NTIS # PB

SSC-416

PREDICTION OF STRUCTURAL RESPONSE IN GROUNDING APPLICATION TO STRUCTURAL DESIGN

SHIP STRUCTURE COMMITTEE

2000

SHIP STRUCTURE COMMITTEE

RADM Robert C. North
U. S. Coast Guard Assistant Commandant,
Marine Safety and Environmental Protection
Chairman, Ship Structure Committee

Mr. Robert McCarthy
Director,
Survivability and Structural Integrity Group
Naval Sea Systems Command

Mr. Joseph Byrne
Director, Office of Ship Construction

Maritime Administration

Mr. Thomas Connors
Director of Engineering

Military Sealift Command

Dr. Donald Liu
Senior Vice President

American Bureau of Shipping

Mr. Bud Streeter
Director General, Marine Safety,
Safety & Security
Transport Canada

Dr. Neil Pegg
Group Leader - Structural Mechanics

Defence Research Establishment Atlantic

CONTRACTING OFFICER TECHNICAL REP.
Lieutenant David J. Martyn / Ms. Dinah Mulligan
U.S. Coast Guard R & D Center

EXECUTIVE DIRECTOR
Lieutenant David J. Martyn
U. S. Coast Guard

SHIP STRUCTURE SUB-COMMITTEE

AMERICAN BUREAU OF SHIPPING
Mr. Glenn Ashe
Mr. Yung Shin
Mr. Phil Rynn
Mr. William Hanzalek

MARITIME ADMINISTRATION
Mr. Chao Lin

NAVAL SEA SYSTEMS COMMAND
Mr. W. Thomas Packard
Mr. Edward E. Kadala
Mr. Allen H. Engle
Mr. Charles L. Null

UNITED STATES COAST GUARD
Captain Mark VanHaverbeke
Mr. Rubin Sheinberg
Mr. Walt Lincoln
Commander Ray Petow

DEFENCE RESEARCH ESTABLISHMENT ATLANTIC
Mr. Layton Gilroy
Mr. John Porter
LCDR Stephen Gibson
Dr David Stredulinsky

MILITARY SEALIFT COMMAND
Mr. Edward Meade
Mr. Rick A. Anderson
Mr. Jeffery E. Beach
Mr. Michael W. Touma

TRANSPORT CANADA
Mr. Nico Pau
Mr. James Reid

CANADIAN COAST GUARD
Mr. Justus Bunckhuysen

Member Agencies:

American Bureau of Shipping
Defence Research Establishment Atlantic
Maritime Administration
Military Sealift Command
Naval Sea Systems Command
Society of Naval Architects & Marine Engineers
Transport Canada
United States Coast Guard

Ship Structure Committee

Address Correspondence to:

Executive Director
Ship Structure Committee
U.S. Coast Guard (G-MSE/SSC)
2100 Second Street, SW
Washington, D.C. 20593-0001
Ph: (202) 267-0003
Email: dmartyn@comdt.uscg.mil

An Interagency Advisory Committee

SR-1407
SSC-416

November 2000

RISK BASED LIFE CYCLE MANAGEMENT OF SHIP STRUCTURES

This report provides risk-based guidelines for managing and maintaining the structural integrity of ship structures in a life cycle 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 risk measures can be obtained by a risk-based methodology for maintaining and managing the structural integrity of ship systems. Therefore, managers can make informed decisions that account for risk, among other considerations, in a decision-making process. The guidelines' presentation and style are suitable for direct implementation and use by managers.

The guidelines are provided herein in five chapters and three appendices. Chapter 1 provides background information, problem definition, objective statement, scope and report structure. Chapter 2 constitutes the core of 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. Chapter 3 demonstrates the guidelines and the methodology using quantitative and qualitative case studies and examples. Chapter 4 provides conclusions and recommendations. A bibliography is provided in Chapter 5 that includes all of the cited references along with other sources that provide background information on risk methods and their applications.

In Appendix A, various risk methods that are needed in the suggested methodology of Chapter 2 are summarized with examples. Appendix B defines the life cycle of structural systems of ships as required by the methodology. Another detailed case study at the system level using a naval vessel is provided in Appendix C to describe the proposed methodology in detail.

R. C. NORTH
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Technical Report Documentation Page

1. Report No. SSC-	2. Government Accession No. PB	3. Recipient's Catalog No.	
4. Title and Subtitle Risk-based Life Cycle Management of Ship Structures		5. Report Date September 2000	
		6. Performing Organization Code	
7. Author(s) Bilal M. Ayyub, U. O. Akpan, Gilberto F. De Souza, T. S. Koko, and X. Luo		8. Performing Organization Report No. SR-1407	
9. Performing Organization Name and Address BMA Engineering, Inc. 11429 Palatine Drive Potomac, MD 20854		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. DTCG39-99-C-E00222	
12. Sponsoring Agency Name and Address Ship Structure Committee U. S. Coast Guard (G-MSE/SSC) 2100 Second Street, SW Washington, DC 20593		13. Type of Report and Period Covered Final Report **9/99-9/00**	
		14. Sponsoring Agency Code **G-M**	
15. Supplementary Notes Sponsored by the Ship Structure Committee. Jointly funded by its member agencies.			

16. Abstract

This report provides risk-based guidelines for managing and maintaining the structural integrity of ship structures in a life cycle 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 risk measures can be obtained by a risk-based methodology for maintaining and managing the structural integrity of ship systems. Therefore, managers can make informed decisions that account for risk among other considerations in a decision-making process. The guidelines' presentation and style are suitable for direct implementation and use by managers.

The guidelines are provided herein in five chapters and three appendices. Chapter 1 provides background information, problem definition, objective statement, scope and report structure. Chapter 2 constitutes the core of 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. Chapter 3 demonstrates the guidelines and the methodology using quantitative and qualitative case studies and examples. Chapter 4 provides conclusions and recommendations. A bibliography is provided in Chapter 5, at the end report, that includes all the cited references along with other sources that provide background information on risk methods and their applications.

In Appendix A, various risk methods that are needed in the suggested methodology of Chapter 2 are summarized with examples. Appendix B defines the life cycle of structural systems of ships as required by the methodology. Another detailed case study at the system level using a naval vessel is provided in Appendix C to describe the proposed methodology in detail.

17. Key Words		18. Distribution Statement	
inspection, lifecycle, management, naval ships, reliability, tanker ships, risk, structures, structural inspection		Distribution is available to the public through: National Technical Information Service U.S. Department of Commerce Springfield, VA 22151 Ph. (703) 487-4650	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages **284**	22. Price

CONVERSION FACTORS

(Approximate conversions to metric measures)

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

TABLE OF CONTENTS

Disclaimer iii
Abstract iv
Table of Contents v
1. Introduction 1
1.1. Background 1
1.2. Risk-Based Methods 1
1.3. Life Cycle Management of Ship Structures 2
1.4. Objectives, Scope and Report Structure 2
2. Risk-based Guidelines for Managing the Integrity of Structural Systems 4
2.1. Risk-Based Methodology for Assessing and Managing Structural Integrity 4
2.2. Analysis Objectives and Definition of the Structural System 6
2.3. Hazards and Failure Scenarios 9
2.3.1. Hazard Analysis 9
2.3.2. Preliminary Hazard Analysis 9
2.3.3. Definition of Failure Scenarios 12
2.4. Collection of Data in a Life Cycle Framework 15
2.5. Qualitative and Quantitative Risk Assessment 16
2.5.1. Qualitative Risk Assessment 16
2.5.2. Quantitative Risk Assessment 17
2.5.3. Risk Profiles 18
2.5.4. Time-Dependent Risk Profiles 22
2.6. Life Cycle Management of System Integrity 23
3. Cases Study: Demonstration of Risk-Based Life Cycle Management 25
3.1. Introduction 25
3.2. Quantitative Risk-Based Assessment and Management 25
3.2.1. Introduction 25
3.2.2. Objective of Analysis 26
3.2.3. System Definition 26
3.2.4. Hazard Analysis 28
3.2.5. Structural Risk Assessment 29
3.2.6. Limitation of Results 37
3.2.7. Discussion of Results and Application to Risk Management 38
3.3. Qualitative Risk-Based Assessment and Management 45
3.3.1. Introduction 45
3.3.2. Objective of Analysis 45
3.3.3. System Definition for Tanker Structures 46
3.3.4. Hazard Analysis 46
3.3.5. Qualitative Risk Assessment 52
3.3.6. Risk Based Life Cycle Management 58
4. Conclusions and Recommendations 63
4.1. Conclusions 63

TABLE OF CONTENTS

Table of Contents ..... A-ii
A. Risk-Based Technology Methods A-1
A.1. Introduction A-1
A.2. Risk Terminology A-1
A.2.1. Hazard A-1
A.2.2. Reliability A-1
A.2.3. Failure Consequences A-1
A.2.4. Risk A-2
A.2.5. Uncertainty A-4
A.2.6. Performance A-5
A.2.7. Risk-based Technology A-5
A.2.8. Safety A-6
A.2.9. Engineering Systems A-7
A.3. Risk Assessment A-7
A.3.1. System Definition A-8
A.3.2. Preliminary Hazard Analysis A-10
A.3.3. Failure Mode and Effects Analysis A-10
A.3.4. Event Modeling: Event, Success and Fault Trees A-11
A.3.5. Qualitative/ Quantitative Risk Measurement A-17
A.4. Human Reliability Analysis A-17
A.4.1. Human Error Identification A-17
A.4.2. Human Error Modeling A-18
A.4.3. Human Error Quantification A-18
A.4.4. Reducing Human Errors A-19
A.5. Assessment of Component Failure Likelihood A-19
A.5.1. Structural Reliability A-19
A.5.2. Time-Dependent Reliability A-21
A.6. Assessment of Consequences A-27
A.7. Data Needs for Risk Assessment A-29
A.7.1. Data Definition, Classification and Sources A-29
A.7.2. Expert-Opinion Elicitation Process A-30
A.8. Risk Management and Control A-41
A.8.1. Risk Acceptance A-42
A.8.2. Risk-Based Ranking A-51
A.8.3. Decision Analysis A-51
A.9. Risk Communication A-58

TABLE OF CONTENTS

Table of Contents .... B-ii
B. Life Cycle Management of Structural Systems B-1
B.1. Introduction B-1
B.2. Life Cycle Concepts B-2
B.2.1. Life Cycle Assessment B-2
B.2.2. Life Cycle Cost B-3
B.2.3. Life Cycle Management B-7
B.3. Phases in Life Cycle of Ship Structural Systems B-7
B.3.1. Conception and Design B-7
B.3.2. Construction and Production B-7
B.3.3. Operation and Maintenance (O&M) Phase B-8
B.3.4. Disposal Phase B-8
B.4. Service Life Management of Existing Structures B-9
B.4.1. Introduction B-9
B.4.2. Modes of Structural Failure B-9
B.4.3. Degradation of Ship Structures B-12
B.4.4. Inspection B-15
B.4.5. Maintenance B-24
B.4.6. Repairs B-25
B.5. Life Extension and Replacement B-30

4.2. Recommendations.....63
5. Bibliography.....65
Acknowledgements.....77
Appendix A. Risk-Based Technology Methods
Appendix B. Life Cycle Management of Structural Systems
Appendix C. Guidelines Detailed Using a Naval Vessel

DISCLAIMER

This report was prepared through the efforts of the BMA Engineering, Inc. and its associates (hereafter referred to as the BMA) with sponsorship of the U. S. Coast Guard and members of the Ship Structure Committee (referred to hereafter as the Sponsors).

Neither the BMA nor the Sponsor, nor BMA's subcontractors, nor others involved in the preparation or review of this report, nor any of their respective employees, members, or persons acting on their behalf, make any warranty, expressed or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its uses would not infringe privately owned rights.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the BMA, the Sponsors, or others involved in the preparation or review of this report, or agency thereof. The views and opinions of the authors, contributors, and reviewers of the report expressed herein do not necessarily reflect those of the BMA, the Sponsors, or others involved in the preparation or review of this report, or any agency thereof.

ABSTRACT

The aging fleets of marine industry and the use of new system configurations and materials in designing new systems have raised new challenges and concerns for the industry. These challenges include decisions on life expectancy of structural systems, remaining life, acceptance of aged structural systems in meeting safety requirements, acceptable reliability levels, selection of inspection intervals and methods, repair methods, and systems upgrade and replace options. The shipbuilding and marine industry needs a framework and guidance on managing the life cycle of ship structures.

This report provides risk-based guidelines for managing and maintaining the structural integrity of ship structures in a life cycle 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 risk measures can be obtained by a risk-based methodology for maintaining and managing the structural integrity of ship systems. Therefore, managers can make informed decisions that account for risk among other consideration in a decision-making process. The guidelines' presentation and style are suitable for direct implementation and use by managers.

The guidelines are provided herein in five chapters and three appendices. Chapter 1 provides background information, problem definition, objective statement, scope and report structure. Chapter 2 constitutes the core of 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. Chapter 3 demonstrates the guidelines and the methodology using quantitative and qualitative case studies and examples. Chapter 4 provides conclusions and recommendations. A bibliography is provided in Chapter 5, at the end report that include all the cited references along with other sources that provide background information on risk methods and their applications.

In Appendix A, various risk methods that are needed in the suggested methodology of Chapter 2 are summarized with examples. Appendix B defines the life cycle of structural systems of ships as required by the methodology. Another detailed case study at the system level using a naval vessel is provided in Appendix C to describe the proposed methodology in details.

1. INTRODUCTION

1.1. Background

The U. S. shipbuilding and marine industry are increasingly faced with concerns and challenges that arise primarily from their aging fleets, and to a lesser extent from using new system configurations and materials in designing new systems. These concerns and challenges require decisions on life expectancy of structural systems, remaining life, acceptance of aged structural systems in meeting safety requirements, acceptable reliability levels, selection of inspection intervals and methods, repair methods, and systems upgrade and replace options. Issues related to these concerns and challenges are often raised by various ship owners and/or operators, both in the Government and commercial arenas. For example, in its oversight plan dated February 11, 1999, the Committee on Transportation and Infrastructure of the 106th Congress reported that "The Coast Guard is currently engaged in a major vessel and aircraft acquisition project to replace its aging fleet typically employed more than 50 miles from U.S. shores. This project, the Deepwater Capability Replacement Project, involves replacing or modernizing many of the Coast Guard's 92 ships and 209 airplanes and helicopters." These challenges and concerns highlight the needs in this area. The shipbuilding and marine industry needs a framework and guidance on managing the life cycle of ship structures that can be adopted and used for other systems as well.

This report provides the essential background information, and develops the needed guidance for managing the life cycle of ship structures using a systems framework and risk-based technology methods. This chapter provides definitions of risk-based technology methods, life cycle assessment, and the objectives and scope of the report.

1.2. Risk-Based Methods

The process of structural design and management of the life cycle of structural systems that include subsystems, components and details can be improved by utilizing risk-based methods and tools by using them to manage the life cycle of ship structures, assess existing practices, regulations and standards, and to develop new ones that are cost effective to the society. 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 ships 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 managing these systems by assessing their failure probabilities and consequences and managing associated risks are needed. A systematic approach allows an engineer to evaluate and regulate complex engineering systems for safety and risk under different operational conditions. This provides the engineer with the ability to quantitatively evaluate these systems and helps cut the cost of their use. A risk-based framework is compatible with decision analysis methods that are based on cost-benefit tradeoffs. Ayyub, et al. (1997 and 1998) recently discussed the marine-industry needs in these areas. Appendix A provides the needed background information on risk-based technology methods.

1.3. Life Cycle Management of Ship Structures

The life cycle of a ship structure may be divided into four primary phases, namely, conception and design, acquisition or construction, in-service and operation, and disposal. For marine structural systems, there are many influences that affect system safety. Sources of risk include degradation mechanisms, external events, human errors, and institutional errors (Wilcox et al. 1996). Degradation mechanisms such as fatigue and corrosion are the most recognized hazard and can be divided into several sub-categories including independent failures and common cause failures. Humans provide another source of risk to these systems due to lack of skill, mistakes, fatigue, or sabotage. Institutional failure represents risks from poor management including training, management attitude, poor communications, and morale.

This project was developed to aid ship owners and operators in managing the structural systems of their vessels and thus aid in linking all aspects of a vessel's life cycle management and planning including: design, construction, acquisition, repair and maintenance and removal from service. The decision-making processes in vessel life cycle management need to consider the following issues:

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

An owner's decisions regarding the purchase, continued operation or maintenance of a vessel are ideally based on developing the greatest return on each invested dollar. In order to estimate the costs associated with the operation of a vessel the initial cost, maintenance cost, failure cost and its associated probabilities, and probable residual value at the end of the operational period should be assessed. Appendix B provides the needed background information on life cycle assessment methods.

1.4. Objectives, Scope and Report Structure

This study provides risk-based guidelines for managing and maintaining the structural integrity of ship structures in a life cycle 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 risk measures can be obtained by a risk-based methodology for maintaining and managing the structural integrity of ship systems. Therefore, managers can make informed decisions that account for risk among other consideration in a decision-making process. The guidelines' presentation and style are suitable for direct implementation and use by managers.

The guidelines are provided herein in five chapters and three appendices. Chapter 1 provides background information, problem definition, objective statement, scope and report structure. Chapter 2 constitutes the core of 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. Chapter 3 demonstrates the guidelines and the methodology using quantitative and qualitative case studies and examples. Chapter 4 provides conclusions and recommendations. A bibliography is provided in Chapter 5, at the end report that include all the cited references along with other sources that provide background information on risk methods and their applications.

In Appendix A, various risk methods that are needed in the suggested methodology of Chapter 2 are summarized with examples. Appendix B defines the life cycle of structural systems of ships as required by the methodology. Another detailed case study at the system level using a naval vessel is provided in Appendix C to describe the proposed methodology in details.

2. RISK-BASED GUIDELINES FOR MANAGING THE INTEGRITY OF STRUCTURAL SYSTEMS

This chapter provides guidelines for risk-based management of the structural integrity of marine systems. The guidelines are developed based on risk methods, life cycle modeling, and experiences of guideline development for risk-based management of system in other industries. The underlying methodology was developed in a systems framework that provides managers with risk-based guidance on significant failure location by assessing failure modes, failure probabilities and consequences, and using them in decision models.

2.1. Risk-Based Methodology for Assessing and Managing Structural Integrity

The basic philosophy of the proposed methodology is to utilize experiences gathered from databases, ship personnel including managers, risks assessment models, experiences from other industries and experts, in conjunction with ship structural analysis and damage evaluation/prediction tools. 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. These include 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 proposed is capable of taking direct advantage of previously verified residual strength assessment models and engineering experience that has been compiled over the time form the operation of vessel systems.

In this section, the overall methodology is provided in the form of a work flow or block diagram. The various components of the methodology are described in subsequent sections. Figure 2-1 provides an overall description of the proposed methodology for risk-based management of structural systems. The methodology consists of the following primary steps:

1. Definition of analysis objectives and systems for life cycle management
2. Hazard analysis, definition of failure scenarios, and hazardous sources and their terms
3. Collection of data in a life cycle framework
4. Qualitative risk assessment
5. Quantitative risk assessment
6. Management of system integrity through failure prevention and consequence mitigation using risk-based decision making

These steps are briefly described in subsequent sections in this chapter with additional background materials provided in subsequent chapters and the appendices.

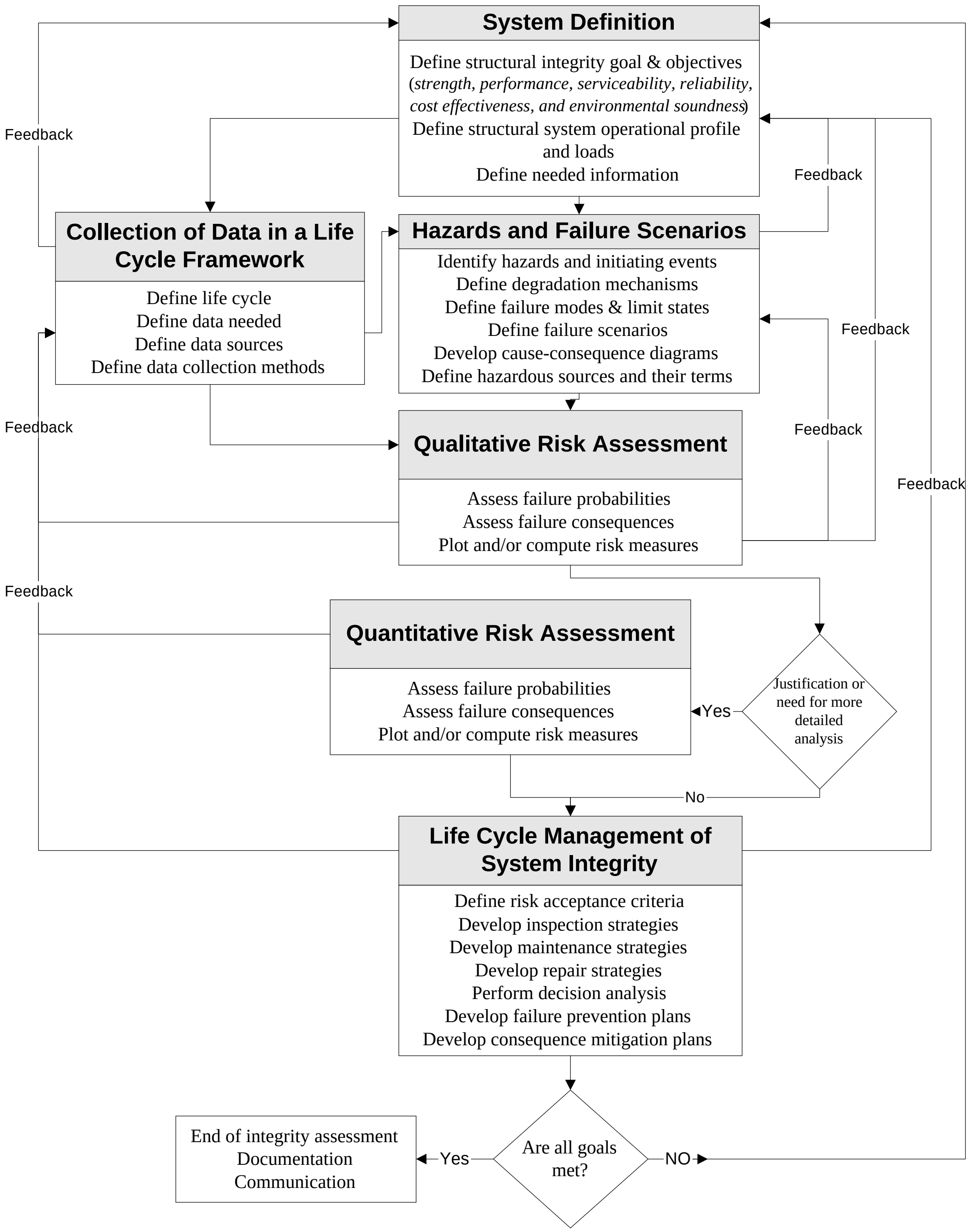


Figure 2-1. Methodology for Risk-Based Life Cycle Management of Structural Systems

2.2. Analysis Objectives and Definition of the Structural System

The first step of the methodology is to define the structural system. This definition should be based on a 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 shown in Figure 2-2, and are to

- Define the goal and objectives of the analysis
- Define the system boundaries
- Define the success criteria in terms of measurable performances
- Collect information for assessing failure likelihood
- Collect information for assessing failure consequences

The structural integrity goal can include objectives stated in terms of strength, performance, serviceability, reliability, cost effectiveness, and environmental soundness. 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 structural system can be considered to contain individual structural elements such as plates, stiffened panels, stiffeners, longitudinals, …, etc. These elements could be further separated 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 life cycle on each item so that failure rates, repair frequencies and failure consequences can be estimated. The system definition might need to include non-structural subsystems and components that would be affected in case of failure. The subsystems and components are needed to assess the consequences.

In order to understand failure and the consequences of failure, the states of success need to be defined. For the system to be successful, it must be able to perform its designed functions by meeting measurable performance requirements. But the system may be capable of various levels of performance, all of which might not be considered a successful performance. While a vessel may be able to get from point A to point B only at a reduced speed due to a fatigue failure that results in excessive vibration at the engine room, its performance 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 vessel's success and failure impacts should be based on the overall vessel performance that 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 in the maintenance and operating histories of the systems and equipment, and based on judgment and expert opinion. This information might not be accessible, and its extraction from its current source might be difficult. Also, assembling it in a manner that is suitable for the risk-based methodology might be a challenge.

Operation, maintenance, engineering and corporate information on failure history needs to be collected and analyzed for the purpose of assessing the consequences of failures. The consequence information might not be available from the same sources as the information on the failure itself. Typically there are documentations of 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 on other systems, the cost of shifting resources to cover lost production, and things like environmental, safety-loss or public-relations costs. These may be attained through carefully organized discussions and interviews with cognizant personnel including the use of expert-opinion elicitation.

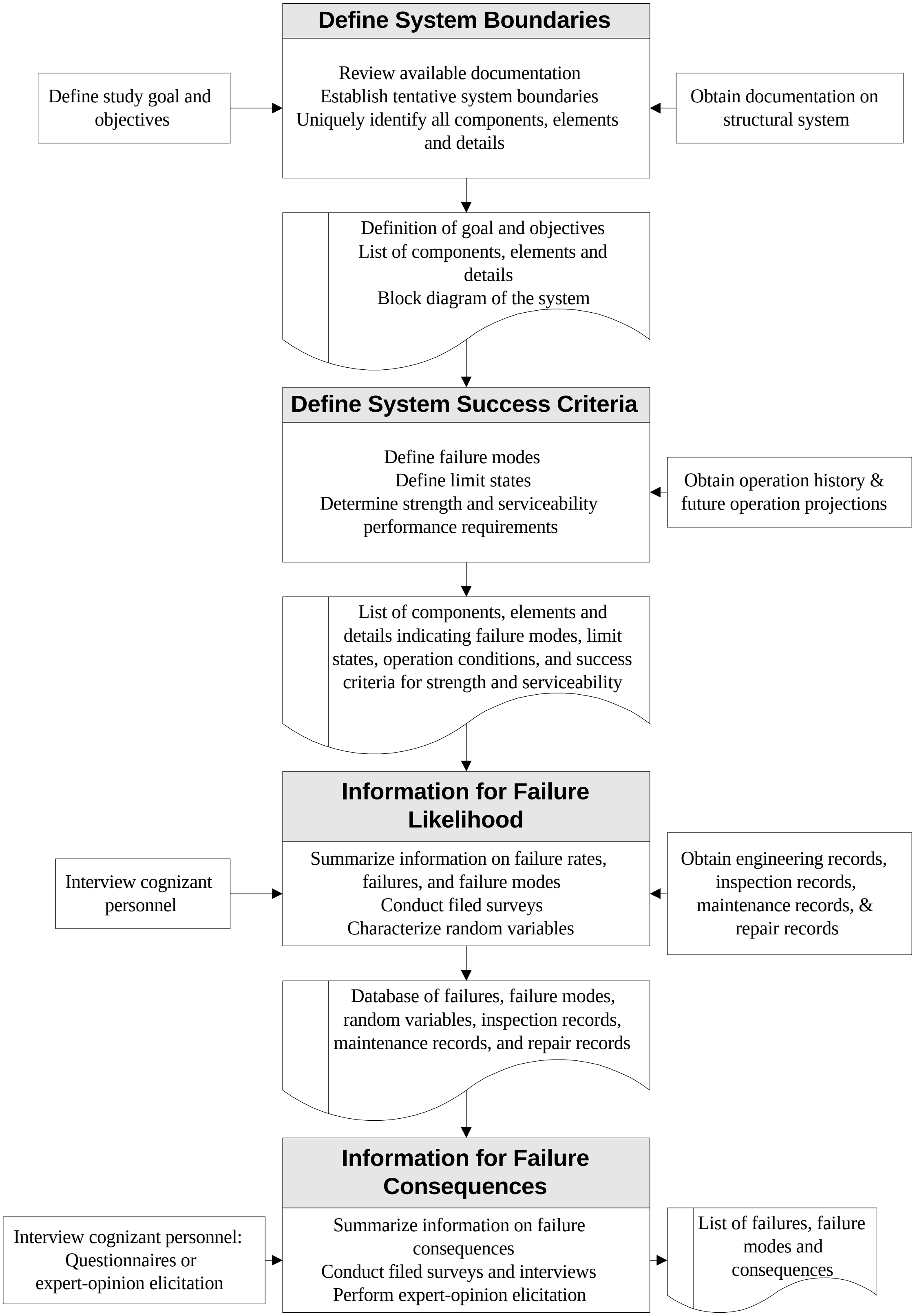


Figure 2-2. System Definition Phase

2.3. Hazards and Failure Scenarios

2.3.1. Hazard Analysis

A hazard is defined in Appendix A as 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 is a hazard. The methodology requires the performance of preliminary hazard analysis that should results in a list of hazards that are suitable for system analysis and effect assessment due to such hazards. Preliminary Hazard Analysis (PHA or commonly PrHA) identifies and prioritizes hazards leading to undesirable consequences early in the life of a system. Also, it determines recommended actions to reduce the frequency and/or consequences of the prioritized hazards. Hazard analysis methods are described in Appendix A.

2.3.2. Preliminary Hazard Analysis

Preliminary Hazard Analysis (PHA) is a common risk-based technology (RBT) tool with many applications. In PHA, hazards are defined as initiating events coupled with consequences, and classes of hazards are used such as Classes I to IV for Negligible effect to Catastrophic effects, respectively. The initiator groups are typically taken as five groups from frequent (of about E-1 to E10, where E is for the exponent or power therefore the range means 0.01 to 100) to infrequent (of about E-6 or 10^{-6}). The consequence groups can be also considered as five groups from trivial consequences to non-repairable with fatalities or health effects. This technique requires experts to identify and rank the possible accident scenarios that may occur. It is frequently used as a preliminary way to identify and reduce the risks associated with major hazards of a system. The level of effort in performing the PHA might vary depending on available resources by owners, however it should not be eliminated on reduced to a non-meaningful level.

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

The methodology can produce findings recorded in the form of hazard scenarios; recommendations for changes in design, procedures, etc.; and recommendations for areas needing further evaluation. Also, it can produce prioritized lists of recommendations based on risk rankings estimated by the team using predetermined guidelines for assigning likelihood and severity of consequences from various scenarios.

Figure 2-3 provides a PHA definition that was specifically developed for the use with the suggested methodology. The methods shows detailed steps that are needed in order to effectively achieve the goals of PHA. The PHA process and results are commonly provided in tables with the following tables' column headings:

- Subsystem or Function
- Mode (or phase of operation)
- Hazardous Element (gas, steam)
- Event Causing Hazardous Condition (error, malfunction)
- Hazardous Condition
- Event Causing Potential Accident
- Potential
- Effects
- Hazard Class
- Accident Prevention Measures (Hardware, Procedure & Personnel)
- Validation

The PHA has the advantages that it can be used at the concept design stage by relying on team expertise; lists of risk-ranked hazardous scenarios; is a creative process for identifying hazardous scenarios that can be readily used in quantitative risk analysis; and can address both potential safety and productivity losses. However, it has the following limitations:

- It requires an interdisciplinary team of at least four persons including a scribe and leader trained in PHA.
- 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.
- If properly applied, can require level of effort approaching significant fraction of time required for HAZOP analysis or FMEA or PRA.

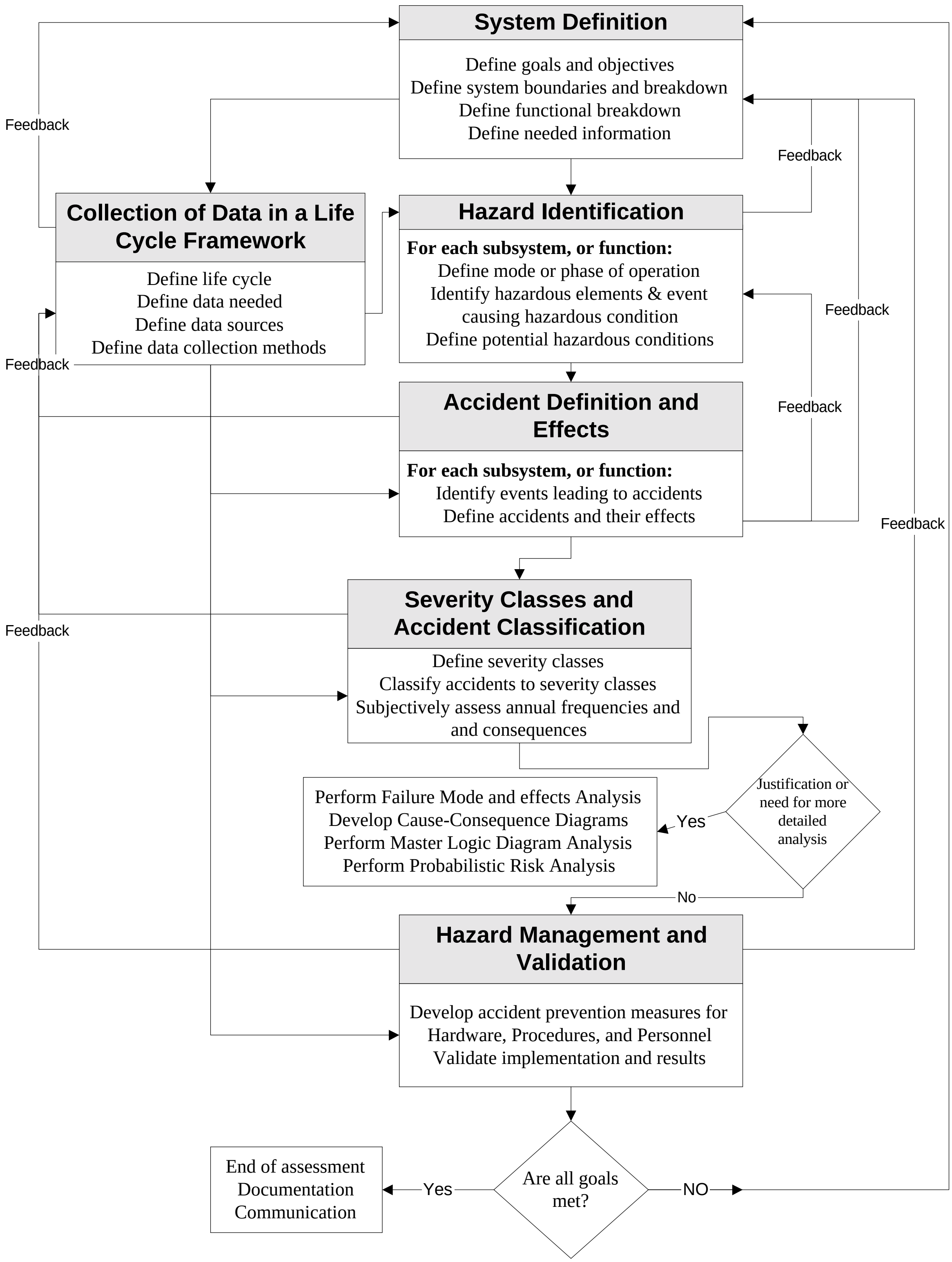


Figure 2-3. Preliminary Hazard Analysis (PHA)

2.3.3. Definition of Failure Scenarios

Once the hazards are identified, they form a basis for defining the initiating events. Initiating events are considered bad beginnings or 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 a basic 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 2-4 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 to each initiating event are identified to the extent necessary to estimate the needed 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 vent 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 the initiating event, and is used to calculate both the likelihood and the consequences of each accident scenario. The occurrence likelihood for each event presented in the cause-consequence diagram can be determined by breaking down the event with the use of fault tree analysis until basic events are reached. The occurrence probabilities of the basic events can be computed using any available data or modeling methods such as structural reliability assessment methods.

The procedure for constructing the consequence scenario is first to take the initiating event and each later event by asking the following questions:

1. Under what conditions does the event lead to further events?
2. What alternative plant conditions lead to different events?
3. What other components or sub-systems does the event affect?
4. What further events does this event cause?

The fault tree analysis method is used for the definition of the occurrence likelihood for a given event as described in Appendix A.

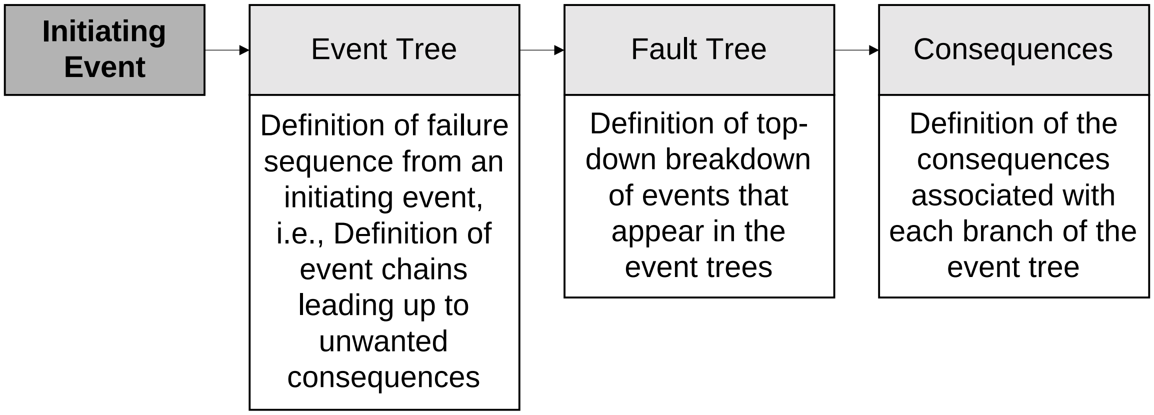


Figure 2-4. Basic Steps for Performing a Cause-Consequence Analysis

2.3.3.1. Initiating Events (Structural Aspects Only)

Generally, ship structures experience the following failure modes that can degrade the ship structural safety and performance:

1. Failure due to yielding or plastic flow of deck or bottom hull girder,
2. Failure due to elastic-plastic buckling of deck or bottom panels, and
3. Failure in a fatigue and fracture mode.

These failure modes can be conveniently split into: 1) ultimate failures that could lead to the loss of the ship, and 2) serviceability failures that would decrease the operational performance the ship structure, perhaps making it unsuitable for service. Table 2-1 provides a possible classification of ultimate and serviceability failures for reliability analysis. These failure modes can be viewed as initiating events. Appendix C provides an example of additional details on structural initiating events for naval vessels. The appendix uses the initiating events to develop failure scenarios for the purpose of demonstration. The following consequence types were assessed using cause consequence diagrams: (1) crew, (2) cargo, (3) environment, (4) non-crew, corresponding to a population that is not part of the ship crew, but can suffer consequences of the accident of the ship, (5) ship machinery, and (6) ship structure.

Table 2-1. Classification of Structural failures as a Function of the Damage to the Ship Structure

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

2.3.3.2. Cause-Consequence Diagrams

Cause-consequence (CS) diagrams can be used to assess and propagate the effects of initiating events in the form of failure scenarios. Cause-consequence diagrams can be developed for the purpose of assessing and propagating the conditional effects of a failure using a tree representation. The analysis according to CS starts with selecting a *critical event or initiating event*. Critical events are commonly selected as convenient starting points for the purpose of developing the CS diagrams. For a given critical event, the consequences are traced using logic trees with event chains and branches. The logic works both backward (similar to fault trees) and forward (similar to event trees). Additional information on cause-consequence diagrams is provided in Appendix A.

In this section, the failure scenarios developed based on the initiating event “buckling of unstiffened side shell panel in a naval-vessel cargo space” is used to demonstrate the process. These failure scenarios are classified in two groups: (1) failure scenarios related to the failure of ship systems other than structural failure, and (2) failure scenarios involving the ship structural system failure. Failure scenarios for other initiating events are provided in Appendix C.

1. Failure of Non-structural (Other) Ship Systems

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure 2-5, which presents the sequence of events that should be considered for the development of the cause-consequence diagram as provided in Appendix C. The consequences associated with this failure scenario are:

1. Crew: possible injuries,
2. Cargo: possible damage to containers,
3. Environment: none,
4. Non-crew: none,
5. Structure: possible hull fatigue and corrosion, and
6. Cost of inspection, and possible cost of repair, in case of buckling detection.

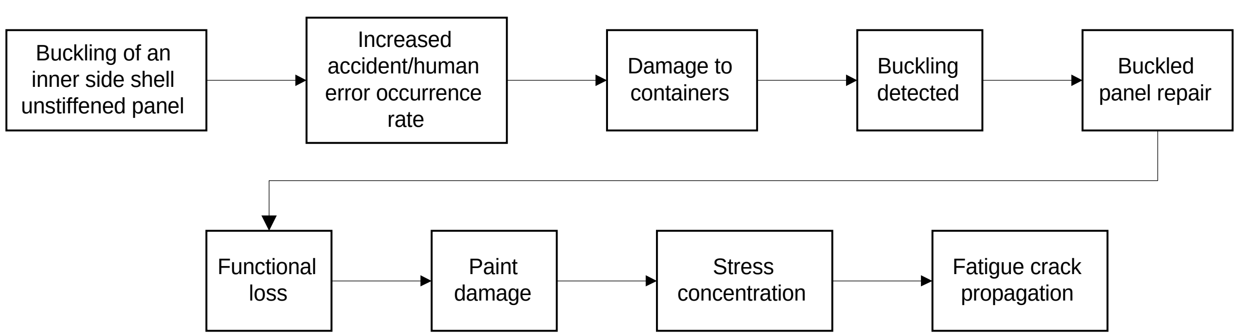


Figure 2-5. Buckling of an Unstiffened Side Shell Panel – Consequences for the Ship Structure in the Vicinity of Cargo Hold Areas

2. Failure of Ship Structural Systems

The failure scenarios associated with this initiating event for its impact on the structural system can be developed based on the diagram shown in Figure 2-6, which presents the sequence of events that should be considered for the development of the cause-consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: possible injuries and deaths as a result of an overall hull girder failure, i.e., hull collapse;
2. Cargo: possible loss of cargo, in case of hull failure;
3. Environment: possible contamination with fuel and lubricant oil, and cargo, in case of hull collapse;
4. Non-crew: none;
5. Structure: extensive hull damage, considering the failure of a primary structural member;
6. Ship: possible loss of ship in case of hull failure;
7. Cost of inspection, and possible cost of repair, in case of buckling detection.

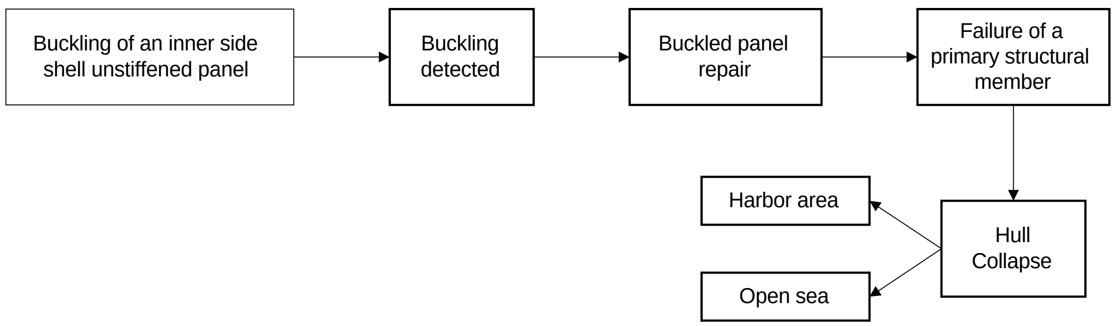


Figure 2-6. Buckling of an Unstiffened Side Shell Panel – Consequences for the Hull Girder of Ship Structure

2.4. Collection of Data in a Life Cycle Framework

Failure data sources, such as maintenance, operation, engineering and corporate records, need to be identified and located. Data sources need to be screened, and duplication or low priority sources should be eliminated from the list. The accumulation of maintenance history is used to document alterations, modifications and repairs that may have been made in the past. The accumulation of the original design and construction drawings (including modifications and repairs), specifications, design calculations, inspection requirements and operating history can assist in completing this activity. The collected information should be summarized in a manner that can assist in calculating failure likelihood and consequences. The information and data can define relationships among system, element and component failures, and the consequences of these failures. Consequences can be production loss, repair cost, cleanup cost, safety loss, environmental damages, public-relations costs. Also, the effects on other systems as a result from the failure need to be considered. Another important source for determining the consequences of failure is experience and expertise of the plant technicians, operators and managers. Life cycle and methods for data collection in a life cycle framework is provided in Appendix B.

2.5. Qualitative and Quantitative Risk Assessment

Qualitative and quantitative risk assessment methods have the similar procedures; however they differ in their information needs and outputs. They require qualitative and quantitative types, respectively.

Probabilistic risk assessment starts with the definition, and transforms initiating events into risk profiles. The risk management process then follows through initiating-event prevention, initiating-event propagation prevention, onsite consequence mitigation, and offsite consequence mitigation. They include the following steps for systems with hazardous materials:

- Definition of initiating events;
- Identification of accident sequences and assignment of probability values;
- Distribution of hazardous source based on its terms to the environment;
- Accident propagation, human effects (immediate and latent) and property damage;
- Overall risk assessment and development of risk profiles;
- Analysis of other risks;
- Risk mitigation through initiating-event prevention, initiating-event propagation prevention, onsite consequence mitigation, and offsite consequence mitigation; and
- Uncertainty analysis.

2.5.1. Qualitative Risk Assessment

Qualitative and 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 numeric or non-numeric form. An example numeric form for an annual failure probability is 0.00015, and for a mean time between failures is 10 years. An example non-numeric form for “an annual failure likelihood” is large, and for a “mean time between failures” is medium. In the latter non-numeric form, guidance needs to be provided regarding the meaning of terms such as large, medium, small, very large, very small, etc. The selection of the form should be based on the availability of information, the ability of the personnel providing the needed the information to express it in one form or another, and the importance of having numeric versus non-numeric information in formulating the final decisions.

The types of failure consequences that should be considered in the study need to be selected. They can include production loss, property damage, environmental damage, and safety loss in the form human injury and death. 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 is 1000 units. An example non-numeric form for production loss is large. In the latter non-numeric form, guidance needs to be provided regarding the meaning of terms such as large, medium, small, very large, very small, etc. The selection of the form should be based on the availability of information, the ability of the personnel providing the needed the information to express it in one form or another, 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 of estimating failure likelihood and consequences are used for this purpose. Risk estimates can be determined as a pair of the likelihood and consequences, and 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 can be developed. Then, approximate ranking of them as groups according to risk estimates, failure likelihood, and/or failure consequences can be developed.

2.5.2. Quantitative Risk Assessment

The primary objective of this activity is to quantitatively assess risk by quantitatively assessing its likelihood and consequence components. The failure likelihood needs to be based on the identified failure modes. The failure likelihood should be in the final form of a lifetime or an annual failure probability. However, in gathering the needed the information for the annual failure probability, the mean time between failures, or failure rate can be utilized. The needed information for establishing an annual failure probability can be obtained from the following sources: (1) in-house failure databases, (2) failure information from other vessels or studies performed for them, (3) industry failure data bases, (4) published results based on literature review, (5) probabilistic analysis, and/or (6) expert elicitation. Figure 2-5 shows an outlined procedure for assessing the failure probability of a structural element for some specified failure mode defined in terms of a limit state.

