e., corrosion-enhanced fatigue). Depending on the primary damage mechanism of interest, any of the limit state functions developed in section 4.2.8 may be applied. For illustrative purposes, the corrosion-enhanced crack growth relations defined in Equations 4-15 and 4-16 will be applied in conjunction with the limit state function defined by Equation 4-6. The damaged component is described by the parameters summarized in Table 4-17.

Table 4-17. Probabilistic Characteristics of Principal Random Variables for Component Damaged Due To Corrosion-Enhanced Fatigue Cracking

Random Variable	Mean Value	Coefficient of Variation	Distribution Type
Critical Crack Length, a_c	21.7	0.20	Lognormal
Initial Crack Length, a_0	0.61	-	Fixed
Crack Growth Coefficient (Intercept), Q	0.81	0.10	Normal
Crack Growth Coefficient (Slope), b	0.01	0.01	Normal
Corrosion Coefficient, C_{corr}	1.01	0.01	Normal
Reduction in Capacity Due to Repair (%)	5.8	-	Fixed

Assuming that the affected component remains unrepaired throughout its lifetime, the time-dependent reliability predictions are given by Figure 4-19. Assuming instead that major inspections are scheduled upon reaching a threshold failure probability of $P_{f,th}=10^{-3}$, Figure 4-20 illustrates the corresponding improvements for the same component as a result of scheduled repairs. The dashed line in Figure 4.20 depicts the effect of the repair efficiency (94.2%) assumed for this case.

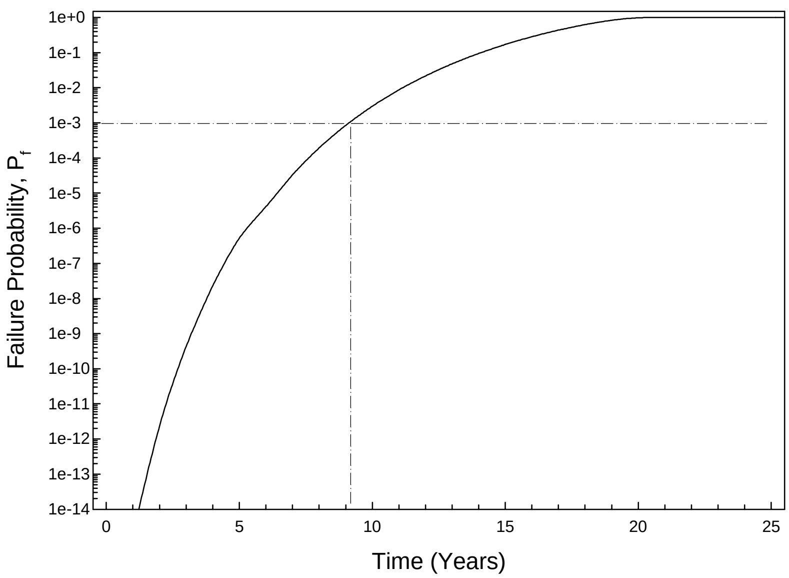

Figure 4-19. Time-Dependent Reliability for Component (3) Subjected to Corrosion-Enhanced Fatigue Cracking – No Repairs

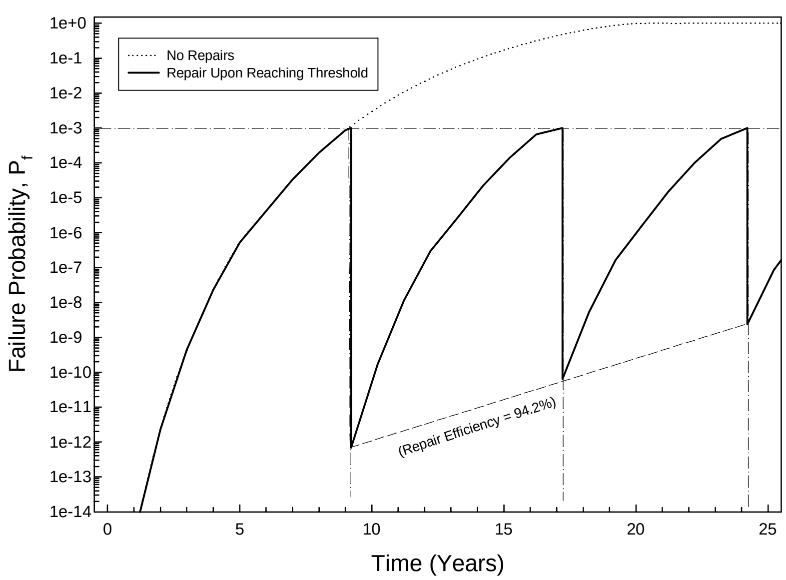

Figure 4-20. Time-Dependent Reliability for Component (1) Subjected to Corrosion-Enhanced Fatigue Cracking – With Repairs