The failure consequences at the identified levels of decision making need to be determined. The failure consequences can be estimated using the following sources: (1) in-house failure and loss records, (2) in-house failure databases, (3) published results based on literature review, (4) cause-consequence diagrams or event tree analysis, and/or (5) expert-opinion elicitation. The assessment of failure consequences should account for all consequence types. The consequence assessment of structural components needs to be propagated at the system level by examining its effects on other systems that can be of non-structural type. For a given failure, the impact of this failure of the system needs to be assessed, and the failure is classified as of some type. Figure 2-6 shows a procedure for assessing the impact of failure on other ship systems and the creation of failure classification database. An automated failure recognition and classification that can be implemented in a simulation algorithm for reliability assessment purposes as shown in Figure 2-7. The failure classification is based on matching a deformation or stress field with a record within a knowledge base of response and failure classes. In cases of no match, a list of approximate matches is provided, with assessed applicability factors. The user is prompted for any changes to the approximate matches and their applicability factors. In the case of poor matches, the user has the option of activating the failure recognition algorithm shown in Figure 2-6 to establish a new record in the knowledge base. The adaptive or neural nature of this algorithm allows the updating of the knowledge base of responses and failure classes. The failure recognition and classification algorithm shown in Figure 2-6 evaluates the impact of the computed deformation or stress field on several systems of a ship. The impact assessment includes evaluating the remaining strength, stability, repair criticality, propulsion and power systems, combat systems, and hydrodynamic performance. The input of experts in ship performance is needed to make these evaluations using either numeric or linguistic measures.

Then, the assessed impacts need to be aggregated and combined to obtain an overall failure recognition and classification within the established failure classes. The result of this process is then used to update the knowledge base.

For the element, component or detail levels, risk estimates need to be evaluated. The risk-based methodology is focusing on calculating risk that is viewed as an ordered pair of failure likelihood and failure consequences. Risk terminology and concepts are provided in Appendix A, and life cycle modeling and assessment methods are provided in Appendix B. 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 together to produce an expected loss or a measure of loss potential, although the product does not account for risk aversion. Risk can be shown either figuratively or numerically. In both cases, the resulting risks are grouped into a handful of risk categories. The categories range 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 (depending on the situation) risk categories. Events that fall into the high-risk category can be the result of high consequences, high probabilities of occurrence, or both. Events falling into the high-risk categories should be examined to find ways of risk reduction or management. A formal treatment of risk management and decision making is provided in Appendix A.

2.5.3. Risk Profiles

Based on the cause-consequence analysis presented in previous sections, a risk profile analysis can be performed, in order 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 taking part in defining the scenario. A consequence rating of five levels can be developed and provided for each scenario as shown in Appendix C. These probabilities of occurrence of the scenarios and the consequence rating associated with each scenario can be used to define the Farmer curve or risk profile related to a given initiating event. Figure 2-8 provides an example risk profile associated with the occurrence of a fatigue crack in the main engine foundation stiffener that was developed in Appendix C. The figure also shows four risk quadrants that correspond to four levels of differing implication and mitigation requirements.

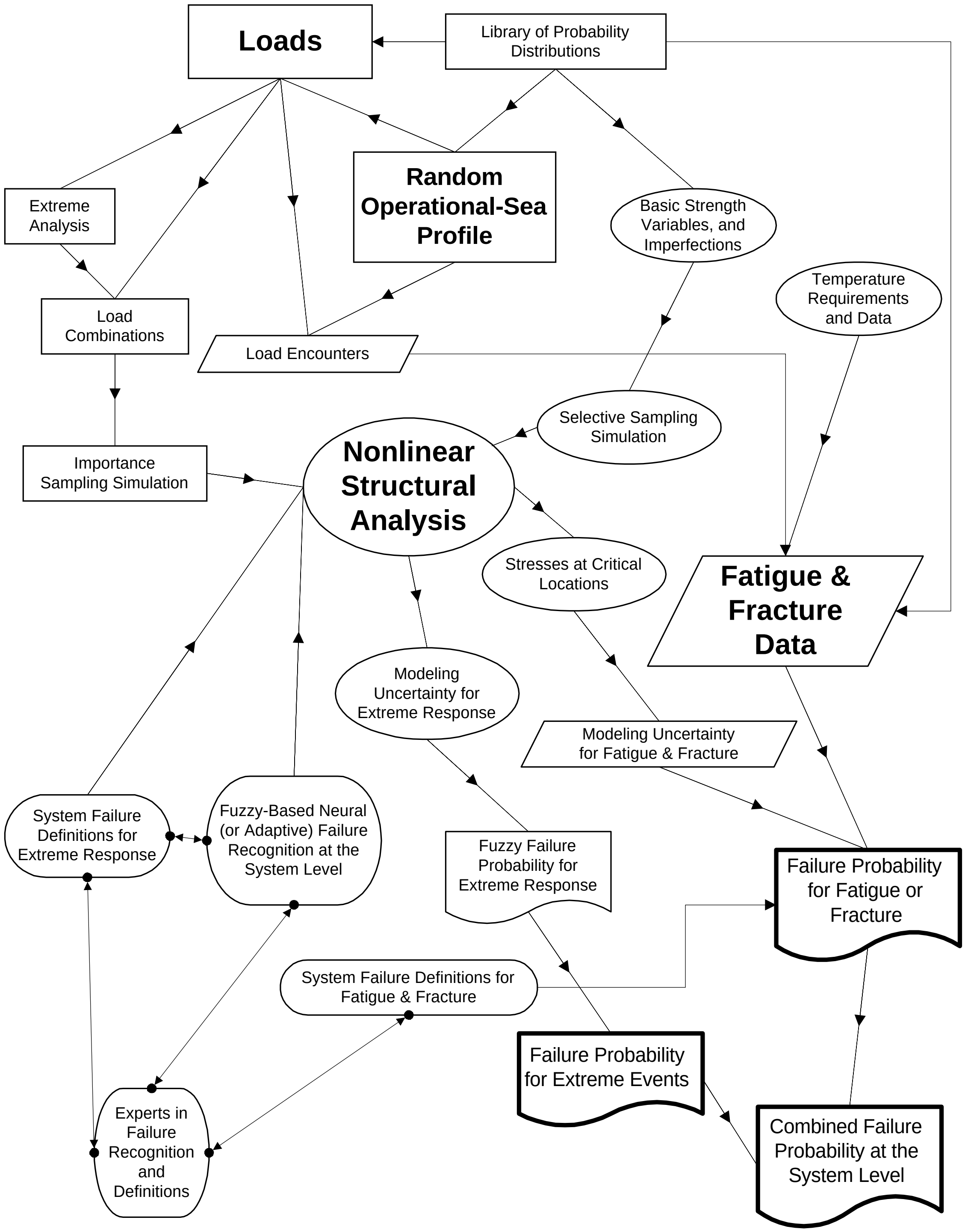


Figure 2-5. Reliability Assessment for Ship Structures

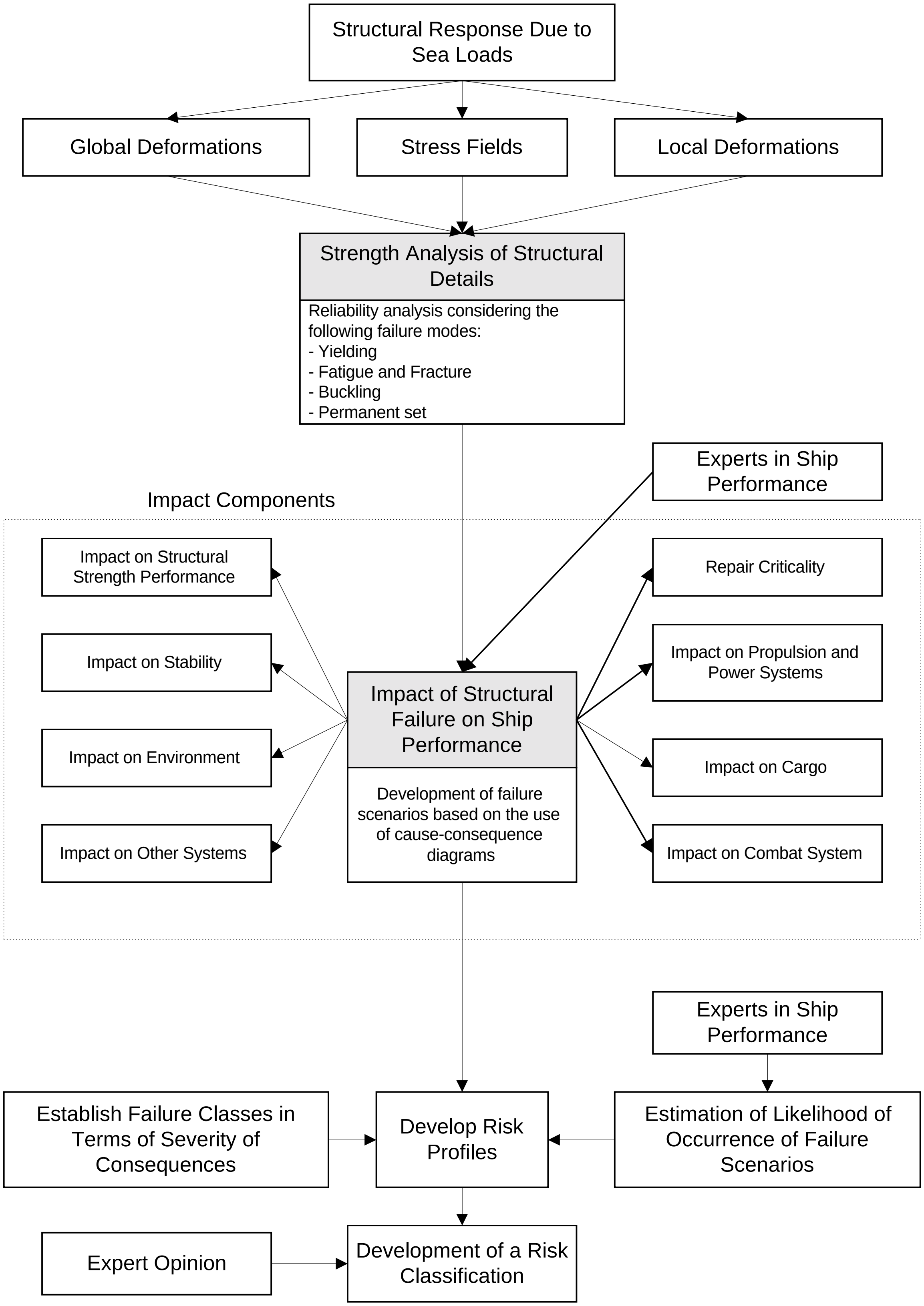


Figure 2-6. Failure Recognition and Creation of Failure Classification Database

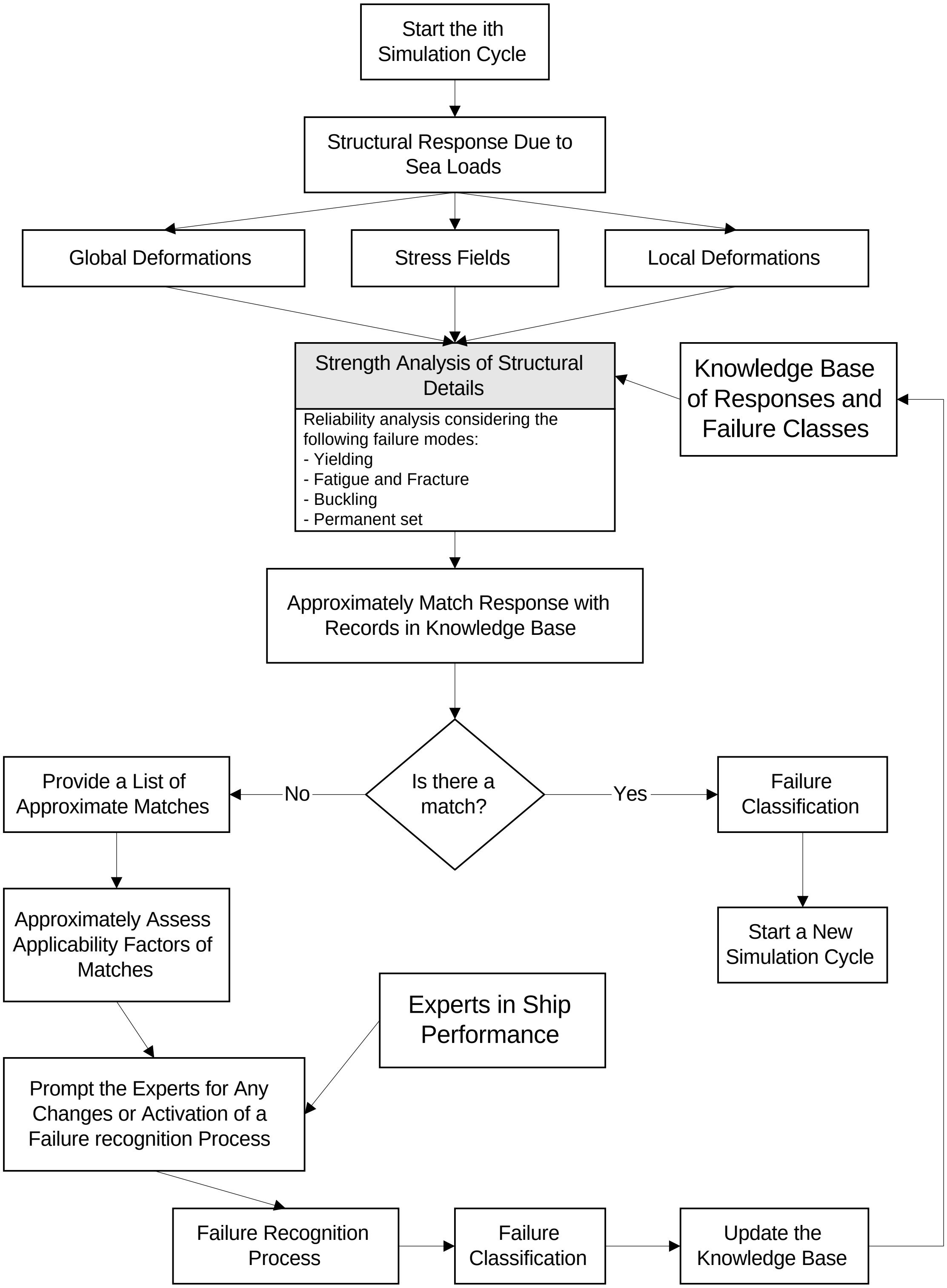


Figure 2-7. Failure Classification

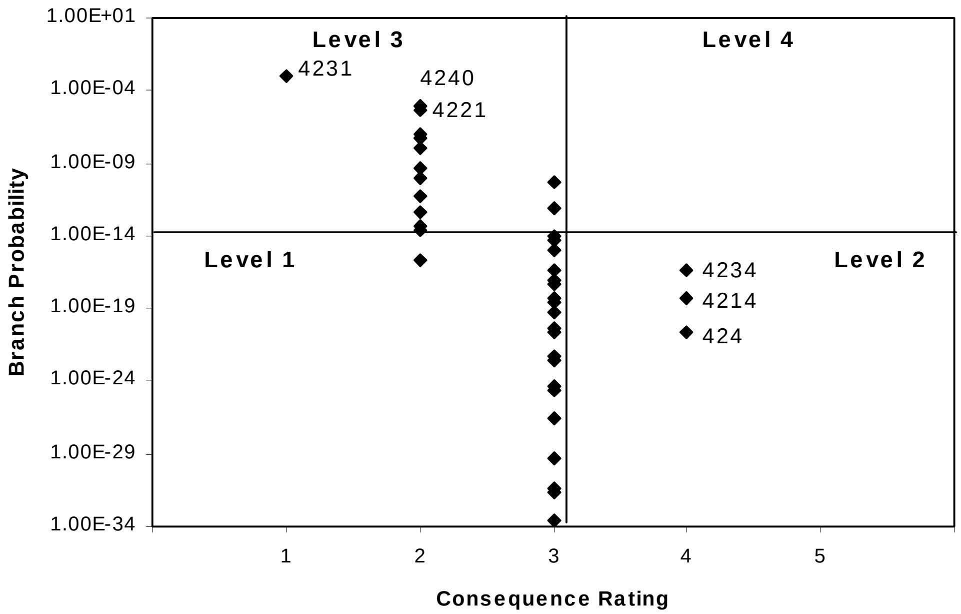


Figure 2-8. Risk Profile Associated with the Occurrence of the Fatigue of a Main Engine Foundation Stiffener

2.5.4. Time-Dependent Risk Profiles

A risk profile is a graphical representation of probabilities of occurrence of failure scenarios and their associated consequence as illustrated in Figure 2-8. Both dimension of the plot are time dependent. The probabilities of occurrence of failure scenarios are affected by time-dependent degradation mechanisms such as fatigue and corrosion. Models to account for time dependency in reliability assessment are discussed in detail and provided in Section A.5.2. The failure consequences on the other hand, if expressed in monetary value, are also time dependent due to the time-value of money. Appendix B provides economic models to account for the time-value of money; however, the effect of time on the value that a society attaches to failure consequences might go beyond the time-value of money. For example, societies tend to appreciate diminishing natural resources such as wildlife and coastal lines at an increasing rate that is nonlinearly and inversely related to the diminishing rate of these resources. As a result, projecting future failure consequences can be problematic requiring an appropriate treatment of uncertainties as a result of changes in society values, expectations, and needs. Similar problematic and complicating considerations can be heuristically constructed for the time-dependent value of human life. Such a treatment is beyond the scope of this report, and needs to be considered subjectively herein in an approximate manner.

2.6. Life Cycle Management of System Integrity

In order to make decisions based on risk, a level of acceptable risk must be determined that depends on risk aversion. Appendix A provides guidance on risk acceptance. 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. Agreeing upon a reasonable value in cases of novel structures without prior history.
2. Calibrating reliability levels implied in currently successfully used design codes.
3. 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 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.

According to the Project Technical Committee advisor, Mr. R. T. Huang, events that have a higher risk than the set level of acceptable risk should be flagged and assigned a priority level as provided, for demonstration purposes, in the following:

Priority	Example Interpretation
1	Events should receive immediate attention and any reason for deferral should be eliminated as quickly as possible.
2	Events should receive attention in the very near future. While not as critical as Priority 1 events, they are very important.
3	Events should receive attention when economically feasible. High-risk events will fall into priority 1 or 2 while priority 3 events are primary ones which involve costs.
4	Events should receive attention when time permits. They include items of lesser importance and low cost.

Each flagged event should be studied to determine why its risk level is too high. High risk could be the result of high consequence, low reliability or a combination both. Usually, the event's reliability is the variable that is easiest to improve through changes in system configuration or system upgrades. The components that result in high-risk scenarios must be studied, so that their individual reliability values are increased resulting in higher system reliability. If component reliability cannot practically or economically be heightened, then back up or redundant subsystems or components can be introduced to improve overall system reliability and consequently reduce risk. Risk acceptance might not follow the lines of constant risk in areas on high failure probability as such events become nuisance, and in areas on high failure consequences as such events become intolerable.

Maintenance, inspection and repair are key aspects of managing the structural integrity of vessel systems in a life cycle framework. For example, an inspection program can be developed with the objective of maintaining the structural integrity of a vessel. It can follow the system definition, the qualitative risk assessment, and the quantitative risk assessment with the objective of performing risk-based decision making for maintaining system integrity. The decisions of interest in this phase include, for example, what to inspect, the level of inspection, and how to inspect. In general, this phase consists of the following activities for each of inspection, maintenance, and repair:

1. Selection of candidate inspection, maintenance, and repair strategies
2. Selection of inspection, maintenance, and repair strategies using decision analysis
3. Performance of inspection, maintenance, and repair
4. Selection and implementation of appropriate actions

One of the outcomes of this phase is the gained knowledge and information that can be used as a feedback into the four earlier phases. The resulting feedback aspect is important in creating a "living" process that is current and dynamic with proper documentation, recording and knowledge updating.

The risk management process then follows through initiating-event prevention, initiating-event propagation prevention, onsite consequence mitigation, and offsite consequence mitigation. The failure prevention can be achieved by increasing safety margins, standardization, inspection & maintenance, engineering and materials changes, and quality assurance program. Also, human-error prevention is needed by resolving violations of procedures, incorrect mindset, unawareness of conditions; and errors that result from individuals, teams, and organizations. Reduction of human error can be achieved through improved training. Replacing human functions with automation also has the potential to reduce error, if the system is properly designed, including proper inclusion of human factors engineering.

Failure propagation prevention can be achieved by introducing physical barriers such as safety glass, helmets and space; normal control systems; engineered safety features and systems; interdependence (i.e., redundancy) and outer-dependence; recovery procedures (i.e., response of operators in timely manner); automatic actuation; and symptom-based procedures. Also, fail-safe design can be used in which if an element fails, it puts the system in a no-damage state. A fail-soft design can be used in which if an element fails, it puts the system in a partial performance state. The system can be improved in terms of its robustness, in this case an element is designed to operate beyond its normal (design) ranges, and environment (pressure, temperature, etc.) so that it has an enhanced ability to cope with events not anticipated in the design phase.

The consequence mitigation can be classified into two types: (1) onsite consequence mitigation, and (2) offsite consequence mitigation. The onsite consequence mitigation includes restoring a vessel to a safe state, and procedures and ad-hoc operations. The offsite consequence mitigation includes coordination with local authorities and communications, procedures and ad-hoc operations, emergency plans, accident mitigation, mitigation of the events beyond the design bases, and development of scenarios for accident mitigation.

3. CASES STUDY: DEMONSTRATION OF RISK-BASED LIFE CYCLE MANAGEMENT

3.1. Introduction

This chapter consists of a two-part case study on tanker ships. The first part demonstrates quantitative risk-based assessment and management of a tanker vessel whereas the second part demonstrates a quantitative risk-based assessment and management of a tanker vessel. The case study is intended for demonstration purposes. The qualitative and quantitative parts of the case study are written in such a way that they can be used as two independent case studies. A demonstration of the risk based life cycle management strategy on naval vessels is presented in Appendix C. The case study in Appendix C provided a detailed description of the methodology in its generalized form by considering the ship system to include non-structural ship systems.

3.2. Quantitative Risk-Based Assessment and Management

3.2.1. Introduction

A quantitative risk-based life cycle management methodology is demonstrated in this section. The case study presented in this section is for the purpose of demonstrating the application of the methodology to only structural systems. The two requirements for managing the risk associated with operating a vessel are estimates of probabilities of failure and consequences of failure. The scope of the case study in this section was defined to consist only of the ship hull structural system with the failure scenarios that would lead to the loss of the hull. Therefore, the failure consequence of interest is only hull loss and is the same for all failure scenarios considered in this chapter. Consequently, the risk of failure is governed by the failure probabilities as the failure consequence is invariant among the scenarios. The focus of the methodology in this section is to estimate the time-dependent probabilities of failure as a measure of the risk of operating a vessel. Therefore, methods for estimating consequences of failure are not needed in this section.

The data and modeling requirements for computing time-dependent probabilities of failure of an existing tanker are identified, formulated and discussed. The principal dimensions of a demonstration tanker vessel are defined. Prominent hazards that degrade the structural integrity are identified, reviewed and modeled. Models that define the global performance of a tanker, that is, the ultimate collapse of the hull structure based on the midship hull girder, are formulated. The impacts of degrading hazards on the primary structural member are included in the formulations. Reliability solution strategies for estimating structural risk measures, namely, instantaneous and time dependent failure probabilities are developed. The limitations of the results are presented in section 3.2.6 and they results are discussed in section 3.27.

3.2.2. Objective of Analysis

The primary objective of the analysis is to estimate the risk of operating a tanker vessel that has prominent degrading mechanisms, namely, corrosion and fatigue cracks. The analysis is focused on general corrosion and cracks in the longitudinal primary structure. It is assumed that there is no repair or maintenance of the vessel during the risk projection period. Measures of structural risk, namely, instantaneous and time dependent probabilities of failures of a corroding or cracking primary ship structure are formulated and demonstrated.

3.2.3. System Definition

The system studied is the hull and structural details of an existing tanker vessel with principal dimensions as shown in Table 3-1. Schematic diagrams of the vessel and its cross sectional profile and dimensions are shown in Figures 3-1 and 3-2, and Table 3-2.

The material used in constructing the hull girder is steel of nominal yield strength 34 ksi. The vessel is subjected to various hazards during its operational life as provided in the subsequent section.

Table 3-1. Principal Dimensions of a Tanker Vessel

Item	Dimension
Length (*L*)	721’ 10”
Breadth (*B*)	125’
Depth (*D*)	57’
Draft (*T*)	44’ 2”
Block Coefficient	0.75

Table 3-2. Stiffener Dimensions

Stiffener Dimensions (Inches)		
Stiffener #	Web	Flange
1	17.7x1.40	
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

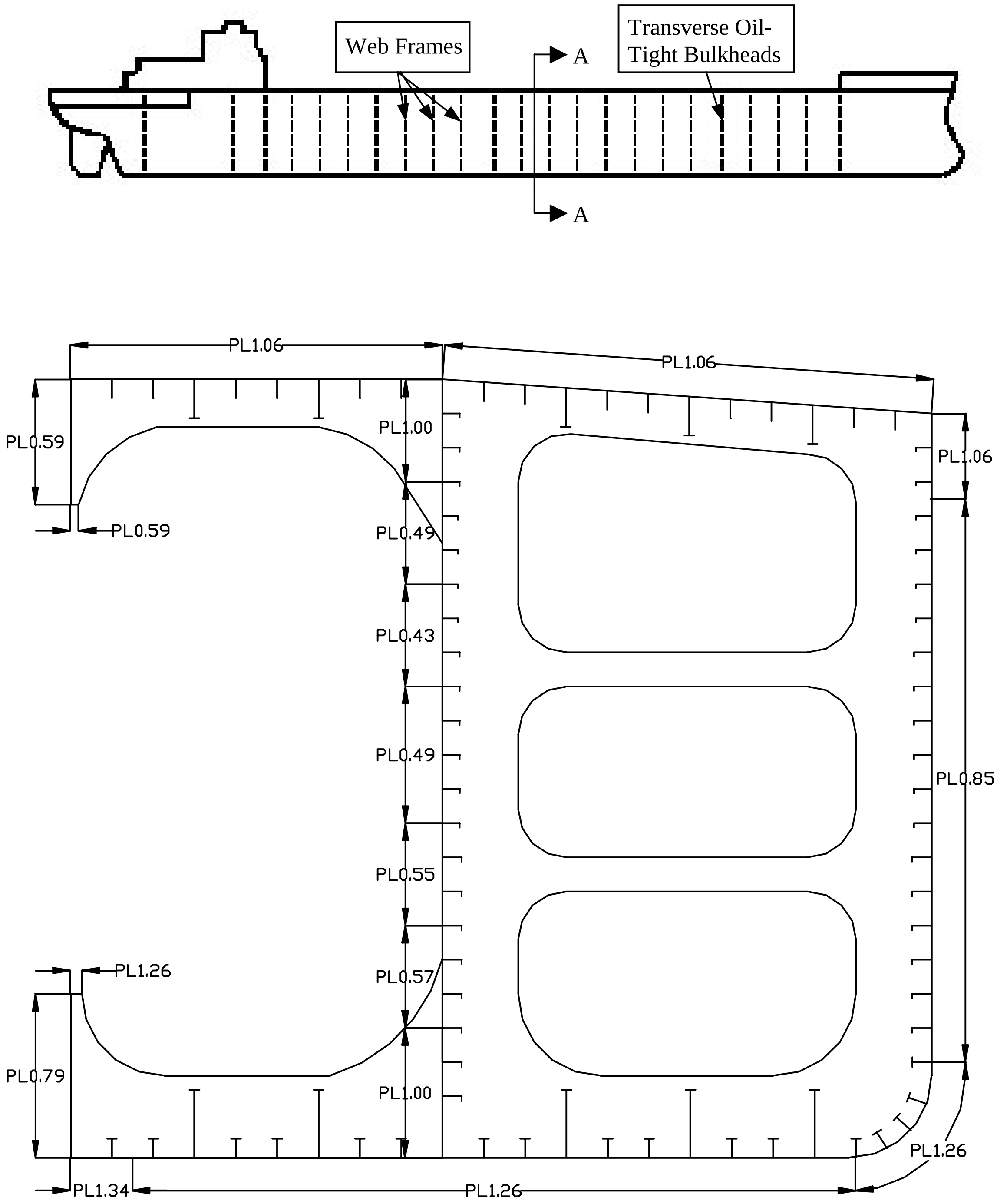


Figure 3-1. A Typical Transverse Web Frame of a Single Hull Tanker (Section A-A): Showing Plating Thicknesses (Inches)

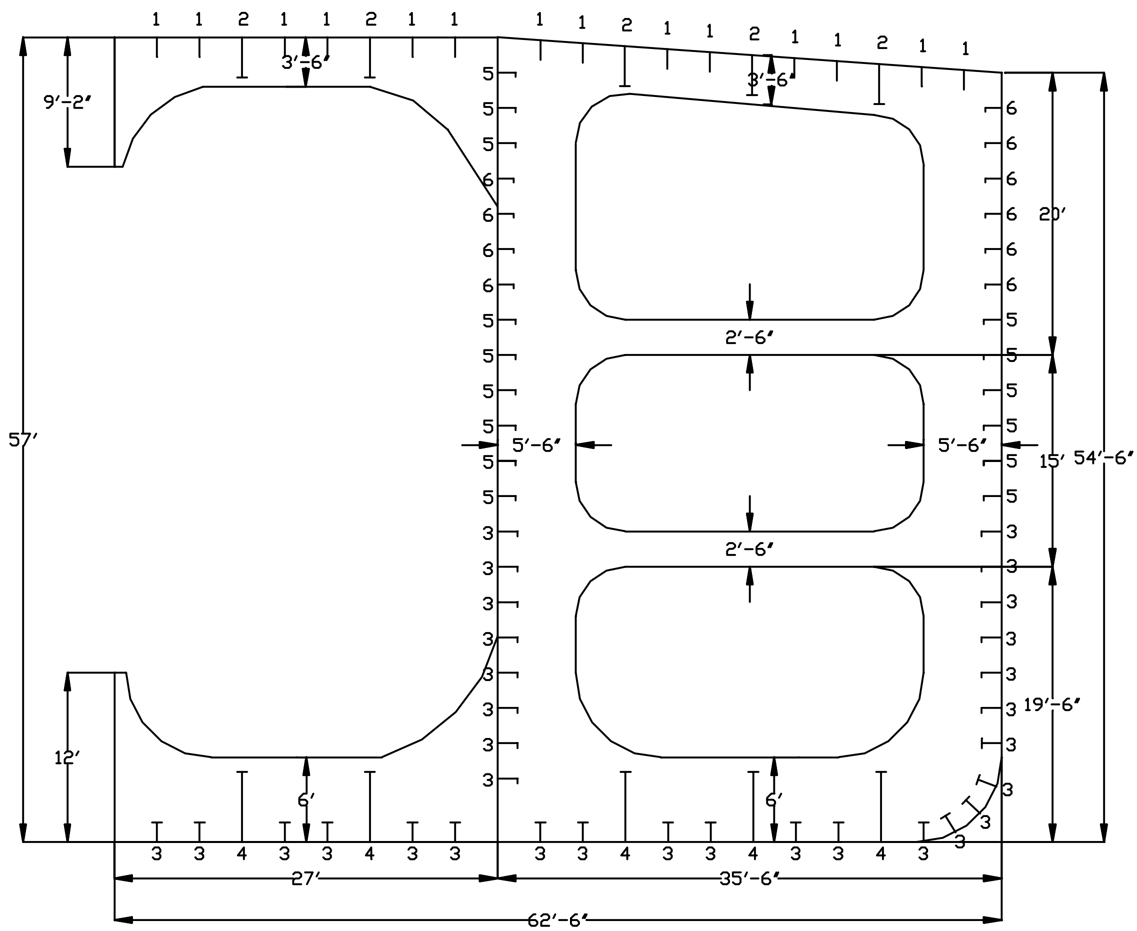


Figure 3-2. A Typical Transverse Web Frame of a Single Hull Tanker (Section A-A): Showing Web Depths (Feet & Inches)

3.2.4. Hazard Analysis

Hulls and structural details of most existing tankers are made of steel. This is because steel has desirable properties such as durability, stiffness and strength. The hulls and structural details are exposed to various hazards that undermine the structural integrity of vessels during their operational lives. Prominent hazards experienced by tankers include extreme sea waves, still water bending moments, continuous loading and unloading of the vessel, corrosion and fatigue cracking. Other hazards include accidental loads, such as grounding, fire and blast. Research over the past several years (Ma et al., 1997) has shown that corrosion and fatigue cracking are the most dominant hazards experienced by tanker structures. These two hazards have been extensively studied and several reports and guidelines have been written on them (ABS, 1992; DNV, 1995; TSCF, 1986, 1992, 1997). The tanker is subjected to the two prominent damage modes. A brief review of these hazards is undertaken.

3.2.4.1. Corrosion

Corrosion is the most prevalent damage mechanism encountered by tanker structures. Corrosion (internal and external) manifests in several forms that include general corrosion, pitting and grooving. Corrosion is a continuous degradation process in uncoated steel, and usually resumes after the coating has broken down in coated steel. Table 3-3 gives typical corrosion rates for uncoated steel of longitudinal primary members in cargo oil tanks. These rates which have been compiled by TSCF are used in the study. More detail discussion on corrosion is given in section 3.3.

Table 3-3. 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

3.2.4.2. Fatigue Cracking

Fatigue cracking resulting from cyclic stresses represents another prominent hazard that degrades the structural integrity of tankers. Various studies (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. More detailed discussion on fatigue cracking is presented in Section 3.3.4.2.

3.2.5. Structural Risk Assessment

3.2.5.1. Ultimate Strength Limit State

Assessing the structural risk of a degrading tanker vessel requires the development of an ultimate strength limit state function with reference to the primary ship hull structure. Reference is usually made to the midship section. The ship hull is considered to behave globally as a beam under transverse load subjected to still water and wave-induced effects. The governing limit state model for the ultimate strength can be defined by

$$g(t) = U(t) - L(t) \tag{3-1}$$

where $U(t)$ is a model of 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 ultimate strength capacity. Equation (3-1) can be defined in terms of the vertical bending moment that induces bending of the hull. For the ultimate collapse of a tanker hull girder, the underlying random variables can be defined as

$$U(t) = M_u(t) \tag{3-2}$$

and

$$L(t) = M_{sw}(t) + M_w(t) \tag{3-3}$$

where $M_u(t)$ is the hull girder bending moment capacity, and $M_{sw}(t)$ is the still water bending moment and $M_w(t)$ is the wave bending moment, both can be functions of time. However, in this study they are assumed to be independent of time in order to simply the demonstration of the suggested 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).

3.2.5.2. Hull Girder Bending Moment Capacity

Various formulations for estimating the ultimate hull girder bending moment capacity, $M_u(t)$, of ship structures have been developed. They range from simple analytical to complicated numerical models. A review of the methods, their advantages and limitations is given in Mansour et al., 1997 [SSC 398] and Thayamballi et al., 1987. These formulations have the following characteristics:

1. Ultimate strength obtained by applying a buckling knockdown factor to the hull girder fully plastic bending moment (Caldwell 1965; Mansour and Hoven 1994);
2. Ultimate strength obtained by reduced elastic section modulus accounting for plate buckling at deck and bottom (Billingsley 1980);
3. Ultimate strength obtained by longitudinally stiffened single cell rectangular construction; compression flange treated by a beam-column idealization (Ostapenko 1981);
4. Ultimate strength based on load and end-shortening curves for beam column and tripping failure; aimed at longitudinally stiffened vessel (Adamchak 1984);
5. Ultimate strength based on load and end-shortening curves; hard spots subjectively treated; elasto-plastic *FEM* for load and end-shortening curves of plate-stiffener combinations (Dow et al., 1981); and
6. Ultimate strength based on dynamic non-linear elasto-plastic finite element analysis of a large portion of the hull using beam elements and isotropic and orthotropic plate elements (ABS, 1992).

Computer programs for computing ultimate strength capacities, for example ALPS/ISUM (Paik, 1993), have been developed. The formula in Wirshing et al., 1998, and Mansour and Hoven, 1994, are used in the current structural risk assessment. The hull girder bending moment capacity is estimated by

$$M_u(t) = \phi\sigma_u Z(t) \tag{3-4}$$

where ϕ is a non-dimensional factor known as buckling knock down factor; σ_u is the ultimate strength of the ship hull material; $Z(t)$ is the midship hull elastic section modulus. Structural degradations, namely, corrosion and cracking will affect the hull girder capacity by reducing the section modulus $Z(t)$ with time. The impact of the degradation mechanisms and the modeling strategies that are adopted herein are presented in the following sections. The buckling knock down factor is of high variability and depends on ship type or class and the location of a section, i.e., station.

Modeling the Effect of General Corrosion

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

$$r(t) = C_1(t - t_0)^{c_2} \tag{3-5}$$

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

$$M_u(t) = \phi\sigma_u \begin{cases} Z(r(t_0)) & t \le t_0; \quad r(t_0) = 0 \\ Z(r(t)) & t > t_0; \quad r(t) > 0 \end{cases} \tag{3-6}$$

Formula for calculating midship section modulus $Z(r(t))$ can be found in any standard monograph on ship structures such as Hughes (1983). The mean values of the corrosion rate, C_1, given in Table 3-3 are used in the example problem.

Modeling the Effect of Fatigue Cracks

The presence of a fatigue crack can lead to loss of effectiveness of a structural element when the crack reaches a critical size. Thus, the net section modulus that resists longitudinal loads is reduced. The reduction may be such as to increase nominal stress levels amidship which in turn increases the rate of crack growth. The two main approaches for assessing fatigue strength are

(i) *S-N* for crack initiation assessment, and
(ii) 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

$$\frac{da}{dN} = C\Delta K^{m} \tag{3-7}$$

$$\Delta K = \Delta\sigma Y(a)\sqrt{\pi a} \tag{3-8}$$

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. 3-7 gives

$$a(N) = [a_0^{1-m/2} + (1-\frac{m}{2})C\Delta\sigma^{m}Y^{m}\pi^{\frac{m}{2}}N] \qquad m \neq 2 \tag{3-9}$$

$$a(N) = a_0 \exp(C\Delta\sigma^{2}Y^{2}\pi \;\; N] \qquad m = 2 \tag{3-10}$$

where a_o is the initial crack size; m and C are constants. In order to use Eqs. 3-9 and 3-10 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 previous 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. The study suggested that the crack length after N load cycles can be expressed by

$$a(N) = a_0 + \sum_{i=1}^{N}\frac{da}{dN}; \qquad \frac{da}{dN} = C\Delta K^{m} \tag{3-11}$$

The study also showed that $C = 1.77\text{x}10^{-9}$, $m = 2.54$ for HY-80 and $C = 2.54\text{x}10^{-9}$, $m = 2.53$ for CS material. Threshold values of stress intensity factor ΔK needed for crack growth was set at 5-6$ksi/\sqrt{in}$ in the study. In order to use Eq. 3-11, the stress intensity factors at critical structural details have to be estimated and this is not a trivial task.

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

$$\frac{da}{dt} = Q[a(t)]^{b} \tag{3-12}$$

where b and Q are crack growth parameters. Integration of Eq. 3-11 gives the crack size as:

$$a(t) = \begin{cases} [\exp(tQ) + In(a_0)] & b = 1 \\ [tQ(1-b) + a_0^{1-b}]^{1-b} & b \neq 1 \end{cases} \tag{3-13}$$

Equation 3-13 can be applied to an existing tanker structure with measured crack sizes at critical joints and details. The crack growth parameters a_o, b and Q can be calibrated for each critical detail. The advantage of using Eq. 3-13 is that it circumvents the need to mechanically model the complex mechanism of crack growth (i.e., Eqs. 3-9 and 3-11) especially at critical structural details where the knowledge of the stress intensity factor under complex loading is not well understood. Since a database to calibrate Q, b, and a_o does not exist for the current tanker, Eq. 3-9 is used to demonstrate the risk assessment procedure.

The crack at a joint in the hull girder is modeled by considering two different cracks both in the stiffener and the plate at the joint. It is assumed that crack can be initiated at the weld between the plate and the stiffener and it can propagate in each of them as shown in Figure 3-3 for the purpose of demonstration. The crack in the plate is modeled as a through-thickness crack that propagates away from the stiffener in the transverse direction decreasing the net section of the plate that resist longitudinal load. The crack in the stiffener initiates on the edge connected to the weld and propagates across the stiffener decreasing its net effective area to resist longitudinal load.

The stiffener is modeled as a flat bar with height h_{so} and thickness b_s. The variation of the net sectional area with time depends on the crack size $a(t)$. Thus

$$h_{si}(t) = h_{s0}(t) - a(t) \tag{3-14}$$

The area of the stiffener i is given by

$$A_{si}(t) = b_{si} h_{si}(t) \tag{3-15}$$

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

$$i_{oi}(t) = \frac{b_{si} h_{si}^3(t)}{12} = \frac{b_{si}(h_{s0} - a(t))^3}{12} \tag{3-16}$$

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

$$A_{pi}(t) = h_{pi} b_{pi}(t) \tag{3-17}$$

$$b_{pi}(t) = b_{p0}(t) - a(t) \tag{3-18}$$

and the moment of inertia of the *i-th* plate element is

$$i_{oi}(t) = \frac{b_{pi} h_{pi}^3(t)}{12} = \frac{h_{pi}^3(b_{p0} - a(t))}{12} \tag{3-19}$$

Equations 3-16 and 3-19 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

$$M_u(t) = \phi\sigma_u \begin{cases} Z_0 & t < t_0 \\ Z(a(t) & t \geq t_0 \end{cases} \tag{3-20}$$

where Z_o is the section modulus with no crack and t_o is the time it takes for crack initiation.

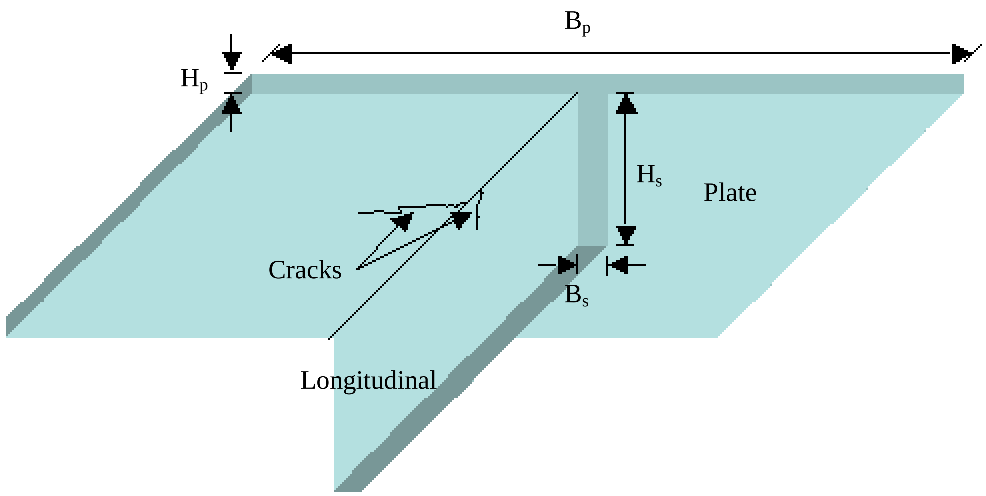


Figure 3-3. Details Indicating the Assumed Location of Cracks

3.2.5.3. Load Modeling

The primary total bending moment on the hull can be decomposed into two components: the still water bending moment M_{sw} and the wave induced bending moment M_w. Strategies for modeling ship loads have been presented in Mansour et al., 1997 (SSC 398), where it is shown that M_{sw} and M_w are correlated. In this demonstration example, the total bending moment is calculated as the linear summation of M_{sw} and M_w.

Still Water Bending Moment (M_{sw})

The still water bending moment is calculated from the IACS design guidance formula (Nitta et al. 1992)

$$M_{sw}(t) = \begin{cases} +14.97CL^2B(8.167 - C_b)(lb - in) & hogging \\ -64.88CL^2B(0.7 + C_b)(lb - in) & sagging \end{cases} \tag{3-21}$$

where

$$C = \begin{cases} 2.917x10^7 L & L < 3540\,in \\ 1.559x10^{-3} - \left(\frac{11810-L}{1426575}\right)^{1.5} & 3540 < L < 11810\,in \\ 1.559x10^{-3} & 11810 < L < 13780\,in \\ 1.559x10^{-3} - \left(\frac{L-13780}{2139860}\right)^{1.5} & L > 13780\,in \end{cases} \tag{3-22}$$

The above formulae are usually used to provide estimates of the deterministic design still water bending moments for a vessel. They are thus 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.

Wave Induced Bending Moment (M_w)

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

3.2.5.4. Reliability Assessment Strategy

The reliability of an existing tanker can be defined as the likelihood of it maintaining its ability to fulfill its design purpose for some time period. In this demonstration the goal is to calculate both instantaneous and time dependent reliabilities based on its ultimate strength when extreme loads act upon the vessel. The time limit state function used in the current analysis is

$$g(t) = x_u \phi \sigma_u Z(t) - x_{sw} M_{sw}(t) - x_w x_s M_s(t) \tag{3-23}$$

where x_u is the random variable representing modeling uncertainty in ultimate strength; x_{sw} is the random variable representing modeling uncertainty in still water bending moment; x_w is the modeling uncertainty in wave bending moment; and x_s is a model that accounts for non-linearity in wave bending moment. Typical values for model uncertainties random variables are given in Mansour and Hoven (1994).

Instantaneous Reliability

The instantaneous reliability of a tanker structure may be obtained based on the limit state defined in Eq. 3-23 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

$$P_f(t) = \int_{\Omega} f(x(t))dx \tag{3-24}$$

where $f(x(t))$ is 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 including first order reliability method (FORM), second order reliability method (SORM) and Monte Carlo Simulation are usually used.

Second order reliability method available any general purpose reliability analysis software such as COMPASS by Orisamolu et al. (1993) is used in the demonstration example. The theory of FORM, SORM, and Monte Carlo Simulation are well established and can be found in Ayyub and McCuen (1997).

Time Dependent Reliability

In the presence of degradation mechanisms, the ship hull ultimate strength $U(t)$ is a decreasing function of time, therefore, the 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 Eq. 3-24.

Successive, yearly loading and decreasing values of yearly ship ultimate strength are however dependant events and must be accounted for in reliability estimation. This is accomplished by using time-dependent or progressive reliability estimates that are 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 tanker is given by

$$\gamma_p(t) = \exp\left(-\int_0^t \lambda(\tau)d\tau\right) \tag{3-25}$$

where τ = variable of integration, and $\lambda(t)$ is a conditional probability function called the hazard rate (Akpan and Luo, 2000, Soaves and Ivanov, 1989, Heller and Thanjitham, 1993, Guedes Soares and Ivanov 1989, Ellingwood and Mori 1993) and is defined by $\lambda(t) = Prob$[*Failure between time t and t+dt* | *no failure up to time t*]. Denoting the instantaneous probability of failure between time t, and time $t+dt$ by $P_f(t)$ and the reliability or probability of survival up to time t in years and one-year increments, by $RL(t-1)$, based on the law of conditional probabilities, the hazard rate is given by:

$$h(t) = \frac{P_f(t)}{RL(t-1)} \tag{3-26}$$

Substituting Eq. 3-26 into Eq. 3-25 gives the time dependent or progressive reliability as

$$RL(t) = \exp\left(-\int_0^t \frac{P_f(\tau)}{RL(\tau-1)}d\tau\right) \tag{3-27}$$

where τ = integration variable. The time-dependent failure probability is given by

$$P_{ft}(t) = 1 - RL(t) \tag{3-28}$$

where the subscript *ft* is for time dependent failure probability. Equation 3-27 is used to estimate the progressive or time dependant reliability in the demonstration problem. Appendix A.5.2 provides additional information on instantaneous probability of failure and time-dependent failure probability assessment. According to Ellingwood and Mori (1993), the time dependent reliability can be computed as

$$RL(t) = \int_0^{\infty} \exp\left[-\lambda t\left(1 - \frac{1}{t}\int_0^t F_L(g(t)r)dt]\right)\right] f_R(r)dr \tag{3-29}$$

where RL = reliability, $f_R(r)$ is the pdf of initial strength R, and $g(t)$ is 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

$$h(t) = -\frac{d}{dt}\ln RL(t) \tag{3-30}$$

which can be expressed as

$$RL(t) = \exp[-\int_0^t h(\xi)d\xi \tag{3-31}$$

Ellingwood (1995) later notes that the time-dependent reliability $RL(t)$, or conversely the probability of failure, $P_{ft}(t)$, are cumulative, i.e., they should be used to define the probability of successful performance during a service life interval $(0,t)$. Ellingwood (1995) 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. This is a very important point that is lacking in much of the literature that is available.

3.2.6. Limitation of Results

The following limitations apply to the results to be discussed in the next sub section

1. International Association of the Classification Societies (IACS) has guidelines on minimal allowable corrosion margins for ship structural members. Operators of tankers are expected to renew those members once the allowable corrosion margins are reached. Renewal of structural members is not included in the analyses.
2. General corrosion does not operate independent of pitting, and cracks are accelerated by the presence of corrosion. It is well known that cracks and corrosion usually operate simultaneously in vessels. The simultaneous effects or interactions is not considered in the analyses; therefore, the value of time dependent probabilities that are estimated could be non-conservative. Furthermore, the presence of pitting corrosion could lead to leaks resulting in environmental risk and this is not considered in the presentation.
3. The rate of corrosion growth is assumed to be fixed with years, this might not be true in all locations and cases.
4. The fidelity of the reliability results depends on the integrity of the structural model used for ultimate strength capacity. An analytical model is used in the demonstration example, however numerical models such as ISUM method might improve the quality of the result.
5. The wave bending moment and the still water bending moment used in the analysis is assumed to be invariant with time. This might not be true in all cases.

6. Extreme loading conditions are used in the analyses, therefore, it is expected that the time dependent structural integrity results can be conservative.

7. The numerical results obtained and conclusions drawn are applicable to the example problem; therefore, they cannot be applied to any other tanker. However, the procedure for obtaining the results can be applied to any tanker structure, using relevant data for that structure.

3.2.7. Discussion of Results and Application to Risk Management

Time-dependent structural integrity analyses, based on the ultimate strength capacity of the example tanker, have been executed for the following cases:

1. Vessel with no corrosion or cracks in primary structure for 50 years;
2. Vessel with general corrosion of primary hull structure after 5 years. The corrosion grows at a constant rate for 45 years.
3. Vessel with cracking of major and minor structures in the midship area after 5 years. The cracks grow according to Paris law for 45 years.

The external loads applied to the cases are the same. Short-term extreme wave conditions that result in the largest wave induced bending moments among the various sea states that are encountered by the vessel are used in the yearly analyses. A significant wave height of 10*m* is used to model the wave load and the vessel is assumed to operate at 12 knots. The long term mean value of the still water bending moment is calculated based on IACS formulae (i.e., Eq. 3-21). The probabilistic characteristics of the stillwater bending moment and the wave induced bending moment used in the analyses are presented in Table 3-4. The probabilistic characteristics of the modeling uncertainly factors are shown in Table 3-5. Although, the buckling knock down factor is of high variability and depends on ship type or class and the location of a section, i.e., station, it was considered as a constant in this study for demonstration purposes.

It is assumed that each and every member in the hull cross-section is subjected to general corrosion after 5 years and that there is no painting, steel renewal or corrosion repair. The probabilistic characteristics of the yearly corrosion rates for the different members are given in Table 3-6. The effect of spatial variability of the general corrosion is not considered by assuming the corrosion to be homogeneous (i.e., uniform) in its distribution for each member. It is assumed that cracking starts after 5 years and the crack sizes are the same at all stiffeners and plating, although it is recognized that in practice, crack sizes vary with joints. Table 3-7 presents the crack growth parameters. Furthermore, it is assumed that there is no repair to fix the cracks.

Figure 3-4 shows the mean values of the hull section modulus without corrosion or cracks, with cracks and with corrosion. Also, Figure 3-4 shows the limitation for the minimum allowed hull-girder section modulus for old ships which can be taken, as an example, 90% of the minimum required hull-girder section modulus for new designs. It can be observed that cracks have dominant influence between 5 and 13 years and corrosion has more impact on the section modulus after 13 years. Plots of the instantaneous and time dependent probabilities of failure and reliabilities of the primary hull structure without corrosion or cracks are shown in Figure 3-5 and Figure 3-6; with corrosion are shown in Figure 3-7 and Figure 3-8; and with cracks are shown in Figure 3-9 and Figure 3-10. Plots of the time dependent probabilities of failure and reliabilities are shown in Figure 3-11 and 3-12. The following general comments are applicable to the results:

1. Instantaneous failure probabilities are always smaller than time dependent failure probabilities, therefore, instantaneous failure probabilities might not be very reliable for risk management. A measure of structural risk, in the absence of estimates of consequences of failure, is the time dependent probability of failure.
2. The impact of structural degradation with age, namely corrosion or cracks, is reflected in the increase value of instantaneous failure probabilities with age. However, the instantaneous failure probability does not reflect the effect of operating the vessel in the previous years on structural integrity. The combined effect of operation and degradation is accounted for in the estimate of time dependent probabilities of failure.
3. For the vessel in this demonstration, the time dependent probabilities of failure are higher for corrosion degradation than crack degradation (see Figure 3-7 and 3-9).
4. The retirement age of a vessel depends on the value of the target reliability and classification societies, experts and experience usually can determine this value based on methods such as code calibration and expert-opinion elicitation. The selection of this value can reflect the gravity of failure consequences. Using a target reliability of 0.95, the current vessel without corrosion or cracks could be operated for 50 years with minimal risk; a vessel with cracks has to be retired by 33 years; and a vessel with corrosion has to be retired by 29 years (see Figure 3-12).
5. The values of the time dependent reliabilities can be used to set maintenance and inspection dates based on targeted values. For example, based on a target reliability of 0.99, cracks and corrosion should be repaired by 10 years (see Figure 3-12).

Table 3-4. Probabilistic Characteristics of Random Variables

Random Variable	Mean Value	Coefficient of Variation (COV*)	Distribution Type
Ultimate Stress, σ_u	40.8 ksi	0.1	Lognormal
Knockdown Factor, *c*	0.95		Fixed
Stillwater Moment, M_{sw}	$1.817\text{x}10^{10}$lb-in	0.4	Normal
Wave Induced Moment, M_w	$2.837\text{x}10^{10}$lb-in	0.1	Extreme

* COV = standard deviation/mean value

Table 3-5. Probabilistic Characterization of Random Variables Related to Model Uncertainties (Mansour & Hoven, 1994)

Random Variable	Distribution Type	Mean	Coefficient of Variation (COV*)
x_u	Normal	1.0	0.15
x_{sw}	Normal	1.0	0.05
x_w	Normal	0.9	0.15
x_s	Normal	1.15	0.03

* COV = standard deviation/mean value

Table 3-6. Probability Characteristics of Corrosion Rate Random Variables

Corrosion Rates			
Location	Mean (in/yr)	Coefficient of Variation	Distribution Type
Deck Plating	2.5591E-03	0.5	Weibull
Deck Longitudinals (Web)	2.5591E-03	0.5	Weibull
Side Shell Plating	1.1811E-03	0.1	Weibull
Side Shell Plating Longitudinals (Web)	1.1811E-03	0.1	Weibull
Bottom Shell Plating	6.6929E-03	0.5	Weibull
Bottom Shell Longitudinals (Web)	2.5591E-03	0.5	Weibull
Longitudinal Bulkhead Plating	2.5591E-03	0.5	Weibull
Longitudinal Bulkhead Longs. (Web)	2.5591E-03	0.5	Weibull

Table 3-7. Probabilistic Characteristics of Random Variables Related to Cracks

Random Variable	Mean	Coefficient of Variation	Distribution Type
A_o	1.0	0.1	Extreme
M	2.5	1.0	Fixed
C	$1.16\text{x}10^{-9}$	0.1	LogNormal
Y	1.0	1.0	Fixed

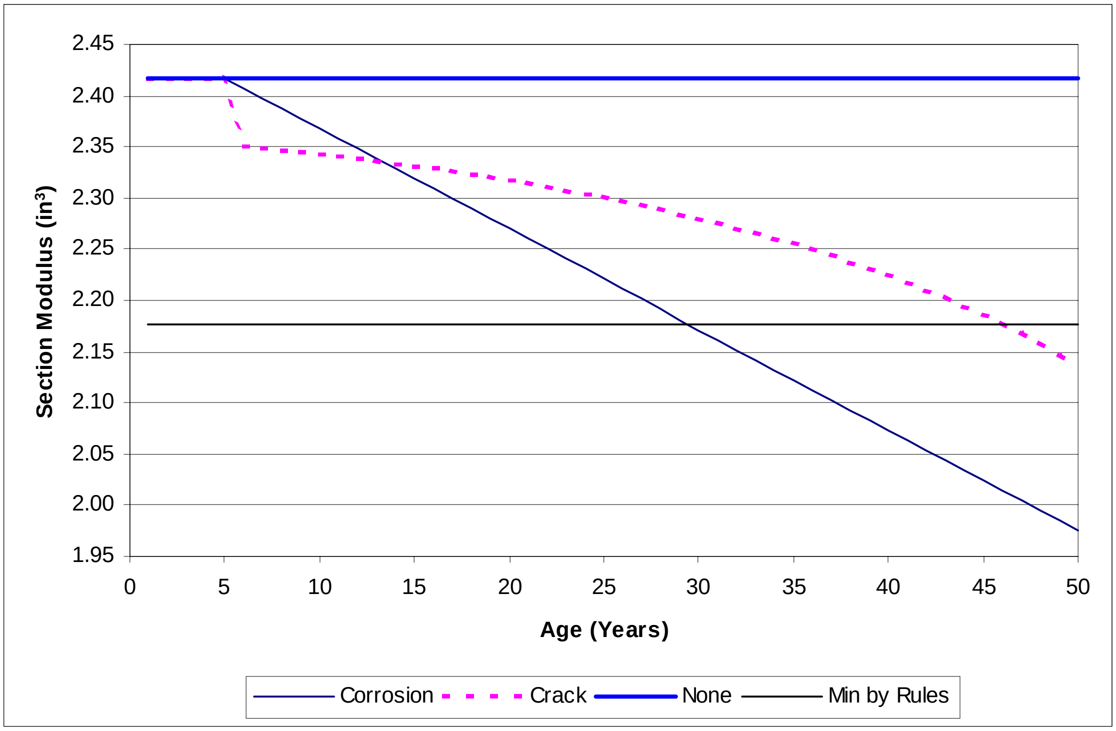


Figure 3-4. Variation of Section Modulus with Age

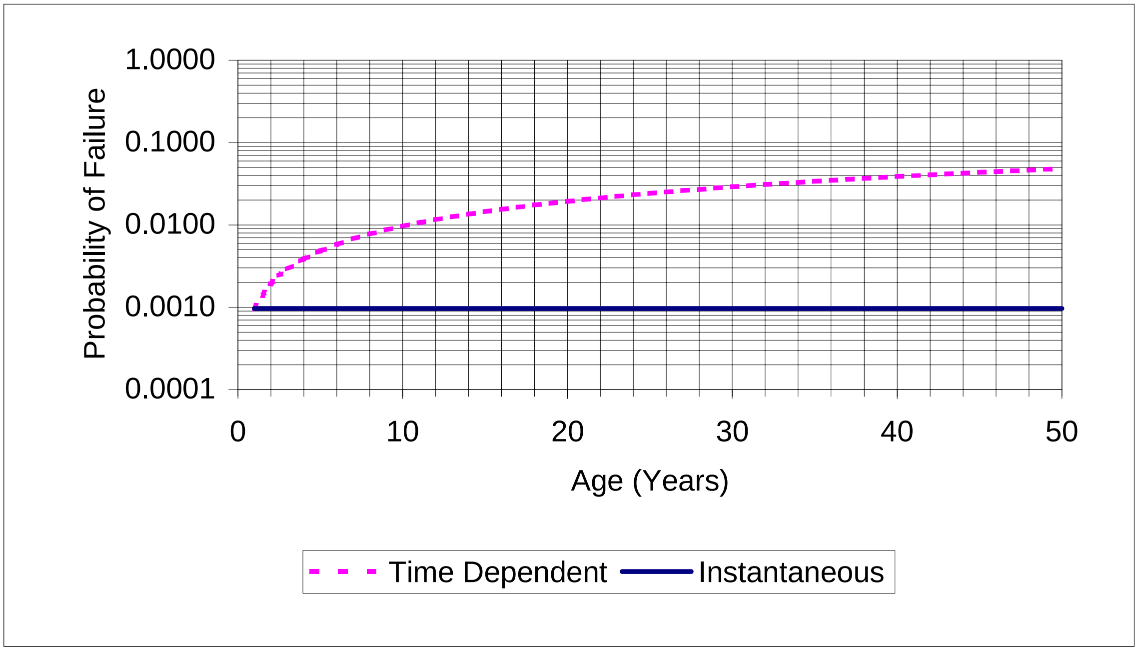


Figure 3-5. Instantaneous and Time Dependent Probabilities
of Failure for a Tanker with no Cracks or Corrosion

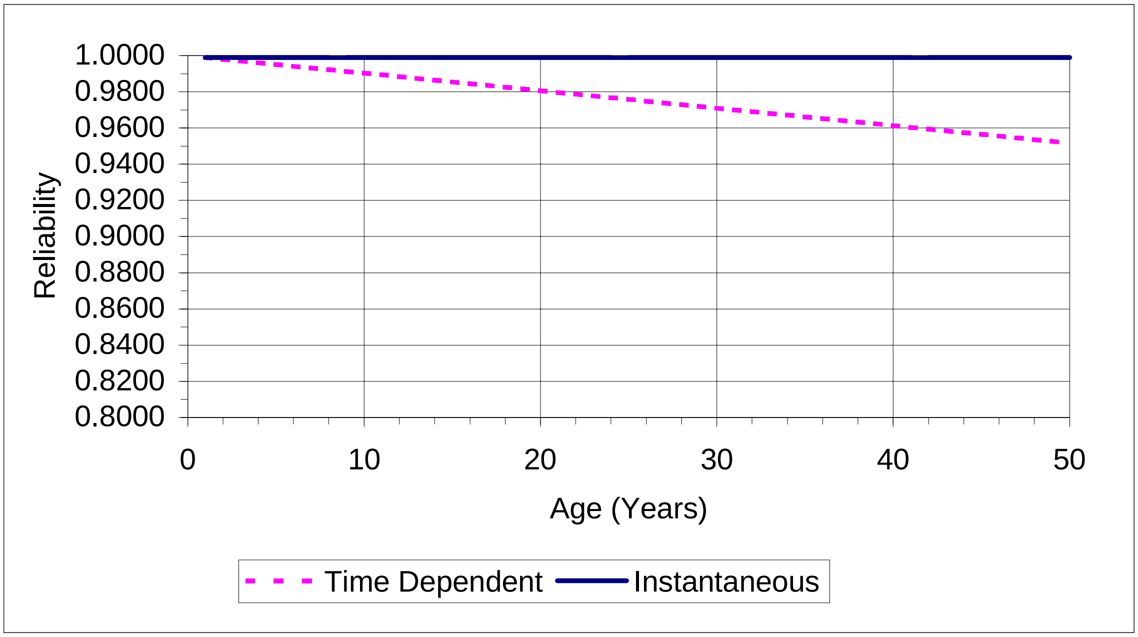


Figure 3-6. Instantaneous and Time Dependent Reliabilities for a Tanker with no Cracks or Corrosion

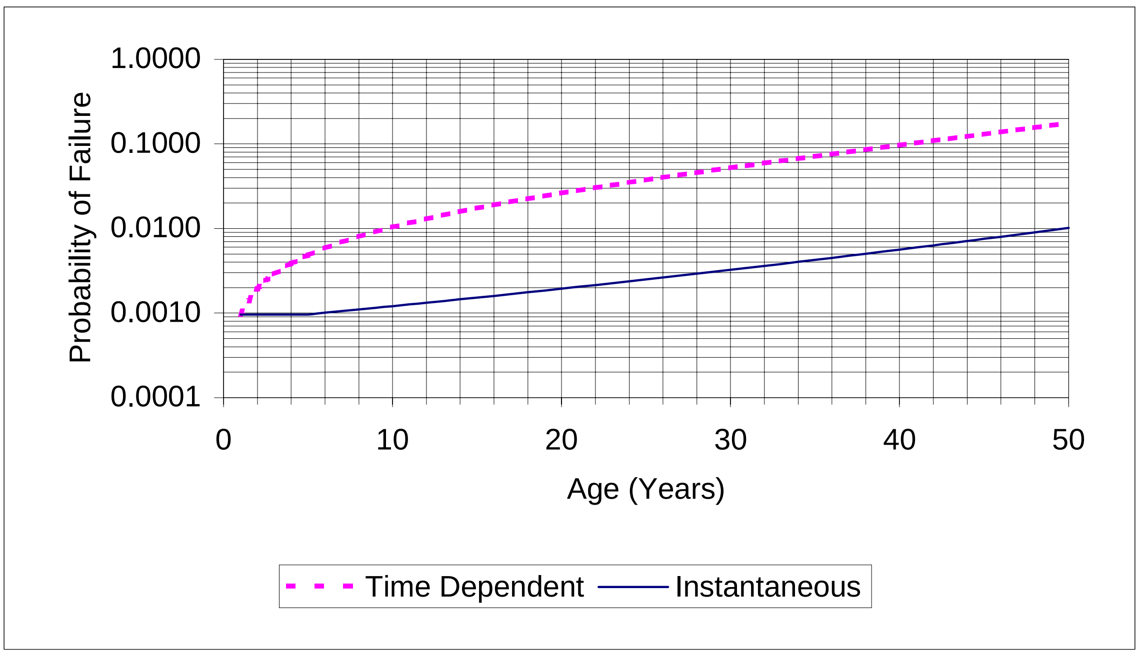


Figure 3-7. Instantaneous and Time Dependent Probabilities of Failure for a Tanker with Corrosion

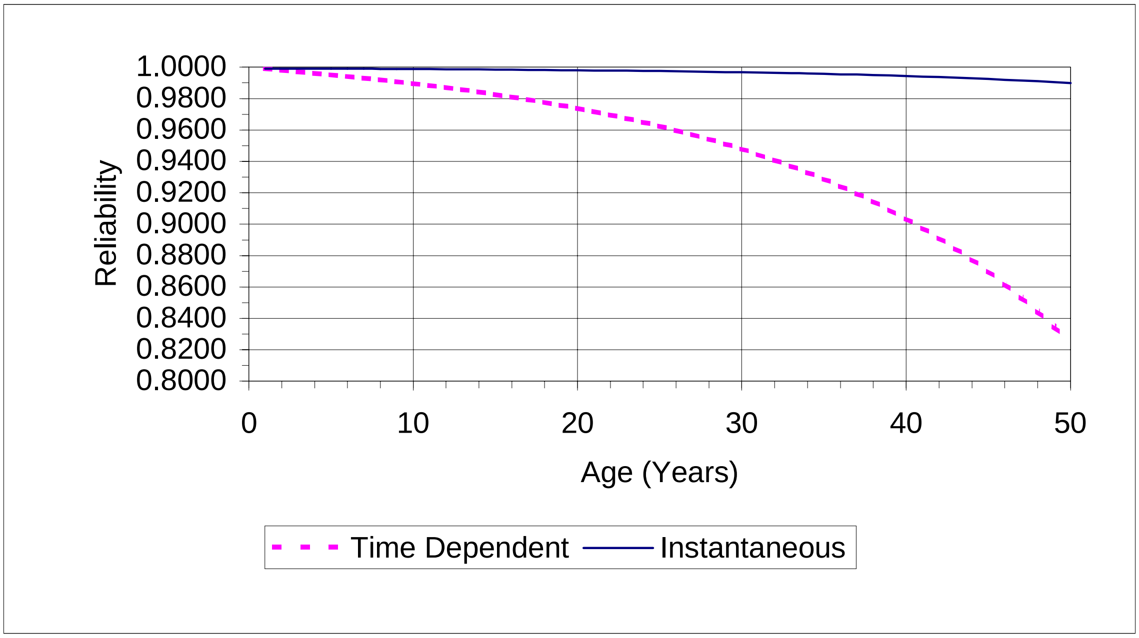


Figure 3-8. Instantaneous and Time Dependent Reliabilities for a Tanker with Corrosion

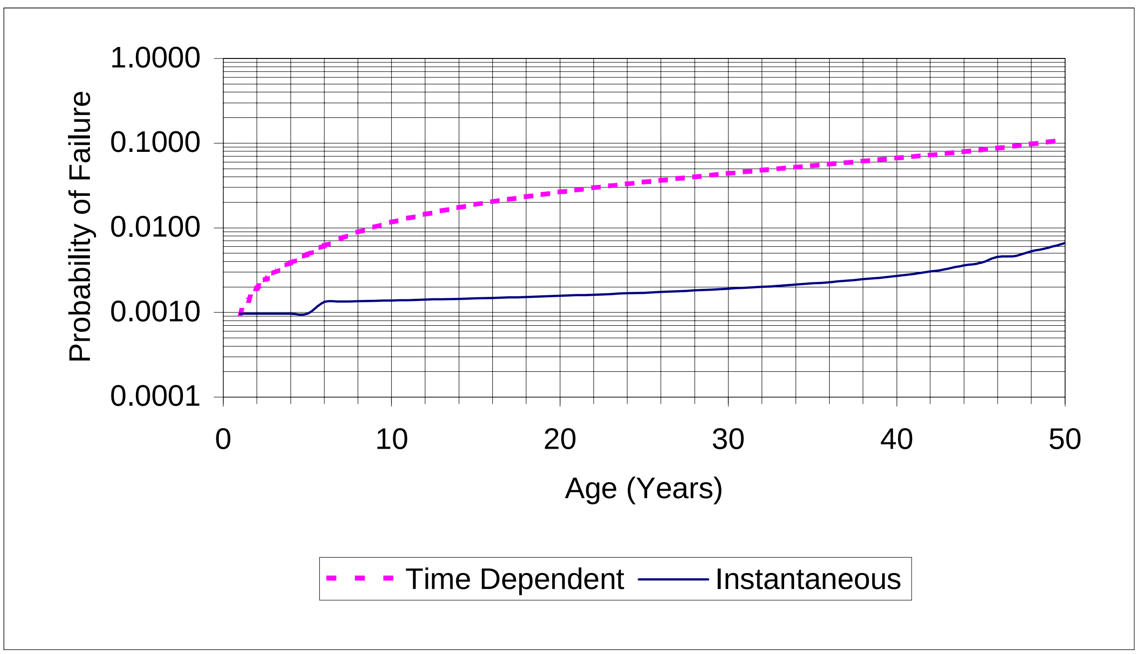


Figure 3-9. Instantaneous and Time Dependent Probabilities of Failure for a Tanker with Cracks

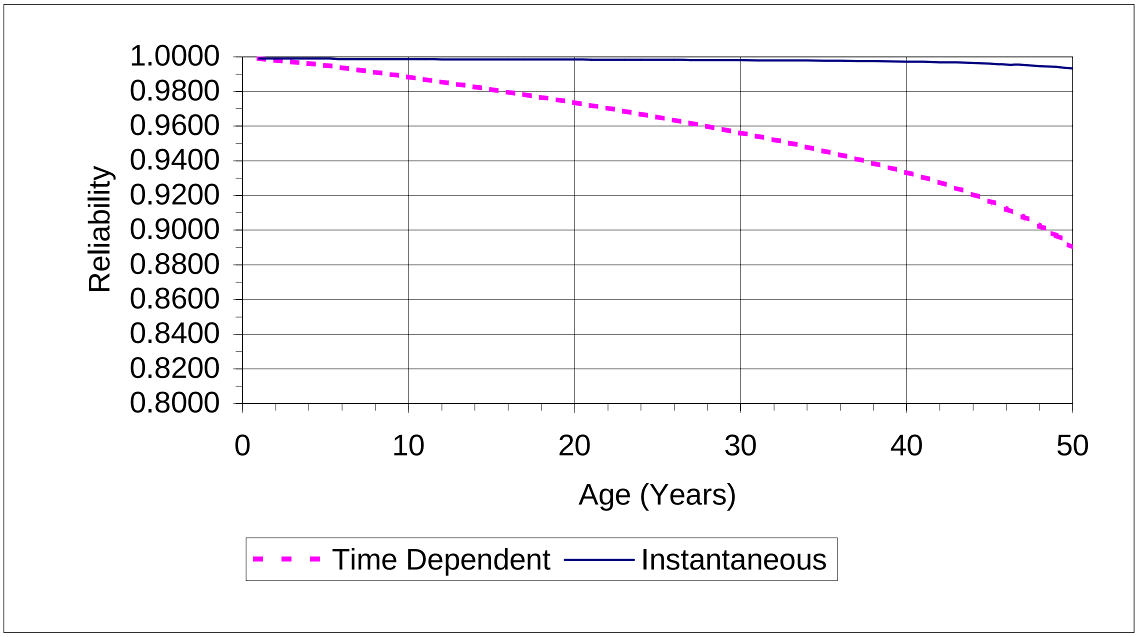


Figure 3-10. Instantaneous and Time Dependent Reliabilities for a Tanker with Cracks

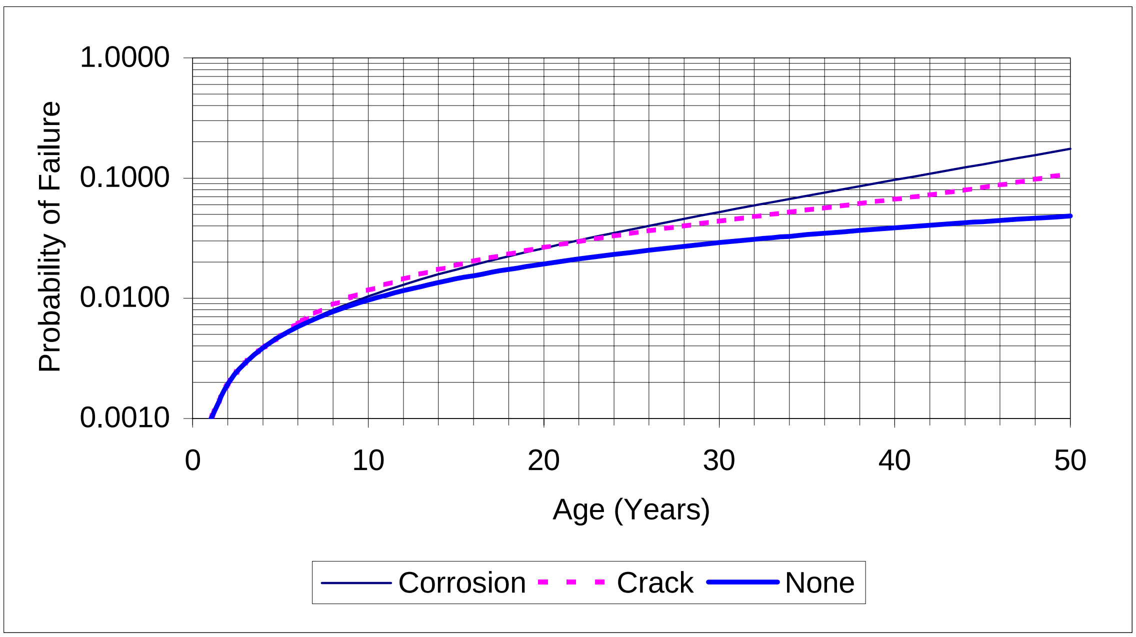


Figure 3-11. Time Dependent Probabilities of Failure

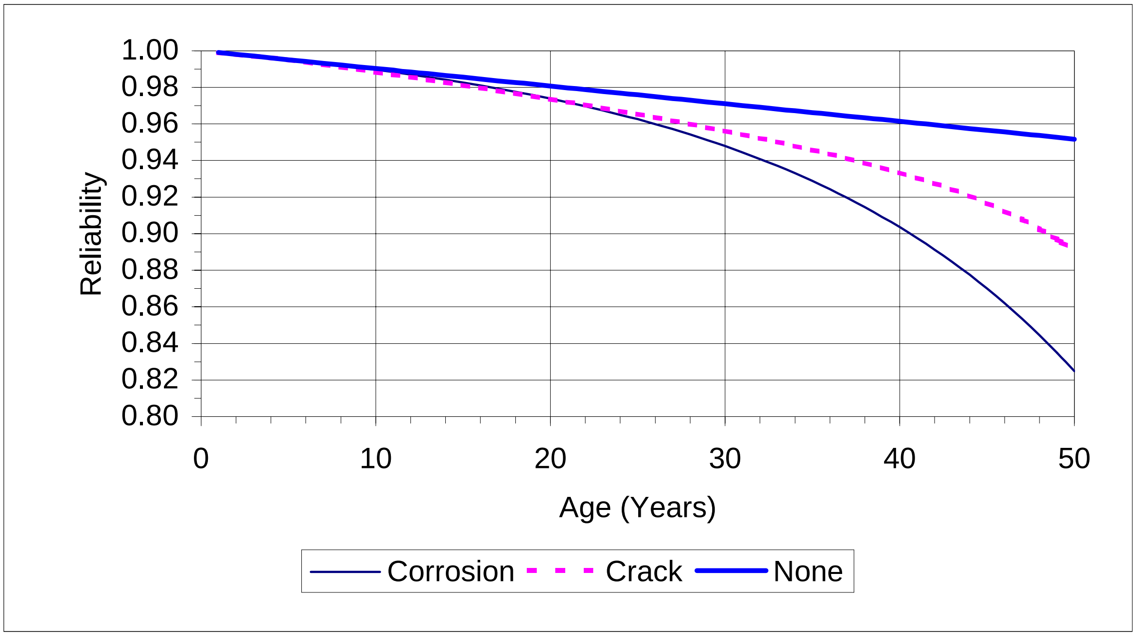


Figure 3-12. Time Dependent Reliabilities

3.3. Qualitative Risk-Based Assessment and Management

3.3.1. Introduction

The present section is devoted to demonstrating how the qualitative risk-based life cycle management strategy developed in Chapter 2 can be applied to any existing tanker structure. The demonstration is based on general information on existing tankers that can be used for estimating failure properties and failure consequences. The information used herein is available in the open literature and in-house to the project team. It is hoped that tanker owners or operators that have access to their particular data can readily apply the methodology presented in this section to their specific vessel.

3.3.2. Objective of Analysis

The objective of analysis is to develop risk measures of integrity to help focus a vessel condition manager's attention on the most risk-significant degradation modes and sites so that managers can make informed decision that account for risk among other consideration in a decision making process. The goal of a risk-based life cycle management of an existing tanker structure can therefor be stated as making good choices that maximize safety and economy during the remianing life of the structure. This is accomplished by minimizing the risk associated with operating the stucture subject to the maximization of the net revenue generated by the structure. Strutural safety, environmental and classification societies requirements have to be considered in the anlysis. Because the net revenue depends on the cost of items such as drydocking the ship, frequency and types of repairs, maintenace and inspection of defects, these items have to be accounted for in the analysis.

A two step risk assessment procedure in which qualitative risk assessment is performed before quantitative risk was developed in Chapter 2. This procedure is applied to tanker structures. It should however, be noted that for most existing tankers, it may not be possible to perform quantitative risk assessment. This is because the required data base may not be available and in strutures that have the data base, quantitative risk assessment might be too costly due to the high cost of computing failure probabilities. Therefore, for most structues, qualitative risk analysis which might be the only viable approach will be emphasized in this section. It is therefore suggested in this study that quantitative risk assesssment should be used only when there is a need for refinement of qualitative results. Furthermore, it should only be applied to structural details with high values of qualitatitive risk. Procedures for estimating qunatitive risk measures, namely, time dependent probability of failure that has been demosntarted in the previous section can be used for qunatitative risk analysis.

3.3.3. System Definition for Tanker Structures

The system under consideration is the hull and structural details of a tanker. The scope of the risk based life cycle is restricted to an existing structure although the result of the analysis can aid in new designs. Depending on the quality of initail design, the age range of the tanker under consideration can start from 7 to 10 years. The structural system needs to defined to a sufficient detail level that would permits the use of the methodology.

3.3.4. Hazard Analysis

Most hulls and structural details of existing tanker ships are made from steel. This is because steel has desirable propeties such as durability, stiffness and strength. However, tanker structures are exposed to different hazards that degrade the desirable properties of steel and could lead to structural failure. Hazards experienced by tankers include extreme sea waves, strong wind, continuous loading and unloading of vessels, corrosion and fatigue cracking. Other hazards are accidental loads, such as, grounding, fire and blast. A cursory look at the hazards show that corrosion and fatigue cracking are two main hazards that can be controlled by inspection, maintenace and repair. Therefore, they are managable hazards. Furthermore, the two hazards are the most prominent hazards experienced by tankers. If left unchecked, they can grow in size resulting in cargo spill when the hull is penetrated or cracked leading to eventual collapse of the structure. A risk-based management strategy for tanker structures must miminize the risk associated with fatigue and corrosion among other hazards. An understanding of the two hazards and identification of structural details that are prone to them is the first step in the management process. To aid the understanding, an overview of the literature on corrosion and fatigue in tankers structures is undertaken in the subsequent sections.

3.3.4.1. Corrosion

Corrosion represents the most prevalent damage hazard encountered by tanker structures. Corrosion (internal or external) manifests itself in several forms. These include general corrosion, pitting and grooving. Current corrosion measurement and inspection techniques/equipment are geared toward thickness gauging for general corrosion and pit size (depth and width) gauging for pitting corrosion and grooving. Locations to be inspected, repaired and maintained are usually defined on the basis of prior experience of a particular ship class. Based on past observations, the Berkeley Ship Maintenance Project (Ma and Bea, 1992) has identified and defined the following critical areas for localized corrosion in oil tankers:

1. Top and bottom of ballast tanks;
2. Bottom of cargo tanks where pitting corrosion could occur;
3. Any horizontal surface which can entrap water, in particular, horizontal stringers on transverse bulkheads;
4. Welds, sharp edges, and any areas in which coating is difficult to apply;
5. Local stiffening members which can become the sites of grooving corrosion; and
6. Structures adjacent to heating devices.

In segregated water ballast tanks, general corrosion can take place everywhere, if they are uncoated. The top and bottom of ballast tanks tend to have more wastage. A necking effect (grooving) often occurs at the junction of the longitudinal bulkhead plating and longitudinals. If the adjacent cargo tank is heated, corrosion or coating breakdown is more serious. For partially filled ballast tanks, the water level constantly surges in the splash zone due to the ship motions. This accelerates the corrosion rates in uncoated ballast tanks and accelerates coating breakdown in coated ballast tanks.

Cargo tanks carry oil throughout the ship’s service life, although some designated cargo tanks may be used for heavy weather ballast in emergency situations. Because of the protection by oil, the corrosion risk within these tanks is, therefore, normally very low except in the upper surfaces of horizontal structural components. These horizontal surfaces, especially on the bottom plates, can be attacked by pitting and grooving corrosion which is caused by the residual water settling out from cargo oil. The aft end of these surfaces tends to suffer more corrosion than the fore end because of the ship’s normal trimming by the stern.

Coating existence and its maintenance significantly affect vessel structural performance and safety. While the coating system is intact, no corrosion will occur. However, most coating systems will only be guaranteed for a specific period followed by a slow breakdown of the coating. Coatings normally last from 7 to 15 years, depending upon whether zinc or epoxy-based coatings are used (Sipes, 1990). Many paint manufacturers claim a hard coating to have approximately 10 years of life provided that proper coating procedures are applied. However it should be noted that localized coating breakdown usually occurs much earlier than that. This implies that starting from the second special survey (around 10 years old) coating conditions become an important item to be monitored.

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.

3.3.4.2. Fatigue Cracking

Another prominent hazard that is experienced by tanker structures is fatigue cracking due to cyclic stresses in the structural details. An earlier Ship Structure Committee study (Jordan and Cochran, 1978) was conducted with the objective of providing data on the performance of structural details, and to identify what types of details crack most frequently. The study includes the results of a survey of approximately fifty different ships. The fifty ships were drawn from seven ship categories and not just tankers. Structural detail failure data were collected and classified into 12 detail families to provide guidance in the selection of structural detail configurations. The survey showed that 2252 of the total 6856 damaged locations, or 33%, were found in beam bracket connections. Tripping brackets comprise the second highest percentage, with 23%. Other common locations for cracking are cut-out details.

Bea et al. (1995) created a crack database based on data gathered from 10 tankers including 2 double hulls, 2 double bottoms, and 6 single hulls (4 of which were sister ships). The data base consisted of 3600 cracks, of which about 2000 were in the 4 sister ships. The study indicated that 40 % of the total 3600 cracks occurred in connections of side shell longitudinals to transverse bulkheads or web frames. About 10 % of all cracks were found in the bottom longitudinal end connections. A further 10 % were in horizontal stringers. Figure 3-13 shows the crack distribution by tanks along the vessel length, for the four sister ships. There is a trend for more cracks to occur in the mid body region for this class of vessels. However, this trend is formed partly because of the smaller sizes of the fore-peak tank and aft tank. All factors being equal, smaller tanks should have less cracks than larger ones. If the number of cracks in each tank is normalized according to its tank size, the trend shown in Figure 3-13 becomes less clear. The study also presented the crack distribution along the vessel height which was divided into three regions. Most side shell cracks and longitudinal bulkhead cracks tend to occur in the middle third of the vessel height (see Figure 3-14). The side shells have significantly more cracks than the longitudinal bulkheads in these 10 ships.

A study conducted by NK (Yoneya, 1993) has investigated the hull cracking of relatively young 2nd-generation VLCCs built with a considerable amount of high-tensile steel. These vessels experienced cracks at the intersection of side longitudinals with transverse bulkheads. The cracks start at the flange of side longitudinals and propagate into the longitudinal's web plates toward the side shell. If not found in time, they may lead to cargo oil spill from wing oil tanks. The study surveyed 18 vessels thoroughly. An average of about 10 cracks was found in each vessel. The crack trend is shown in Figures 3-15 and 3-16. Nearly 80 % of the cracks were found in the mid-body tanks. Cracks are concentrated within the range of 2-5 meters under the full load waterline (Nakajima et al., 1993).

On the basis of the results from the studies just reviewed, it can be concluded that fatigue cracks tend to be concentrated in the side shell region from the load water line to about 8 meters below. Many cracks occurred at the intersection of side shell longitudinals to transverse bulkheads or web frames. This region is one that experiences the highest dynamic loads. A study conducted by DNV (1991) has shown that the cyclic stress range in the side shell is significantly higher than that in the bottom. In bottoms or decks, the fluctuating stresses are mainly axial stresses caused by hull girder bending. In side shells, the dominating fluctuating stresses are caused by local fluctuating hydrodynamic pressures due to roll and heave motion of the vessel, and due to pressures induced by waves. Therefore, based on past experience, in the case of tankers, side shell structure is one of the most fatigue critical areas.

The trend along the vessel length, however, is not clear. The NK study shows an extreme concentration of cracks in the midship tank. Data analysis performed in that study on two vessels shows no trend along the vessel length. It was found that the water ballast tanks tend to have more cracks than the cargo oil tanks because of their heavy corrosion. The study by Bea et al. (1995) shows slightly more cracks toward the mid-ship tanks, but the trend is less clear if the crack numbers are normalized according to their tank sizes.

According to Ma and Bea (1992), fatigue critical areas in tankers that are of concern include:

- Intersections of longitudinal stiffeners (particularly side shell longitudinal) with transverse bulkheads or transverse web frames (see Figure 3-17), particular, in the region between full load and ballast waterlines (see Figure 3-16);
- Bracketed end connections of primary and secondary supporting components;
- Discontinuities in high stressed face plates, stiffeners, and longitudinal members; and
- Openings and cut-outs in primary structures.

Figure 3-5 shows the typical cracks experienced at side shell longitudinal connections to transverse frames or bulkheads. The basic mechanics of these typical cracks can be explained by considering the load transmission path. The cyclic load on side shell plates is mainly transmitted through longitudinal stiffeners to web frames. This load is then conveyed into the web frames by the flat bar stiffeners and lugs (collar rings). In some designs, the longitudinal cutout is left open without an attachment of a lug. Then the load has to be transmitted through the small footage of a flat bar stiffener. This creates a high stress that causes crack initiation in the flat bar toe or heel. The crack (type B in Figure 3-17) will then grow along the flat bar weld. After the flat bar stiffener is completely cracked through and detached from the longitudinal, a progressive redistribution of loading takes place and normally results in another fatigue crack (type D) initiated in the cutout corner of the web frame. If these two cracks are left un-repaired, the web frame crack may grow into the shell plate or new cracks will initiate in the web frame weld to the shell plate (type C and C1). Eventually a shell plate collapse, possibly together with a cargo spill, will occur. This crack sequence, however, is favorable, because type A, which is a more serious crack, comes late in the sequence. This type of crack starts from the toe or heel of a flat bar stiffener or a bracket into the web of a longitudinal. The crack can quickly grow into the side shell and lead to an oil spill. In most tankers, this crack sequence is more common. However, some designs such as those in the 2nd-generation VLCCs in the NK study tend to create an unfavorable crack sequence where the type A cracks occur first. More attention may need to be paid on ships of these designs. Detailed presentation on corrosion and faitigue cracking in ship structures has been provided in a related study TR-97-22 (Ma et al., 1997).

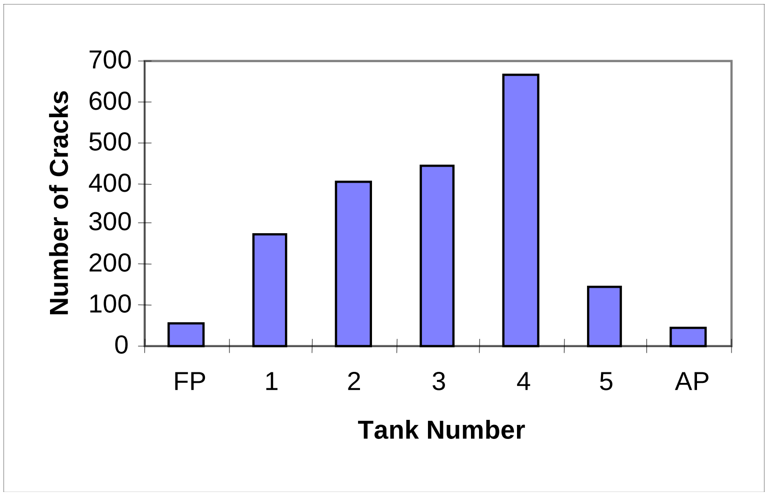


Figure 3-13. Crack Distribution Along the Vessel Length of 4 Tankers in the Same Class (Schulte-Strathaus, 1991)

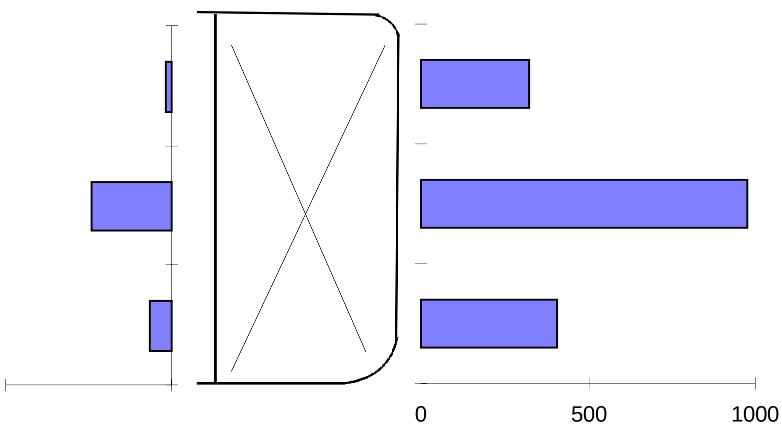


Figure 3-14. Crack Distribution Along the Longitudinal Bulkheads (Left) and Side Shells (Right) of 10 Tankers (Schulte-Strathaus, 1991)

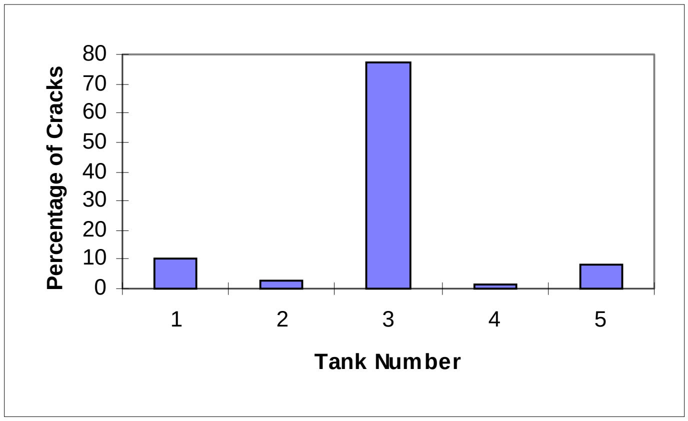


Figure 3-15. Crack Distribution Along the Vessel Length of Some 2nd-Generation VLCCS (Yoneya 1993)

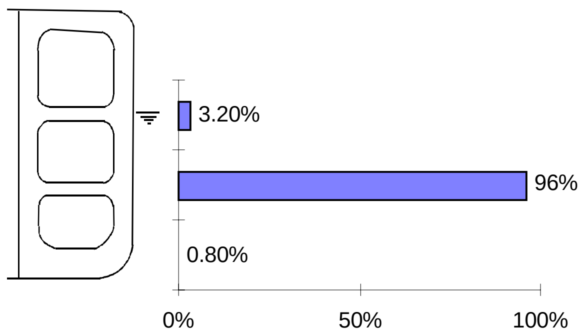


Figure 3-16. Crack Distributions Along the Side Longitudinals of 2nd-Generation VLCCS (Yoneya, 1993)

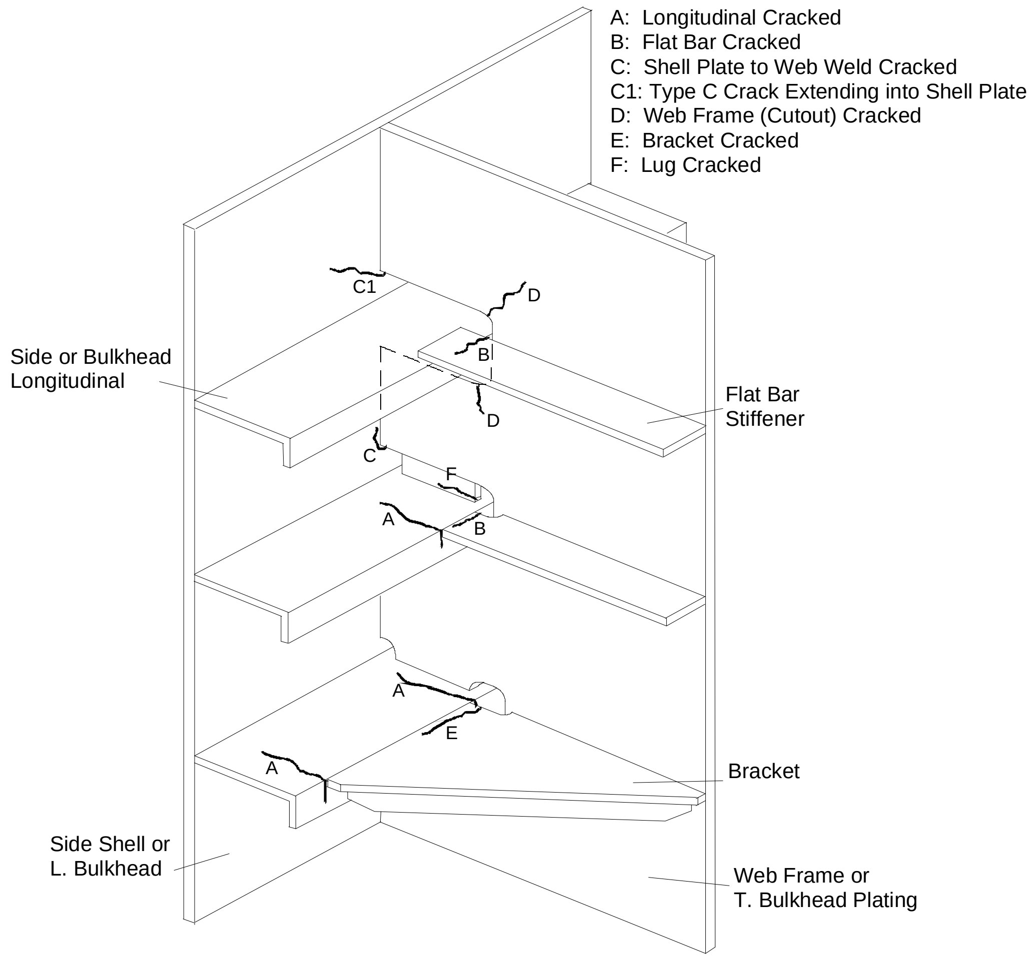


Figure 3-17. Typical Cracks in Side Shells or Longitudinal Bulkheads (TSCF 1992)

3.3.5. Qualitative Risk Assessment

The system under consideration is the hull and structural details of any tanker structure. This is a very complex system, and qualitative risk analysis of the entire system taken as a unit might not be practical or feasible. Since the objective of this project is to aid management to focus their resources on high risk areas or components a practical risk management approch should be based on components as oppose to the entire tanker structure taken as a unit. This can be accomplish by computing the risk levels for various components of structural details. Structural details can then be ranked or prioritized according to their risk levels. In particular, the risk level associated with each detail is estimated in terms of consequence of defect/damage/hazard and likelihood of defect/damage/hazard (qualitative estimate of failure probability). The four step qualitative risk assessment procudere can be used in ranking the criticality of structural details are can be summarized as follows:

1. Oualitative evaluation of probability of failure of each structural detail;
2. Estimation of consequence of damage of each structural detail;
3. From the consequence of damage and likelihood of damage, evaluate the qualitative risk associated with each struatural detail; and
4. Rank or priotize the structural detail according to their associated risk.