Figure 4-19 indicates that the failure probability threshold is violated for the first time during year 9. Figure 4-20 depicts the extent to which component reliability is recovered as a result of repairs performed at the suggested intervals. Following the initial major inspection during year 9, Figure 4-20 suggests that a second major survey be carried out during year 17, and a third be performed during year 24. Once again, this implies an equivalent failure probability threshold between major surveys, and assumes that similar repair techniques/efficiencies are employed throughout the service life of the component. As has been observed thus far, the duration between major inspections tends to decrease as the component ages, a result of the degradation in the quality or efficiency in subsequent repairs.

For this case, in which a third component is affected by both corrosion and fatigue damage, the resulting failure probabilities are not necessarily higher than reported for the two previous cases, since three individual components are being considered.

Decision Analysis Using Component Results

The concepts and procedures demonstrated in Section 4.4.1 should be repeated for all high-risk components within the vessel. It is very plausible that one may encounter conflicting timeframes suggested for performing major surveys of each high-risk component. For example, the suggested timeframes for major surveys of the three components considered above are highlighted in Table 4-18.

Table 4-18. Recommended Schedules for Major Surveys of Vessel Components (1), (3), and (4)

Component ID and Description	Suggested Timeframes for Major Surveys of Components				
	1st Major Survey	2nd Major Survey	3rd Major Survey	4th Major Survey	5th Major Survey
Component (1): Fatigue-Induced Damage	7.04 yrs	13.04 yrs	18.04 yrs	22.04 yrs	25.04 yrs
Component (3): Corrosion-Enhanced Fatigue Damage	9.22 yrs	17.22 yrs	24.22 yrs	-	-
Component (4): Corrosion-Induced Damage	6.67 yrs	11.67 yrs	16.67 yrs	20.67 yrs	23.67 yrs

In the event of such conflicting recommendations, an alternative, compromised schedule must be suggested, based on factors such as budget limitations, vessel operating schedule, classification society requirements, and engineering experience. However, before drawing conclusions and reaching a compromised schedule based on component results, it may be helpful to evaluate the impact that delaying or executing the suggested major surveys/repairs would have on a major subsection of the vessel. To this end, a reliability analysis of a major vessel subcomponent will be carried out.

4.4.2. Demonstration of Strategy on Major Subsection of Vessel – Midship

It is easily seen that results for tanker components (1), (3), and (4) suggest conflicting timeframes during which to schedule major inspections. Ultimately, vessel management must make the decisions necessary to resolve such conflicts. For demonstration purposes, we will assume that all the high-risk components lie within the midship region, and that all damaged components in this region suffer from only corrosion-induced damage. The methodology employed here involves determining the extent of damage to all components affected by corrosion, and subsequently evaluating their collective impact on the overall strength of the vessel subsection. Such an analysis requires application of the methodologies outlined in Section 4.2.8.

Description of Midship Section of a Typical Tanker Vessel

Details regarding the midship section of a typical vessel are discussed in this section. The general layout of the vessel, showing longitudinal stiffener locations and hull/bulkhead plating thicknesses, is illustrated in Figure 4-21. The vessel's principal dimensions are summarized in Table 4-19. The vessel's cross-sectional dimensions and stiffener type codes are depicted in Figure 4-22. Scantling information for each stiffener type code is provided in Table 4-20.