Experience and analysis should be used as a complementary means in evaluating likelihood of damage due to corrosion, fatigue cracking and other forms of in-service damage (e.g. deformation due to accidental damage, berthing damage, loading / unloading) and consequence of damage. The four step risk priotization scheme is demonstrated in Figure 3-18. Issues considered in the four step are presented in the subsequent sections.

3.3.5.1. Qualitative Estimation of Failure Probability

Qualitative evaluation of failure probability, also referred to as likelihood of damage, can be defined as a measure of the proneness of a structural detail to damage. This proneness has to be estimated and can be viewed as a qualitative estimate of failure probability. A structural detail may be prone to one type of damage mode, or several damage modes, and in some cases they may be related (e.g. fatigue cracks in areas experiencing corrosion). In a qualitative framework, a simple statistical analysis combined with engineering judgment can be used to estimate its likelihood of damage.

A likelihood of damage categorization scheme can be designed and notional ratings can be assigned to each category as illustrated in Table 3-8. The categorization scheme in Table 3-8 has four classes: Extreme, High, Moderate and Low. Engineers should design a rating system according to their requirements. For demonstration purposes, structural details that are highly susceptible to damage are assigned an annual likelihood of damage (probability of failure per year) of 10^{-2}, while those unlikely to experience a failure are assigned an annual damage rating of 10^{-5}. Table 3-8 also summarizes the approximate rating scheme that can be applied to likelihood of experiencing damage. Expert opinion elicitation and experience from other industries and classification society rules could be used as guides in assigning likelihood of damage. Some of the experiences are described below.

DNV (1992) has defined acceptable annual probabilities of failure for reliability analysis on marine structures. The acceptable failure probabilities range from 10^{-3} to 10^{-6} depending on the consequence of failure and class of failure. The class of failure depends on the level of structural redundancy and also on the degree of warning provided by the failure mode under consideration. For redundant structures associated with less serious failure consequence, a failure probability lower than 10^{-3} (or target reliability of 3.09) is acceptable. For structures associated with serious failure consequence and no failure warning, a failure probability lower than 10^{-6} (or target reliability of 4.75) is required. These values roughly provide a reference to the actual reliability of existing marine structures.

ASME (The American Society of Mechanical Engineers) has developed a table to convert qualitative statements to equivalent numerical probabilities, in an effort to apply a probabilistic risk assessment to mechanical systems such as nuclear power plants (ASME 1991). The table gives some definitions to failure probability from 10^{-1} to 10^{-8}. It notes that converting qualitative assessments of an expert to a probability value is a process with potential pitfalls and should be approached most carefully. These conversions can be used as a guide when developing a likelihood of damage classification table such as Table 3-8.

Past experience or in-service data is valuable in helping determine the likelihood of damage of structural details that are prone to several forms of damage. For instance, experience has indicated that tankers tend to have fatigue cracks in the intersection of transverse webs and longitudinals in side shell areas between high and low water lines. In bulk carriers, cracks can often be found in the corners of hold openings, side frames, welds of corrugated bulkheads and stools. Therefore, these areas are considered to have high likelihood of damage. A few past studies have compiled collections of structural details with high failure rates (IACS, 1994; TSCF, 1995; Jordan, 1978, 1980) and can be used as guides in estimating likelihood of damage.

Assigning a likelihood of damage rating to a structural detail is a difficult task and should be handled with care. In cases where substantial in-service (experience) records of damage are available, simple statistical techniques may be applied in conjunction with engineering judgment to estimate the likelihood of damage for a given structural detail. For example, if a record shows that the fatigue failure rate of a structural detail is roughly four times or higher in the design life of 25 years, it then has an extremely high annual likelihood of damage of 4×10^{-2}. This structural detail should be rated “Extreme” as defined in Table 3-8. Other structural details of the same design at similar locations should then be assigned this same level of likelihood of damage.

Likelihood of damage should be evaluated independently for each of the main failure modes, which normally include fatigue cracking and corrosion. In determining likelihood of damage due to corrosion, operating-environmental factors such as the exposure to salt water, heat, and caustic elements are key factors. Structural configuration and condition of protection systems are also important. Corrosion rates of different conditions have been studied and published by Tanker Structure Co-operative Forum (TSCF, 1997). Past experiences provide valuable information on structural details that are prone to corrosion.

Table 3-8. An Example of Structure 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 in the ship's life).
Moderate	10^{-4}	This mode of damage occurs very rarely, perhaps once or twice during the ship's life.
Low	10^{-5}	It is extremely unlikely that the structure in consideration will experience this damage mode during the ship's life.

3.3.5.2. Estimation of Consequences of Damage

Structural details, elements, and components (assemblies of details and elements) have consequences associated with their failure. Evaluation of the potential consequences may be based on historical data (experience) and analysis to define details critical to hull structural integrity. A rating system that measures the consequence of failure has to be developed. This is an important factor in risk ranking of structural details since similar details at two different locations can have dramatically different consequences of failure. For example, a crack in the side shell of a cargo oil tank may have much more serious consequences than the same crack in a water ballast tank because the former can cause pollution potentially. For a tanker structure, the potential major consequences of failure include:

1. Loss of vessel, lives and cargo
2. Pollution
3. Repair cost and down time

Loss of Vessel

Loss of vessel, lives and cargo is rare for most types of ships. However, with a series of bulk carrier casualties in the recent past, this has become noticeable. This kind of consequence may be the most serious. Typically, then net worth of a tanker can assume a wide range of values (from 1 to 100 million US dollars depending on its age, size and condition). The incident of a vessel sinking, therefore, implies a loss of at least one million dollars or more. If the loss of lives and cargo are included, the value of the total loss is much higher.

Pollution

Pollution from oil spills is another type of failure consequence. Major oil spills can occur as a result of collisions or groundings. Oil spills can also result from fatigue cracking in the outer shell of cargo tanks, or from severe pitting corrosion that penetrates bottom shell plates. For single hull tankers, side shell plates and bottom plates that encompass cargo oil are considered as having a “high” or “extreme” failure consequence. Longitudinal bulkheads between cargo oil and ballast water should also receive the same high level of failure consequence. For double hull tankers, inner bottoms and inner sides are the structures that form a boundary for cargo oil. If failed, oil can leak into ballast tanks, and pollution will occur during the de-ballasting process. Therefore, longitudinal bulkheads and inner bottoms between cargo and ballast space should receive a high level of consequence of failure rating.

Costs related to pollution fall under three categories (Liu & Thayamballi, 1995): clean-up expenses, restoration costs and lost use values. The third category includes intrinsic values such as the depletion of sea life. Clean-up costs are typically high, the highest to date being the Exxon Valdez, which was reported in excess of $2 billion. However, many of the oil spill incidents are due to non-structural related causes such as grounding, collisions, fire and explosions which have little to do with structural integrity. Only some of the incidents are due to structural causes and may be prevented by inspections. Such usually result in much less oil spillage than those of other causes. The failure consequence of an oil spill is not easy to estimate, because oil spills are an emotionally charged societal issue. A consensus on their costs is hard to reach. One way to judge the total cost of a spill is through legal claim payments in the past. A study done by National Research Council has estimated that it is about $30,000 per ton of oil spilled typically, but can be as large as $100,000 per ton (quoted by Liu & Thayamballi, 1995). Also, the data of an insurance company confirms that pollution is one of the more expensive incidents involving claims. Their major pollution claims have an average claim amount of one million dollars each.

Since oil spills due to structural failures are normally less severe, their average cost should be less than that.

Repair Cost and Downtime

The more common failure consequence is simply unscheduled maintenance or repair. As many of the fatigue cracks tend to stop or grow at a slow pace, their consequences constitute only local repairs. Veeing and welding which is one of the most common temporary crack repair methods has relatively low cost. If a design modification or a plate insert is involved, their costs may be higher, but still relatively low comparing to the other two consequences, i.e. vessel lost and pollution. The total cost of a repair should include material, labor, dry dock charge, tank cleaning, staging and down time. Some of the items such as dry dock charge, 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 GRT. The charge for each subsequent day is about $ 0.2 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 yard in the Far East, and they vary between yards. However, they may be used to provide a relative ranking of the costs involved.

Other consequences such as effect on personal safety and loss of serviceability have to be analyzed. In a risk assessment, the consequence of failure can be measured by a monetary value which is the sum of the consequences caused directly or indirectly by the failure. The monetary costs of a severe failure can generally include costs other than those associated with the repair of the damage to the ship. There may be various costs of a societal nature that may need to be included; the most difficult to assess in this category of costs are failures involving the loss of life.

For the purposes of this demonstration, a categorization scheme has been designed for consequences of failure and notional ratings have been assigned for each category as shown in Table 3-9. These ratings can be considered to be a very rough measure of the consequential costs of a failure, and ideally they would be based on the actual estimated costs for the category concerned. Of course, the actual figures must be appropriate to the nature of the loss. For example, the consequential loss of an oil spill in coastal waters in the vicinity of a highly populated area will be much more expensive than a loss in the high seas. If the cargo lost is of a toxic nature the consequential costs will be higher than cases where the cargo is more benign. These are just two of many factors that need to be considered in the process of assigning quantitative criticality ratings.

The notional consequence of failure ratings given in Table 3-9 is developed merely for demonstration purposes, and should not be used as a reference. Different companies or organizations may develop their own rating systems. Their assigned rating numbers may be different for the same type of consequence of failure depending on the function, size and condition of their ships and the nature of their cargo. For instance, oil spills from a small vessel may have a milder consequence than the one from a VLCC. Companies should design their own rating system to fit their service and operational profile.

Table 3-9. An Example of Consequence of Failure Classification Scheme for Structural Details

Classification	Rating	Consequences of Failure
Extreme	10^8	• Loss of ship and cargo, • Loss of ship, • Loss of lives, or • Major oil spill involving several cargo tanks.
High	10^6	• Minor oil spill, • Major structural failure, • Cargo loss, • Loss of serviceability, or • Salvage.
Moderate	10^4	• Unscheduled repair on a moderate damage, or • Reduction of serviceability.
Low	10^3	• Temporary repair, or • Nuisance defects (no immediate repair).

3.3.5.3. Qualitative Risk for Structural Details

The risk associated with each structural detail can be computed by

$$R_i = P_{fi} \cdot C_i \tag{3-32}$$

where R_i is risk of i-th structural detail, P_{fi} is probability of failure of i-th structural detail, and C_i is consequence of failure of i-th structural detail. The risk associated with each structural detail can alternatively be represented by the pair (P_{fi}, C_i). A classification scheme based on risk levels, as demonstrated in Figure 3-9 can be applied to structural details. It should be noted that the risk classification scheme presented in Figure 3-9 could change within the life cycle of an existing ship structure.

3.3.5.4. Risk Based Decision Scheme

Once the probability of failure and consequence of failure or risk levels have been determined, a risk-based decision scheme has to be developed as shown in Figure 3-18. In this demonstration a priority rating of each structural detail based on the levels of risk at the details is used. The risk levels at the details are readily obtained using Eq. 3-32. A risk based priority ranking is defined as the expected loss due to damage which is the product of likelihood of failure and consequence of failure. If consequence of failure is expressed in terms of monetary value, then the ranking should be expressed in terms of monetary value as well. Threshold values for classifying the risk levels at the structural details have to be set. This can be done based on expert opinions and experience from other industries. For example, the risk levels at the structural details could be classified into high, moderate and low. A structural detail with a high-risk priority rating has high risk associated with it, implying a high expected loss when it fails. For most tanker structures, the qualitative risk assessment procedure that has been described will be sufficient for risk based life cycle management of the structure. For some structures, for example VLCC and expensive tankers, there might be a need to execute quantitative risk evaluation of structural details. It is suggested this be done only for structural details with high values of qualitative risks.

Quantitative risk assessment involves an objective evaluation of failure probability and failure consequences. The goal of a qualitative risk assessment is to re-evaluate and re-risk structural details for management decisions. In the context of the current demonstration example, it is suggested that this should be carried out only for structural details with high qualitative risk levels. The failure consequence classification scheme that is used for qualitative risk can also be applied to quantitative risk. The main difference between qualitative and quantitative risk is in estimation of failure probability. In qualitative risk it is based solely on historical data, expert opinion and engineering judgment, but in quantitative risk, it is estimated with structural reliability tools as demonstrated in Section 3.2. Based on the numerical values of failure probabilities for structural details and the consequence of failure, the details can be re-ranked for risk based life cycle maintenance management.

3.3.6. Risk Based Life Cycle Management

Life cycle management of an existing tanker structure requires that management decisions be made on the frequency, type of inspection, maintenance and repair of structural details. A risk-based management scheme implies that these decisions are based on the risk associated with each structural detail. The risk-based priority ranking scheme that has been discussed can be used to determine how the various structural details are maintained. Figures 3-19 and 3-20 demonstrates how a risk-ranking scheme can aid in selecting the type of maintenance, inspection and repair procedures that are applied to structural details. Also, risk acceptance as implicitly governed by currently used rules, such as limit on section modulus to 90% of initial value or as an example 20% reduction in thickness of members, can be used for this purpose.

An example of a risk priority classification rating system is shown in Table 3-10 Risk levels are classified into four classes: Extreme, High, Moderate and Low. Structural details with extreme priorities, have extremely high risk associated with them and should be maintained most frequently, while those with low priority ratings should have less frequent maintenance. The rating numbers chosen in Table 3-10 are, again, for demonstration purpose only and not to be used as a reference.

To demonstrate the use of a risk based priority scheme, two simple examples are given here. Consider two typical structural details in a tanker, named Detail A and Detail B. Assume that Detail A is located in the side shell area of a cargo wing tank and Detail B is in a similar location of an adjacent water ballast wing tank. Assume that this tanker is relatively young so that corrosion has not had much effect on accelerating fatigue in the ballast tanks. Thus, the likelihood of failure ratings of both details are on the same level, say 10^{-3}. Since Detail A has a potential for oil spill, a consequence of failure rating of 10^{6} is assigned to it according to Table 3-

9. Detail B is assigned a moderate consequence of 10^4 assuming that its failure constitutes only an unscheduled repair. As a result, the maintenance priority of detail A and B are 1000 and 10, respectively. According to the risk-based life cycle maintenance priority classification scheme in Table 3-10, Detail A should receive a higher maintenance priority than Detail B. Based on this result, monitoring, inspection and maintenance and repair schemes can be designed to allow more maintenance for Detail A.

For the second example, consider the same two details when the ship is 15 years old. Because of fatigue damage accumulation with time, both details have higher likelihood of failure now. Assume that their likelihood of failure is estimated to be 10^{-2} and $2x10^{-2}$. Detail B has twice the likelihood of experiencing fatigue because of the effect of corrosion since corrosion accelerates cracks. By giving Detail A and B the same consequence of failure ratings as in Example 1, Detail A will have a maintenance priority rating of 10,000 which is again higher than Detail B's 200. As a result, Detail A should also receive higher priority for inspections, monitoring, repair and maintenance. These examples demonstrate that a risk based priority scheme provides a rational approach for developing maintenance schemes.

It should be noted that the outcome of a risk-based priority ranking scheme is sensitive to the design of the rating system for consequence of failure. If the rating scheme for consequence of failure is not scaled properly, the result can be misleading or wrong. This can be shown by using the second example above. If an oversimplified consequence of failure rating system is employed using, say, 1, 2, 3 and 4 to represent the four classes (Low, Moderate, High and Extreme), Detail A and B in Example 2 will have likelihood of failure ratings of 3 and 2. Detail A will turn out to have a lower priority rating of $3x10^{-2}$ than Detail B's $4x10^{-2}$. This is the opposite result to that obtained earlier. This serves to illustrate that this procedure must be applied with care. Hence arbitrary assignment of numerical values to ratings schemes is not recommended. The numerical values should reflect, as much as possible, actual estimated monetary values. In this regard expert opinions elicitation process outlined in Chapter 2 might be a valuable tool.

The risk-informed ranking scheme allows for proper management of the maintenance resources in a life cycle framework since the resources are allocated to structural details according to their risk needs. Furthermore, it provides a rational framework for determining the scope, extent and cost of maintenance. An illustration of the risk based life cycle maintenance management scheme that can be applied to an existing tanker is shown in Figure 3-21. This figure summarizes all the essential elements of the management strategy that has been discussed in this chapter for tanker structures.

Table 3-10. An Example of Risk-Based Structural Detail Maintenance Decision Scheme

Risk Level	Rating	Maintenance Frequency
Extreme	100,000 or above	Structural details should be given the highest priority for maintenance. They are recommended for inspection, monitoring and repair most frequently. They should be subject to a close-up survey, if possible.
High	1000 - 9,999	Structural details should be given the second highest priority for maintenance. They are recommended for inspection, monitoring and repair frequently.
Moderate	10 – 999	Structural details should be given a moderate priority for maintenance. They should be inspected, monitored at normal frequency.
Low	Below 10	Structural details should be given the lowest priority for maintenance. Inspection, monitoring and repair for these details should be conducted at a minimum frequency.

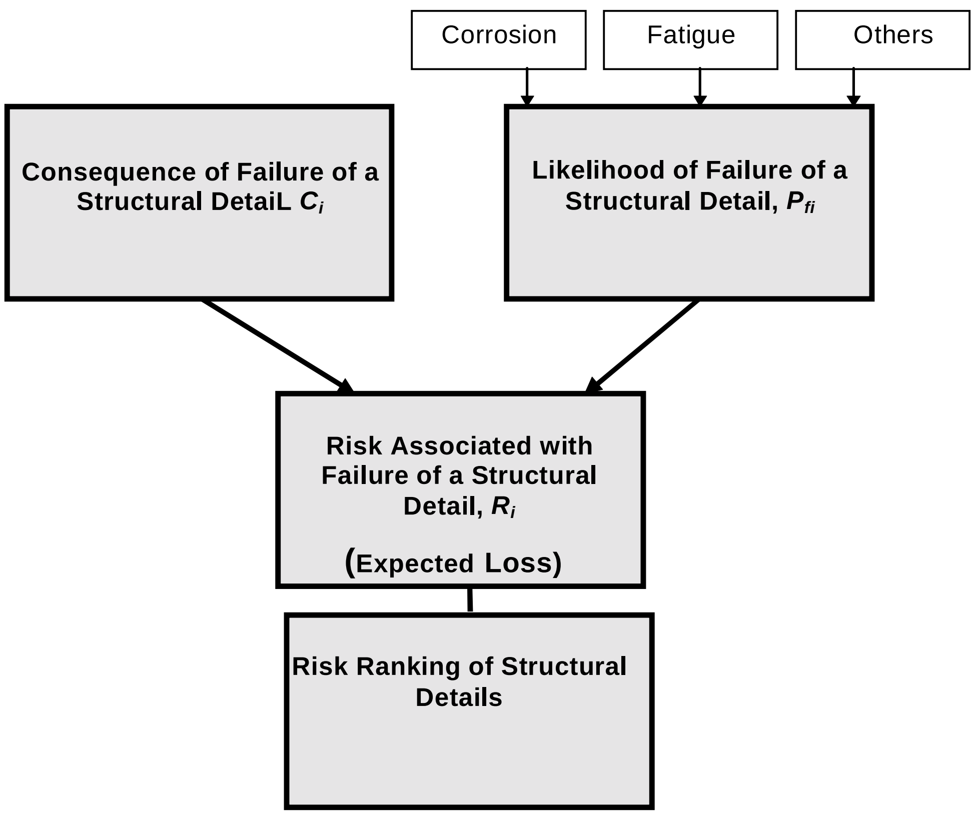


Figure 3-18. A 4-Step Risk Ranking Scheme for a Ship Structural Details

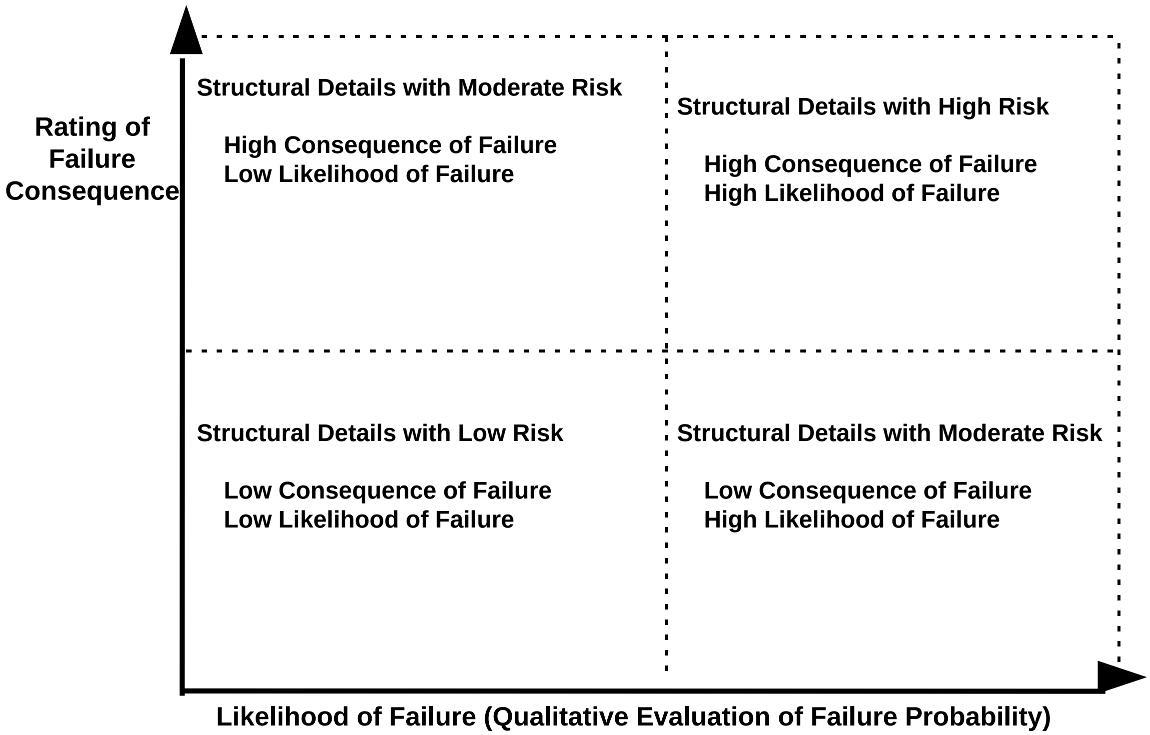


Figure 3-19. A Classification Scheme for Structural Details According to the Risk Levels

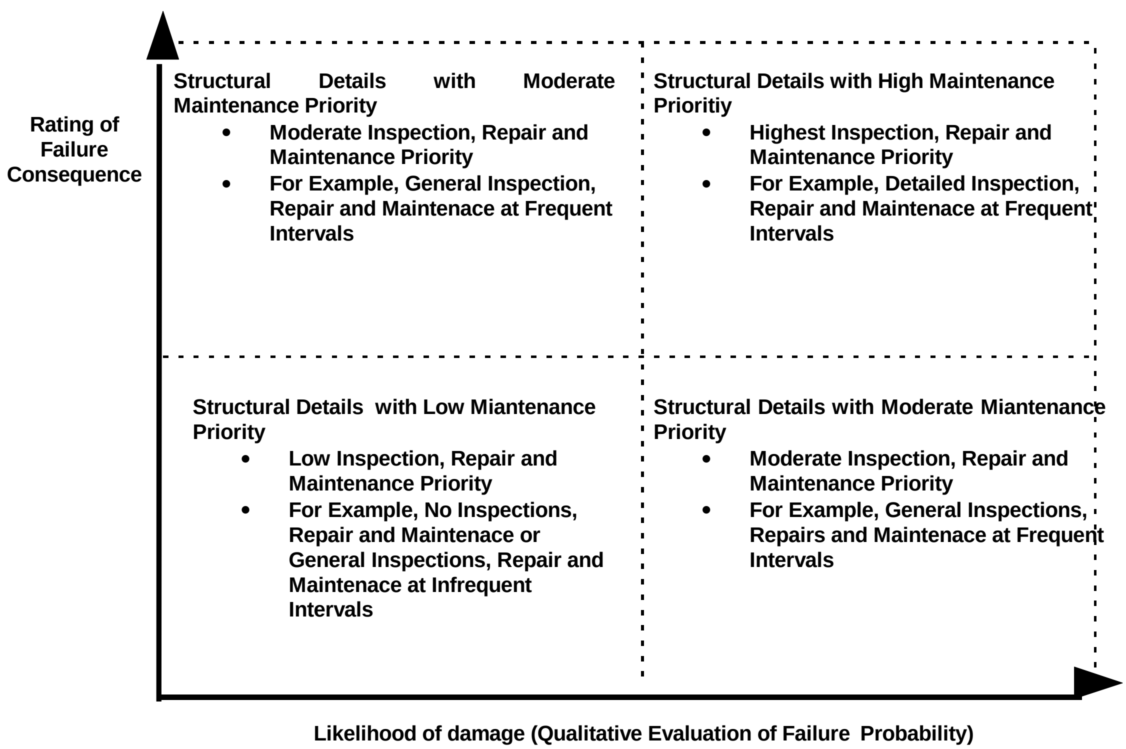


Figure 3-20. Application of Qualitative Risk Ranking Scheme in Maintenance Management of a Ship Structural Details

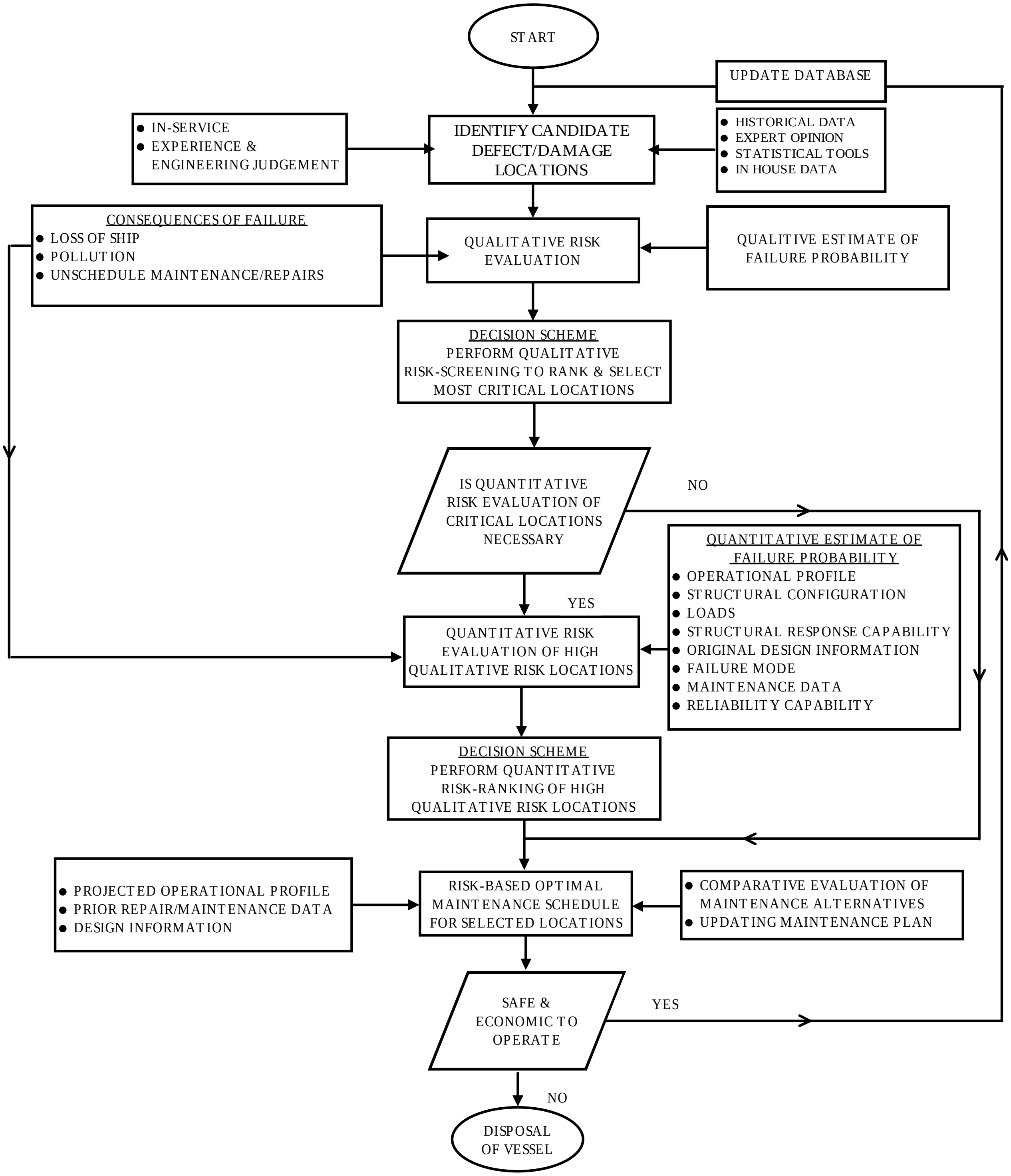


Figure 3-21. Illustration of Risk-Based Life Cycle Management
For Maintenance of an Existing Tanker Structure

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

As a result of its aging fleets and the use of new system configurations and materials in designing new systems, the marine industry is faced with new challenges. These challenges include decisions on life expectancy of structural systems, remaining life, acceptance of aged structural systems in meeting safety requirements, acceptable reliability levels, selection of inspection intervals and methods, repair methods, and systems upgrade and replace options. The shipbuilding and marine industry needs a framework and guidance on managing the life cycle of ship structures. This study is a step towards meeting these needs, and resulted in the following conclusions:

1. Managing and maintaining the integrity of ship structures can be performed in a life cycle framework as was provided and demonstrated in the risk-based guidelines presented in this report.
2. The risk-based guidelines provide risk measures that can help focus a vessel condition manager's attention on the most risk-significant degradation modes and sites. The risk measures can be obtained by a risk-based methodology for maintaining and managing the structural integrity of ship systems.
3. Managers can make informed decisions that account for risk among other considerations in a decision-making process.
4. The proposed methodology and guidelines are suitable for the marine industry based on their demonstrated use to ship structures in the case studies.
5. The methodology and guidelines require data and an assessment of uncertainties that might not be readily available. In cases of data deficiency or insufficiency, data collection programs and expert opinion elicitation might be needed to fill up data gaps.

4.2. Recommendations

The proposed risk-based methodology and guidelines for managing the life cycle of ship structures are a step towards meeting the needs of the marine industry to make decisions such as life expectancy, remaining life, acceptance of aged structural systems in meeting safety requirements, acceptable reliability levels, selection of inspection and repair strategies, and systems upgrade and replace options. Based on the this study, the following needs were identified are recommended for future studies:

1. The proposed methodology and guidelines need to be adapted and demonstrated for specific ship classes in detail.
2. A risk-based management system for the life cycle of ship structures is needed, and can be based on the proposed methodology and guidelines. Computer programs with appropriate user interfaces need to be developed to facilitate the use of the methodology and guidelines.

3. Data collection strategies and data banks need to be established to help in the implementation of the proposed methodology and guidelines.
4. Validation and verification of the results of the methodology and guidelines cannot be performed at this stage; however, they need to be performed in the future after the use of the methodology and guidelines and the availability of an experience base.
5. The time-dependent nature of failure consequences needs to be examined in order to account for changes in societal values that are attached to the environment and human life.
6. Effect of the interaction of corrosion and fatigue on life expectancy needs to be investigated.

5. BIBLIOGRAPHY

The bibliography presented herein includes all the cited references in the main body of the report. It also includes other sources that were not cited, but provide additional information on risk methods and their applications.

ABS, “Fracture Mechanics and Fitness for Service”, Surveyor, pp. 21-27, American Bureau of Shipping, March, 1996.

ABS, “Guide for Fatigue Strength Assessment of Tankers”, American Bureau of Shipping, June, 1992.

ABS, “Rules for Building and Classing Steel Vessels - Part 1, Classification, Testing and Surveys”, American Bureau of Shipping, 1995.

Adamchak, J.C., (1984) “An Approximate Method for Estimating the Collapse of a Ship’s Hull in Preliminary Design” in *Proceedings,* SSC-SNAME Ship Structure Symposium, Arlington, Va., Oct. 1984.

Akpan, U.O. and Luo, X., (2000), “Probabilistic Analysis of Solid Rocket Motors; Martec Technical Report TR-00-11.

Allen, D. E., (1981). “Criteria for design safety factors and quality assurance expenditure,” Structural Safety and Reliability, Elsevier, 667-678.

American Society of Civil Engineers (ASCE), (1966). “Rx for risk communication.” Civil Engineering Magazine, Reston, VA.

American Society of Mechanical Engineers (ASME). (1993). “The use of decision-analytic reliability methods in codes and standards work.” CRTD-Vol.23, New York, N.Y.

Ames, B., Megaw, R., and Golds, S., (1990). “Ranking possible carcinogen hazards.” Readings in Risk, 17-92.

Ang, A. H-S. and Tang, W. H., (1990) “Probability Concepts in Engineering Planning and Design.” Volume II- Decision, Risk, and Reliability. John Wiley & Sons, Inc. New York.

Ang, A.-H., Cheung, M.C., Shugar, T.A., Fernie, J.D. (1999) “Reliability-Based Fatigue Analysis and Design of Floating Structures.” Proceedings of the Third International Workshop on Very Large Floating Structures, R.C. Ertekin and J.W. Kim, eds., Honolulu, USA, 375-380.

Ayyub, B. M. (1999). “Guidelines on expert-opinion elicitation of probabilities and consequences for corps facilities.” Institute for Water Resources, USACE.

Ayyub, B. M. 1994. "The Nature of Uncertainty in Structural Engineering," in Uncertainty Modelling and Analysis: Theory and Applications, edited by Ayyub, and Gupta, North-Holland-Elsevier Scientific Publishers, 195-210.

Ayyub, B. M. and Haldar, A. (1984) “Practical Structural Reliability Techniques.” Journal of Structural Engineering, ASCE, 110(8), 1707-1724.

Ayyub, B. M., (1991). "Systems framework for fuzzy sets in civil engineering." International Journal of Fuzzy Sets and Systems, North-Holland, Amsterdam, 40(3), 491-508.

Ayyub, B. M., (1992). "Generalized treatment of uncertainties in structural engineering." Analysis and Management of Uncertainty: Theory and Applications, Edited by Ayyub and Gupta, Elsevier Science Publisher, NY, 235-246.

Ayyub, B. M., and Moser, D. A., 2000. Economic Consequence Assessment of Floods in the Feather River Basin of California Using Expert-Opinion Elicitation, Technical Report, Institute for Water Resources, USACE.

Ayyub, B. M., and White, G. J., (1990b) "Structural Life Expectancy of Marine Vessels," Marine Structures: Design, Construction and Safety, published by Elsevier Applied Science and International Ship & Offshore Structures Congress, 3(4), April 1990, 301-317.

Ayyub, B. M., Assakkaf, I., Popescu, C., and Karaszewski, Z. (1998). "Methodology and guidelines for risk-informed analysis for the engine room arrangement model." Tech. Rep. No. CTSM-98-RIA-ERAM-2, Center for Technology and Systems Management, University of Maryland at College Park, MD.

Ayyub, B. M., Fault Tree Analysis of Cargo Elevators Onboard Ships, BMA Engineering Report, prepared for Naval Sea System Command, U.S. Navy, Crystal City, VA, 1992.

Ayyub, B. M., Handbook for Risk-Based Plant Integrity, BMA Engineering Report, prepared for Chevron Research and Technology Corporation, Richmond, CA, 1993.

Ayyub, B. M., McCuen, R. H. (1997). Probability, Statistics, and Reliability for Engineers. CRC Press, FL.

Ayyub, B. M., Riley, B. C., and Hoge, M. T., 1996. Expert Elicitation of Unsatisfactory-Performance Probabilities and Consequences for Civil Works Facilities, Technical Report, USACE, Pittsburgh District, PA.

Ayyub, B.M., "Guidelines for Probabilistic Risk Analysis of Marine Systems," U. S. Coast Guard, 1997, 83 pages.

Ayyub, B.M., & White, G.J. (1990a) "Life Expectancy of Marine Structures." Marine Structures, Vol. 3, 301-317.

Ayyub, B.M., (Editor), (1998). Uncertainty Modeling and Analysis in Civil Engineering. CRC Press.

Ayyub, B.M., and Chao, R.-J., 1998. "Chapter 1. Uncertainty Modeling in Civil Engineering with Structural and Reliability Applications," in Uncertainty Modeling and Analysis in Civil Engineering, edited by B. Ayyub, CRC Press, 1-32.

Ayyub, B.M., and Gupta, M.M., (Editors), 1997, Uncertainty Analysis in Engineering and the Sciences: Fuzzy Logic, Statistics, and Neural Network Approach, Kluwer Academic Publisher.

Ayyub, B.M., and White, G.J. (1995) " Chapter 18. Probability-Based Life Prediction," in Probabilistic Structural Mechanics Handbook, edited by C. Sundararajan, Chapman and Hall, 1995, 416-428.

Ayyub, B.M., and Wlicox, R. 1999. "A Risk-based Compliance Approval Process for Personal Flotation Devices," Final Report, prepared for U.S. Coast Guard, Office of Design and Engineering Standards, Lifesaving and Fire Safety Standards Division, Washington, DC, 165 pages.

Ayyub, B.M., Assakkaf, I., Atua, K., Engle, A., Hess, P., Karaszewski, Z., Kihl, D., Melton, W., Sielski, R.A., Sieve, M., Waldman, J., and White, G. J. Reliability-based Design of Ship Structures: Current Practice and Emerging Technologies, Research Report to the US Coast Guard, SNAME, T & R Report R-53, 1998.

Ayyub, B.M., Baecher, G., and Johnson, P., "Guidelines for Risk-Based Assessment of Dam Safety," U. S. Army Corps of Engineers, 1998, about 100 pages.

Ayyub, B.M., Guran, A., and Haldar, A., (Editors), 1997, Uncertainty Modeling in Vibration, Control, and Fuzzy Analysis of Structural Systems, World Scientific, 1997.

Ayyub, B.M., White, G.J., & Purcell, E.S. (1989) "Estimation of Structural Service Life of Ships." Naval Engineers Journal, 156-166.

Ayyub, B.M., White, G.J., Bell-Wright, T.F., & Purcell, E.S. (1990c) "Comparative Structural Life Assessment of Patrol Boat Bottom Plating." Naval Engineers Journal, 253-262.

Bailey, K. D. (1994). Methods of Social Research. The Free Press, Maxwell Macmillan, NY.

Balkey, K.R., Abramson, L., Ayyub, B.M., Vic Chapman, O.J., Gore, B.F., Harris, D.O., Karydas, D., Mauney, D.A., Phillips, J.H., Simonen, F.A., Smith, H., Smith, L.G., Tomes, C.A., and Vo, T.V., "Risk-Based Inspection - Development of Guidelines, Volume 3 - Fossil Fuel-Fired Electric Power Generating Station Applications," CRTD - Vol. 20-3, The American Society of Mechanical Engineers, Washington, DC, 1994, 177 pages.

Balkey, K.R., Ayyub, B.M., Vic Chapman, O.J., Gore, B.F., Harris, D.O., Karydas, D., Simonen, F.A., and Smith, H., "Risk-Based Inspection - Development of Guidelines, Volume 1 - General Document," CRTD - Vol. 20-1, The American Society of Mechanical Engineers, also NUREG/GR - 0005 Vol. 1 by Nuclear Regulatory Commission, Washington, DC, 1991, 200 p.

Balkey, K.R., Ayyub, B.M., Vic Chapman, O.J., Gore, B.F., Harris, D.O., Phillips, J.H., Krishnan, F.A., Karydas, D., Simonen, F.A., Smith, H., and Vo, T.V., "Risk-Based Inspection - Development of Guidelines, Volume 2 - Part 1 Light Water Reactor Nuclear Power Plant Components," CRTD - Vol. 20-2, The American Society of Mechanical Engineers, also NUREG/GR - 0005 Vol. 2 - Part 1 by Nuclear Regulatory Commission, Washington, DC, 1993, 130 pages.

Balkey, K.R., Simonen, F.A., Gold, J., Ayyub, B.M., Abramson, L., Vic Chapman, O.J., Gore, B.F., Harris, D.O., Mauney, D., McNeill, A., Phillips, J.H., Siu, N., Smith, H., Smith, L., Tomes, C.A., and Vo, T.V., "Risk-Based Inspection - Development of Guidelines, Volume 2 - Part 2 Light Water Reactor Nuclear Power Plant Components," CRTD - Vol. 20-4, The American Society of Mechanical Engineers, 1998, 140 pages.

Bea, R. G, 1992, *Marine Structural Integrity Programs (MSIP),* Report to Ship Structure Committee, SSC-365, Washington, DC.

Bea, R. G., 1993, "Marine Structural Integrity Programs," *Proceedings of the Ship Structures Symposium 93,* Society of Naval Architects and Marine Engineers and the Ship Structure Committee, Arlington, VA.

Bea, R. G., 1994b, "Marine Structural Integrity Programs," *Journal of Marine Structures*, Vol. 7, Elsevier Science Limited, England.

Bea, R. G., "Marine Structural Integrity Programs", Ship Structure Committee Report No. 365, 1992.

Bea, R. G., 1994c, "Evaluation of Alternative Marine Structural Integrity Programs," *Journal of Marine Structures*, Vol. 7, Elsevier Science Limited, England

Bea, R. G., and Xu, T., 1997, "In-Service Inspection Programs for Marine Structures," *Proceedings of the 16th International Offshore Mechanics and Arctic Engineering Conference*, American Society of Mechanical Engineers, New York, NY.

Bea, R. G., Cramer, E., Schulte-Strauthaus, R., Mayoss, R., Gallion, K., Ma, K., Holzman, R., Demsetz, L., "Ship's Maintenance Project", Conducted at University of California, Berkeley for U.S. Coast Guard/Ship Structure Committee (SSC), SSC-386, 1995.

Bea, R. G., Schulte-Strathaus, R., and Dry, M., 1996, "Ship Quality Information Systems", *Proceedings of Safe and Efficient Ships - New Approaches for Design, Operation and Maintenance*, The Institute of Marine Engineers, London.

Billingsley, D., (1980), "Hull Girder Response to Extreme Bending Moments" in *Proceedings,* SNAME STAR Symposium, Coronado, Calif., June 1980.

Blackman, H. S. (1997) "Human Reliability Assessment Training Course." University of Maryland Center for Technology and Systems Management, University of Maryland, College Park, Maryland

Brannigan, V. and Smidts, C. (1998). "Fire risk models involving intentional uncertainty."

Brannigan, V., and Smidts, C. (1996). "Risk based regulations using probabilistic risk assessment in undefined environments." Probabilistic Safety Assessment Conference Proceedings.

Caldwell, J.B., (1980),"Ultimate Longitudinal Strength" *Trans.* RINA, 1965.

Chen, Y.K., Kutt, L.M., Piaszczyk, C.M., and Bieniek, M.P., (1983), "Ultimate Strength of Ship Structures," *Trans.* SNAME, Vol. 91, 1983.

Chevron Shipping Company, "Chevron Shipping Company Standards for Sacrificial Anodes", 1990.

Committee III.1 Report, Proceedings of the Seventh International Ship Structures Congress, Paris, 1979.

Daidola, J.C. and Basar, N.S. Probabilistic Structural Analysis of Ship Hull Longitudinal Strength. AD-A099118, 1981.