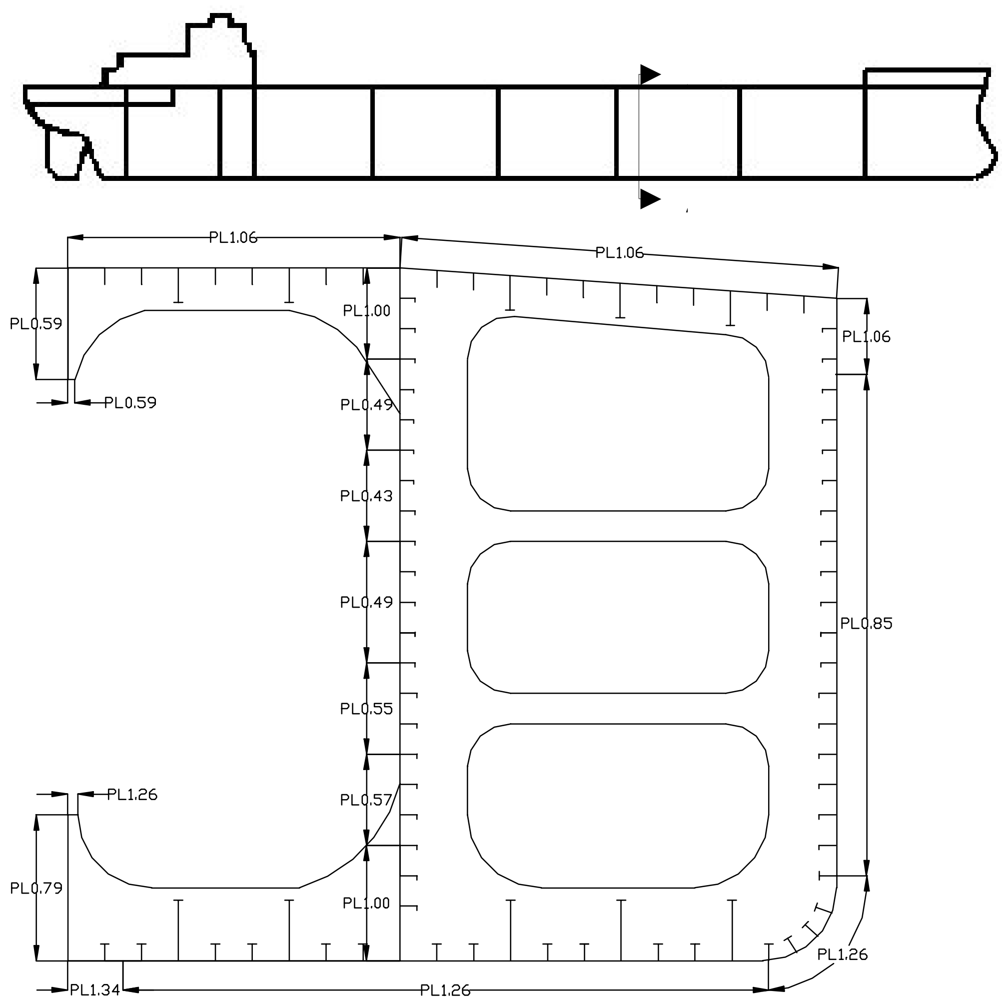

Figure 4-21. Schematic Diagram of Tanker Vessel (Section A-A), Showing Hull and Bulkhead Plating Thickness (Inches)

Table 4-19. Principal Dimensions of a Tanker Vessel

Parameter	Dimension
Length (L)	721' 10"
Breadth (B)	125'
Depth (D)	57'
Draft (T)	44' 2"
Block Coefficient	0.75

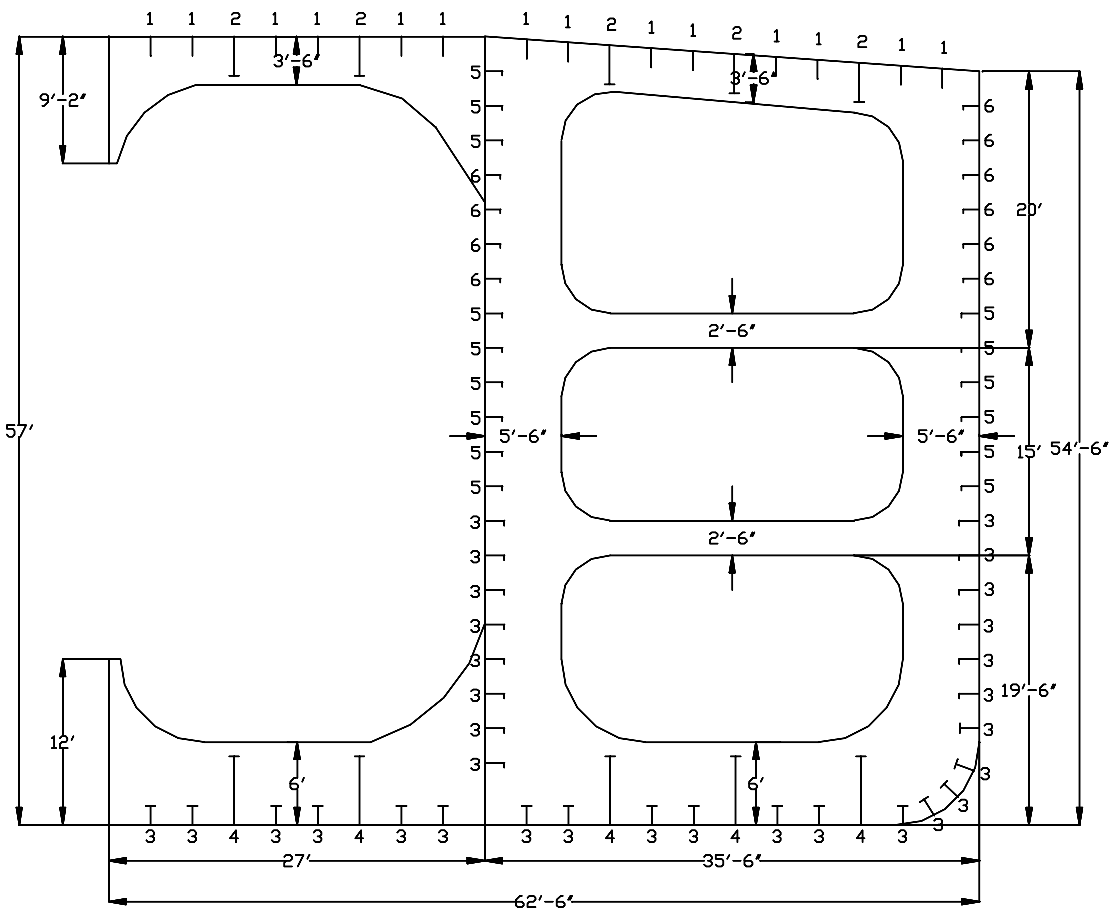

Figure 4-22. Schematic Diagram of Tanker Vessel Showing Cross-Sectional Dimensions (Feet and Inches) and Stiffeners Type Codes

Table 4-20. Dimensions of Typical Longitudinal Stiffeners

Stiffener Type	Stiffener Dimensions (in.)	
	Web	Flange
1	17.7x1.40	N/A
2	39.4x0.63	15.75x0.63
3	18.3x0.71	7.50x1.00
4	48.0x0.63	13.8x1.00
5	14.6x0.63	3.94x0.63
6	11.7x0.45	3.94x0.63

As previously mentioned, the integrity of the midship section will be assessed using the performance function and related equations discussed in Section 4.2.8. Evaluation of midship performance requires definition of a number of random variables. The probabilistic characteristics of all principal random variables affecting the strength of the midship section are summarized in Table 4-21 below. In addition, the random variables concerning model uncertainty are presented in Table 4-22.

Table 4-21. Probabilistic Characteristics of Principal Random Variables

Random Variable	Mean Value	Coefficient of Variation	Distribution Type
Ultimate Stress, σ_u	40.8 ksi	0.1	Lognormal
Knockdown Factor, c	0.95	-	Fixed
Stillwater Moment, M_{sw}	0.606×10^{10} lb-in	0.4	Gumbel
Wave Induced Moment, M_w	1.578×10^{10} lb-in	0.1	Normal
Dynamic Bending Moment, M_d	0.606×10^{10} lb-in	0.4	Gumbel
Reduction in Capacity Due to Repair (%)	1.2	-	Fixed

Table 4-22. Probabilistic Characterization of Model Uncertainty Random Variables (Mansour & Hoven, 1994)

Random Variable	Distribution Type	Mean	Coefficient of Variation
x_u	Normal	1.00	0.15
x_{sw}	Normal	1.00	0.05
x_w	Normal	0.90	0.15
x_s	Normal	1.15	0.03

Depending on location, the range of typical corrosion rates for a vessel may vary. Corrosion rate characteristics for typical tanker vessels are presented in Tables 4-23 and 4-24.

Table 4-23. Typical Corrosion Rates for Tanker Members (TSCF, 1997)

Corrosion rates			
Location	Mean (in/yr)	Min (in/yr)	Max (in/yr)
Deck Plating	0.00256	0.00118	0.00394
Deck Longitudinals (Web)	0.00256	0.00118	0.00394
Side Shell Plating	0.00118	0.00118	0.00118
Side Shell Plating Longitudinals (Web)	0.00118	0.00118	0.00118
Bottom Shell Plating	0.00669	0.00118	0.01181
Bottom Shell Longitudinals (Web)	0.00256	0.00118	0.00394
Longitudinal Bulkhead Plating	0.00256	0.00118	0.00394
Longitudinal Bulkhead Longs. (Web)	0.00256	0.00118	0.00394

Table 4-24. Probabilistic Characterization of Random Variables Related to Corrosion

Corrosion rates			
Location	Mean (in/yr)	Coefficient of Variation	Distribution Type
Deck Plating	0.00256	0.5	Weibull
Deck Longitudinals (Web)	0.00256	0.5	Weibull
Side Shell Plating	0.00118	0.1	Weibull
Side Shell Plating Longitudinals (Web)	0.00118	0.1	Weibull
Bottom Shell Plating	0.00669	0.5	Weibull
Bottom Shell Longitudinals (Web)	0.00256	0.5	Weibull
Longitudinal Bulkhead Plating	0.00256	0.5	Weibull
Longitudinal Bulkhead Longs. (Web)	0.00256	0.5	Weibull

The impact of corrosion-induced damage on time-dependent reliability of the vessel midship section is presented in the following subsection.