Demsetz, L. A., Cairio, R., and Schulte-Strathaus, R., 1996, "Inspection of Marine Structures," Ship Structure Committee Report No. 389, 1996a.

Derby, S. L., and Keeney, R. L. (1990). "Risk analysis: understanding how safe is safe enough." Readings in Risk, 43-49.

Dexter, R. J., and Pilarski, P., 2000. SR 1392, Ship Structure Committee.

DNV, "Fatigue Assessment of Ship Structures", Draft Det Norske Veritas Classification Note, January, 1995.

DNV, "Inspection, Monitoring, Maintenance/Repair", Report of Committee V.2, 11th International Ship & Offshore Structures Congress, China, 1991.

DNV, "Structural Damage - Corrosion", Casualty Information No. 5/92, Det Norske Veritas Classification AS, 1992.

DNV, "Structural Reliability Analysis of Marine Structures", Classification Notes No. 30.6, Det Norske Veritas Classification AS, July, 1992.

Dobson, W.G., Brodrick, R.F, Wheaton, J.W., Giannotti, J., and Stambaugh, K.A., (1983), "Fatigue Considerations in View of Measured Load Spectra," SSC 315.

Douglas, J. (1985). "Measuring and managing environmental risk." EPRI Journal, July/August, 7-13.

Dow, R.S., Hugill, R.C., Clark, J.D., and Smith, C.S., (1981), "Evaluation of Ultimate Ship Hull Strength" in *Proceedings* SSC-SNAME Extreme Loads Response Symposium. Arlington, Va., Oct. 1981.

Drury, C. G., Lock, M. W. B. (1996). "Ergonomics in Civil Aircraft Inspection," Human Error in Aircraft Inspection and Maintenance, Paper Presented to Marine Board Committee on Human Performance, organizational Systems, and Maritime Safety, National Academy of Engineering, National Research Council, Washington, D. C.

Ellingwood, B.R. (1995) "Engineering Reliability and Risk Analysis for Water Resources Investments; Role of Structural Degradation in Time-dependent Reliability Analyses." Contract Report ITL-95-3, U.S. Army Corps of Engineers, Vicksburg, MS., 1-56.

Ellingwood, B.R., & Mori, Y. (1993) "Probabilistic Methods for Condition Assessment and Life Prediction of Concrete Structures in Nuclear Plants." Nuclear Engineering and Design, Vol. 142, 155-166.

Farmer, F. R., (1967). "Reactor safety and siting: a proposed risk criterion." Nuclear Safety, 8(6), 539-548.

Faulkner, D., (1975),"A Review of Effective Plating for Use in the Analysis of Stiffened Plating in Bending and Compression," *Journal of Ship Research*, Vol. 19, No. 1, March 1975.

Feldman A. D., and Owen, H. J., (1997). "Communication of flood-risk information." Proceedings of a Hydrology & Hydraulics Workshop on Risk-Based Analysis for Flood Damage Reduction Studies, HEC, USACE, Davis, CA.

Ferguson, J.M., "Bulk Carriers - The Challenge", Lloyd's Register of Shipping, May 1991b.

Ferguson, J.M., "Some Considerations Regarding Tank Inspection Priorities for Oil Tankers", SNAME, Paper presented at the Marine Structural Inspection, Maintenance, and Monitoring Symposium, Arlington, Virginia, March 18-19 1991a.

Fuchs, H.O., and Stephens, R.I. (1980) "Metal Fatigue in Engineering." John Wiley&Sons, USA.

Fujimoto, Y., et al., 1991, "Inspection Planning for Deteriorating Structures Based on Sequential Cost Minimization Method," *Proceedings of the 11th Offshore Mechanics and Arctic Engineering Conference*, American Society of Mechanical Engineers, New York, NY.

Gallion, Keith A., "Repair Management System - A System to Aid in the Diagnosis of Ship Structural Failures and the Evaluation of Repair Alternatives", Project Report No. SMP 4-1, Structural Maintenance for New and Existing Ships, Dept. of Naval Architecture & Offshore Engineering, U.C. Berkeley, 1992.

Gallion, Keith A., "Structural Maintenance Project Volume 3 Repairs and Maintenance", Ship Structure Committee Report (SSC) SSC-386 1995.

Gertamn, D. I., and Blackman, H. S., (1994). Human Reliability & Safety Analysis Data Handbook. John Wiley & Sons, Inc, NY.

Goodwin, Michael J. and Hansen, Kurt A., "Evaluation of Innovative Vessel Inspection Techniques (Phase II, Advanced Technology)", Report prepared for U.S. Coast Guard and U.S. Department of Transportation, July, 1995.

Grose, V. L., (1987). Managing Risk, Obega System Group, Arlington, Va.

Gruhn, P. “The pros & cons of qualitative & quantitative analysis of safety systems.” ISA Transactions. Volume 30 No 4, 79-86.

Guedes Soares, C., and Ivanov, L. D., 1989. Time-Dependent Reliability of the Primary Ship Structures, Reliability Engineering and System Safety, No. 26, 59-71.

Hanes, B. J., Chess, C., Sandman, P. M. (1991). Industry Risk Communication Manual: Improving Dialogue with Communities. CRC Press, Fl.

Hansen, K. A., “Evaluating Technology for Marine Inspectors”, U.S. Coast Guard Research and Development Center, 1995.

Harrald, J., (1999). The Washington State Ferry Risk Assessment, Washington State Department of Transportation.

Hart, C. J., (1988). A Study of the Factors Influencing the Rough Water Effectiveness of Personal Flotation Devices. DTRC-88/026.

Heller, R.A. and Thanjitham, S., (1993), “A Survey of Probabilistic Service Life Prediction Models for Structures,” IUTAM Symposium on Probabilistic Structural Mechanics, eds. Spanos, P.D. and Wu, Y.T., Springer, NY, pp 237-267.

Helmer, O., (1968). “Analysis of the future: the Delphi method,” and “The Delphi method – an illustration,” in J. Bright (ed.), Technological Forecasting for Industry and Government, Prentice Hall, Englewood Cliffs, NJ.

Holzman, Robert S., Lt., USCG, “Advancements In Tankship Internal Structural Inspection Techniques”, Dept. of Naval Architecture, Univ. of California, Berkeley, 1992.

Huang, R. T., 1999. “Corrosion Protection of Ballast & Cargo Tanks of Crude Oil Tankers,” The International Workshop on Corrosion Control for Marine Structures and Pipelines, Galveston, TX, February 9-11, 1999.

Hughes, O.F. (1988) “Ship Structural Design: A Rationally-Based Computer-Aided Optimization Approach.” John Wiley&Sons, USA.

Hughes, O.F., (1983), Ship Structural Design: A Rationally-based Computer-aided Optimization Approach, Wiley Interscience Publication.

IACS (International Association of Classification Societies), “Bulk Carriers - Guidelines for Surveys, Assessment and Repair of Hull Structure”, 1994.

IMO, “ANNEX 2: Information on Bulk Carrier Losses 1990-1994”, pp.1-pp.9, Bulk Carrier Safety, Maritime Safety Committee, 65th session, MSC 65/INF.15, 31 March, 1995.

International Code of Safety for High-Speed Craft. (1995). International Maritime Organization, pp 175-185 (Annex 4: Procedure for Failure Mode and Effects Analysis)

International Maritime Organization. (1995). International Code of Safety for High-Speed Craft (HSC Code). Resolution MSC.36(63) adopted on May 20, 1994.

Ivanov, L. D., 1986. “Statistical Evaluation of the Ship Hull Cross Section Geometrical Characteristics as a Function of Her Age,” International Shipbuilding Progress, November 1986, No. 387, 198-203.

Ivanov, L. D., and Caldwell, J. B., 1976. “On the Use of Statistical Dynamics in the Calculation of the Reliability of Ship Structures,” International Shipbuilding Progress, March 1976, No. 259, 198-203.

Jensen, J.J. and Petersen, P.T., (1979), "Wave Induced Bending Moments in Ships – A Quadratic Theory," *Trans.* RINA, Supplementary Paper, vol. 121, pp 151-165.

Jones, R. B., 1995, *Risk-Based Management - A Reliability-Centered Approach*, Gulf Publishing Co., Houston, TX.

Jordan and Cochran, C.S., Newport News Shipbuilding, "In-Service Performance of Structural Details", Ship Structure Committee, Report No. SSC-272, 1978.

Jordan and Knight, L.T., Newport News Shipbuilding, "Further Survey of In-Service Performance of Structural Details", Ship Structure Committee, Report No. SSC-294, 1980.

Kahn, H., and Wiener, A. J. (1967). The Year 2000: A Framework for Speculation, Macmillan, NY.

Kirkhope, K.J., R.I. Basu, J.D. O'Reilly and M. Smith, An Analysis of Structural Repair Histories of Canadian Warships and its Implications, presented at Canadian Maritime Industries Association 46th Annual Technical Conference, Ottawa, Canada, February 1994.

Kirwan, B., (1992). "Human error identification in human reliability assessment. Part 1: Overview of approaches." Applied Ergonomics. Volume 23 No 5, 299-318.

Kjellander, "Hull Damages on Large Swedish-Built Ships", 1972.

Klir, G. J., and Folger, T. A. (1988). Fuzzy Sets, Uncertainty, and Information, Prentice Hall, N.J.

Kumamoto, H., and Henley, E.J., 1996, *Probabilistic Risk Assessment and Management for Engineers and Scientists*, Second Edition, IEEE Press, New York.

Kutt, L.M., Piaszcayk, C.M., Chen, Y.K., and Liu, D., (1985), "Evaluation of the Longitudinal Ultimate Strength of Various Ship Hull Configurations," *Trans.* SNAME, vol. 93, 1985.

Linstone H. A., and Turoff, M. (1975). The Delphi Method, Techniques and Applications. Addison Wesley, MA.

Litai, D. (1980). "A risk comparison methodology for the assessment of acceptable risk." PhD thesis, Mass. Institute of Technology, Cambridge, Mass.

Liu, D. & Thayamballi, A., "Local Cracking in Ships - Causes, Consequences, and Control", Symposium and Workshop on the Prevention of Fracture in Ship Structure, National Research Council, Washington, DC, March 30-31, 1995.

Lloyd's Register, "Breaking the Back of the Bulker Problem", 100A1 Magazine, Lloyd's Register of Shipping, Issue 1, 1995.

Lloyd's Register, "Rules and Regulations for the Classification of Ships - Periodical Survey Regulations", Lloyd's Register of Shipping, January, 1996.

Lotsberg and Kirkemo, F., "A Systematic Method for Planning In-Service Inspection of Steel Offshore Structures," Proceedings of OMAE Europe 89-8th International Conference on Offshore Mechanics and Arctic Engineering, The Hague, The Netherlands, March 18-23 (1989).

Loukakis, T.A. and Chryssostomidis, C., (1975), "Seakeeping Series for Cruiser Ships," *Trans.* SNAME vol 83.

Ma, K.T., Orisamolu, I.R., Bea, R.G., and Huang, R.T., (1997), "Towards Optimal Inspection Strategies for Fatigue and Corrosion Damage," *Proceedings*, The Society of Naval Architects and Marine Engineers SNAME Meeting, Ottawa, paper No. 3.

Ma, Kai-tung and Bea, Robert G., “Durability Considerations for New & Existing Ships - Design and Maintenance Procedures to Improve the Durability of Critical Internal Structural Details in Oil Tankers”, SMP Report-5-1, Department of Naval Architecture & Offshore Engineering, University of California, Berkeley, September, 1992.

Ma, Kai-tung and Bea, Robert G., “RMS--Repair Management System (Further Development)”, SMP Report No. 4-2, Department of Naval Architecture & Offshore Engineering, University of California, Berkeley, September 1993.

Ma, K-T, Orisamolu, I. R. and Bea, R. G., 1998. “Optimal Strategies for Inspection of Ships for Fatigue and Corrosion Damages”, Final Report submitted to the Ship Structure Committee, SR-1365, U. S. Coast Guard, Washington, DC, USA, 1998

Ma, K-T., and Bea, R.G. (1995) “A Repair Management System for Fatigue Crack in Ships.” Society of Naval architects and Marine Engineers, Transactions, 103, 343-369.

Madsen, H.O., Torhaug, R., and Cramer, E.H. (1991) “Probability Based Cost Benefit Analysis of Fatigue Design, Inspection and Maintenance.” Proceedings, Marine Structural Inspection, Maintenance and Monitoring Symposium, The Ship Structure Committee and The Society of Naval Architects, eds., New York.

Mansour, A., Wirsching, P., Lucket, P., and Plumpton, A., (1997), “Assessment of Reliability of Ship Structures”, SSC-398.

Mansour, A.E., and Hoven, L., (1994), “Probability-based Ship Structural Safety Analysis,” *Journal of Ship Research*, Vol. 38, No. 4, pp 329-339.

Mansour, A.E., Wirsching, P.H. Lucket, M.D., and Lin, Y.H., (1997), “Structural Safety of Ships,” *Proceedings*, The Society of Naval Architects and Marine Engineers SNAME Meeting, Ottawa, paper No. 3.

Marshall, K. T. and Oliver, R. M. (1995). Decision Making and Forecasting. McGraw Hill, NY.

Modarres, M. (1993). What every engineer should know about reliability and risk analysis. Mercel Deccer, Inc. New York.

Morgan, M. (1990). “Choosing and managing technology induced risk.” Readings in Risk, 17-30.

Munse, W.H., Wilbur, T.W., Twllalian, M.L., Nicoll, K., and Wilson, K., “Fatigue Characterization of Fabricated Ship Details for Design”, Ship Structure Committee (318) Report 318, 1983.

Nakajima, Y., Iino, N., Neki, I., Ushirokawa, O., Maeda, M., and Sasajima, H., “Fatigue Strength Design of Ship Structure”, IHI Engineering Review, Vol. 26, No. 2, April, 1993.

National Research Council, 1983a, Risk Assessment in the Federal Government: Managing the Process, National Academy Press, Washington, D.C.

National Research Council, 1989, Improving Risk Communication, National Academy Press, Washington, D.C.

National Research Council, 1991, Ecological Risks: Perspectives from Poland to the United States, National Academy Press, Washington, D.C.

National Research Council, 1991, Use of Risk Analysis to Achieve Balanced Safety in Building Design and Operation, National Academy Press, Washington, D.C.

National Research Council, 1994, Science and Judgment in Risk Assessment, National Academy Press, Washington, D.C.

National Research Council, 1995, Flood Risk Management and the American River Basin: An Evaluation, National Academy Press, Washington, D.C.

National Research Council, 1996, Understanding Risk: Informing Decisions in a Democratic Society, National Academy Press, Washington, D.C.

Nuclear Regulatory Commission, (1997). Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Expert Use, prepared by the Senior Seismic Hazard Analysis Committee, NUREG/CR-6372, UCRL-ID-122160, Vol. 1 and 2, Washington, DC.

Nuclear Regulatory Commission, 1996. NUREG/CR 2300, Washington, DC.

NUREG/CR 2300. (1983). PRA Procedures Guide: A guide to the performance of probabilistic risk assessments for nuclear power plants. U.S. Nuclear Regulatory Commission, Washington, D.C.

NUREG-0492. (1981). Fault Tree Handbook, U.S. Nuclear Regulatory Commission, Washington, D.C.

Ohyagi, M. (1987). *Statistical Survey on Wear of Ship's Structural Members*. NK Technical Bulletin; also *Statistical Survey on War of Ship's Structural Members by Thickness Measurement Data*. Research Institute of Nippon Kaiji Kyokai (1983).

Omega Systems Group. (1994) "Risk realities, provoking a fresh approach to managing risk."

Orisamolu, "Probabilistic Cost-Optimal Strategies for Reliability-Based Maintenance of Aircraft Structures," presented at the Second Canadian Forces Aircraft Structural Integrity Program (ASIP) Symposium, DAS Eng/NRC, Ottawa, Ontario, May (1993).

Orisamolu, I. R., et al., "Pilot Studies for Structural Risk Assessment Program (STRAP)", Technical Report submitted to the Defence Research Establishment Atlantic (DREA), Halifax, Nova Scotia, 1993

Orisamolu, I. R., Luo, X and Lichodzijewski, M, "Development of Optimal Strategies for Inspection/Monitoring/Maintenance/Repair and Life Extension," Canadian Department of National Defense Final Report, 1999 about 120 pages.

Orisamolu, I.R., Akpan, U.O., Brennan, D.B., (1999), "Application of Probabilistic Corrosion Models for Reliability Assessment of Ship Structural Panels," presented at the 8th CF/CRAD Meeting on Naval Application of Materials Technology and Inter-naval Corrosion Conference, Halifax, NS, 1999.

Orisamolu, I.R., Brennan, D.B., and Akpan, U.O., (1999), "Probabilistic Modeling of Corroded Ship Structural Panels," presented at the 8th CF/CRAD Meeting on Naval Application of Materials Technology and Inter-naval Corrosion Conference, Halifax, NS, 1999.

Orisamolu, I.R., Brennan, D.B., and Akpan, U.O., (1999), "Proobabilistic Residual Strength Assessment of Damaged Pipelines," Martec Technical Report, TR-98-07.

Orisamolu, Liu, Q., and Chernuka, M.W., "Development of Computational Algorithms for Probabilistic Fatigue and Fracture Reliability," Martec Technical Report No. TR-93-07, July (1993).

Park, J.K., (1993), "ALPS/ISUM: A Computer Program for Non-linear Analyses of Large Plated Structures Using the Idealized Structural Unit Method," Pusan National University, Pusan.

Park, J.K., Kim, S.K., and Lee, S.K., (1998), "Probabilistic Corrosion Rate Estimation Model for Longitudinal Strength Members of Bulk Carriers," Ocean Engineering, vol. 25, no. 10, pp. 837-860.

Parker, S. P. (1994). McGraw-Hill dictionary of Scientific and Technical Terms, Fifth Edition.

Parry, G. (1996) “The Characterization of Uncertainty in Probabilistic Risk Assessments of Complex Systems.” Reliability Engineering and System Safety, Vol. 54, 119-126.

Pate-Cornell, E. M. (1996). “Global risk management.” Journal of Risk and Uncertainty, 12, 239-255.

Pate-Cornell, M. E. (1996). “Treatment of uncertainties in risk analysis: management relevance and comparison issues.” PSA Conference Proceedings.

Pegg, N. G., and Brinkhurst, P., (1993). “Naval Ship Structures Risk Assessment Project Definition,” DREA TM/93/209.

Pegg, N. G., and Gibson, S., (1997). “Applications of Advanced Analysis Methods to the Life Cycle Management of Ship Structures,” Proceedings of the International Conference on Advances in Marine Structures III, Session 9, Paper 25, Dera Rosyth, UK, 16 pages.

Proceedings of the Workshop on Model Uncertainty and Quantification. (1993). “Model uncertainty: its characterization and quantification.” Annapolis, MD, 241-251.

Rasmussen, N. C. (1981) “The application of probabilistic Risk Assessment Techniques to Energy Technologies.” Annual Review of Energy. Vol. 6, 123-138.

Reason, J. (1990) Human Error. Cambridge University Press.

Rolfe, S.T., and Barsom, J.M. (1987) “Fracture & Fatigue Control in Structures: Applications of Fracture Mechanics.” Prentice-Hall Inc., New York, USA

Rowe, W. D. (1977). An Anatomy of Risk, Wiley, N.Y.

Schall and Öestergaard, C., “Planning of Inspection and Repair of Ship Operation,” Proceedings of the Marine Structural Inspection, Maintenance and Monitoring Symposium, SNAME pp. V-F-1 V-F-7, (1991).

Schulte-Strathaus, Rolf, “Fatigue Database Development and Analysis”, Project Report No. SMP-4, Structural Maintenance for New and Existing Ships, Dept. of Naval Architecture & Offshore Engineering, U.C. Berkeley, 1991.

Shinozuka, “Relation of Inspection Findings to Fatigue Reliability,” Ship Structure Committee, Report No. SSC-355, (1990).

Shinozuka, P. M. and Chen, Y.N., “Reliability and Durability of Marine Structures,” ASCE, Journal of Structural Engineering, Vol. 113, No. 6, pp. 1297-1314 (1987).

Ship Structure Committee (1999) "Fatigue Resistance Detail Design.” Ship Structure Committee report SSC-405, U.S. Coast Guard, Washington, D.C., USA.

Sipes, J.D., “Follow-up Report on the Trans-Alaska Pipeline Service (TAPS) Tanker Structural Failure Study”, Office of Marine Safety, Security and Environmental Protection, United States Coast Guard, Washington, D.C., May, 1991.

Sipes, J.D., “Report on the Trans-Alaska Pipeline Service (TAPS) Tanker Structural Failure Study”, Office of Marine Safety, Security and Environmental Protection, United States Coast Guard, Washington, D.C., June 25, 1990.

Skjong and Torhaug, R., “Rational Methods for Fatigue Design and Inspection Planning of Offshore Structures,” Marine Structures, Vol. 4, pp. 381-406 (1991).

Skjong, "Reliability-Based Optimization of Inspection Strategies", in: Proceedings of the 4th International Conference on Structural Safety and Reliability, 1985, Vol. III, pp. 614-618, IASSAR (1985).

Skjong, M. R., Tallin, A.G. and Kirkemo, F., "Probabilistic Fatigue Crack Growth Analysis of Offshore Structures with Reliability Updating Through inspection," in: Proceedings of the Marine Structural Reliability Symposium, SNAME, pp. 455-56 (1987).

Slovic, P., Schhoff, B., and Lechtenstein, S. (1990). "Rating the risks." Readings in Risk, 61-74.

Soares, C.G., and Ivanov, L.D. (1989) "Time-dependent Reliability of Primary Ship Structure." Reliability Engineering and System Safety, Vol. 26, pp 59-71.

Soares, C.G., and Garbatov, Y. (1996) "Influence of Inspection and Repair on The Fatigue Reliability of Oil Tankers." Proceedings, 15th Conference on Offshore Mechanics and Artic Engineering, C. G. Soares, R.G. Bea, B.J. Leira, N.K. Shetty, W.S. Atkins, and J.E. Vinnem, eds., ASME, New York, 245-254.

Soares, C.G., and Ivanov, L.D., (1989), "Time-dependent Reliability of the Primary Ship Structure," Reliability Engineering and Systems Safety, vol. 28, pp 59-71.

Stambaugh, K.A. and Wood, W.A. *Part 1 – Ship Fracture Mechanisms Investigation.* Ship Structure Committee Report SSC-337, 1991.

Stanley, Robert, "Comments on the Draft Report of SSC Project SR-1365, Optimal Strategies for Inspection of Ships for Fatigue and Corrosion Damage", Maritime Overseas Corporation, October, 1996.

Starr, C. (1969). "Social benefit vs. technical risk." Science, Vol. 165,1232-1238.

Starr, C. (1971). "Benefit cost studies in socio-technical systems, in perspectives on benefit-risk decision making." National Academy of Engineering, Washington, D.C.

Strange, G. (1986) Introduction to applied mathematics. Wllesley-Cambridge Press, Wellesley, Mass.

Suzuki, H., (1999). "Safety target of very large floating structures used as a floating airport," Proceedings of the Third International Workshop on Very Large Floating Structures, Honolulu, Hawaii, 607-612.

Tagart, R. (1980) "Ship Design and Construction." The society of Naval Architects and Marine Engineers.

Thayamballi, A. K., Chen, Y.K., and Chen, H.H., (1987), "Deterministic and Reliability Based Retrospective Strength Assessment of Oceangoing Vessels," *Trans.* SNAME, vol. 95, pp 159-187.

Tikka, Kirsi K., Chevron Shipping, "Inspection and Structural Maintenance of Chevron Double Hull Tankers", 1991.

Trauth, K. M., Hora, S. C., and Guzowski, R. V., (1993). Expert Judgement on Markers to Deter Inadvertent Human Intrusion into the Waste Isolation Pilot Plant, Report SAND92-1382, Sandia National Laboratories, Albuquerque, NM.

TSCF (Tanker Structure Cooperative Forum), "Condition Evaluation and Maintenance of Tanker Structure", TSCF Work Group report, 1992.

TSCF (Tanker Structure Cooperative Forum), “Guidance Manual for the Inspection and Condition Assessment of Tanker Structures”, International Chamber of Shipping Oil Companies International Marine Forum, 1986.

TSCF (Tanker Structure Cooperative Forum), “Guidance Manual for Tanker Structures”, Issued by Tanker Structure Co-operative Forum in association with International Association of Classification Societies, Witherby & Co. Ltd., 1997.

TSCF (Tanker Structure Cooperative Forum), “Guidelines for the Inspection and Maintenance of Double Hull Tanker Structures”, Issued by Tanker Structure Co-operative Forum in association with International Association of Classification Societies, Witherby & Co. Ltd., 1995.

U. S. Army Corps of Engineers (USACE). (1993). Guidebook for Risk Perception and Communication in Water Resources, IWR Report, USACE, Report 93-R-13, Alexandria, VA.

USAF Aeronautical Systems Division, “Aircraft Structural Integrity Program,” Airplane Requirements, MIL-STD-1530A, December, (1973).

USCG, IACS and NKK, “Bulk Carriers Inspection Guidance for Owners/Operators, Terminal Personal, and Crew”, Compiled for the International Maritime Organization (IMO), U.S. Coast Guard Headquarters, Washington, D.C., June, 1995.

Viner, A.C., (1986),“Development of Ship Strength Formulations,” *Proceedings*, Symposium on Advances in Marine Structures, ARE, Dunfermline, U.K. May 1986; Elsevier Applied Science Publishers, London and New York, 1986.

Vo, T. V., and Balkey, K.R. (1995) “Chapter 17:Risk-Based Inspection and Maintenance.” In Probabilistic Structural Mechanics Handbook, edited by C. Sundararajan, Chapman and Hall, 388-415.

Whipple, C. (1986). “Dealing with uncertainty about risk in risk management.” Hazards: Technology and Fairness, National Academy of Engineering.

White, G. J. and Ayyub, B. M. (1985) “Reliability Methods for Ship Structures.” Naval Engineers Journal, 86-96.

Whitman, R. V. (1984). “Evaluating calculated risk in geotechnical engineering.” ASCE Journal of Geotchnical Engineering, Vol. 110, No. 2, February.

Yang and Manning, (1990), “Stochastic Crack Growth Analysis Methodologies for Metallic Structures,” Engineering Fracture Mechanics, vol. 37, No. 5, pp 1105-1124.

Yang, J. N., 1993, "Application of Reliability Methods to Fatigue, Quality Assurance and Maintenance", *Proceedings of the 6th International Conference on Structural Safety and Reliability*, ICOSSAR 93, University of Innsbruck, Austria.

Yoneya, T., Kumano, A., Yamamoto, N. and Shigemi, T., “Hull Cracking of Very Large Ship Structures”, Integrity of Offshore Structures - 5, 1993.

A. RISK-BASED TECHNOLOGY METHODS

A.1. Introduction

Risk studies require the use of analytical methods at the system level that considers subsystems and components in assessing their failure probabilities and consequences. Systematic, quantitative, qualitative or semi-quantitative approaches for assessing the failure probabilities and consequences of engineering systems are used for this purpose. A systematic approach allows an engineer to evaluate expediently and easily complex engineering systems for safety and risk under different operational and extreme conditions. The ability to quantitatively evaluate these systems helps cut the cost of unnecessary and often expensive re-engineering, repair, strengthening or replacement of components, subsystems and systems. The results of risk analysis can also be utilized in decision analysis methods that are based on cost-benefit tradeoffs. The objective of this appendix is to introduce needed terminology and methods for performing risk studies including risk analysis, management and communication.

A.2. Risk Terminology

This section provides definitions that are needed for presenting risk-based technology methods and analytical tools.

A.2.1. Hazard

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 is a hazard. In order for the hazard to cause harm, it needs to interact with person(s) or thing(s) in a harmful manner. The magnitude of the hazard is the amount of harm that might result, including the seriousness and the exposure levels of people and the environment.

A.2.2. Reliability

Reliability can be defined for a system or a component as its ability to fulfill its design functions under designated operating or environmental conditions for a specified time period. This ability is commonly measured using probabilities. Reliability is, therefore, the occurrence probability of the complementary event to failure resulting in the following expression:

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

A.2.3. Failure Consequences

For an event of failure, consequences can be defined as the degree of damage or loss from some failure. Each failure of a system has some consequence(s). A failure could cause economic damage, environmental damage, injury or loss of human life, or other possible events.

Consequences need to be quantified using relative measures for various consequence types to facilitate risk analysis.

A.2.4. Risk

The concept of risk is used to assess and evaluate uncertainties associated with an event (Ayyub et al. 1998). Risk can be defined as the potential of losses resulting from exposure to a hazard. Risk should be based on an identified failure scenario, its occurrence probability, its consequences, consequence significance, and the population at risk; however, it is commonly and can be fundamentally measured as a pair of the probability of occurrence of an event, and the outcomes or consequences associated with the event's occurrence. This pairing can be represented by the following equation:

$$Risk \equiv \left[(p_1, c_1), (p_2, c_2), \ldots, (p_x, c_x)\right] \tag{A-2}$$

In Eq. A-2, p_x is the occurrence probability of event x, and c_x is the occurrence consequences or outcomes of the event. Risk is commonly evaluated as the product of likelihood of occurrence and the impact of an accident:

$$RISK\left(\frac{Consequence}{Time}\right) = LIKELIHOOD\left(\frac{Event}{Time}\right) \times IMPACT\left(\frac{Consequence}{Event}\right) \tag{A-3}$$

In Eq. A-3, the likelihood can also be expressed as a probability. A plot of occurrence probabilities, and consequences is called a risk profile or a Farmer curve (1967). An example farmer curve is given in Figure A-1 that was taken from Kumamoto and Henley (1996) based on a nuclear case study. It should be noted that the abscissa provides the number of fatalities, and the ordinate provides the annual exceedence probability or annual exceedence frequency for the corresponding number of fatalities.

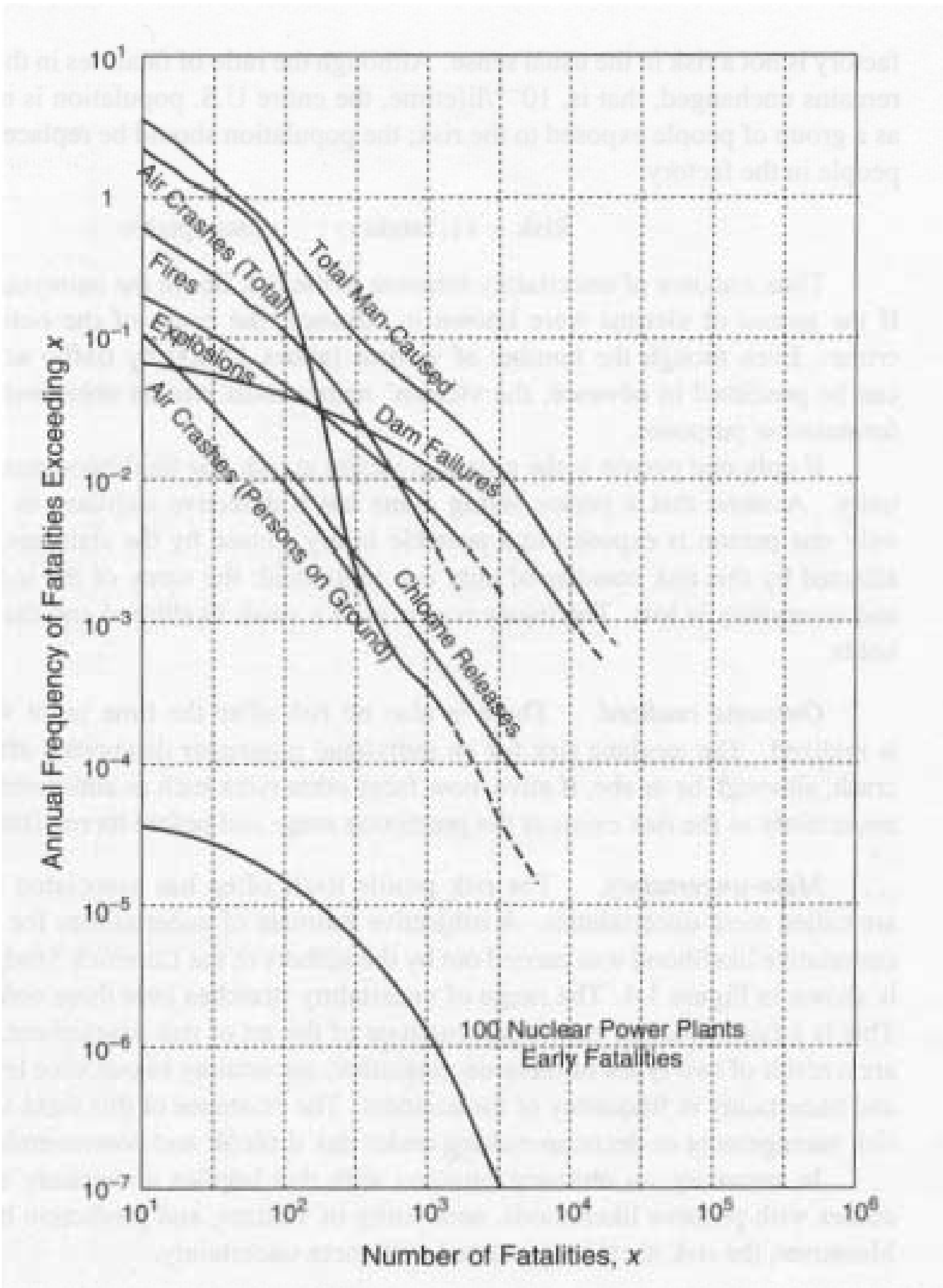


Figure A-1. Example Risk Profile (Kumamoto and Henley 1996)

A.2.5. Uncertainty

The analysis of an engineering system often involves the development of a model of the system. The model can be viewed as an abstraction of some aspects of the system. In performing this abstraction, an analyst or engineer must decide which aspects of the system to include and which to leave out. Also, depending on the state of knowledge about the system and the background of the analyst or engineer, other aspects of the system might not be known, thus increasing the overall uncertainty of the system. In these three categories, i.e., abstracted, non-abstracted, and unknown aspects of the system, several types of uncertainty can be present. Some of these uncertainty types that can be dealt with using probability, statistics, reliability and Bayesian methods (Ayyub 1991, 1992, 1994 and 1998, Ayyub and McCuen 1997). Uncertainty can be viewed as a subset of ignorance in the context of human knowledge.

Knowledge regarding some domain of interest may be broadly understood as the body of justified true beliefs pertaining to the domain. It is always defined in the context of humankind experiences, from which it cannot be removed. As a result, knowledge would always reflect the imperfect nature of humans that can be attributed to their reliance on their senses for knowledge acquisition, and mind for extrapolation, creativity and imagination, biasedness, and their preconceived notions due to time asymmetry. Engineering is a practice that often tries to make statements about the future especially in designing new systems. However, Aristotle asserted that contingent statements about the future have no truth value, unlike statements made about the past and present which are determinably either true or false. Ayyub (1999) provided a classification of ignorance in various categories including uncertainty. Klir and Folger (1988) developed and used various mathematical models and uncertainty measures to analyze and quantify uncertainty. These models are based not only on probability theory, but also on various combinations of fuzzy-set and rough-set theories with evidence theory, possibility theory, and various other theories formulated in terms of non-additive measures. Consistent methods of uncertainty measuring and modeling are needed that would allow combining the results from the models.

Parker (1994) viewed uncertainty as an estimated amount by which an observed or predicted value differs from the true value. The imprecision between a model and the real system may be due to lack of information, modeling assumptions, and incompleteness of the model. Uncertainty generally refers to two different concepts. One type of uncertainty is concerned with the random variability in some parameter or measurable quantity; often referred to as ambiguity or non-cognitive or aleatory uncertainty. Imprecision in an analyst's knowledge about models, their parameters, and predictions, is often referred to as vagueness or cognitive or epistemic uncertainty. For example, the Poisson model for estimating the inherent randomness of an event can be considered to represent an ambiguity uncertainty due to the inherent variability of this value. However, the uncertainty with choosing the Poisson model itself to represent the failure rate parameter is considered epistemic since there is some uncertainty with the knowledge of choosing this distribution. Also, classifications such as small, medium and large are vague yet meaningful classifications, thus have uncertainty of the vagueness type.

Three main types of uncertainty in risk assessment are commonly identified: parameter uncertainty, model uncertainty, and completeness uncertainty. Parameter uncertainties are the result of the estimation of parameters, contained in the model, through limited data or knowledge. Model uncertainty addresses the ability of the model to represent reality. Completeness uncertainty addresses the uncertainty of the model in representing all possible risk contributions. It is important to understand the differences of these uncertainties because a "complete" consideration of one type of uncertainty may still lead to insufficient understanding of the model. For example, parameter uncertainty is the most frequently addressed uncertainty type since this can be treated using well-established techniques such as probability and statistics theories. Model and completeness uncertainties are often avoided in uncertainty analysis because the analysis techniques are available but not commonly used, and the ability of the analyst to determine these uncertainties is often difficult.

A.2.6. Performance

The performance of a system or component can be defined as its ability to meet functional requirements. The performance of an item can be described by various elements including such items as reliability, capability, efficiency, and maintainability (Modarres 1993). The design and operation of the product or system influence performance.

A.2.7. Risk-based Technology

Risk-based technologies (RBT) are scientific methods or tools and processes used to assess and manage the risks of a component or system. RBT methods can be classified into risk management that includes risk assessment/risk analysis and risk control using failure prevention and consequence mitigation, and risk communication as shown in Figure A-2 (Ayyub et al. 1998).

Risk assessment consists of hazard identification, event-probability assessment, and consequence assessment. Risk control requires the definition of acceptable risk and comparative evaluation of options and/or alternatives through monitoring and decision analysis. Risk control also includes failure prevention and consequence mitigation. Risk communication involves perceptions of risk, which depends on the targeted audience, hence, classified into risk communication to the media and the public and to the engineering community.

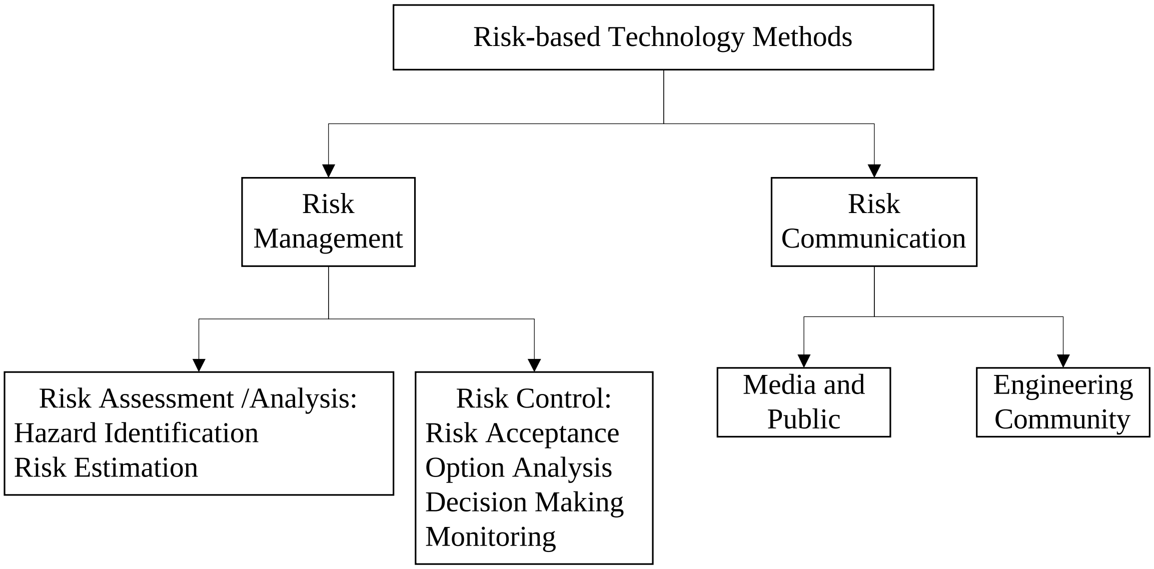


Figure A-2. Risk-based Technology Methods (Ayyub et al. 1998)

A.2.8. Safety

Safety can be defined as the judgment of risk acceptability for the system (Ayyub et al. 1998). Safety is a relative term since the decision of risk acceptance may vary depending on the individual making the judgment. Different people are willing to accept different risks as demonstrated by different factors such as location of residence, method of transportation, occupation, and lifestyle. The selection of these different activities demonstrates an individual’s safety preference despite a wide range of risk values. Table A-1 identifies varying risks for different activities.

Perceptions of safety may not reflect the actual level of risk in some activity. In a study performed by Slovic et al. (1979) several conclusions were obtained about the publics perception of safety. Uncertainty in risk for an activity is often denied by an individual causing an unwarranted confidence in a person’s perception of safety. Rare causes of death are often overestimated and common causes of death are often underestimated. Perceived risk is often biased by the familiarity of the hazard. The significance or the impact of safety perceptions stems from that decisions are often made on subjective judgments (Slovic et al. 1979). If the judgments hold misconceptions about reality, the bias will effect the decision. For example, the choice of transportation– train, automobile, motorcycle, bus, bicycle, etc. will result in a decision concerning many criteria including such items as cost, speed, convenience, and safety. The weight and evaluation of the decision of selecting a mode of transportation will rely on the individual’s perception of safety that may vary from the actual value of risk. Understanding these differences in risk and safety perceptions is vital to performing risk management decisions and risk communications as provided in the section on risk control and management.

Table A-1. Relative Risk of Different Activities (Douglas 1985)

Risk of Death	Occupation	Lifestyle	Hobby
High (10^{-2} to 10^{-3})	Stuntman Racecar Driver Fireman Miner	Smoking	Skydiving Rock Climbing
Medium (10^{-3} to 10^{-4})	Policeman Truck Driver	Heavy Drinking	Canoeing Driving Automobile
Low (10^{-4} to 10^{-5})	Banker Engineer Insurance Agent	Light Drinking Vaccinations Radiation	Skiing Fishing

A.2.9. Engineering Systems

A system can be defined as a deterministic entity comprising an interacting collection of discrete elements (NUREG-0492 1981). The word "deterministic" implies that the system is identifiable and not uncertain in its architecture. The definition of the system is based performing some functions and/or has performance requirements. A description of a system may be a combination of functional and physical elements. Usually functional descriptions are used to identify high levels of a system. A system may be divided into subsystems that interact. Additional detail leads to a description of the physical elements, components and various aspects of the system.

A.3. Risk Assessment

Risk assessment is a technical and scientific process by which the risk of a given situation for a system are modeled and quantified. Risk assessment can require and/or provide both qualitative and quantitative data to decision makers for use in risk management.

Risk assessment or risk analysis provides the process for identifying hazards, event-probability assessment, and consequence assessment. The risk assessment process answers three basic questions: (1) *What can go wrong?* (2) *What is the likelihood that it will go wrong?* (3) *What are the consequences if it does go wrong?* The development of the scenarios for risk evaluation can be created deductively (e.g. fault tree) or inductively (e.g. failure mode and effect analysis (FMEA)). The likelihood or frequency can be expressed either deterministically or probabilistically. Varying consequence categories may be evaluated including such items as: economic loss, loss of life, or injuries.

Risk assessment requires the utilization of several formal methods as shown in Table A-2. These different methods contain similar approaches to answer the basic risk assessment questions; however, some techniques may be more appropriate than others for risk analysis depending on the situation.

Table A-2. Risk Assessment Methods

Method	Scope
Safety/Review Audit	Identify equipment conditions or operating procedures that could lead to a casualty or result in property damage or environmental impacts.
Checklist	Ensure that organizations are complying with standard practices.
What-If	Identify hazards, hazardous situations, or specific accident events that could result in undesirable consequences.
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.
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.
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.
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.
Fault Tree Analysis (FTA)	Identify combinations of equipment failures and human errors that can result in an accident. This is n deductive modeling approach.
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.

A.3.1. System Definition

Defining the system is an important first step in performing a risk assessment. The examine of a system needs to be made a well-organized and repeatable fashion so that risk analysis can be consistently performed, therefore insuring that important elements of a system are defined and extraneous information is omitted. The formation of system boundaries is based upon the objectives of the risk analysis.

The establishment of boundaries assists in developing the system definition. The decision on what the system boundary will be is partially based on what aspects of the system's performance are of concern (NUREG-0492 1981). The selection of items to include within the external boundary region is also reliant on the goal of the analysis. This is an important step to system modeling since the comprehensiveness of the analysis will depend on the defined system boundary. Beyond the established system boundary is the environment of the system.

Boundaries beyond the physical/functional system can also be established. For example, time may also be a boundary since an overall system model may change, as a product is further along in its lifecycle. The lifecycle of a system is important because some potential hazards can change throughout the lifecycle. For example, material failure (corrosion or fatigue) may not be a problem early in the life of a system; however, this may be an important concern later in the lifecycle of the system.

Along with identifying the boundaries, it is also important to establish a resolution limit for the system (NUREG-0492 1981). The selected resolution is important since it limits the detail of the analysis. Providing too little detail will not provide enough information for the problem. Too much information may make the analysis more difficult and costly due to the added complexity. The depth of the system model needs to be sufficient for the specific problem. Resolution is also limited by the feasibility of determining the required information for the specific problem. For failure analysis, the resolution should be to the components level where failure data is available. Further resolution is not necessary and would only complicate the analysis.

The system breakdown structure is the top-down division of a system into subsystems and components. This architecture provides internal boundaries for the system. Often the systems/ subsystems are identified as functional requirements that eventually lead to the component level of detail. The functional level of a system identifies the function(s) that must be performed for operation of the system. Further decomposition of the system into “discrete elements” lead to the physical level of a system definition identifying the hardware within the system. By organizing risk hierarchy (top down) rather than fragmentation of specific systems, a rational, repeatable and systematic approach to safety is achieved as described by Omega System Group 1994.

While the system model provides boundaries for the systems/subsystem/components, it does not provide for an integrated view. Systems integration is an important part in evaluating the ability of a system to perform. The problem with segregating a system is that when the subsystems are assembled to form the overall system, failures may occur that are not obvious while viewing the individual subsystems/components (NUREG-0492 1981). Therefore, the interfaces should be evaluated. This is especially important for consideration of human factors on the performance of a system. The potential for human error must be considered in performing a systems analysis. Also, the potential for corrective actions from fault situations should be considered (NUREG-CR2300 1983). Different people have varying views on how to operate and maintain systems. The ability to perform these functions may also be a human factors problem.

Further system analysis detail is addressed from modeling the system using some of the risk assessment methods described in Table A-2. These techniques develop processes that can assist in decision making about the system. The logic of modeling the interaction of a system’s components can be divided into induction and deduction. This difference in the technique of modeling and decision making is significant. Induction provides the reasoning of a general conclusion from individual cases (NUREG-0492 1981). This logic is used when analyzing the effect of a fault or condition on a systems operation. Inductive analysis answers the question, “what are the system states due to some event?” In reliability and risk studies this “event” is some fault in the system. Several approaches using the inductive approach include: PrHA, FMEA, and ETA. Deductive approaches provide reasoning for a specific conclusion from general conditions. For system analysis this technique attempts to identify what modes of a system/subsystem/component failure can be used to contribute to the failure of the system. This technique answers the question, "how a system state can occur?" Inductive reasoning provides the techniques for FTA or its complement success tree analysis (STA).