Results of Midship Section Subjected to Corrosion-Induced Damage

Corrosion-induced damage scenarios have been discussed previously in Section 4.2.8. The midship section of a vessel may contain numerous components affected by corrosion. In general, the extent to which each is affected will vary. An assessment of the overall impact of the corroded components on the strength of the midship section will greatly assist management personnel in making decisions regarding vessel inspection. For the midship section components considered collectively, a failure probability threshold of P_f=3x10^{-5} is assumed for the suggestion of major surveys. This threshold value is assumed for demonstration purposes only, and is not meant as a basis for maintenance decisions. The integrity of the midship section will be assessed using the performance function and related equations discussed in Section 4.2.8. For demonstration purposes, it is assumed that the corrosion-induced depth reduction is of primary interest according to Equation 4-2. Assuming that no repairs are performed on the midship section during its lifetime, the time-dependent reliability projections are shown in Figure 4-23 below. Assuming that major inspections are scheduled upon reaching a threshold risk level of 3x10^{-5}, Figure 4-24 illustrates the reliability profile for the same region of the vessel. The dashed line in Figure 4.24 illustrates the successive reduction in capacity as a result of the assumed 98.8% repair efficiency.

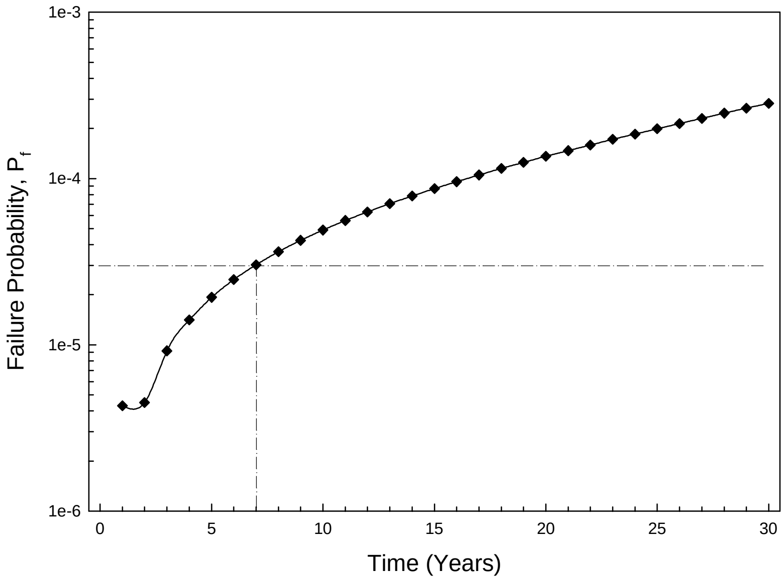

Figure 4-23. Time-Dependent Reliability for Midship Section Subjected to Corrosion Damage – No Repairs

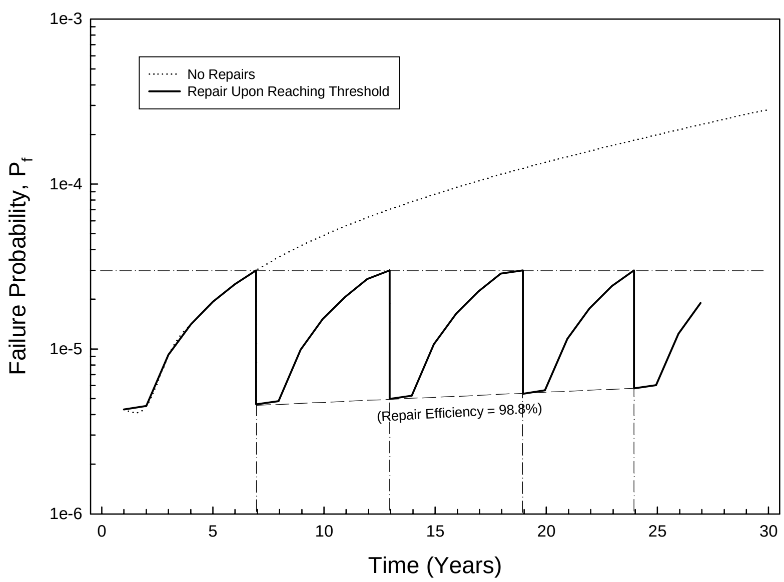

Figure 4-24. Time-Dependent Reliability for Midship Section Subjected to Corrosion Damage – With Repairs