A.3.2. Preliminary Hazard Analysis

Preliminary Hazard Analysis (PrHA) is a common risk-based technology tool with many applications. The general process is shown below in Figure A-3. This technique requires experts to identify and rank the possible accident scenarios that may occur. It is frequently used as a preliminary way to identify and reduce the risks associated with major hazards of a system.

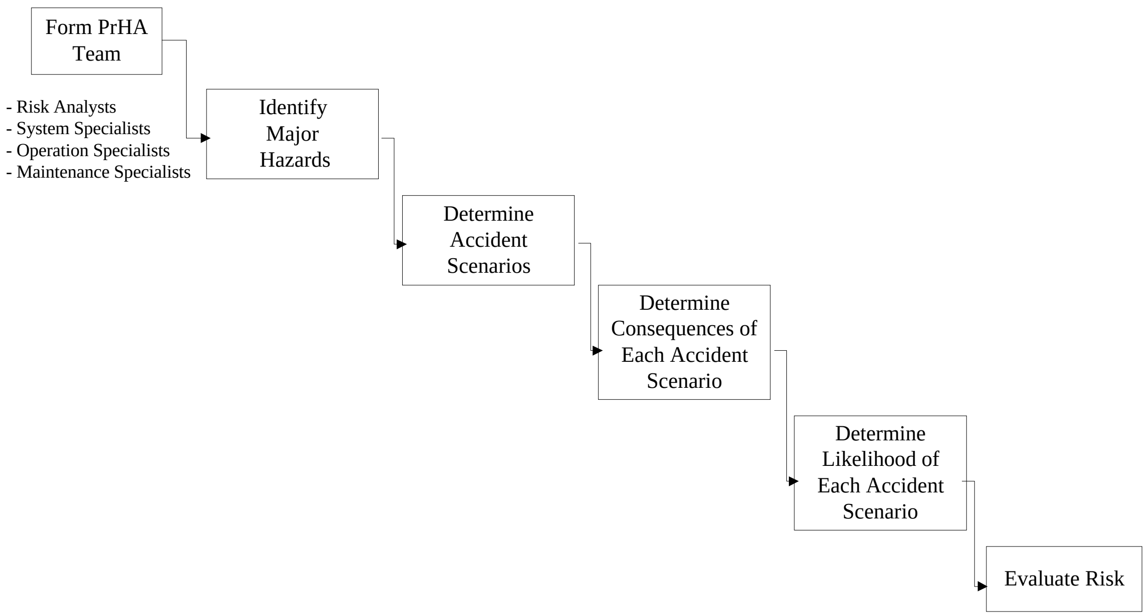


Figure A-3. Preliminary Hazard Analysis (PrHA) Process

A.3.3. Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) is another popular risk-based technology tools as shown in Figure A-4. This technique has been introduced both in the national and international regulations for the marine industry. This analysis tool assumes a failure mode occurs in a system/component through some failure mechanism; the effect of this failure on other systems is then evaluated. A risk ranking can be developed for each failure mode for the effect on the overall performance of the system. Existing applications of this technique include the International Maritime Organizations (1995) High Speed Craft Code, Title 46 Code Part 62 of Federal Regulations "Vital System Automation" by mentioning the use of qualitative failure analysis for equivalence determination stated as "Demonstration of functional equivalence must include comparison of qualitative failure analysis based on requirements of this of this part with a comparable analysis of the proposed substitute." FMEA is predominantly used for this requirement. Also, the Navigation and Inspection Circular 5-93 "Guidance for Certification of Passenger Carrying Submersibles" uses FMEA.

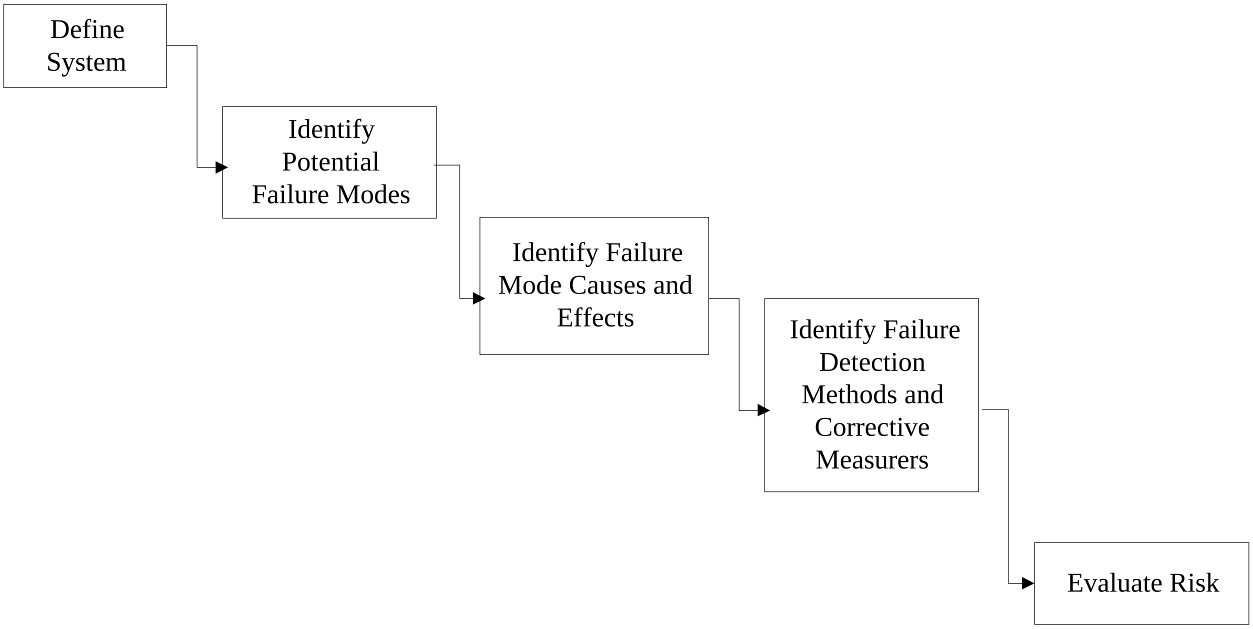


Figure A-4. Failure Mode and Effects Analysis (FMEA) Process

A.3.4. Event Modeling: Event, Success and Fault Trees

Event modeling is a systematic, and often most complete, way to identify accident scenarios and quantify risk for risk assessment. This risk-based technology tool provides a framework for identifying scenarios to evaluate the performance of a system or component through system modeling. The combination of event tree analysis (ETA), success tree analysis (STA) and fault tree analysis (FTA) can provide a structured analysis to system safety.

Event tree analysis is often used if the successful operation of a component/system depends on a discrete (chronological) set of events. The initiating event is first followed by other events leading to an overall result (consequence). The ability to address a complete set of scenarios is developed since all combinations of both the success and failure of the main events are included in the analysis. The probability of occurrence of the main events of the event tree can be determined using a fault tree or its complement the success tree. The scope of the analysis for event trees and fault trees depends on the objective of the analysis (NUREG-CR-2300 1983).

A.3.4.1. Event Tree Analysis

Event tree analysis is appropriate if the operation of some system/component depends on a successive group of events. Event trees identify the various combinations of event successes and failures as a result of an initiating event to determine all possible scenarios. The event tree starts with an initiating event followed by some reactionary event. This reaction can either be a success or failure. If the event succeeds, the most commonly used indication is the upward movement of the path branch. A downward branch of the event tree marks the failure of an event. The remaining events are evaluated to determine the different possible scenarios. The scope of the events can be functions/systems that can provide some reduction to the possible hazards from the initiating event. The final outcome of a sequence of events identifies the overall state resulting from the scenario of events. Each path represents a failure scenario with varying levels of probability and risk. Different event trees can be created for different event initiators. Figure A-5 shows an example event tree for the basic elements of a sprinkler system that might be critical for maintaining the structural integrity of a vessel.

Based on the occurrence of an initiating event, event tree analysis examines possible system outcomes or consequences. This analysis tool is particularly effective in showing interdependence of system components which is important in identifying events, that at first might appear insignificant, but due to the interdependency result in devastating results (Ayyub et al. 1998, Ayyub and McCuen 1997). Event tree analysis is similar to fault tree analysis because both methods use probabilistic reliability data of the individual components and events along each path to compute the likelihood of each outcome.

A quantitative evaluation of event tree probability values can be used for each event to evaluate the probability of the overall system state. Probability values for the success or failure of the events can be used to identify the probability for a specific event tree sequence. The probabilities of the events in a sequence can be provided as an input to the model or evaluated using fault trees. These probabilities for various events in a sequence can be viewed as conditional probabilities and therefore can be multiplied to obtain the occurrence probability of the sequence. The probabilities of various sequences can be summed up to determine the overall probability of a certain outcome. The addition of consequence evaluation of a scenario allows for generation of a risk value.

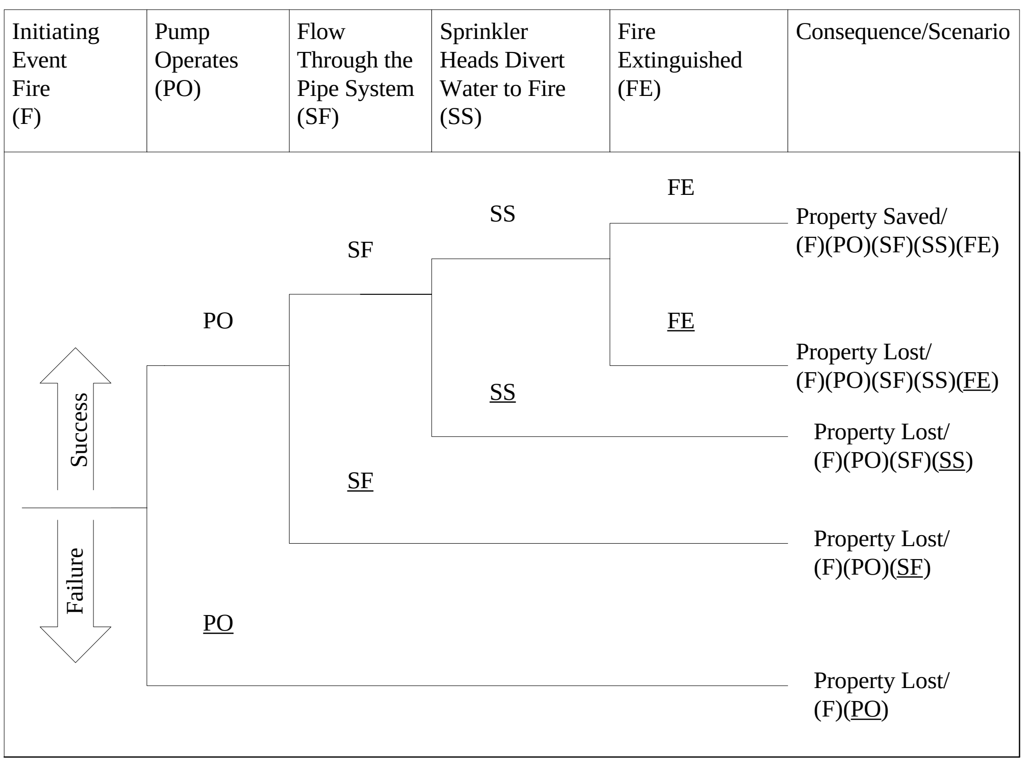


Figure A-5. Event Tree Example for Sprinkler System

A.3.4.2. Fault and Success Tree Analyses

Complex systems are often difficult to visualize and the effect of individual components on the system as a whole is difficult to evaluate without a tool. Two methods of modeling that have greatly improved the ease of assessing system reliability/risk are fault trees (FT) and success trees (ST). A fault tree is a graphical model created by deductive reasoning leading to various combinations of events that lead to the occurrence of some top event failure (Ayyub and McCuen 1997, Modarres 1993). A success tree shows the combinations of successful events leading to the success of the top event. A success tree can be produced as the complement (opposite) of the fault tree as illustrated in this section. Fault trees and success trees are used to further analyze the event tree headings (the main events in an event tree) to provide further detail to understand system complexities. In constructing the FT/ST only those failure/success events which are considered significant are modeled. This determination is assisted by defining system boundaries.

Fault Tree Analysis (FTA) starts by defining a top event, which is commonly selected as an adverse event. An engineering system can have more than one top event. For example, a ship might have the following top events for the purpose of reliability assessment: power failure, stability failure, mobility failure, or structural failure. Then, each top event needs to be examined using the following logic: in order for the top event to occur, other events must occur. As a result, a set of lower-level events is defined. Also, the form in which these lower level events are logically connected (i.e., in parallel or in series) needs to be defined. The connectivity of these events is expressed using "AND" or "OR" gates. Lower level events are classified into the following types (Ayyub and McCuen 1997):

1. *Basic events.* These events cannot be decomposed further into lower level events. They are the lowest events that can be obtained. For these events, failure probabilities need be obtained.
2. *Events that can be decomposed further.* These events can be decomposed further to lower levels. Therefore, they should be decomposed until the basic events are obtained.
3. *Undeveloped events.* These events are not basic and can be decomposed further. However, because they are not important, they are not developed further. Usually, the probabilities of these events are very small or the effect of their occurrence on the system is negligible, or can be controlled or mediated.
4. *Switch (or house) events.* These events are not random, and can be turned on or off with full control.

The symbols shown in Figure A-6 are used for these events. Also, a continuation symbol is shown, which is used to break up a fault tree into several parts for the purpose of fitting it in several pages.

FTA requires the development of a tree-looking diagram for the system that shows failure paths and scenarios that can result in the occurrence of a top event. The construction of the tree should be based on the building blocks and the Boolean logic gates.

The outcome of interest from the fault tree analysis is the occurrence probability of the top event. Since the top event was decomposed into basic events, its occurrence can be stated in the form of "AND," and "OR" of the basic events. The resulting statement can be restated by replacing the

"AND" with the intersection of the corresponding basic events, and the "OR" with the union of the corresponding basic events. Then, the occurrence probability of the top event can be computed by evaluating the probabilities of the unions and intersections of the basic events. The dependence between these events also affects the resulting probability of the system.

For large fault trees, the computation of the occurrence probability of the top event can be difficult because of their size. In this case a more efficient approach is needed for assessing the reliability of a system, such as the minimal cut set approach. According to this approach, each cut set is defined as a set of basic events where the joint occurrence of these basic events results in the occurrence of the top event (NUREG-0492 1981). A minimal cut set is a cut set with the condition that the non-occurrence of any one basic event from this set results in the non-occurrence of the top event. Therefore, a minimal cut set can be viewed as a subsystem in parallel. In general, systems have more than one minimal cut sets. The occurrence of the top event of the system can, therefore, be due to any one of these minimal cut sets. As a result, the system can be viewed as the union of all the minimal cut sets for the system. If probability values are assigned to the cut sets, a probability for the top event can be determined.

A simple example of this type of modeling is shown in Figure A-7 for a pipe system. If the goal of the system is to maintain water flow from one end of the system to the other, then the individual pipes can be related with a Boolean *logic* (Ayyub and McCuen 1997). Both pipe (a) and pipe (d) and pipe (b) or pipe (c) must function for the system to meet its goal as shown in the success tree Figure A-8a. The compliment of the success tree is the fault tree. The goal of the fault tree model is to determine every point in the logic of a system that might fail as shown in Figure A-8b. Once these tree elements have been defined, possible failure scenarios of a system can be defined.

For complicated systems, the number of failure paths can be quite large. The number of possible failure scenarios (assuming only two possible outcomes for each basic event) is given by:

$$\text{Failure Paths} = 2^n \tag{A-4}$$

Where n is the number of basic events or components in the system. For a complicated system, the number of failure paths can be very high. The amount of time needed to perform a reliability/risk assessment including all of the possible failure paths is extremely high.

As was previously described, a failure path is often referred to as a cut set. One objective of the analysis is to determine the entire minimal cut sets (minimum failure combinations of basic/intermediate events that can result in the failure of the top event). These failure combinations are used to compute the failure probability of the top event. There are several methods for generating a set of minimal cut sets. One of the methods is based on a top-down search of the Boolean logic. Another algorithm for generating cut sets is based on a bottom up approach that substitutes the minimal cut sets from lower level gates into upper level gates. NUREG-0492 1981 provide a more rigorous discussion of these methods.

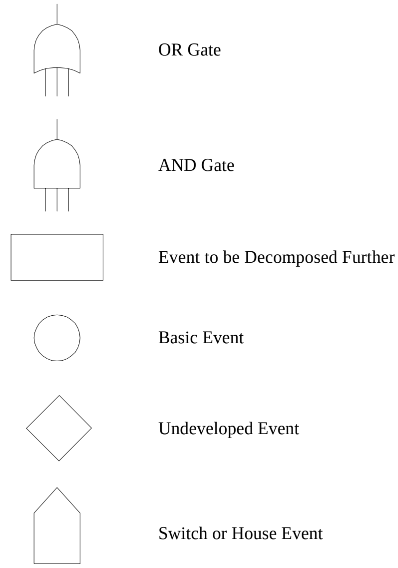


Figure A-6. Symbols Used in Fault Tree Analysis (Ayyub and McCuen 1997)

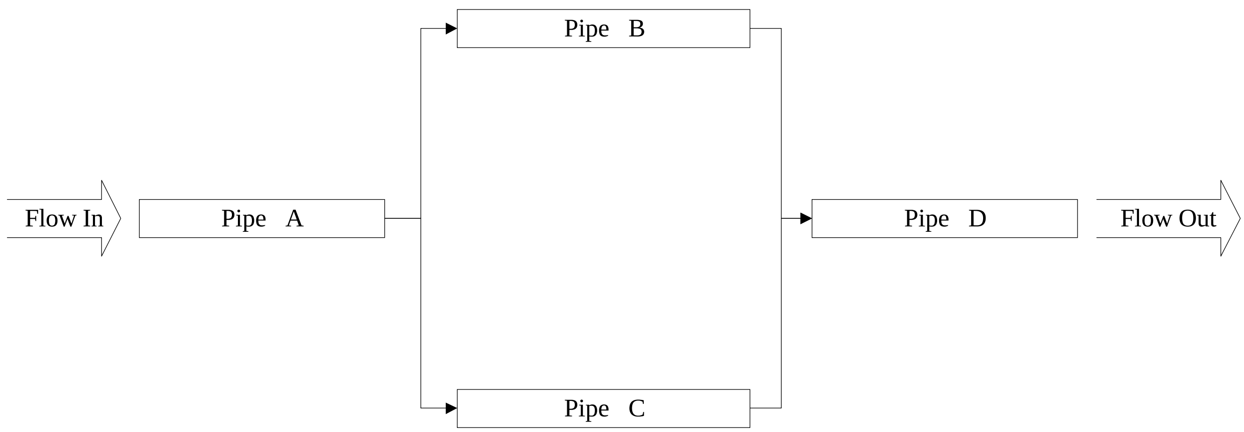


Figure A-7. Piping System

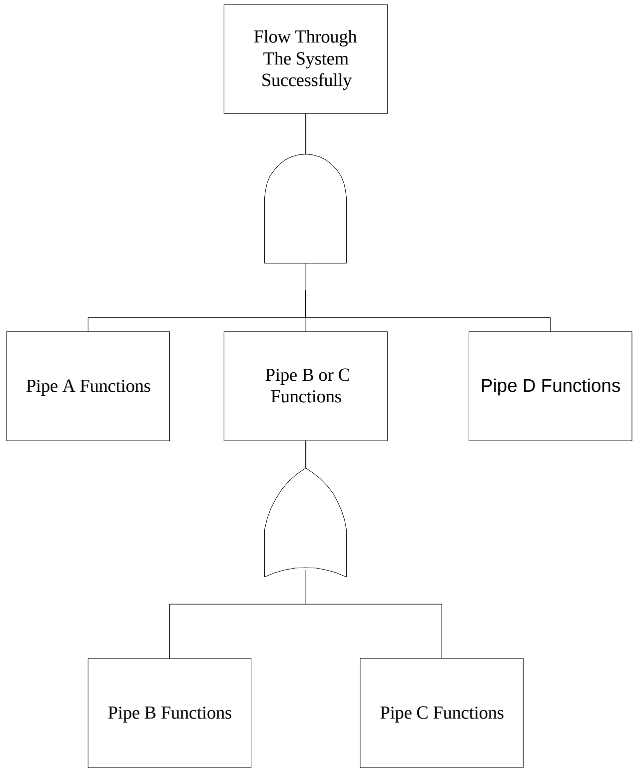


Figure A-8a. Success Tree for the Pipe System Example

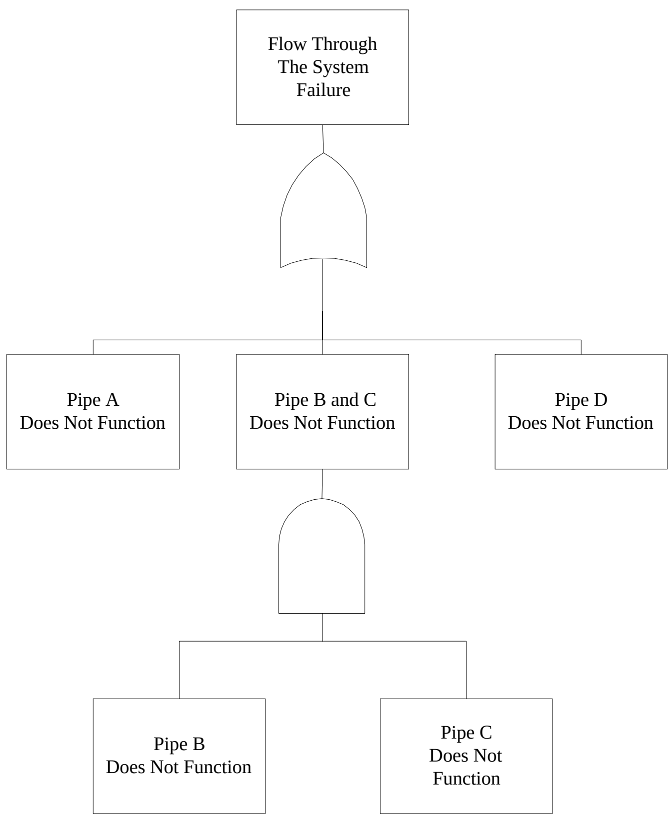


Figure A-8b. Fault Tree for the Pipe System Example

A.3.5. Qualitative/ Quantitative Risk Measurement

The risk assessment methods can also be categorized as to how the risk is determined, by quantitative or qualitative analysis. Qualitative risk analysis uses judgment and sometimes "expert" opinion to evaluate the probability and consequence values. This subjective approach may be sufficient to assess the risk of a system, depending on the available resources.

Quantitative analysis relies on probabilistic and statistical methods, and databases that identify numerical probability values and consequence values for risk assessment. This objective approach examines the system in greater detail to assess risks.

The selection of a quantitative or qualitative method depends upon the availability of data for evaluating the hazard and the level of analysis needed to make a confident decision (Gruhn 1991). Qualitative methods offer analyses without detailed information, but the intuitive and subjective processes may result in differences in outcomes by those who use them. Quantitative analysis generally provides a more uniform understanding among different individuals, but requires quality data for accurate results. A combination of both qualitative and quantitative analyses can be used depending on the situation.

A.4. Human Reliability Analysis

Risk assessment requires the performance analysis of an entire system composed of a diverse group of components. The system definition readily includes the physical components of the system; however, humans are also part of most systems and provide significant contributions to risk. It has been estimated that nearly 90% of the accidents at sea are contributed to human error (Blackman 1997). The human contribution to risk can be estimated from an understanding of behavioral sciences. Both the "hardware failure" and human error should be addressed in the risk assessment since they both contribute to risks associated with the system. Once the human error probabilities are determined, human error/failures are treated in the same fashion as hardware failures in performing risk assessment quantification.

The determination of the human error contribution to risk is determined by human reliability analysis (HRA) tools. HRA is the discipline that enables the analysis and impact of humans on the reliability and safety of systems. Important results of HRA are determining the likelihood of human error as well as ways in which human errors can be reduced. When combined with system risk analysis, HRA provides the detrimental effects of humans on the performance of the system. Human reliability analysis is generally considered to be composed of three basic steps: error identification, modeling, and quantification.

A.4.1. Human Error Identification

Human errors are unwanted circumstances caused by humans that result in deviations from expected norms that place systems at risk. It is important to identify the relevant errors to make a complete and accurate risk assessment. Human error identification techniques should provide a comprehensive structure for determining significant human errors within a system. Quality HRA allows for accuracy in both the HRA assessment and overall system risk assessment.

Identification of human errors requires knowledge about the interactions of humans with other humans or machines (the physical world). It is the study of these interfaces that allows for the understanding of human errors. Potential sources of information for identifying human error may be determined from task analysis, expert judgment, laboratory studies, simulation and reports. Human errors may be considered active or latent depending on the time delay between when the error occurs and when the system fails.

It is important to note the distinction between human errors and human factors. Human errors are generally considered separately from human factors that applies information about human behavior, abilities, limitations, and other characteristics to the design of tools, machines, systems tasks, jobs, and environments for productive, safe, comfortable, and effective human use. Human factors are determined from performing descriptive studies (characterizing populations) and experimental research. However, human factors analysis may contribute to the human reliability analysis.

A.4.2. Human Error Modeling

Once human errors have been identified they must be represented in a logical and quantifiable framework along with other components that contribute to the risk of the system. This framework can be determined from development of a risk model. Currently, there is no consensus on how to model human reliably, however, since 1980, at least 38 different HRA techniques have been developed (Gertman and Blackman 1994). Many of these models utilize human event trees and fault trees to predict human reliability values. The identifications of human failure events can also be identified using Failure Mode and Effects Analysis. The human error estimates are often based on simulation tests, models, and expert estimation (Gertman and Blackman 1994).

A.4.3. Human Error Quantification

Quantification of human error reliability promotes the inclusion of the human element in risk analysis. This is still a developing science requiring understanding of human performance, cognitive processing, and human perceptions. Since an exact model for human cognition has not been developed, much of the current human reliability data relies on accident databases, simulation and other empirical approaches. Many of the existing data sources were developed for from specific industry data such as nuclear and aviation industries. The application of these data sources for a specific problem should be thoroughly examined prior to application for a specific model. The result of the quantification of human reliability in terms of probability of occurrence is typically called a human error probability (HEP). There are many techniques that have been developed to help predict the HEP values. The Technique for Human Error Rate Prediction (THERP) is one of the most widely used methods for HEP. This technique is based on data gathered from the nuclear and chemical processing industries. THERP relies on HRA event tree modeling to identify the events of concern. Quantification is performed from data tables of basic HEP for specific tasks that may be modified based on the circumstances affecting performance.

The degree of human reliability is influenced by many factors often called performance shaping factors (PSF). PSFs are those factors that affect the ability of people to carry out required tasks. For example, the knowledge people have on how to don/activate a PFD will affect the performance of this task. Training (another PSF) in donning PFD's can also assist in the ability to perform this task. Often the quantitative estimates of reliability are generated from a base error rate that is then altered based on the PSFs of the particular circumstances. Internal performance shaping factors are an individual's own attributes (experience, training, skills, abilities, attitudes) that affect the ability of the person to perform certain tasks. External PSFs are the dynamic aspects of situation, tasks, and system that affect the ability to perform certain tasks. Typical external factors include environmental stress factors (such as heat, cold, noise, situational stress, time of day), management, procedures, time limitations, and quality of man-machine interface. With these PSF it is easy to see the dynamic nature of HEP evaluation based on the circumstances of the analysis.

A.4.4. Reducing Human Errors

Error reduction is concerned with lowering the likelihood for error in an attempt to reduce risk. The reduction of human errors may be achieved by human factors interventions or by engineering means (Kirwan 1992). Human factors interventions include improving training or improving the human-machine interface (alarms, codes, etc.) based on an understanding of the causes of error. Engineering means of error reduction may include automated safety systems or interlocks. The selection of the corrective actions to take can be done through decision analysis considering cost-benefit criteria.

A.5. Assessment of Component Failure Likelihood

A.5.1. Structural Reliability

The reliability of the component is achieved when the strength is greater than the load. Engineering models comparing the applied load effect (*S*) and the structural strength or resistance (*R*) are used to develop algebraic performance equations of the form:

$$g = \text{Structural Capacity - Load Effects} = R - L \qquad \text{(A-5)}$$

where g = limit state function, R = structural strength, and L = loading acting on the structural component. The failure of the component occurs when $g<0$.

Uncertainties in the limit state model are modeled in terms of the mean, the variance, and the probability density and distribution functions of the structural strength and loading. Due to the variability in both strength and loads, there is always a probability of failure that can be defined as

$$p_f = P(g \le 0) = P(R \le L) \qquad \text{(A-6)}$$

As the probability of failure for structural members is small, the safety of a structural component under a given external loading is expressed in terms of a reliability index that reflects the probability of failure of the structural component. The higher the reliability index, the greater the structural safety. The required level of structural safety for the structural component is expressed in terms of a target reliability index.

The reliability index associated with a given structural member can be defined in terms of time, considering the exposure of the ship to a loading condition. The end of the structural component life, in a simplified point of view, corresponds to the instant of time where the reliability index associated with the member is lower than the target reliability index. Therefore, a reliability-based procedure is adequate to estimate the life expectancy of a vessel, once it deals with the uncertainties in the variables that affect the ship operational life, such as the structural strength and external loading, and allows the modeling of progressive degradation mechanism that can affect the structural strength.

Table A-3 suggests a possible classification of ultimate and serviceability failures as for reliability analysis. According to this table, the ultimate failure modes include flexural strength and buckling, and the serviceability failure modes include permanent deformation and first yield. The fatigue failure is included in both modes, depending on the extent of fatigue damage.

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

a) Primary: a failure mode that may affect great part of the structure and cause the loss or great major degradation of the structure performance,
b) Secondary: a failure mode that may affect a part of the structure and cause damage or degradation of the structure performance, and
c) Tertiary: a failure mode that may affect a small part of the structure and cause minor damage or degradation of the structure performance.

Many methods have been proposed for structural reliability analysis, such as first-order second moment (FOSM) method, advanced second moment (ASM) method, computer-based Monte Carlo simulation (e.g., Ayyub and McCuen 1997, Ang and Tang 1990, Ayyub and Haldar 1984, White and Ayyub 1985), and conditional expectation simulation (e.g., Ayyub and McCuen 1997). These reliability analysis methods may be used to estimate the time-dependent or conditional reliabilities.

A likelihood of damage categorization scheme can be designed and notional ratings can be assigned to each category as illustrated in Table A-4. The categorization scheme in Table A-4 has four classes: Extreme, High, Moderate and Low. Engineers should design a rating system according to their requirements. For demonstration purposes, structural details that are highly susceptible to damage are assigned an annual likelihood of damage (probability of failure per year) of 10^{-2}, while those unlikely to experience a failure are assigned an annual damage rating of 10^{-5}. Expert opinion elicitation and experience from other industries and classification society rules could be used as guides in assigning likelihood of damage.

Table A-3. Classification of the Structural Failures as a Function of the Extension of Damage to the Ship Structure

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

Table A-4. An Example of Structure 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 in the ship's life).
Moderate	10^{-4}	This mode of damage occurs very rarely, perhaps once or twice during the ship's life.
Low	10^{-5}	It is extremely unlikely that the structure in consideration will experience this damage mode during the ship's life.

A.5.2. Time-Dependent Reliability

A.5.2.1. Strength Limit States

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

Ayyub and White (1990a and 1990b), and Ayyub et al. (1989) developed a methodology for assessment of structural life of marine structures using the basic concepts of probabilistic analysis, and statistics of extremes. According to these authors, it is expected in general, that as the service life of a structure progresses, expected extreme load effects increase. Then the resulting extreme value probability distribution can be used in the reliability assessment. These authors also considered that the structural strength decreases, usually due to wastage of the hull plating due to corrosion.

This reliability analysis is based on the determination of the probability of failure for a given time *t*. On the basis of the time-dependent load effect $L(t)$ and the structural strength $R(t)$, the probability of failure for the time *t* is computed for a specified failure mode using one of the applicable methods described in the previous section. These functions represent the instantaneous probability density function for the load effect and structural strength at a given time, considering both the extreme value distribution for the load effect and the degradation of the structural resistance at this time. By varying the time period *t* from zero to the design structural life, a plot of the probability of failure as a function of time can be developed. This probability of failure is defined as the instantaneous probability of failure at time *t*, without regard to previous or future performance.

This method is suitable for using in reliability and structural life assessment according to certain failure modes, for example, plastic deformation and buckling. For failure modes, such as fatigue, that the failure event occurs because of the accumulation of damage due to repeated application of cyclic loads of variable amplitudes with varying frequencies, the reliability is defined according to the methods described at the end of this section.

Ayyub, et al. (1990c) applied this methodology in a comparative analysis between two different patrol boats. The comparison is based on the identification of two critical failure modes, plastic plate deformation and fatigue. Most of these concepts were reviewed by Ayyub and White (1995) in order to generalize them for any structural system.

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

$$R(L) = R_0 \exp\left[-\int_{t_0}^{L} h(t)dt\right] \tag{A-7}$$

where $R(L)$ represents lifetime reliability, $h(t)$ represents the hazard function which is the probability that the structure will fail during interval t and $t + dt$, t_o is the time at which the structure is put in service, and R_o is the reliability at that time. For high levels of reliability another relation is suggested by Soares and Ivanov (1989) as

$$R(L) = R_0 \exp[1 - n(1 - R_i)] \tag{A-8}$$

where the lifetime is equal to *n* years, and

$$R_i = 1 - p_f \tag{A-9}$$

$$p_f = \Phi(-\beta) \tag{A-10}$$

where Φ is the Gaussian distribution function. β is the standard safety index. The assumption in Eq. A-10 of a standard normal distribution is not always true.

Ellingwood and Mori (1993) developed a time-dependent methodology for the deterioration of concrete structures at nuclear power plants. This method models significant structural loads as a sequence of pulses which can be described by a Poisson process with mean occurrence rate, λ, random intensity, L_j, and duration, τ. Ellingwood and Mori (1993) define the limit state of the structure at any time as:

$$R(t) - L(t) < 0 \tag{A-11}$$

where $R(t)$ is the strength of the structure at time t and $L(t)$ is the load at time t. The probability of failure can then be defined at time t as $P[R(t) < L(t)]$. Ellingwood and Mori (1993) define the reliability function, $RL(t)$ as the probability that the structure survives during interval of time $(0,t)$. The equation for reliability function becomes

$$RL(t) = \int_0^{\infty} \exp\left[-\lambda t\left(1 - \frac{1}{t}\int_0^t F_L\,(g(t)r)dt]\right)\right] f_R\,(r)dr \tag{A-12}$$

where $f_R(r)$ is the pdf of initial strength, R and $g(t)$ is 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

$$h(t) = -\frac{d}{dt} \ln RL(t) \tag{A-13}$$

which can be expressed as

$$RL(t) = \exp[-\int_0^t h(\xi)d\xi \tag{A-14}$$

Ellingwood (1995) later notes that the time-dependent reliability $RL(t)$, or conversely the probability of failure, $P_{ft}(t)$, are cumulative, i.e., they should be used to define the probability of successful performance during a service life interval $(0,t)$. Ellingwood (1995) 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. This is a very important point that is lacking in much of the literature that is available.

Although the method developed by Ellingwood and Mori (1993) was used to analyze the reliability of concrete structures, it can be used to calculate the time-dependent reliability of ship structures. The main advantage of this methodology is the development of a closed function expressing the structure reliability, considering the time dependency of structural strength degradation. The probabilistic characteristics of the loading are considered as time invariant.

A.5.2.2. Fatigue Limit States

Traditionally, the design of marine structures takes into account the fatigue analysis based on *S-N* curves and some models proposed to analyze the fatigue reliability of ships structures are based on *S-N* curves and Miner's rule. These models represent this failure mode up top crack initiation. Fracture mechanics modeling deal with this failure mode differently using crack propagation methods. In this section, both methods are briefly discussed.

According to Miner's rule, the total fatigue life under a variety of stress ranges is the weighted sum of the individual lives at constant stress range *S* as given by the *S-N* curves, with each being weighted according to a fractional exposure to that level of stress range (Fuchs and Stephens 1980). The mathematical expression of Miner's rule is

$$D = \sum_{i=1}^{n_S} \frac{n_i}{N_i} \tag{A-15}$$

where n_i = number of stress cycles in block *i*, N_i = number of cycles to failure at constant stress range S_i, and n_S = number of stress blocks.

The fatigue behavior of different types of structural details is generally evaluated using constant-cycle fatigue tests, and the results are presented in terms of nominal applied stresses and the number of cycles that produce failure. The resulting *S-N* curves are expressed by the following relation

$$NS^b = A \tag{A-16}$$

where *A* = constant of *S-N* curve, *N* = number of cycles to fatigue failure, *S* = constant amplitude stress range at *N* , and *b* = slope of the *S-N* curve.

The reliability function for fatigue analysis suggested by Ang et al. (1999) is based on the hypothesis that as fatigue is a process of cumulative damage, the conditional probability that failure will occur in the next loading cycle should be monotonically increasing with the life spent, i.e., the hazard function should be monotonically increasing. Ang et al. (1999) used the Weibull probability distribution to express the fatigue reliability. The corresponding reliability function ($L(t_L \mid N=n)$) for a given time interval $(0, t_L)$ is expressed by

$$L\left(t_L \middle| N = n\right) = \exp\left[-\left(\frac{n}{E(N)}\Gamma\left(1+\frac{1}{k}\right)\right)^k\right] \tag{A-17}$$

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

The fracture mechanics approach is based on crack growth data. For the structural detail under analysis the crack initiation phase is assumed to be negligible and the life can be predicted using the fracture mechanics method. The fracture mechanics approach is more detailed and it involves examining crack growth and determining the number of load cycles that are needed for small initial defects to grow into cracks large enough to cause fracture. The growth rate is proportional to the stress range. It is expressed in terms of a stress intensity factor *K*, which accounts for the magnitude of the stress, current crack size and geometry, and structure geometry. According to Fuchs and Stephens (1980) the basic equation that governs crack growth, named Paris Law, is given by:

$$\frac{da}{dN} = C\Delta K^{m} \tag{A-18}$$

where a = crack size, N = number of fatigue cycles, ΔK = range of stress intensity factor, and C and m are crack propagation parameters that come from fracture mechanics. The range of the stress intensity factor is given by Fuchs and Stephens (1980) as:

$$\Delta K = Sf(a)\sqrt{\pi a} \tag{A-19}$$

in which $f(a)$ is a function of crack geometry and structure geometry and S is the stress range induced by the cyclic loading. When the crack size a reaches some critical crack size a_{cr}, failure is assumed to have occurred. Although most laboratory testing is typically performed with constant amplitude stress ranges, Eq. A-19 is always applied to variable stress range models that ignore sequence effects (Rolfe and Barsom 1987). Rearranging the variables in Eq. A-19, the number of cycles for the crack grow from the initial size (a_i) to a given crack size (a) can be computed from:

$$N = \frac{1}{C(S)^{m}} \int_{a_i}^{a} \frac{da}{f(a)^{m}\left(\sqrt{\pi a}\right)^{m}} \tag{A-20}$$

The crack propagation parameter C in both equations is treated as a random variable (Madsen et al. 1991).

For the case of structures subjected to a great variety of external loading, due to changes in environmental conditions, such as marine, offshore and aeronautical structures, the limit state function is modified to account for the influence of each loading condition, according to the method proposed by Hughes (1988), named “Lifetime Weighted Sea Method”, and can be expressed as:

$$Z_{\Delta K} = g_{\Delta K}(\underline{x}) = \int_{a_i}^{a_f} \frac{da}{(f(a))^{m}\left(\sqrt{\pi a}\right)^{m}} - C\sum_{j=1}^{k} p_j \left[\sum_{i=1}^{n} (S_i)^{m}\right]_j \tag{A-21}$$

where $\left[\sum_{i=1}^{n} (S_i)^{m}\right]_j$ = cumulative stress range acting on the structure due to loading condition j, and p_j = probability of occurrence of this loading condition. So in this method, the long term cumulative stress range associated to the structure is composed by the combination of short-term cumulative stress range related to each loading condition acting on the structure.

A.5.2.3. Corrosion

An ultimate strength failure of a ship structure is generally a result of an extreme load event and/or the reduction in structural resistance due to progressive degradation. For example, cumulative structural wastage due to corrosion will reduce local scantlings and thus the hull girder section modulus and render the ship more susceptible to local bucking or hull girder failure in response to an extreme loading event or fatigue crack growth will increase the risk (probability) of fracture. For these reasons, one should consider the long-term effects of progressive degradation in design. Design rules have generally incorporated corrosion allowances or the idea of net scantlings to preclude the deleterious effects of corrosion. The effect of corrosion on a ship's hull cross-section geometrical characteristics was investigated by Ivanov (1986).

In a reliability-based design approach it is necessary to express these degradation rates explicitly. A reasonable amount of work has been conducted to identify degradation rates of ship structures. Information is available to estimate corrosion rates based on the quality of the initial construction and protection systems as well as the vessel service and structural location. For example the pitting corrosion of the bottom plating of a tanker structure has been expressed as shown in Figure A-9. This type of information could be used to develop the statistical distribution necessary for reliability analysis. Huang (1999) provides information on corrosion protection of ballast and cargo tanks of crude oil tankers.

For fatigue damage, the crack growth rate is dependent on the vessel operational profile, since the crack growth depends on the wave-induced load. Furthermore, the crack growth is dependent on the presence of structural defects, induced during the hull fabrication, including weld defects and stress raisers, such as misalignment between structural parts.

The quality of the fabrication and materials used in the construction of a vessel play a significant role in defining the life expectancy of a vessel. Misalignment, poor weld toe profiles, poor quality of paint application and cathodic protection systems, amongst other factors, can accelerate the degradation of a structural system. The degradation of the structural system can increase the probability of an ultimate structural failure, thus reducing the life expectancy of the structure, and consequently, reducing the vessel operational life.

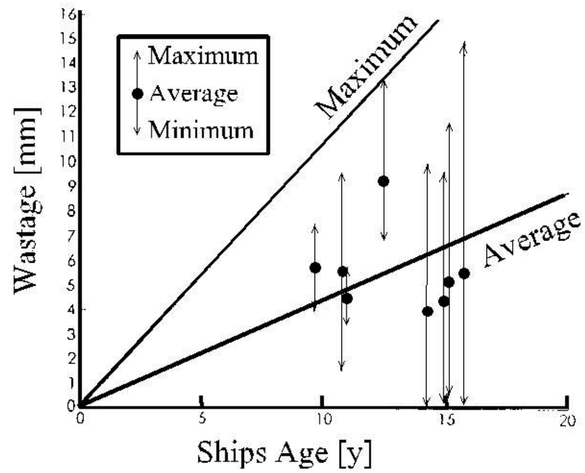


Figure A-9. Pitting Corrosion of Bottom Shell Plating under Bellmouth, in Cargo Tank

A.6. Assessment of Consequences

The failure consequences need to be assessed in a systems framework using a life cycle approach. Each system failure that can arise has a consequence. A consequence from a failure can be many different things. A failure could cause economic damage such as reduced productivity, temporary or permanent loss of production, loss of capital, or bad publicity. It could also result in more serious events such as environmental damage, injury or loss of human life, or public endangerment. Consequence estimations are formed from either event in past history or on educated guesses. In order to calculate the overall risk each failure must have some degree of failure consequence assigned to it. The failure can be described as a numeric value or a standardized consequence. One of the most difficult and debated steps in determining the risk associated with a system can be the quantification of the consequences. For instance, the value of property can be easily determined based on the expense required to replace or restore the damage caused by a failure, but other consequence types are not so easy to place numeric values on them. Two of the most difficult consequences to quantify are the loss of human life and damage to the environment. One way of quantifying these consequences is to place different levels of loss in different categories. For example, any event which results in the loss of 1-2 lives might be labeled as a Category 4 loss, an event resulting in A-4 lives lost would be a Category 3 loss, 5-6 lives lost would be associated with a Category 2 loss, and 7 or more lives lost would be a Category 1 loss. Certain consequences can be judged by different groups of people to have different levels of importance. Therefore in risk analysis, the consequences must somehow be quantified even if it was qualitative, and the definition of the number or quantity assigned to a particular consequence must be clearly defined as part of a complete probabilistic risk analysis. Two approaches for quantifying failure consequences are:

- Cause consequence diagrams; and/or
- Expert opinion elicitation

Cause-consequence (CS) diagrams were developed for the purpose of assessing and propagating the conditional effects of a failure using a tree representation. The analysis according to CS

starts with selecting a *critical event*. Critical events are commonly selected as convenient starting points for the purpose of developing the CS diagrams. For a given critical event, the consequences are traced using logic trees with event chains and branches. The logic works both backward (similar to fault trees) and forward (similar to event trees). The procedure for developing a CS diagram can be based on answering a set of questions at any stage of the analysis. The questions can include, for example, the following:
Can this event lead to other failure events?

- What are the needed conditions for this event to lead to other events?
- What other components are affected by this event?
- What other events are caused by this event?
- What are the associated consequences with the other (subsequent) events?
- What are the occurrence probabilities of subsequent events or failure probabilities of the components?

Chapter 3 includes details of consequence assessment for ship structures for the purpose of demonstration. In the demonstration of Chapter 3, a categorization scheme has been designed for consequences of failure and notional ratings have been assigned for each category as shown in Table A-5. This notional consequence of failure ratings given in Table A-5 is developed merely for demonstration purposes, and should not be used as a reference. Different companies or organizations may develop their own rating systems. Their assigned rating numbers may be different for the same type of consequence of failure depending on the function, size and condition of their ships and the nature of their cargo. For instance, oil spills from a small vessel may have a milder consequence than the one from a VLCC. Companies should design their own rating system to fit their service and operational profile.

Table A-5. An Example of Consequence of Failure Classification Scheme for Structural Details.

Classification	Rating	Consequences of Failure
Extreme	10^8	• Loss of ship and cargo, • Loss of ship, • Loss of lives, or • Major oil spill involving several cargo tanks.
High	10^6	• Minor oil spill, • Major structural failure, • Cargo loss, • Loss of serviceability, or • Salvage.
Moderate	10^4	• Unscheduled repair on a moderate damage, or • Reduction of serviceability.
Low	10^3	• Temporary repair, or • Nuisance defects (no immediate repair).

A.7. Data Needs for Risk Assessment

A.7.1. Data Definition, Classification and Sources

In risk assessment, the methods of probability theory are used to represent engineering uncertainties. However, uncertainty is a vague concept. It refers to events that occur with periodic frequency, such as weather, yet also to conditions that are existent but unknown, such as probability of an extreme wave. It applies to the magnitude of an engineering parameter, yet also to the structure of a model. By contrast, probability is a precise concept. It is a mathematical concept with an explicit definition. We use the mathematics of probability theory to represent uncertainties, despite that those uncertainties are of many forms.