Figure 4-23 suggests that the first major inspection be done late in year six. When repairs are scheduled and performed as a result of these inspections, some integrity of the midship section may be recovered, as shown by Figure 4-24. As previously mentioned, the extent of this recovery depends on not only the repair technique selected, but also the quality with which the repair is performed. Following the initial major inspection during year six, Figure 4-24 suggests a second major survey of the midship section be carried out late in year 12, a third be performed near the end of year 18, and a fourth major survey be carried out at approximately 24 years. As was the case for the discussion regarding component reliability, this assumes the use of similar repair techniques and qualities throughout the lifetime of the affected section, as well as an equivalent risk threshold level between inspections. Should any of these variables change, the resulting failure probability profile will change accordingly. It is seen that the interval between major surveys decreases with age, albeit a much less pronounced trend than was observed for the component-based reliability analysis.

5. A PLAN FOR IMPLEMENTING RISK-BASED INSPECTION SOFTWARE

5.1. Introduction

The effectiveness of the risk-based methodology described in Section 3.0 may be enhanced through the use of risk-based inspection computer software, notionally called the Ship Structural Risk Inspection and Assessment Program (SSRIAP). Ideally, the SSRIAP would support all phases of the inspection and maintenance process in an integrated manner. An initial definition of requirements for such a system is described below. Also described are representative examples of presently available software that addresses certain needs of ship structure risk-based inspection and assessment.

A key aspect of the software implementation plan is to involve the end users in the software development process from the very beginning. This is particularly important with regard to the definition and refinement of software requirements. In successful software implementation projects, the requirements will evolve over time. This is because it is impossible to predict a priori exactly how to design the software for best user satisfaction; some requirements must be defined up front, and the upper level requirements will remain fairly stable, but the need for other functionality of the software (and thus, requirements) will become evident only as the software is prototyped and exercised. A close working relationship between developers and users (e.g., through electronic mock-ups, workshops, and brainstorming) helps ensure that the resulting software will actually be used and not remain on a shelf.

5.2. Definition of Software Requirements

The software requirements include analytical capabilities, data storage, user-friendly graphical user interface (GUI), capability to send and receive data, and report generation. At this notional stage of requirements definition, the focus will be on analytical capabilities, with the understanding borne in mind that the other requirements will be defined at later stages. The following sections are arranged by major element of risk-based inspection methodology as described in Section 3.1:

- System definition – define structural inspection objectives (strength, performance, serviceability, reliability, cost effectiveness, and environmental soundness), define structural system, operational profile and loads, define needed information
- Data collection – define data needed, define data sources, define data collection methods, collect data and identify shortfalls
- Hazards and failure scenarios – identify hazards and initiating events, define degradation mechanisms, define failure modes and limit states, define failure scenarios
- Qualitative risk assessment – assess failure probabilities, assess failure consequences, develop risk profiles and rankings

- Quantitative reliability assessment – assess time-dependent failure probabilities for corrosion, fatigue, buckling, and permanent deformation
- Decision analysis – define risk acceptance criteria, develop inspection strategies, assess probabilities of non-detection, perform decision analysis, assess inspection costs, optimize at the system level.

As described in the following section, these requirements will be confirmed and refined as development of the SSRIAP takes place.

5.3. Software Development Plan

The software development process for the SSRIAP is based on the Rational Unified Process (RUP), where there are four distinct phases to development: Inception, Elaboration, Construction, and Transition (Fowler 1997). Each phase is further characterized by five sequential workflows: Requirements Capture, Analysis, Design, Implementation and Testing. These five workflows are repeated in an iterative manner throughout each phase of development. This process has been adapted to the needs of the SSRIAP and is described in the following sections.

5.3.1. Inception

The business rationale and project scope are established in this phase, through discussions with ship inspection and maintenance organizations (e.g., owners, classification societies, Coast Guard, and Navy) to define global requirements that will benefit organizations (functionally and financially) and users (functionally). A notional prototype may be constructed. This may comprise a series of screen captures of user interfaces and reports.

5.3.2. Elaboration

The Elaboration phase comprises the collection of more-detailed requirements (based on developing consensus among organizations and through consideration of the notional prototype and other additional information), the conduct of a high-level analysis and design to establish a baseline architecture, and the creation of a plan for construction. The requirements are open to change as the development process moves forward, because new information and capabilities become available to those involved in the development effort.

5.3.3. Construction

This phase will be completed with several iterations and builds of the SSRIAP software. Each of the iterations has a planned duration (e.g., two months) and will culminate in a complete build of the software. During the Construction Phase, the existing requirements will be implemented after appropriate analysis and code design workflows. It is anticipated that the software requirements will continue to evolve as a result of experience gained by users and observers in exercising the incremental software builds.