The term probability has a precise mathematical definition, but its meaning when applied to the representation of uncertainties is subject to differing interpretations. The *frequentist* view holds that probability is the propensity of a physical system in a theoretically infinite number of repetitions; that is, the frequency of occurrence of an outcome in a long series of similar trials (e.g., the frequency of a coin landing heads-up in an infinite number of flips is the probability of that event). In contrast, the *Bayesian* view holds that probability is the rational degree of belief that one holds in the occurrence of an event or the truth of a proposition; probability is manifest in the willingness of an observer to take action upon this belief. This latter view of probability, which has gained wide acceptance in many engineering applications, permits the use of quantified professional judgment in the form of subjective probabilities. Mathematically, such subjective probabilities can be combined or operated on as any other probability.

Data are needed to perform quantitative risk assessment or provide information to support qualitative risk assessment. Information may be available if data have been maintained on a system and components of interest. The relevant information for risk assessment included the possible failures, failure probabilities, failure rates, failure modes, possible causes, and failure consequences. In the case of a new system, data may be used from similar systems if this information is available. Surveys are a common tool used to provide some means of data. Statistical analysis can be used to assess confidence intervals and uncertainties in estimated parameters of interest. Expert judgment may also be used as another source of data as described by Ayyub et al. (1998). The uncertainty with the quality of the data should be identified to assist in the decision making process.

Data can be classified to including generic and plant specific types (Ayyub et al. 1998). Generic data are information from similar systems and components. This information may be the only information available in the initial stages of system design. Therefore, potential differences due to design or uncertainty may result from using generic data on a specific system. Plant specific data are specific to the system being analyzed. This information is often developed after the operation of a system. Relevant data need to be identified and collected as data collection can be costly. The data collected can then be used to update the risk assessment. Bayesian techniques can be used to combine objective and subjective data.

Data can be classified as failure probability data and failure consequence data. The failure probability data can include failure rates, hazard functions, times between failures, results from reliability studies, and any influencing factors and their effects. Failure-consequence data include loss reports, damages, litigation outcomes, repair costs, injuries, and human losses. Also, influencing factors, and effects of failure-prevention and consequence-mitigation plans. Areas of deficiency in terms of data availability should be identified, and sometimes failure databases need to be constructed. Data deficiency can be used as a basis for data collection and expert-opinion elicitation.

A.7.2. Expert-Opinion Elicitation Process

A.7.2.1. Background and Process Definition

Expert-opinion elicitation can be defined as a heuristic process of gathering informing and data or answering questions on issues or problems of concern (Ayyub et al. 1998). The expert-opinion elicitation process obtains information or answers to specific questions about specific quantities, called issues, such as unsatisfactory-performance rates, unsatisfactory-performance consequences and expected service life. Expert-opinion elicitation should not be used in lieu of rigorous reliability and risk analytical methods, but should be used to supplement them and to prepare for them. The expert-opinion elicitation process in this section is based on Ayyub (1999) which is a variation of the Delphi technique (Helmer 1968) scenario analysis (Kahn and Wiener 1967), and civil works and nuclear industry recommendations (Ayyub 1999 and NRC 1997).

The Delphi method is by far the most known method for eliciting and synthesizing expert opinions. The RAND corporation developed the Delphi method for the U. S. Air Force in the 1950s. In 1963, Helmer and Gordon used the Delphi method for a highly publicized long-range forecasting study (Helmer 1968). The method was extensively used in a wide variety of applications in the 1960s and 1970s exceeding 10,000 studies in 1974 on primarily technology forecasting and policy analysis (Linstone and Turoff 1975).

The purpose and steps of the Delphi method depend on the nature of use. Primarily the uses can be categorized into (1) technological forecasting, and (2) policy analysis. The technological forecasting relies on a group of experts on a subject matter of interest. The experts should be the most knowledgeable about issues or questions of concern. The issues and/or questions need to be stated by the study facilitators or analysts or monitoring team, and high degree of consensus is sought from the experts. On the other hand, the policy analysis Delphi method seeks to incorporate the opinions and views of the entire spectrum of stakeholders, and seeks to communicate the spread of opinions to decision-makers. In engineering, we are generally interested in the former type of consensus opinion.

The basic Delphi method consists of the following steps (Helmer 1968):

1. Selection of issues or questions and development of questionnaires.
2. Selection of experts who are most knowledgeable about issues or questions of concern.
3. Issue familiarization of experts by providing sufficient details on the issues on the questionnaires.

4. Elicitation of experts about the issues. The experts generally do not know who the other respondents are.
5. Aggregation and presentation of results in the form of median values and an inter-quartile range (i.e., 25% and 75% percentile values).
6. Review of results by the experts and revision of initial answers by experts. This iterative reexamination of issues would sometimes increase the accuracy of results. Respondents who provide answers outside the inter-quartile range need to provide written justifications or arguments on the second cycle of completing the questionnaires.
7. Revision of results and re-review for another cycle. The process should be repeated until a complete consensus is achieved. Typically, the Delphi method requires three or four cycles or iterations.
8. A summary of the results is prepared with argument summary for out of inter-quartile range values.

The responses on the final iteration usually show less spread in comparison to spreads in earlier iterations. The median values are commonly taken as the best estimates for the issues or questions.

Expert-opinion elicitation (EE) can be formally performed as provided in Figure A-10 (Ayyub 1999). The NRC (1997) classified issues for expert-opinion elicitation purposes into three complexity degrees (A, B, or C), and with four levels of study in the expert-opinion elicitation process (I, II, III, and IV) as shown in Table A-6. A given issue is assigned a complexity degree and a level of study that depend on (1) the significance of the issue to the final goal of the study, (2) the issue's technical complexity and uncertainty level, (3) the amount of non-technical contention about the issue in the technical community, and (4) important non-technical consideration such as budgetary, regulatory, scheduling, public perception, or other concerns.

Experts can be classified into three types (NRC 1997): (1) proponents, (2) evaluators, (3) resource experts, (4) observers, and (5) peer reviewers. A proponent is an expert who advocates a particular hypothesis or technical position. In science, a proponent evaluates experimental data and professionally offers a hypothesis that would be challenges by the proponent's peers until proven correct or wrong. An evaluator is an expert who has the role of evaluating the relative credibility and plausibility of multiple hypotheses to explain observations. Evaluators consider available data, become familiar with the views of proponents and other evaluators, question the technical bases of data, and challenge the views of proponents. A resource expert is a technical expert with detailed and deep knowledge of particular data, issue aspects, particular methodologies, or use of evaluators. An observer can contribute to the discussion, but cannot provide expert opinion that enters in the aggregated opinion of the experts. A peer reviewer is an expert that can provide an unbiased assessment and critical review of an expert-opinion elicitation process, its technical issues, and results.

The study level as shown in Table A-6 involves a technical integrator (TI) or a technical integrator and facilitator (TIF). A TI can be one person or a team (i.e., an entity) that is responsible for developing the composite representation of issues based on informed members and/or sources of related technical communities and experts; explaining and defending composite results to experts and outside experts, peer reviewers, regulators, and policy makers; and obtaining feedback and revising composite results. A TIF can be one person or a team (i.e., an entity) that is responsible for the functions of a TI, and structuring and facilitating the discussions and interactions of experts in the EE process; staging effective interactions among experts; ensuring equity in presented views; eliciting formal evaluations from each expert; and creating conditions for direct, non-controversial integration of expert opinions. The primary difference between the TI and the TIF is in the intellectual responsibility for the study where it lies with only the TI, and the TIF and the experts, respectively. The TIF has also the added responsibility of maintaining the professional integrity of the process and its implementation.

The TI and TIF processes are required to utilize peer reviewers for quality assurance purposes. Peer review can be classified according to peer-review method, and according to peer-review subject. Two methods of peer review can be performed: (1) participatory peer review that would be conducted as an ongoing review throughout all study stages, and (2) late-stage peer review that would be performed as the final stage of the study. The former method allows for affecting the course of the study, whereas the latter one might not be able to affect the study without a substantial rework of the study. The second classification of peer reviews is by peer-review subject and has two types: (1) technical peer review that focuses on the technical scope, coverage, contents and results, and (2) process peer review that focuses on the structure, format and execution of the expert-opinion elicitation process. A guidance on the use of peer reviewers is provided in Table A-7 (NRC 1997).

The expert-opinion elicitation process should preferably be conducted to include a face-to-face meeting of experts that is developed specifically for the issues under consideration. The meeting of the experts should be conducted after communicating to the experts in advance to the meeting background information, objectives, list of issues, and anticipated outcome from the meeting. The expert-opinion elicitation based on the technical integrator and facilitator (TIF) concept can result in consensus or disagreement as shown in FigureA-11. Consensus can be of four types as shown in Figure A-11 (NRC 1997). Commonly, the expert-opinion elicitation process has the objective of achieving consensus type 4, i.e., experts agree that a particular probability distribution represents the overall scientific community. The TIF plays a major role in building consensus by acting as a facilitator. Disagreement among experts, whether it is intentional or unintentional, requires the TIF to act as an integrator by using equal or non-equal weight factors. Sometimes, expert opinions need to be weighed for appropriateness and relevance rather than strictly weighted by factors in a mathematical aggregation procedure.

The suggested steps for an expert-opinion elicitation process depend on the use of a technical integrator (TI) or a technical integrator and facilitator (TIF) as shown in Figure A-10. Figure A-10 was constructed based on NRC (1997), supplemented with details, and added steps. The details of the steps involved in these two processes are defined in subsequent subsections.

Table A-6. Issue Degrees and Study Levels (Constructed based on NRC 1997)

1. Issue Complexity Degree	
Degree	*Description*
A	Non-controversial Insignificant effect on risk
B	Significant uncertainty Significant diversity Controversial Complex
C	Highly contentious Significant effect on risk Highly complex
2. Study Level	
Level	*Requirements*
I	A technical integrator (TI) evaluates and weighs models based on literature review and experience, and estimates needed quantities.
II	A technical integrator (TI) interacts with proponents & resource experts, asses interpretations, and estimates needed quantities.
III	A technical integrator (TI) brings together proponents & resource experts for debate and interaction. TI focuses the debate, evaluates interpretations, and estimates needed quantities.
IV	A technical integrator (TI) and technical facilitator (TF) (that can be one entity, i.e., ITF) organize a panel of experts to interpret and evaluate, focus discussions, keep the experts debate orderly, summarize and integrate opinions, and estimates needed quantities.

Table A-7. Guidance on Use of Peer Reviewers (NRC 1997)

Expert-opinion elicitation Process	*Peer Review Subject*	*Peer Review Method*	*Recommendation*
Technical integrator and facilitator	Technical	Participatory	Recommended
		Late stage	Can be acceptable
	Process	Participatory	Strongly recommended
		Risky: unlikely to be successful	
Technical integrator	Technical	Strongly recommended	
		Risky but can be acceptable	
	Process	Strongly recommended	
		Risky but can be acceptable	

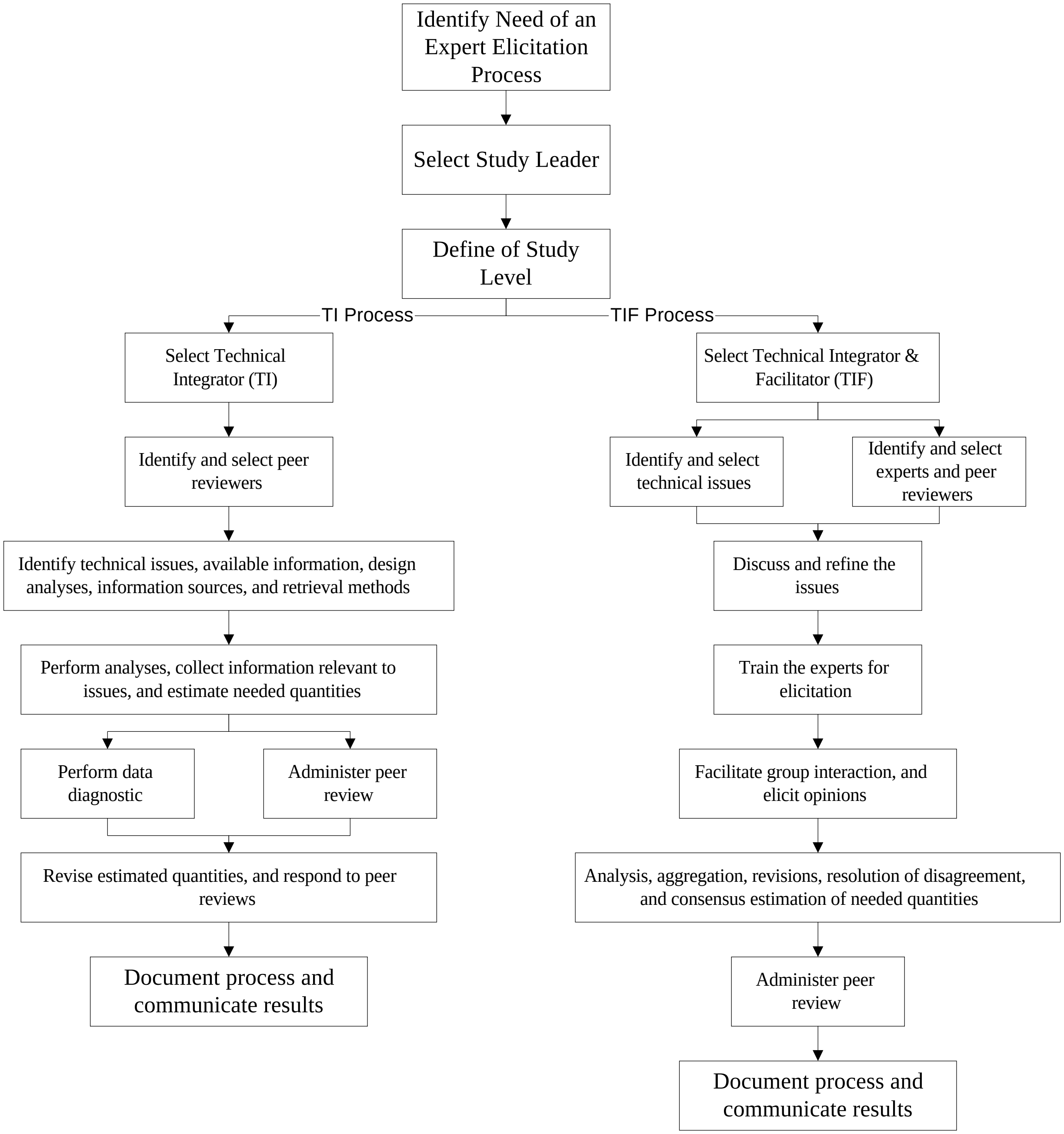


Figure A-10. Expert-Opinion Elicitation Process

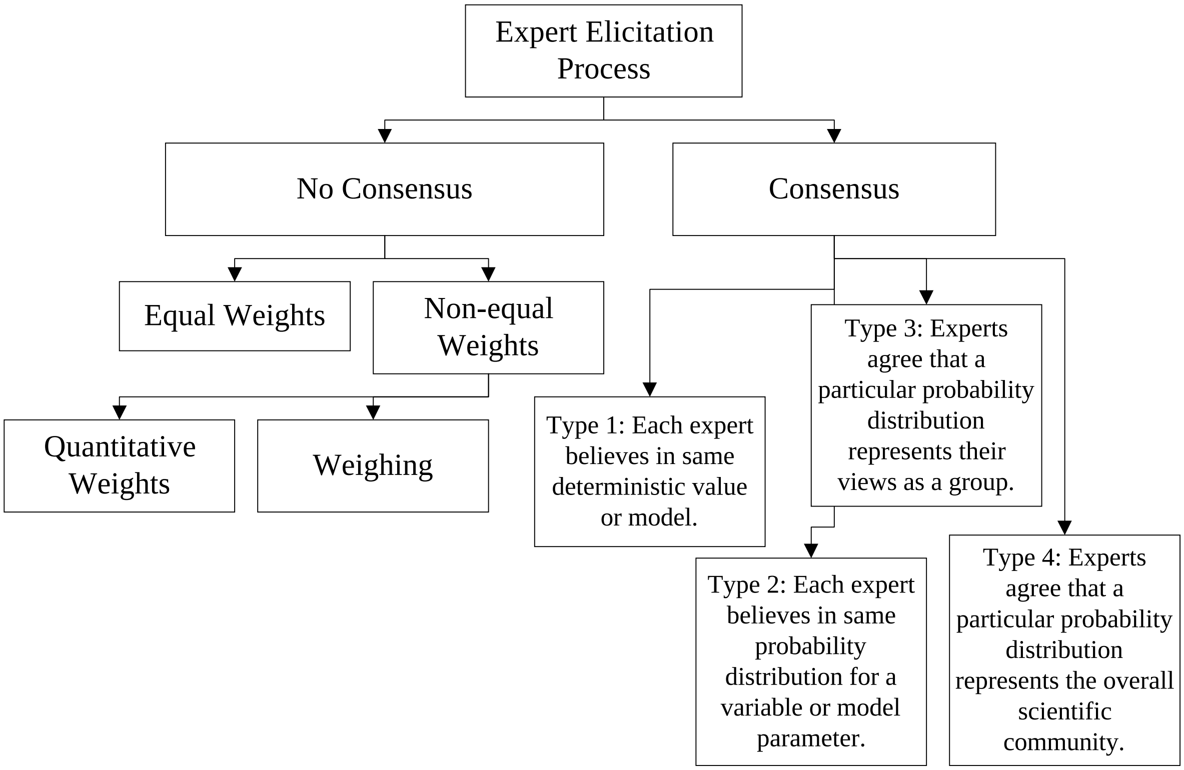


Figure A-11. Outcomes of the Expert-Opinion Elicitation Process

A.7.2.2. Need Identification for Expert-Opinion Elicitation

The primary reason for using expert-opinion elicitation is to deal with uncertainty in selected technical issues related to a system of interest. Issues with significant uncertainty, issues that are controversial and/or contentious, issues that are complex, and/or issues that can have a significant effect on risk are most suited for expert-opinion elicitation. The value of the expert-opinion elicitation comes from its initial intended uses as a heuristic tool, not a scientific tool, for exploring vague and unknown issues that are otherwise inaccessible. It is not a substitute to scientific, rigorous research.

The identification of need and its communication to experts are essential for the success of the expert-opinion elicitation process. The need identification and communication should include the definition of the goal of the study and relevance of issues to this goal. Establishing this relevance would make the experts stake holders and thereby increase their attention and sincerity levels. Relevance of each issues and/or question to the study needs to be established. This question-to-study relevance is essential to enhancing the reliability of collected data from the experts. Each question or issue needs to be relevant to each expert especially when dealing with subjects with diverse views and backgrounds.

A.7.2.3. Selection of Study Level and Study Leader

The goal of a study and nature of issues determine the study level as shown in Table A-6. The study leader can be a technical integrator (TI), technical facilitator (TF), or a combined technical integrator and facilitator (TIF). The leader of the study is an entity having managerial and technical responsibility for organizing and executing the project, overseeing all participants, and intellectually *owning* the results. The primary difference between the TI and the TIF is in the intellectual responsibility for the study where it lies with only the TI, and the TIF and the experts, respectively. The TIF has also the added responsibility of maintaining the professional integrity of the process and its implementation. The TI is required to utilize peer reviewers for quality assurance purposes. A study leader should be selected based on the following attributes: an outstanding professional reputation, and wide recognition and competence based on academic training and relevant experience; strong communication skills, interpersonal skills, flexibility, impartiality, and ability to generalize and simplify; a large contact base of industry leaders, researcher, engineers, scientists, and decision makers; and ability to build consensus, and leadership qualities. The study leader does not need to be a subject expert, but should be knowledgeable of the subject matter.

A.7.2.4. Selection of Peer Reviewers

Peer review can be classified according to peer-review method, and according to peer-review subject. Two methods of peer review can be performed: (1) participatory peer review that would be conducted as an ongoing review throughout all study stages, and (2) late-stage peer review that would be performed as the final stage of the study. The second classification of peer reviews is by peer-review subject and has two types: (1) technical peer review that focuses on the technical scope, coverage, contents and results, and (2) process peer review that focuses on the structure, format and execution of the expert-opinion elicitation process. Peer reviewers are needed for both the TI and TIF processes. Peer reviewers should be selected by the study leader in close consultation with perhaps the study sponsor. The following individuals should be sought after in peer reviewers:

Researchers, scientists, and/or engineers that have outstanding professional reputation, and widely recognized competence based on academic training and relevant experience.

Researchers, scientists, and/or engineers with general understanding of the issues in other related areas, and/or with relevant expertise and experiences from other areas.

Researchers, scientists, and/or engineers who are available and willing to devote the needed time and effort.

Researchers, scientists, and/or engineers with strong communication skills, interpersonal skills, flexibility, impartiality, and ability to generalize and simplify.

A.7.2.5. Identification and Selection of Experts

The size of an expert panel should be determined on case by case basis. The size should be large enough to achieve a needed diversity of opinion, credibility, and result reliability. In recent expert-opinion elicitation studies, a nomination process was used to establish a list of candidate experts by consulting archival literature, technical societies, governmental organization, and other knowledgeable experts (Trauth et al. 1993). Formal nomination and selection processes should establish appropriate criteria for nomination, selection and removal of experts. For example, the following criteria were used in an ongoing Yucca Mountain seismic hazard analysis (NRC 1997) to select experts:

1. Strong relevant expertise through academic training, professional accomplishment and experiences, and peer-reviewed publications;
2. Familiarity and knowledge of various aspects related to the issues of interest;
3. Willingness to acts as proponents or impartial evaluators;
4. Availability and willingness to commit needed time and effort;
5. Specific related knowledge and expertise of the issues of interest;
6. Willingness to effectively participate in needed debates, to prepare for discussions, and provide needed evaluations and interpretations; and
7. Strong communication skills, interpersonal skills, flexibility, impartiality, and ability to generalize and simplify.

In this NRC study, criteria were set for expert removal that include failure to perform according to commitments and demands as set in the selection criteria, and unwillingness to interact with members of the study.

The panel of experts for an expert-opinion elicitation process should have a balance and broad spectrum of viewpoints, expertise, technical points of view, and organizational representation. The diversity and completeness of the panel of experts is essential for the success of the elicitation process. For example, it can include the following:

- Proponents who advocate a particular hypothesis or technical position;
- Evaluators who consider available data, become familiar with the views of proponents and other evaluators, questions the technical bases of data, and challenges the views of proponents; and
- Resource experts who are technical experts with detailed and deep knowledge of particular data, issue aspects, particular methodologies, or use of evaluators.

The experts should be familiar with the design, construction, operational, inspection, maintenance, reliability and engineering aspects of the equipment and components of a facility of interest. It is essential to select people with basic engineering or technological knowledge, however they do not necessarily need to be engineers. It might be necessary to include one or two experts from management with engineering knowledge of the equipment and components, consequences, safety aspects, administrative and logistic aspects of operation, expert-opinion elicitation process, and objectives of this study. One or two experts with a broader knowledge of the equipment and components might be needed. Also, one or two experts with a background in risk analysis and risk-based decision making and their uses in areas related to the facility of interest might be needed.

Observers can be invited to participate in the elicitation process. Observers can contribute to the discussion, but cannot provide expert opinion that enters in the aggregated opinion of the experts. The observers provide expertise in the elicitation process, probabilistic and statistical analyses, risk analysis and other support areas. The composition and contribution of the observers are essential for the success of this process. The observers may include the following:

1. Individuals with research or administrative-related background from research laboratories
2. Individuals with expertise in probabilistic analysis, probabilistic computations, consequence computations and assessment, and expert-opinion elicitation.

A list of names with biographical statements of the study leader, technical integrator, technical facilitator, experts, observers, and peer reviewers should be developed and documented. All attendees can participate in the discussions during the meeting. However, only the experts can provide the needed answers to questions on the selected issues. The integrators and facilitators are responsible for conducting the expert-opinion elicitation process. They can be considered to be a part of the observers or experts depending on the circumstances and the needs of the process.

A.7.2.6. Items to be Sent to Experts and Reviewers before the Expert-Opinion Elicitation Meeting

The experts and observers need to receive the following items before the expert-opinion elicitation meeting:

1. An objective statement of the study;
2. A list of experts, observers, integrators, facilitators, study leader, sponsors, and their biographical statements;
3. A description of the facility, systems, equipment and components;
4. Basic terminology, definitions that should include probability, unsatisfactory-performance rate, average time between unsatisfactory performances, mean (or average) value, median value, and uncertainty;
5. Unsatisfactory-performance consequence estimation;
6. A description of the expert-opinion elicitation process;
7. A related example on the expert-opinion elicitation process and its results, if available;
8. Aggregation methods of expert opinions such as computations of percentiles;
9. A description of the issues in the form of a list of questions with background descriptions. Each issue should be presented on a separate page with spaces for recording an expert's judgment, any revisions and comments. Clear statements of expectations from the experts in terms of time, effort, responses, communication, and discussion style and format.

It might be necessary to personally contact individual experts for the purpose of establishing clear understanding of expectations.

A.7.2.7. Identification, Selection and Development of Technical Issues

The technical issues of interest should be carefully selected to achieve certain objectives. In these guidelines, the technical issues are related to the quantitative assessment of unsatisfactory-performance probabilities and consequences for selected components, subsystems and systems within a facility. The issues should be selected such that they would have a significant impact on the study results. These issues should be structured in a logical sequence starting by background statement, followed by questions, and then answer selections or answer format and scales. Personnel with risk-analysis background that are familiar with the construction, design, operation, and maintenance of the facility need to define these issues in the form of specific questions. Also, background materials about these issues need to be assembled. The materials will be used to familiarize and train the experts about the issues of interest as described subsequent steps.

An introductory statement for the expert-opinion elicitation process should be developed that includes the goal of the study and establishes relevance. Instructions should be provided with guidance on expectations, answering the questions, and reporting. The following are guidelines on constructing questions and issues based social research practices (Bailey 1994):

Each issue can include several questions, however, each question should consist of only one sought after answer. It is a poor practice to include two questions in one.

Question and issue statements should not be ambiguous. Also, the use of ambiguous words should be avoided. In expert-opinion elicitation of failure probabilities, the word “failure” might be vague or ambiguous to some subjects. Special attention should be given to its definition within the context of each issue or question. The level of wording should be kept to a minimum. Also, the choice of the words might affect the connotation of an issue especially by different subjects.

The use of factual questions is preferred over abstract questions. Questions that refer to concrete and specific matters result in desirable concrete and specific answers.

Questions should be carefully structured to reduce biases of subjects. Questions should be asked in a neutral format, sometimes more appropriately without lead statements.

Sensitive topics might require stating questions with lead statements that would establish supposedly accepted social norms to encourage subjects to answers the questions truthfully.

Questions can be classified into *open-ended questions* and *closed-ended questions* as was previously discussed. The format of the question should be selected carefully. The format, scale and units for the response categories should be selected to best achieve the goal of the study.

Once the issues are developed, they should be pre-tested by administering them a few subjects for the purpose of identifying and correcting flaws. The results of this pre-testing should be used to revise the issues.

A.7.2.8. Elicitation of Opinions

The elicitation process of opinions should be systematic for all the issues according to the steps presented in this section.

Issue Familiarization of Experts.

The background materials that were assembled in the previous step should be sent to the experts about one to two weeks in advance of the meeting with the objective of providing sufficient time for them to become familiar with the issues. The objective of this step is, also, to ensure that there is a common understanding among the experts of the issues. The background material should include the objectives of the study, description of the issues and lists of questions for the issues, description of systems and processes, their equipment and components, the elicitation process, selection methods of experts, and biographical information on the selected experts. Also, example results and their meaning, methods of analysis of the results, and lessons learned from previous elicitation processes should be made available to them. It is important to breakdown the questions or issues in components that can be easily addressed. Preliminary discussion meetings or telephone conversations between the facilitator and experts might be necessary in some cases in preparation for the elicitation process.

Training of Experts.

This step is performed during the meeting of the experts, observers and facilitators. During the training the facilitator needs to maintain flexibility to refine wording or even change approach based on feedback from experts. For instance, experts may not be comfortable with "probability" but they may answer on "events per year" or "recurrence interval." The meeting should be started with presentations of background material to establish relevance of the study to the experts, and study goals to establish rapport with the experts. Then, information on uncertainty sources and types, occurrence probabilities and consequences, expert-opinion elicitation process, technical issues and questions, aggregation of expert opinions should be presented. Also, experts need to be trained on providing answers in an acceptable format that can be used in the analytical evaluation of the unsatisfactory-performance probabilities or consequences. The experts need to be trained in certain areas such as the meaning of probability, central tendency, and dispersion measures especially to experts who are not familiar with the language of probability. Additional training might be needed on consequences, subjective assessment, logic trees, problem structuring tools such as influence diagrams, and methods of combining expert evaluations. Sources of bias that include overconfidence, and base-rate fallacy and their contribution to bias and error should be discussed. This step should include a search for any motivational bias of experts due to, for example, previous positions experts have taken in public, wanting to influence decisions and funding allocations, preconceived notions that they will be evaluated by their superiors as a result of their answers, and/or to be perceived as an authoritative expert. These motivational biases, once identified, can be sometimes overcome by redefining the incentive structure for the experts.

Elicitation and Collection of Opinions.

The opinion elicitation step starts with a technical presentation of an issue, and by decomposing the issue to its components, discussing potential influences, and describing event sequences that might lead to top events of interest. These top events are the basis for questions related to the issue in the next stage of the opinion elicitation step. Factors, limitations, test results, analytical models, and uncertainty types and sources need to be presented. The presentation should allow for questions to eliminate any ambiguity and clarify scope and conditions for the issue. The discussion of the issue should be encouraged. The discussion and questions might result in refining the definition of the issue. Then, a form with a statement of the issue should be given to the expert to record their evaluation or input. The experts' judgment along with their supportive reasoning should be documented about the issue. It is common that experts would be asked to provide several conditional probabilities to reduce the complexity of the questions and thereby obtain reliable answers. These conditional probabilities can be based on fault tree and event tree diagrams. Conditioning has the benefit of simplifying the questions by decomposing the problems. Also, it results in a conditional event that has a larger occurrence probability than its underlying events; therefore making the elicitation less prone to biases since experts tend to have a better handle on larger probabilities in comparison to very small ones. It is desirable to have the elicited probabilities in the range of 0.1 to 0.9 if possible. Sometimes it might be desirable to elicit conditional probabilities using linguistic terms such as likely, highly unlikely, most likely, …, etc. as detailed by Ayyub (1999). If correlation among variables exits, it should be presented to the experts in great detail and conditional probabilities need to be elicited. Issues should be dealt with one issue at a time, although sometimes similar or related issues might be considered simultaneously.

Aggregation and Presentation of Results.
The collected assessments from the experts for an issue should be assessed for internal consistency, analyzed and aggregated to obtain composite judgments for the issue. The means, medians, percentile values and standard deviations need to be computed for the issues. Also, a summary of the reasoning provided during the meeting about the issues needs to be developed. Uncertainty levels in the assessments should also be quantified. A summary of methods for combining expert opinions is provided by Ayyub (1999). The methods can be classified into consensus methods and mathematical methods. The mathematical methods can be based on assigning equal weights to the experts or different weights.

Group Interaction, Discussion and Revision by Experts.
The aggregated results need to be presented to the experts for a second round of discussion and revision. The experts should be given the opportunity to revise their assessments of the individual issues at the end of discussion. Also, the experts should be asked to state the rationale for their statements and revisions. The revised assessments of the experts need to be collected for aggregation and analysis. This step can produce either consensus or no consensus as shown in Figure A-12. The selected aggregation procedure might require eliciting weight factors from the experts. In this step the technical facilitator plays a major role in developing a consensus, and maintaining the integrity and credibility of the elicitation process. Also, the technical integrator is needed to aggregate the results without biases with reliability measures. The integrator might need to deal with varying expertise levels for the experts, outliers (i.e., extreme views), non-independent experts, and expert biases.

A.7.2.9. Documentation and Communication

A comprehensive documentation of the process is essential to ensure acceptance and credibility of the results. The document should include complete descriptions of the steps, the initial results, revised results, consensus results, and aggregated results spreads and reliability measures.

A.7.2.10. Model Modification Based on Available Data

Often there are some aspects of the model where data are unavailable. Therefore, adjustments to the model must be made to accommodate this lack of data. For example, a subsystem composed of components with unknown reliability can be modeled by the reliability of the entire subsystem, if that is known. Again, it is of the utmost importance for the model to accurately represent the system being analyzed.

A.8. Risk Management and Control

Adding risk control to risk assessment produces risk management. Risk management is the process by which system operators, managers, and owners make safety decisions, regulatory changes, and choose different system configurations based on the data generated in the risk assessment. Risk management involves using information from the previously described risk assessment stage to make educated decisions about system safety. Risk control includes failure prevention and consequence mitigation.

Risk management requires the optimal allocation of available resources in support of group goals. Therefore, it requires the definition of acceptable risk, and comparative evaluation of options and/or alternatives for decision making. The goals of risk management are to reduce risk to an acceptable level and/or prioritize resources based on comparative analysis. Risk reduction is accomplished by preventing an unfavorable scenario, reducing the frequency, and/or reducing the consequence. A graph showing the risk relationship is shown in Figure A-12 as linear contours of constant risk, although due to risk aversion these lines are commonly estimated as nonlinear curves and should be treated as nonlinear curves. Moreover, the vertical axis is termed as probability whereas it is commonly expressed as an annual exceedence probability or frequency as shown in Figure A-1.

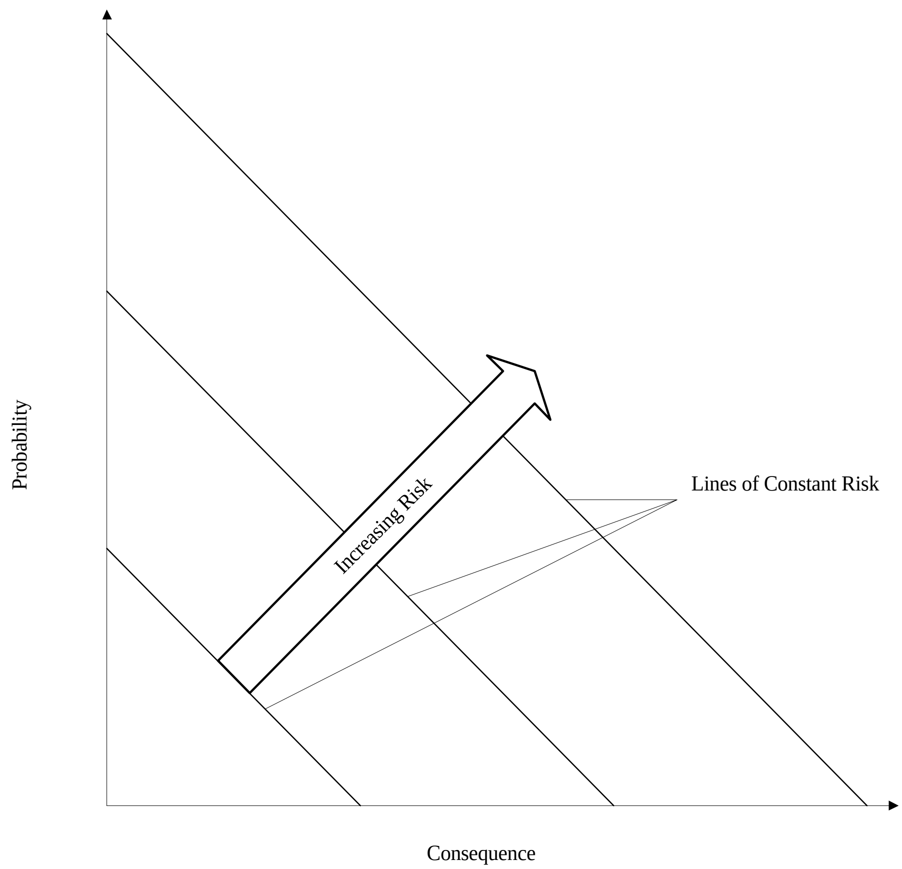


Figure A-12. Risk Graph

A.8.1. Risk Acceptance

Risk acceptance constitutes a definition of safety as discussed in Section A.2.8. Therefore, risk acceptance is considered a complex subject 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 A-8.

Risk managers make decisions based on risk assessment and other considerations including economical, political, environmental, legal, reliability, producibility, safety, and other factors. The answer to the question "How safe is safe enough?" is difficult and constantly changing due to different perceptions and understandings of risk. To determine "acceptable risk," managers need to analyze alternatives for the best choice (Derby and Keeney 1993). In some industries, an acceptable risk has been defined by consensus. For example, the U.S. Nuclear Regulatory Commission requires that reactors be designed such that the probability of a large radioactive release to the environment from a reactor incident shall be less than $1\text{x}10^{-6}$ per year (Modarres 1993). Risk levels for certain carcinogens and pollutants have also been given acceptable concentration levels based on some assessment of acceptable risk. However, risk acceptance for many other activities are not stated.

Qualitative implications for risk acceptance are identified in the several existing maritime regulations. The International Maritime Organization High Speed Craft Code and NVIC 5-93 for passenger submersible guidance both state that if the end effect is hazardous or catastrophic, a backup system and a corrective operating procedure is required. These references also state that a single failure must not result in a catastrophic event, unless the likelihood is extremely remote.

Often the level of risk acceptance with various activities is implied. Society has reacted to risks through the developed level of balance between risk and potential benefits. Measuring this balance of accepted safety levels for various risks provides a means for assessing society values. These threshold values of acceptable risk depend on a variety of issues including the activity type, industry, and users, and the society as a whole.

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. Agreeing upon a reasonable value in cases of novel structures without prior history.
2. Calibrating reliability levels implied in currently successfully used design codes.
3. 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 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.

Table A-8. 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.

A.8.1.1. Risk Categories

Analysis of risks shows that there are different taxonomies that demonstrate the different risk categories often called "risk factors." These categories can be used to analyze risks on a dichotomous scale comparing risks that invoke the same perceptions in society (Litai 1980). For example, the severity category may be used to describe both ordinary and catastrophic events. Grouping events that could be classified as ordinary and comparing the distribution of risk to a similar grouping of catastrophic categories yields a ratio describing the degree of risk acceptance of ordinary events as compared to catastrophic events. The comparison of various categories by Litai (1980) determined the risk conversion values as provided in Table A-9. These factors are useful in comparing the risk acceptance for different activities, industries, etc. By computing the acceptable risk in one activity, an estimate of acceptable risk in other activities can be calculated based on the risk conversion factors. A comparison of several common risks based on origin and volition is shown in Figure A-13.

An additional way commonly used to categorize risk is by the consequence categories. Health risk, financial risk, performance risk are all risk categories that differ by the types of consequence. It is important to be able to categorize the risk for the purpose of performing risk comparisons. For example, health risk would not be compared to financial risk since they are not similar categories.

Table A-9. Risk Conversion Values for Different Risk Factors

Risk "Factors"	Risk Conversion Factor	Value by Litai (1980)
Origin	Natural/man-made	20
Severity	Ordinary/catastrophic	30
Volition	Voluntary/involuntary	100
Effect	Delayed/immediate	30
Controllability	Controlled/uncontrolled	5-10
Familiarity	Old/new	10
Necessity	Necessary/luxury	1
Costs	Monetary/non-monetary	
Origin	Industrial/ Regulatory	
Media	Low profile/ high profile	

		Voluntary		Involuntary	
		Immediate	Delayed	Immediate	Delayed
Man Made	Catastrophic	• Aviation		• Dam Failure • Building Fire • Nuclear	• Pollution • Building Fire
	Ordinary	• Sports • Boating • Autos	• Smoking • Ocupation • Carcinogens	• Homocide	
Natural	Catastrophic			• Earthquakes • Hurricanes • Tornadoes • Epidemics	
	Ordinary			• Lightning • Animal Bites	• Diseases

Figure A-13. Classification of Common Risks (Adapted from Litai 1980)

A.8.1.2. <u>Farmer's Curve</u>

The Farmer's curve (Farmer 1967) is graph of the cumulative probability versus consequence for some activity, industry or design. This curve introduces a probabilistic approach in determining acceptable safety limits. Probability values are calculated for each level of risk generating a curve that is unique to hazard of concern. The area to the right (outside) of the curve is generally considered unacceptable since the frequency and risk are higher than the average value estimated by the curve. The area to the left (inside) of the curve is considered acceptable since frequency and risk are less that the estimated valve of the curve. An example Farmer's curve for different hazards is demonstrated in Figure A-14.

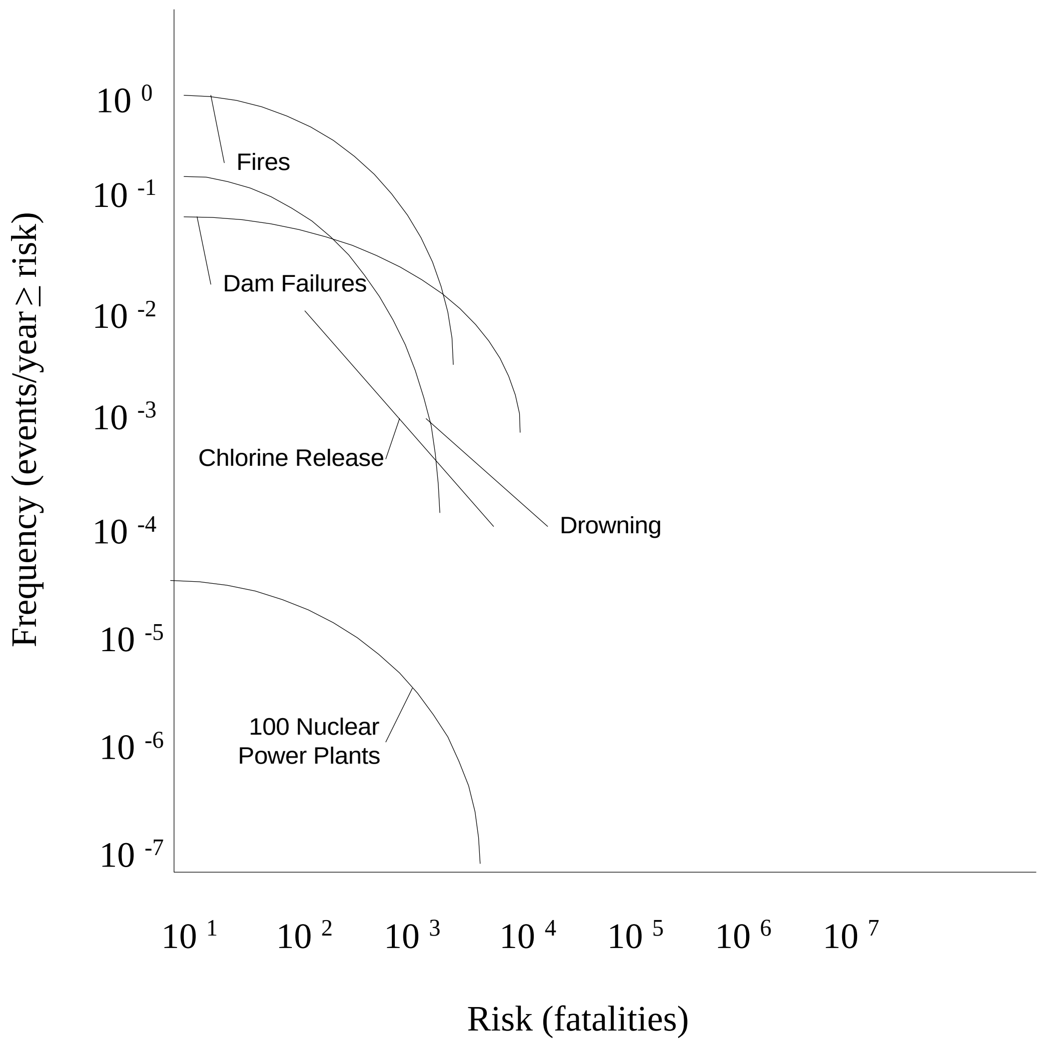


Figure A-14. Farmer's Curve Comparing Different Risks (Rasmussen 1981)

A.8.1.3. Method of Revealed Preferences

The method of revealed preferences provides a comparison of risk versus benefit and categorization for different risk types. The basis for this relationship is that risks are not taken unless there is some form of benefit. Benefit may be monetary or some other item of worth such as pleasure. The different risk types presented by Starr (1969) are for the risk category of voluntary versus involuntary actions as shown in Figure A-15.

This technique assumes that the risk acceptance by society is found in the equilibrium generated from historical data on risk versus benefit. The estimated lines for acceptance of different activities are separated by the voluntary/involuntary risk categories. Further analysis of the data led Starr to estimate the relationship between risk and benefit as follows:

$$Risk \sim Benefit^3 . \tag{A-22}$$

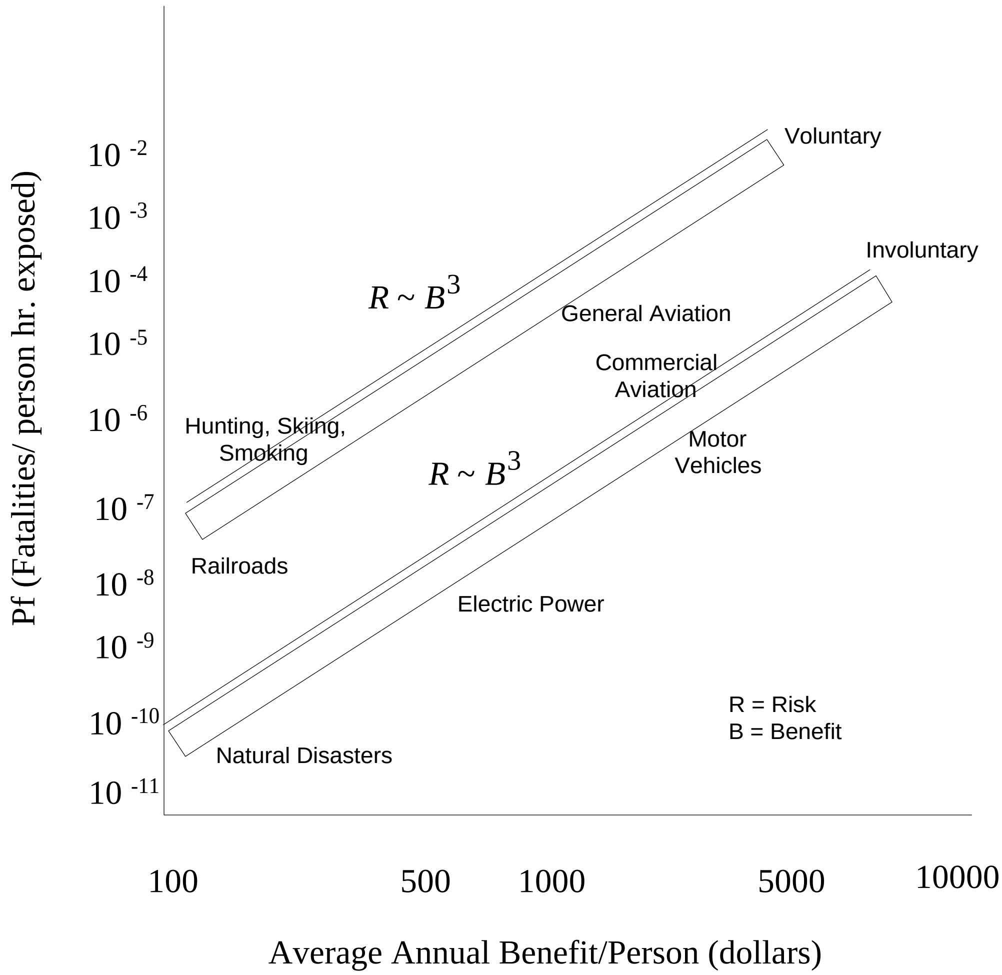


Figure A-15. Accepted Risk of Voluntary and Involuntary Activities (Starr 1971)

A.8.1.4. Evaluation of Magnitude of Risk Consequence

Another factor affecting the acceptance of risk is the magnitude or consequence of the event that can result from some failure. In general, the larger the consequence, the less the likelihood that this event may occur. This technique has been used in several industries to demonstrate the location of the industry within societies risk acceptance based on consequence magnitude as shown in Figure A-16. Further evaluation has resulted in several estimates for the relationship between the accepted probability of failure and the magnitude of consequence for failure as provided by (Allen 1981, and Suzuki 1999) and called herein the CIRIA (Construction Industry Research and Information Association) equation:

$$P_f = 10^{-4} \frac{KT}{n} \tag{A-23}$$

where T is the life of the structure, K is a factor regarding the redundancy of the structure, and n is the number of people exposed to risk. Another estimate is Allen's equation (Allen 1981, and Suzuki 1999) that is given by:

$$P_f = 10^{-5} \frac{TA}{W\sqrt{n}} \tag{A-24}$$

where T is the life of the structure, n is the number of persons exposed to risk, and A and W are factors regarding the type and redundancy of the structure.