5.3.4. Transition

This phase will be completed with two additional iterations and builds of the SSRIAP. As in the previous development phase, the iterations have a planned duration. Since the primary purpose of the Transition Phase of software development is to prepare the code for ‘production’, no additional requirements will be considered, rather the emphasis will shift to testing and refining the code. Any remaining use cases from the Construction Phase will be addressed, but feedback during this phase will be limited to refinement of existing functionality and/or user interface ‘friendliness’. The software will be delivered on a CD, and each of the builds will be accompanied by a document that outlines the implemented use cases, bug fixes and any other germane differences between this and the previously delivered software. A hard copy final report will be delivered, which documents the requirements refinement process, as well as the technical architecture and components of the system. The final development deliverables will include a demonstration of the SSRIAP, installation, and a training workshop.

5.4. Existing and Developmental Risk-Based Inspection Software

Although no software exists that will address all of the ship structure risk-informed inspection requirements, there is software in existence or under development that addresses subsets of those requirements. Representative examples of commercially available risk-informed inspection and reliability assessment software are presented in Table 5-1, and their respective functionality is noted. Each example software package is briefly described in the following paragraphs.

SafeShip (American Bureau of Shipping) is an integrated through-life vessel integrity management program that addresses the structural condition of the vessel and assists the owner to operate more safely, more efficiently, and more cost effectively while meeting the highest standards of classification. Included are electronic storage and supply of 16 specified sets of drawings, and the ABS *SafeNet* Hull Maintenance program (ABS 2002).

ShipCheck (Atlantis Interactive Ltd.) is used by ship’s officers to carry out and record routine inspection of the ship and its equipment, and to provide ship specific historical data. Included is an industry-standard database, help files producing printable checklists for ship inspection routines, hyperlinks to locate appropriate regulatory references or sources, and the capability for the user to develop new inspection criteria (Atlantis Interactive Ltd. 2002).

FaciliWorks® (JBL Systems) is used for scheduling, managing and tracking maintenance tasks, enabling the building of preventive maintenance schedules and generating corrective and scheduled work orders. The system maintains repair histories and summarizes the status of work orders, service requests, labor, contracts, parts and equipment (JBL Systems 2002).

Davison Maintenance (Davison Software) relates corrective work orders and preventive maintenance tasks to equipment (machine, building, vehicle or any other entity which is managed like equipment) components. Any combination of parts is related to equipment, work orders, or preventive maintenance tasks by part group. Work order status is maintained in four categories: working, ready, hold, or completed (Davison Software 2002).

AvSim+ (Isograph, Inc.) is a software package to analyze the availability and reliability of both complex and simple systems. Features include: construction of fault tree (reliability block) diagrams, data verification and consistency checks, exponential and Weibull distributions for failure, analysis of historical data, and reports production (graphs, plots, pie charts, and time profile histograms)

BlockSim (ReliaSoft Corporation) is an integrated system for computations and predictions for advanced complex system reliability analysis and optimization. Features include: block definition, analysis of repairable systems, optimization of repair scheduling, reports generation, integration with observed failure rate database, distributions for failure and repair (including Weibull, exponential, normal, lognormal, and mixed Weibull). This system may be used to calculate the maximum or most cost-effective allocation reliability scenario (ReliaSoft Corporation 2002a).

WSTAR (US Army Corps of Engineers) enables users to perform reliability and risk analyses for the design and rehabilitation of civil works projects. The program can be accessed and used on the Internet, and uses advanced second moment method (ASM), Monte Carlo (MC) simulation, conditional expectation (CE), and time-dependent reliability (TDR) (Ayyub 1998b).

Reliability Analysis Modeling Program (RAMP)(Sandia National Laboratories) models component failure mechanisms of complex equipment and predicts the effects of reliability improvement options. Originally developed for equipment suppliers to the semiconductor industry, RAMP can be used to model virtually any piece of equipment, a process, or a piece of equipment with an integrated process. Modeling results include Mean Time Between Failure (MTBF), Mean Time to Repair (MTTR), Availability (for repairable systems),Reliability Improvement, Component contribution to Subsystem and System Failure, Subsystem contribution to System Failure, and Uncertainty Importance (the relative importance of variability of input data for each failure mechanism)(Version 2.0, 1993)(ITI 2002).

Nauticus (Det Norske Veritas) is a integrated product model which manages (accumulates, processes, and shares) information related to ship classification and ship life cycle. For example, users can access their vessels' classification certificate, survey status, inspection data and ships' drawings (DNV 2002b, Computas 2002).

ITEM Toolkit (Item Software, Inc.) is a modular system of tools with reliability features that include the capability to: carry out failure mode, effects and criticality analyses (in accordance with MIL-STD-1629A); develop reliability block diagram; estimate system reliability; analyze system configurations in trade studies; identify potential design problems; determine system sensitivity to component failures through importance analysis; analyze uncertainty and sensitivity; and carry out fault tree sequencing, initiating, and enabling (Item Software, Inc. 2002).

FARADIP (FAilure RAte Data In Perspective)(Maintenance 2000 Ltd.) is a failure rate and failure mode data bank, based on over 40 published data sources together with a company's own reliability data collection. It provides failure rate data ranges for a nested hierarchy of items covering electrical, electronic, mechanical, pneumatic, instrumentation and protective devices (Maintenance 2000 Ltd. 2002).

LOGAN (RM Consultants Ltd.) is a fault and event tree program that enables the construction and evaluation of fault and/or event trees for quantified risk assessment (QRA). It allows the results from the fault tree analysis to be incorporated into an event tree to provide a complete evaluation of the probability of hazards of various severities (RM Consultants Ltd. 2002).

VisualPlant (Executive Manufacturing Technologies) is a software application to collect data into one large, historical database and provide both the visualization and analysis of the data by users on their web browsers (Executive Manufacturing Technologies 2002).

Weibull++ 6(ReliaSoft Corporation) performs life data analyses utilizing multiple lifetime distributions, including all forms of the Weibull distribution, with tools to extract results, and to create graphs, reports and presentations (Reliasoft Corporation 2002b).

Table 5-1. Representative Examples of Risk-Informed and Reliability Assessment Software

Example Software	Functionality					
	System Definition	Data Collection	Hazards and Failure Scenarios	Qualitative Risk Assessment	Quantitative Reliability Assessment	Decision Analysis
SafeShip	x	x	x	x	x	x
ShipCheck	x	x				
FaciliWorks®	x	x				
Davison Maintenance	x	x	x			
AvSim+	x	x	x	x	x	x
BlockSim	x	x	x	x	x	x
WSTAR	x	x	x	x	x	
RAMP	x	x	x	x	x	
Nauticus	x	x				
ITEM Toolkit	x	x	x	x	x	
FARADIP		x				
LOGAN					x	
VisualPlant		x				
Weibull++ 6	x	x	x	x	x	

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The study developed and demonstrated a practical methodology and procedures for using a risk approach in the decision making process for structural inspection. A systems approach has been developed for risk-based optimal inspection management of ship structures. The following conclusions can be drawn based on this study:

1. Based on surveying the current practice related to inspection, the proposed methodology provides the theory needed for its enhancement.
2. The methodology was demonstrated to be practical, and could save resources or optimize the allocation of inspection resources. The application of the technology is also believed to have substantial potential to realize cost savings in the inspection, maintenance, and repair of aging vessel systems.
3. The methodology was constructed with careful consideration of the needs and practice of ship structural inspection and as such could be implemented in the form of a software product.
4. This methodology realistically accounts for the various types/sources of uncertainties involved in the decision-making process including uncertainties in the defect data gathered from inspections, material types, loads, parameters of the repair method, as well as the engineering strength models that are employed.
5. The proposed methodology could lead to the provision of a capability for quantitatively assessing reliability and risk levels to help ensure the safe operation of existing vessels' structural systems.
6. The methodology could also provide a rational framework and basis for extending the life of current vessels, as well as the re-qualification of such vessels using quantitative risk-based methodologies.
7. The application of such a methodology could lead to improved reliability levels, and significantly reduce incidents/accidents that cause damage to property, personnel and the environment.

The innovative aspects of the study include: (i) the development and application of probabilistic based qualitative and quantitative risk measures, and ranking and screening schemes for optimizing the inspection/maintenance of ship structures; and (ii) the use of a decision framework that incorporates risk and comparative cost models for optimal selection of inspection scheduling. The scope of the study includes: (i) the development and testing of a prototype risk informed methodology for performing marine inspections; (ii) the preparation of a long-term plan to evolve the prototype into a fully mature capability; and (iii) the creation of the infrastructure needed to support the development, use and dissemination of the new technology.

6.2. Recommendations

Based on the insight gained from this study of developing and demonstrating a practical methodology and procedures for using a risk approach in the decision making process for structural inspection, the following recommendations are provided:

1. A detailed case study needs to be constructed to demonstrate the benefits that could be gained from implementing the methodology.
2. A software product should be developed based on the software plan as provided in Chapter 5.
3. The methodology should be examined and adapted by classification societies within their current framework of documents and business practices.
4. A workbook should be developed to facilitate the practical implementation and use of the methodology.

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The following persons were members of the committee that represented the Ship Structure Committee to the Contractor as resident subject matter experts. As such they performed technical review of the initial proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, performed technical review of the work in progress and edited the final report.

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