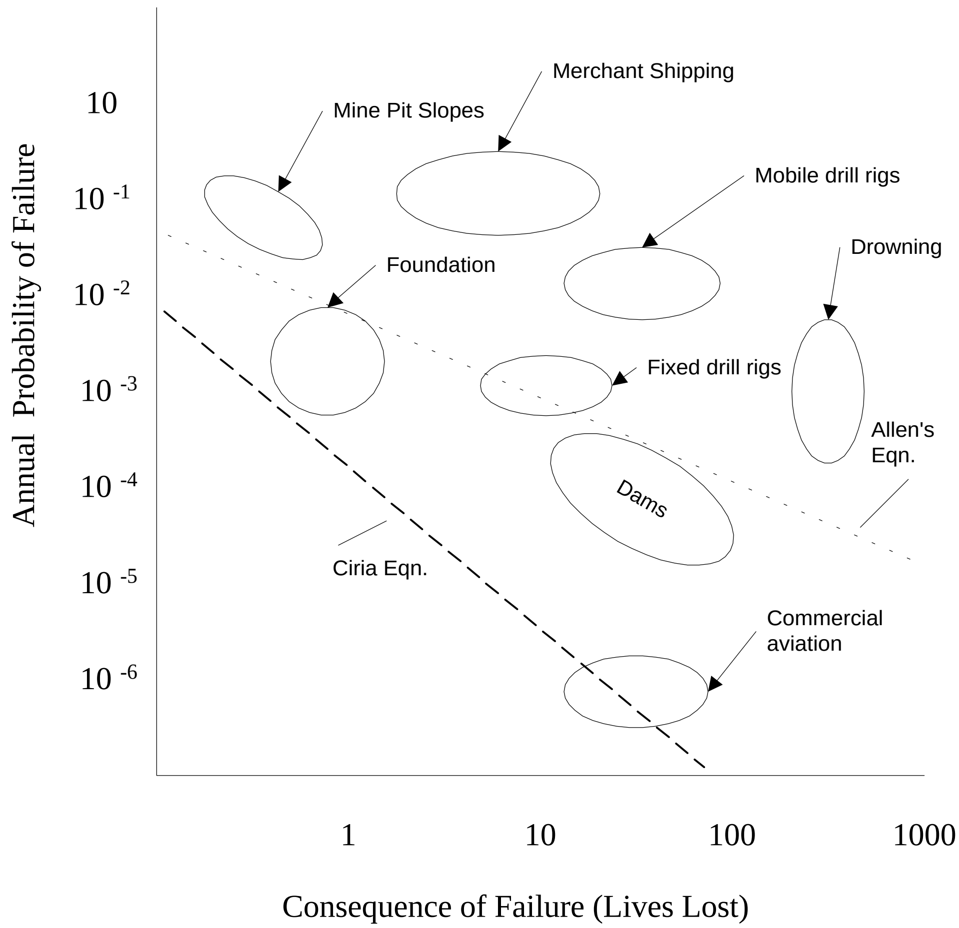


Figure A-16. Target Risk Based on Consequence of Failure for Industries
(Adapted from Whitman 1984)

A.8.1.5. Risk Effectiveness/Cost Effectiveness of Risk Reduction

Another measuring tool to assess risk acceptance is the determination of risk effectiveness:

$$Risk\ Effectiveness = \frac{Cost}{\Delta\ Risk} \tag{A-25}$$

where the cost should be attributed to risk reduction, and *ΔRisk* is the level of risk reduction. Risk effectiveness can be used to compare several risk reduction efforts. The initiative with the smallest risk effectiveness provides the most benefit for the cost. Therefore, this measurement may be used to help determine an acceptable level of risk. The inverse of this relationship may also be expressed as cost effectiveness. This relationship is graphed in Figure A-17 where the equilibrium value for risk acceptance is shown.

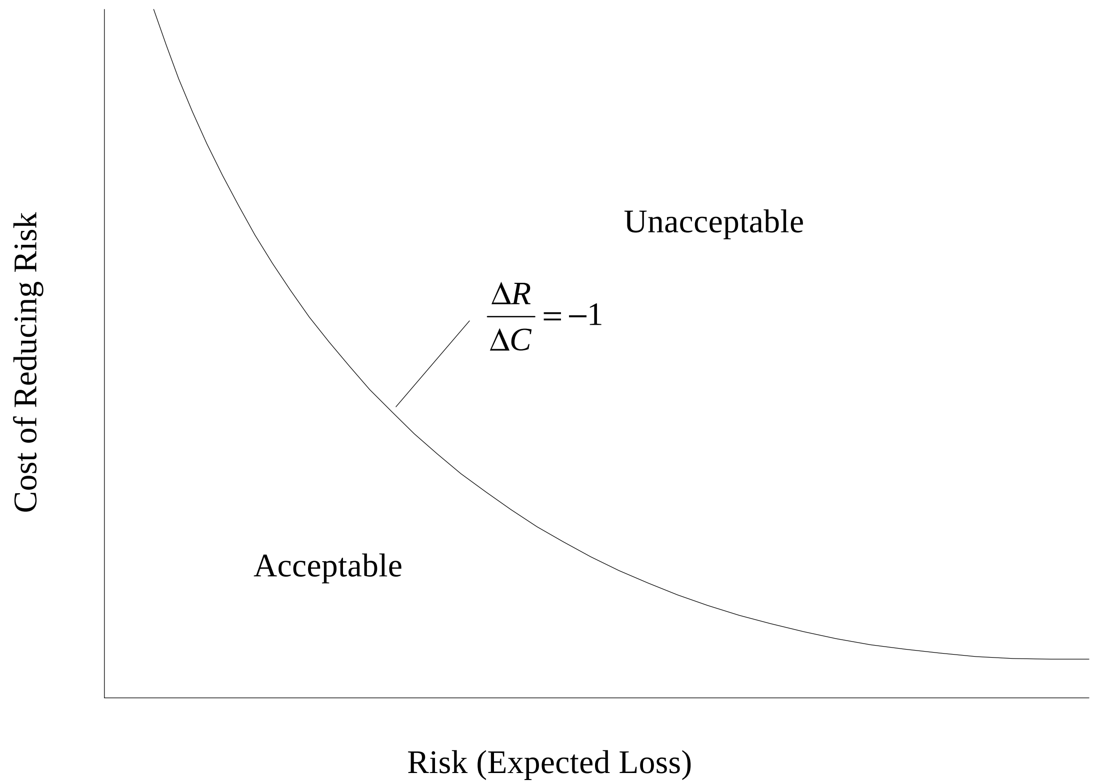


Figure A-17. Cost Effectiveness of Risk Reduction (Rowe 1977)

A.8.1.6. Risk Comparison

This technique uses the frequency of severe incidents to directly compare risks between various areas of interest to assist in justifying risk acceptance. Risks can be presented in different ways that can impact how the data are used for decisions. Often values of risk are manipulated in different forms for comparison reasons demonstrated in Table A-10. Comparison of risk values should be taken in the context of the values' origin and uncertainties involved.

This technique is most effective for comparing risks that invoke the same human perceptions and consequences (categories). Comparing risks of different categories is cautioned since the differences between risk and perceived safety may not provide an objective analysis of risk acceptance. The use of risk conversion factors may assist in transforming different risk categories. Table A-11 demonstrates various estimates of risk of dying from various activities.

Conservative guidelines for determining risk acceptance criteria can be established for voluntary risks to the public from the involuntary risk of natural causes (Modarres 1993).

Table A-10. Ways to Identify Risk of Death

Ways to Identify Risk of Death	Summary
Number of Fatalities	This shows the impact in terms of the number of fatalities on society. Comparison of these values is cautioned since the number of persons exposed to the particular risk may vary. Also the time spent performing the activity may vary. Consideration for the different risk category types is also a concern when comparing fatality rates.
Annual Mortality Rate/Individual	This value shows the mortality risk normalized by the exposed population. This adds additional information about the number of exposed persons, however, the value does not include the time spent on the activity.
Annual Mortality	This Value provides the most complete risk value since the risk is normalized by the exposed population and the duration of the exposure.
Loss of Life Exposure (LLE)	Converts a risk into a reduction in the expected life of an individual. Provides a good means of communicating risks beyond probability values.
Odds	This is a layman format for communicate probability (example: 1 in 4).

Table A-11. Risk Perspective of Different Activities (Douglas 1985, and Litai 1980)

Risk of Death	Occupation	Lifestyle	Accidents/ Recreation	Environmental Risk
1 in 100	Stuntman			
1 in 1,000	Racecar driver	Smoking (1pack/day)	Skydiving Rock climbing Snowmobile	
1 in 10,000	Fireman Miner Policeman	Heavy drinking	Canoeing Automobile Home accident	
1 in 100,000	Truck driver Engineer	Light drinking	Skiing	Living downstream of a dam
1 in 1,000,000		X-Rays Smallpox Vaccination	Fishing	Natural Radiation Nuclear power
1 in 10,000,000				Hurricane Lightening

A.8.2. Risk-Based Ranking

Another tool for risk management is the development of risk ranking. The elements of a system within the objective of analysis can be analyzed for risk and consequently ranked. This relative ranking may be based on the failure probabilities, failure consequences, risks, or other alternatives with concern towards risk. Generally the higher risk items should be given a higher level of priority; however, risk management decisions may consider other factors such as cost in developing risk management priorities. This risk ranking may be presented graphically in a "Risk totem pole" as described by Grose (1987).

A.8.3. Decision Analysis

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).

A.8.3.1. Cost-Benefit Analysis

Risk managers need to weigh various factors. One of the most common comparisons is based on cost and risk. The analysis of three different alternatives is shown graphically in Figure A-18. The graph shows that alternative (C) is the best choice since the level of risk and cost is less than alternatives (A) and (B). However, if the only alternatives were A and B the decision would be more difficult. Alternative (A) has higher cost and lower risk than alternative (B); alternative (B) has higher risk but lower cost than alternative (A). The risk manager needs to weigh the importance of risk and cost in making this decision and make use of risk-based decision analysis.

Risk-Benefit analysis can also be used for risk management. Economic efficiency is important to determine the most effective means of expending resources. At some point the costs for risk reduction do not provide adequate benefit. This process compares the costs and risk to determine where the optimal risk value is on a cost basis. This optimal value occurs, as shown in Figure A-19, when costs to control risk are equal to the risk cost due to the consequence (loss). Investing resources to reduce low risks below this equilibrium point is not providing a financial benefit. This technique may be used when cost values can be attributed to risks. This may be difficult to do for certain risk such as risk to human health and environmental risks since the monetary values are difficult to estimate for human life and the environment.

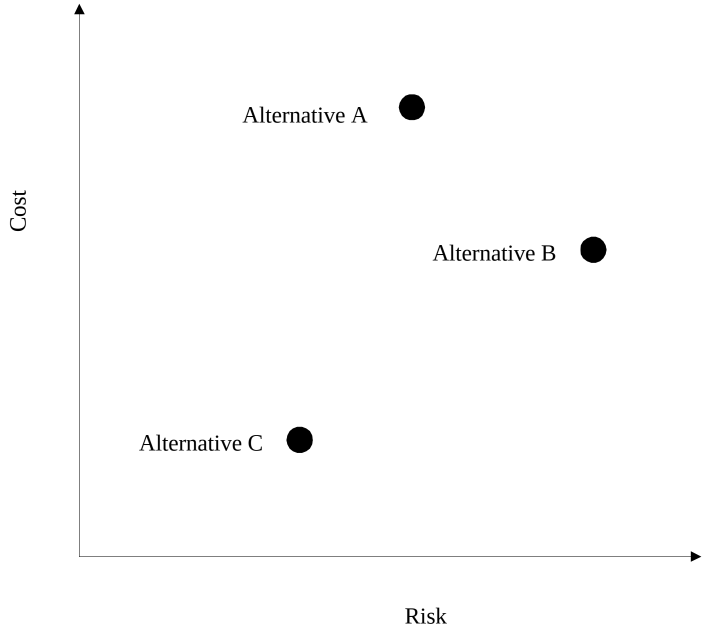


Figure A-18. Risk Benefit for Three Alternatives

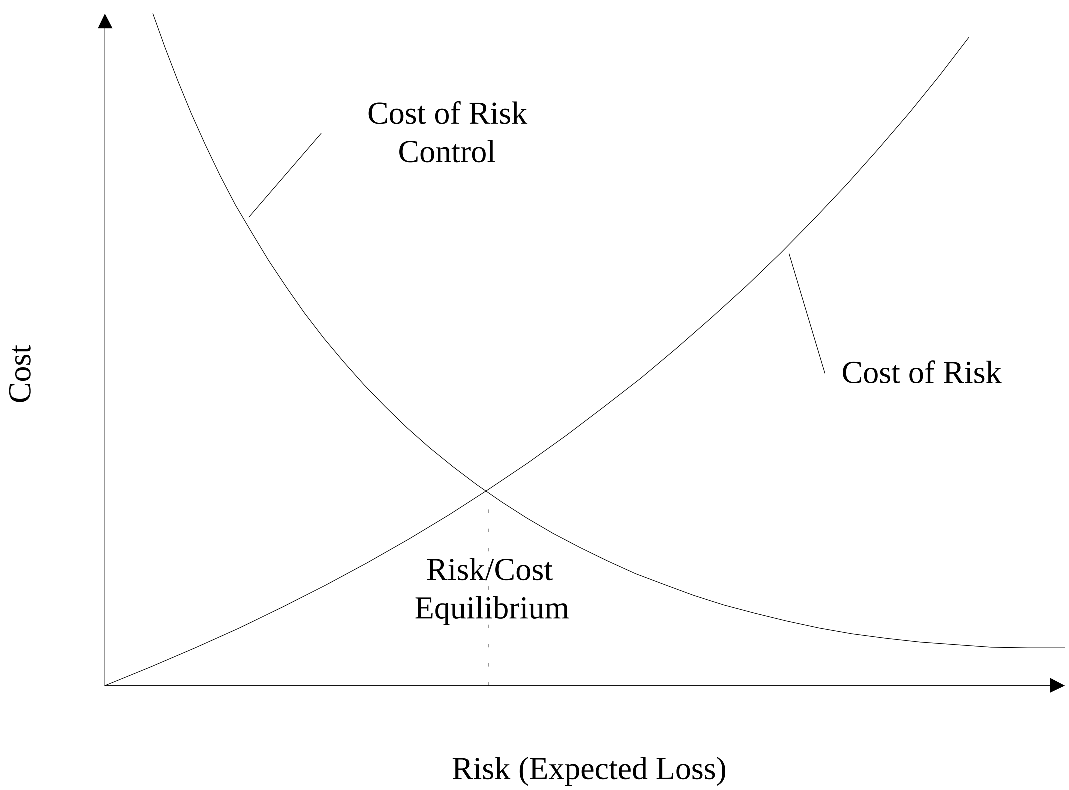


Figure A-19. Comparison of Risk and Control Costs

A.8.3.2. Decision Trees

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 A-20. 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.

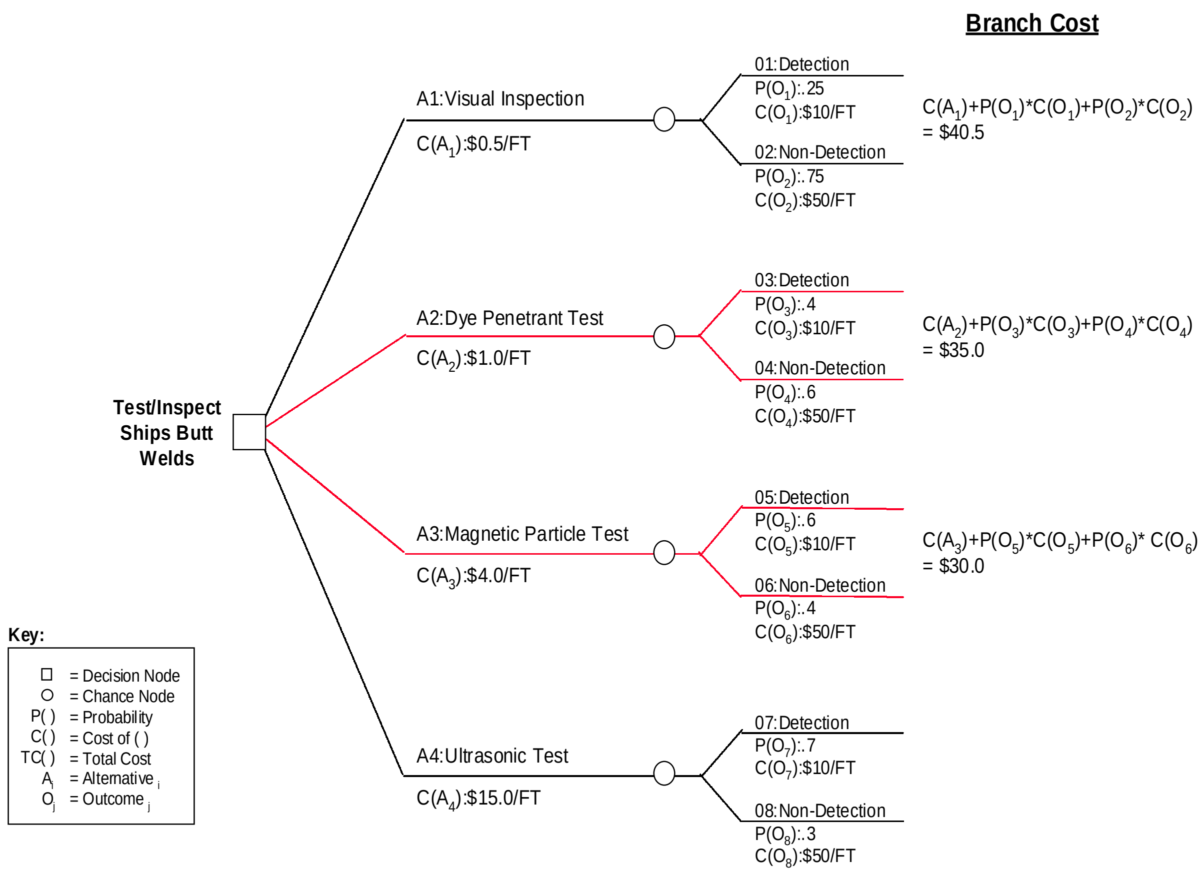


Figure A-20. Decision Tree for Weld Inspection Strategy

A.8.3.3. Influence Diagrams

An influence diagram is a graphical tool that shows the relationship among the decision elements of a system (ASME 1993). This is similar to a decision tree; however, influence diagrams provide compact representations of large decision problems by focusing on dependencies among various decision nodes, chance nodes and outcomes. This compact representations help facilitate the definition and scope of a decision prior to lengthy analysis. They are particularly useful for problems with a single decision variable and a significant number of uncertainties (ASME 1993). Symbols used for creating influence diagrams are shown in Figure A-21. Generally, the process begins with identifying the decision criteria and then further defining what influences the criteria. An example of an influence diagram for selecting weld inspection decision criteria is shown in Figure A-22.

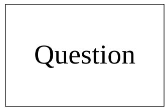
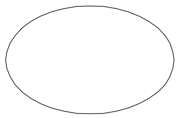
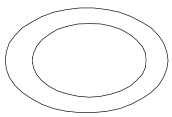
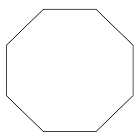
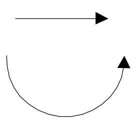
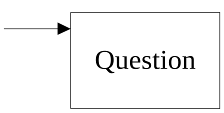
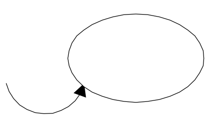
Symbol	Definition
	Decision Node: indicates where a decision must be made.
	Chance Node: represents a probabilistic or random variable.
	Deterministic Node: determined from the inputs from previous nodes.
	Value Node: defines consequences defined over the attributes measuring performance.
	Arrow/Arc: denote influence among nodes.
	Indicates time sequencing (information that must be known prior to a decision).
	Indicates probabilistic dependence upon the decision or uncertainty of the previous node.

Figure A-21. Symbols for Influence Diagrams and Decision Trees

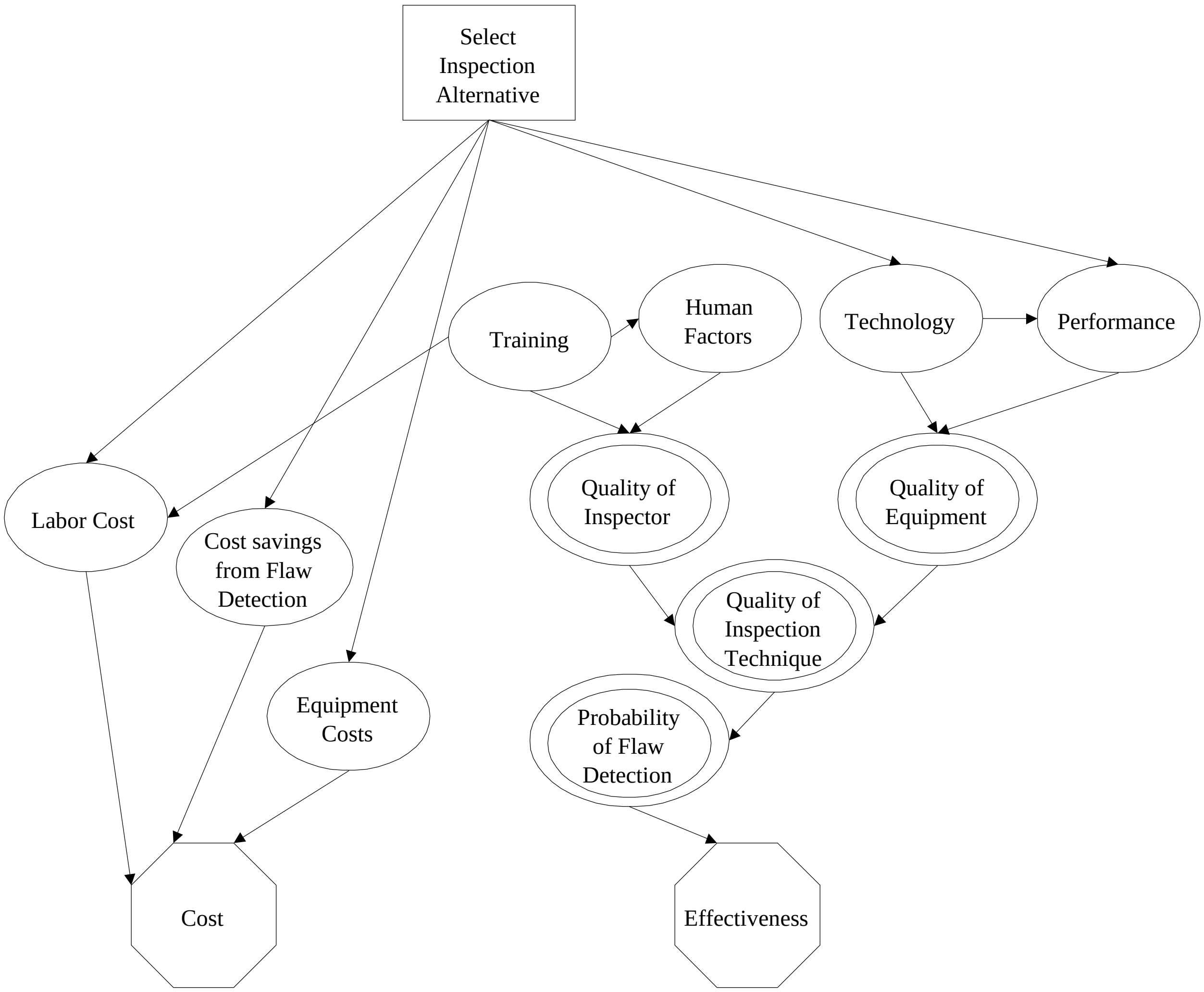


Figure A-22. Influence Diagram for Selection of Weld Inspection Strategy

A.9. Risk Communication

Risk communication can be defined as an interactive process of exchange of information and opinion among stakeholders such as individuals, groups, and institutions (NRC 1989). It often involves multiple messages about the nature of risk or expressing concerns, opinions, or reactions to risk managers or to legal and institutional arrangements for risk management. Risk communication greatly affects risk acceptance and defines the acceptance criteria for safety.

Risk communication provides the vital link between the risk assessors, risk managers, and the public to understand risk. However, this does not necessarily mean that risk communication will always lead to agreement among different parties. An accurate perception of risk provides for rational decision making. The Titanic was deemed the unsinkable ship, yet was lost on its maiden voyage. Space shuttle flights were perceived to be safe enough for civilian travel until the Space Shuttle Challenger disaster. These disasters obviously had risks that were not perceived as significant until after the disaster. Risk communication is a dynamic process that must be considered prior to management decisions.

The communication process deals with technical information about controversial issues (Ayyub et al. 1999). Therefore, it needs to be skillfully performed by risk managers and communicators who might be viewed as adversaries to the public. Risk communication between risk assessors and risk managers is necessary to effectively apply risk assessments in decision making. Risk managers must participate in determining the criteria for determining what risk is acceptable and unacceptable. This communication between the risk managers and risk assessors is necessary for a better understanding of risk analysis in making decisions.

The population-size effect should be considered in risk studies since society responds differently for risks associated with a large population in comparison to a small population. For example, a fatality rate of 1 in 100,000 per event for an affected population of 10 results in an expected fatality of 10^{-4} per event whereas the same fatality rate per event for an affected population of 10,000,000 results in an expected fatality of 100 per event. Although, the impact of the two scenarios might be the same on the society (same risk value), the total number of fatalities per event/accident is a factor in risk acceptance. Plane travel may be "safer" than for example recreational boating, but 200 to 300 injuries per accident are less acceptable to society. Therefore, the size of the population at risk and the number of fatalities per event should be considered as factors in setting acceptable risk.

Risk communication also provides the means for risk managers to gain acceptance and understanding by the public (Derby and Keany 1993). Risk managers need to go beyond the risk assessment results and consider other factors in making decisions. One of these concerns is politics, which is largely influenced by the public. Risk managers often fail to convince the public that risks can be kept to acceptable levels. Problems with this are shown by the public's perception of toxic waste disposal and nuclear power plant operation safety, (Omega Systems Group 1994). As a result of the public's perceived fear, risk managers may make decisions that are conservative to appease the public.

The value of risk calculated from risk assessment is not the only consideration for risk managers. All risks are not created equal and society has established risk preferences based on public preferences (Rasmussen 1981). Decision makers should take these preferences into consideration when making decisions concerning risk.

To establish a means of comparing risks based on the society preferences, risk conversion factors (RCF) may be used. The RCF expresses the relative importance of different attributes concerning risk. An example of possible risk conversion factors identified by Rasmussen (1981) is shown in Table A-12. These values were determined by inferences of public preferences from statistical data with the consequence of death considered.

For example, the voluntary and involuntary classification depends on whether the events leading to the risk are under the control of the persons at risk or not, respectively. Society, in general, accepts a higher level of voluntary risk than involuntary risk by an estimated factor of 100 per

Table A-12. Therefore, an individual will accept a voluntary risk that is 100 times greater than an involuntary risk.

The process of risk communication can be enhanced and improved in three aspects: (1) the process, (2) the message, (3) the consumers (NRC 1989). The risk assessment and management process needs to have clear goals with openness, balance, and competence. The contents of the message should account for audience orientation and uncertainty, provide risk comparison, and be complete. There is a need for consumer's guides that introduce risks associated with a specific technology, the process of risk assessment and management, acceptable risk, decision making, uncertainty, costs and benefits, and feedback mechanisms. Improving risk literacy of consumers is an essential component of the risk communication process.

The USACE has a 1992 EP on risk communication (EP 1110-2-8, 1992), and an IWR report on this subject (USACE 1993). The following are guiding considerations in communicating risk (EP 1110-2-8, 1992, USACE 1993, Feldman and Owen 1997, and ASCE 1966):

- Risk communication must be free of jargon,
- Consensus of expert needs to be established.
- Materials cited, and their sources must be credible.
- Materials must be tailored to audience.
- The information must be personalized to the extent possible.
- Motivation discussion should stress a positive approach and the likelihood of success.
- Risk data must be presented in a meaningful manner.

Table A-12. Risk Conversion Factors

Risk “Factors”	Risk Conversion Factor	Value by Litai (Rasmussan 1981)
Origin	Natural/man-made	20
Severity	Ordinary/catastrophic	30
Volition	Voluntary/involuntary	100
Effect	Delayed/immediate	30
Controllability	Controlled/uncontrolled	5 to 10
Familiarity	Old/new	10
Necessity	Necessary/luxury	1
Costs	Monetary/non-monetary	na
Origin	Industrial/ Regulatory	na
Media	Low profile/ high profile	na

na = not available

B. LIFE CYCLE MANAGEMENT OF STRUCTURAL SYSTEMS

B.1. Introduction

Structural systems, such as, naval (commercial and military), offshore, aerospace and civil structures, are usually conceived and designed to operate for some time frame referred to as the design life of the structure. The concept of life cycle is one of progression through a number of phases from conception and design; construction and production; in service operation and maintenance; and disposal (Figure B-1). A full life-cycle analysis starts from the cradle (conception and design) and goes to the grave (disposal). A service life cycle analysis starts from the current age of the existing ship and extends through the intended remaining service life, whereas a life extension analysis starts from the current age and continues through the intended extension of service life. A life-cycle framework for management of a structural system involves the integration of information from all the phases for decision making. The decision-making process aims at reducing the economic cost and adverse effects that the operation of a vessel might have on humans and the environment. The impact of the environment on the operation of a system is also considered in life cycle analysis. The goal of life cycle analysis, therefore, is a holistic understanding of the long-term economic, social and environmental effects of design, construction, operation and maintenance and disposal of a structural system. This understanding is used for efficient management of the system. In a life cycle analysis, all the short-term and long-term costs (financial, physical, service, environmental), benefits and risks involved in operating the structural system are assessed, evaluated and used for optimal decision making.

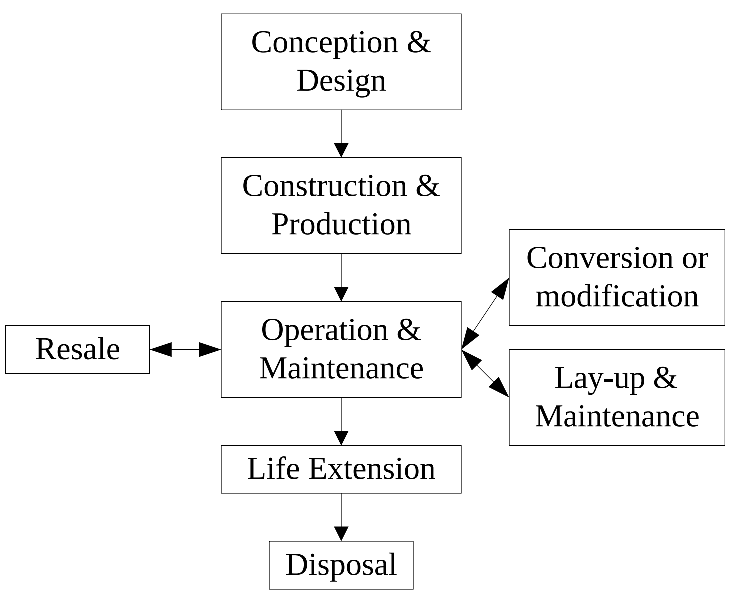


Figure B-1. The Life Cycle of a Ship Structural System

B.2. Life Cycle Concepts

B.2.1. Life Cycle Assessment

Life cycle assessment is a form of product (structure in this context) life cycle analysis that evaluates the environmental impact along the entire chain of a product life (from raw material extraction, through manufacturing/construction, use, recycling and final disposition). The purpose of life cycle assessment is the reconciliation of technology and ecology at each stage of the life span of the product. A typical life cycle assessment methodology has four parts: (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment; and (iv) interpretation.

During goal and scope definition, the application, the depth and subject of the study have to be defined. The functional unit and the system boundaries are also be specified. Inventory analysis is the stage in which emissions and raw material consumption from each process are identified. Impact assessment involves analyzing and assessing the effects of the environmental burdens identified in inventory analysis, and interpretation is the phase in which a synthesis is drawn from the findings of the inventory analysis, the impact assessment, or both. The findings of the interpretation phase may lead to conclusions and recommendations valuable to decision-makers.

The concept of life cycle assessment is demonstrated for steel, which forms a major part of most ship structures (Figure B-2). Steel enters the life of a ship structural system in the construction phase. The environmental impact caused by steel parts depends on the raw material extraction, fabrication and finishing techniques such as welding, grinding, sand blasting and painting, and transportation of steel components and sections. In addition to environmental impacts, other issues reflected in life cycle cost are discussed in life cycle assessment.

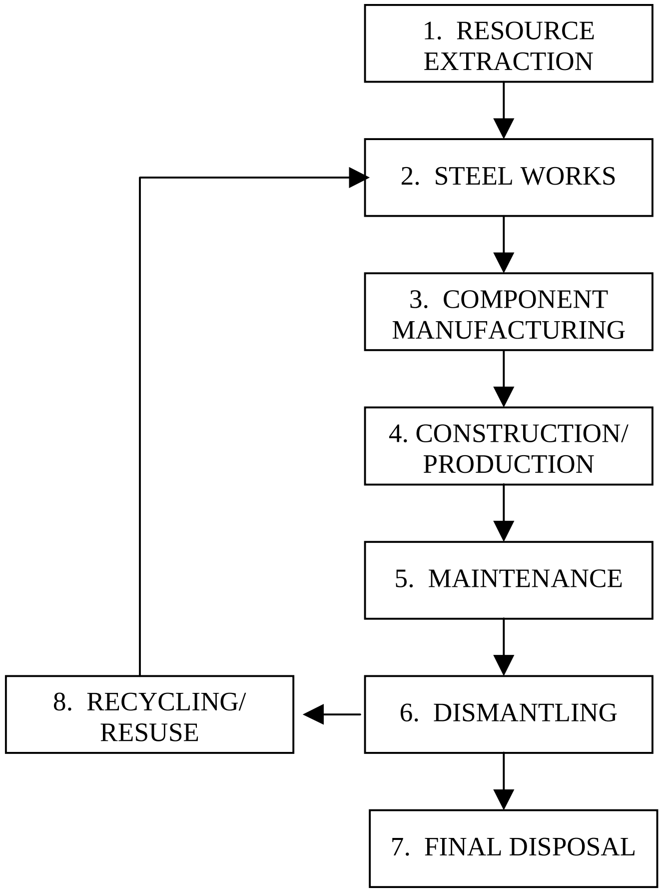


Figure B-2. The Life Cycle of the Steel Part of a Ship

B.2.2. Life Cycle Cost

Life-cycle cost (LCC) is the expected net cost over the lifetime of the structure. Initial cost and all subsequent expected costs of significance, as well as disposal costs, are included in economic life cycle cost. For a typical ship structural system, the total economic life cycle cost is illustrated in Figure B-3 and is given by:

$$C_T = C_O + C_M + C_F + C_D \tag{B-1}$$

where C_T = total cost, C_O = initial cost, C_M = maintenance cost (this could include inspection, repair, layup, conversion and modification and resale costs), C_F = failure cost, and C_D = disposal cost (this could include salvage and resale cost). The time value of money needs to be considered in evaluating Eq. B-1.

Since designers and operators of ship structural systems cannot see into the future, then all the above components of life cycle cost are uncertain. Therefore, probability-based techniques should be used in the costing process. The costing process should be based on analysis, data and experience.

Life cycle costing provides a framework for evaluating the financial cost of owning and operating a structural system. It can be used in the appraisal of long-term implications of using alternative structural designs and in the evaluation of cost differential; for example, between alternative maintenance, inspection and repair options. Life cycle costing can be applied to the entire life or different phases of a structure's life. The steps involved in life cycle cost are summarized in Table B-1 and include (i) definition of purpose (ii) definition of system and scope (iii) development of model and gathering of input data (iv) performance of analysis (v) sensitivity analysis (vi) risk analysis (vii) result interpretation and decision.

In order to conduct a LCC analysis, the purpose of the analysis has to be clearly defined. Comparative, cost effectiveness and cost benefit are possible analysis options. The scope of the system on which LCC analysis is applied has to be clearly defined. For example, the scope could range from conception to disposal for a new structure, to only operation and in-service phase for an existing structure. Input data and models required for LCC analysis have to be gathered and developed from experience, experts opinions and other sources including internal and public domain publications.

Estimates of life cycle cost have to be made. Life cycle cost can be broadly classified into initial and future costs. The initial cost includes the costs of conception, design and construction. Future costs include inspection, repair, maintenance, failure and disposal costs. Evaluation of the total costs involve expression of initial and future cost on a common basis, for example, in terms of the present worth. The initial cost would normally be in present value. The present worth of all future costs have to be estimated and this will depend on the time of occurrence of the various events during the life of the structure. Furthermore, the effect of inflation, interest and rate of returns have to be considered in the analysis. A present value factor (*PVF*) that converts each future cost to present value has to be developed. Two commonly used models for *PVF* are discrete and continuous models. A continuous model of *PVF* uses continuous compounding of the future cost over the service life of the structure, while a discrete model does not. A common future cost is repair cost and this is used to demonstrate how continuous and discrete *PVF* models are employed in practice.

Consider a single repair in n years, the expected monetary value (*EMV*) in present dollar based on a discrete model of *PVF* is

$$EMV = C_i + C_f(n) = C_i(1 + PVF_d(n))$$
$$PVF_d = \left(\frac{1+i}{1+r}\right)^n \tag{B-2}$$

i and r are effective inflation and rate of return per compounding period n. The term PVF_d is the discrete present value factor for a single repair. For multiple repairs during the service life, the total value of present value factor based on discrete model is

$$PVF_{dt} = \sum_{r=1}^{MNR} PVF_d(n_r) \tag{B-3}$$

where MNR is the mean number of repairs, and n_r is the mean time between repairs. The shortcoming of the discrete model is that it does not account for the cost between repairs. A better estimate of future cost is determined by integrating the present future factor over the desired service life based on a continuous model that uses continuous compounding. Specifically for continuous compounding, the *PVF* is defined by

$$PVF_c = e^{(i-r)n} \tag{B-4}$$

Inflation, *i*, and rate of return, *r*, are now be defined as the nominal rate over the total compounding period *n*. The effective interest rate for each compounding periods and the nominal rate over the total number of compounding periods *k* are related by the expression:

$$i_{effective} = \left(1 + \frac{i_{\text{nominal}}}{k}\right)^k - 1 \tag{B-5}$$

For a single repair with no replacement in the future, the *PVF* may be estimated by integrating over the possible life of a repair by:

$$PVF_c = \int_{t=0}^{\infty} f(t) e^{(i-r)n} dt \tag{B-6}$$

where f(t) is the probability density function of failure. For multiple repairs, an estimate of *EMV* is obtained by setting a cut-off probability of failure at which replacement is assumed to occur. Using the mean life as a basis the total *EMV* may be estimated by integrating the probability density function *f*(*t*) of failure times the present value function *PVF* over the service life. This process is represented by the following equation (Gallison, 1995 in SSC, 386):

$$PVF_c \cong 2\left\{\sum_{r=1}^{MNR}\left[\int_{t_a=(r-1)MTBR}^{r(MTBR)} f(t-t_a) e^{(i-r)t} dt\right] + \int_{t_a=MNR(MTBR)}^{T_a} f(t-t_a) e^{(i-r)t} dt\right\} \tag{B-7}$$

where MTBR is the mean time between repair. Similar models for estimating present future factor for other future cost can be developed.

Once the total value of future and present cost are developed, mathematical models that are tailored the goal of the analysis can be formulated. Sensitivity analysis could also be performed to understand the impact of various inputs. Since LCC analysis involves making projections, then uncertainties are inevitable and risk evaluation must be undertaken. The risk evaluation technique could range from coarse level analysis such as qualitative analysis to quantitative level analysis. Result from the life cycle costing have to be documented, interpreted and used in decision making.

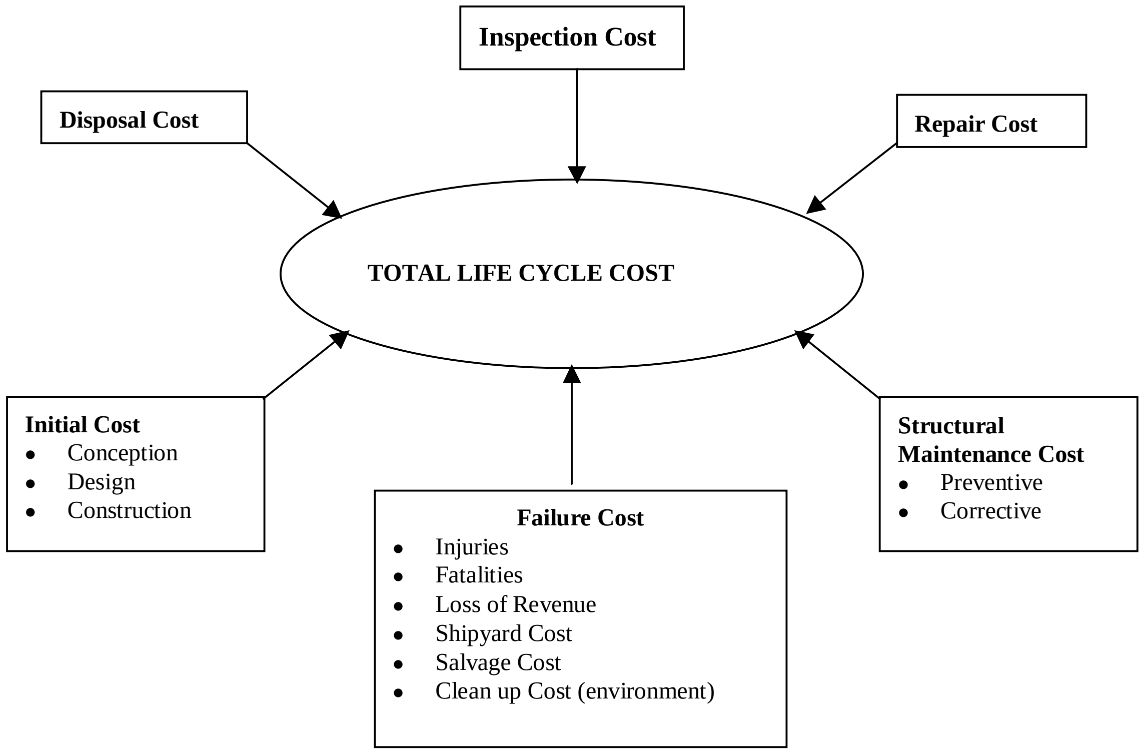


Figure B-3. Total Life Cycle Cost for a Ship Structural System

Table B-1. Steps in Life Cycle Cost Analysis

Step 1: Determination of Purpose	• Comparative Analysis • Cost Effectiveness Analysis • Cost Benefit Analysis
Step2: System Definition and Scope	• Entire Life Phases • Specific Phase • Entire Structure System • Component of System
Step 3: Data & Input Model	• Analysis • Experience • Expert Opinion
Step 4: Life Cycle Cost Analysis	• Rank Alternatives • Apply Discount Factors
Step5: Sensitivity Analysis	• Performance versus Life Cycle Cost • Availability versus Life Cycle Cost • Reliability versus Life Cycle Cost
Step 6: Risk Analysis	• Qualitative • Quantitative
Step7: Results and Documentation	• Interpretation and Decision

B.2.3. Life Cycle Management

Life cycle management is the integration of life cycle assessment and cost to achieve cost-effectiveness and environmentally sound decisions. The goal of life cycle management is to achieve and maintain the structural integrity of a ship throughout its entire lifetime. Cost effectiveness and environmental soundness is an integral part of the process. A risk-based life-cycle management aims at the reduction of risk during the life cycle of a structural system.

B.3. Phases in Life Cycle of Ship Structural Systems

All ship structural systems including naval ships, general cargo, oil tankers, bulk carriers, lumber carriers, chemical tankers, container carriers, car carriers and passenger carriers have life cycles that can be broadly divided into four phases (Figure B-1):

- Phase 1 - Conception and Design
- Phase 2 - Construction and Production
- Phase 3 - In-Service and Maintenance
- Phase 4 - Disposal

A detailed breakdown of the activities in each of the phases is given in Figure B-4.

B.3.1. Conception and Design

This is the first stage in the life cycle of a structural system. At this phase, decisions pertaining to performance requirements, functionality, design philosophy, specifications, material selection, fabrication techniques, aesthetic considerations, environmental impact, owners preference, cost and service life of the structure among others, have to be made. The decisions that are made at this stage have profound impact on the durability, constructability, inspectability, reparability, maintainability and robustness of the structure. Quality standards and regulatory organization requirements such as ABS and USCG should also be included in the decision process. Life cycle assessment and cost analysis have the greatest saving potentials when they are conducted at this stage. Furthermore, potential for minimizing risks is very significant if conducted at this stage, as the cost for making changes in the plans and specifications are much less. This stage is only applicable to structures that are not already in existence.

B.3.2. Construction and Production

Once the conception and design phase is completed, the next phase in the life cycle of a structural system is production. This phase can also be referred to as the birth phase. The aim of this phase is a realization of a structural system that meets the performance and functional requirements that were specified in Phase 1 at minimum cost.

Ship structural systems in particular have traditionally been constructed from steel. Highly stiffened thin steel plates are commonly used to achieve minimum weight structure at optimal cost. Welding is the most common fabrication technique that is used for constructing ship structures. Various types of welding techniques, ranging from standard arc welding to sophisticated inert gas methods, are usually employed. The life cycle of a structure depends on the quality of construction, which is affected by the type of welding technique (continuous or intermittent), type of electrode, nature of the surface, qualification and experience of the welders and inspection of the welds. Low quality welds can lead to rapid development of fatigue failure, corrosion and cracks resulting in low performance, high cost of maintenance and shorter service life. Thus the quality of fabrication and corrosion protection affects subsequent phases of the life cycle. Once a structure has been commissioned it has to go into service.

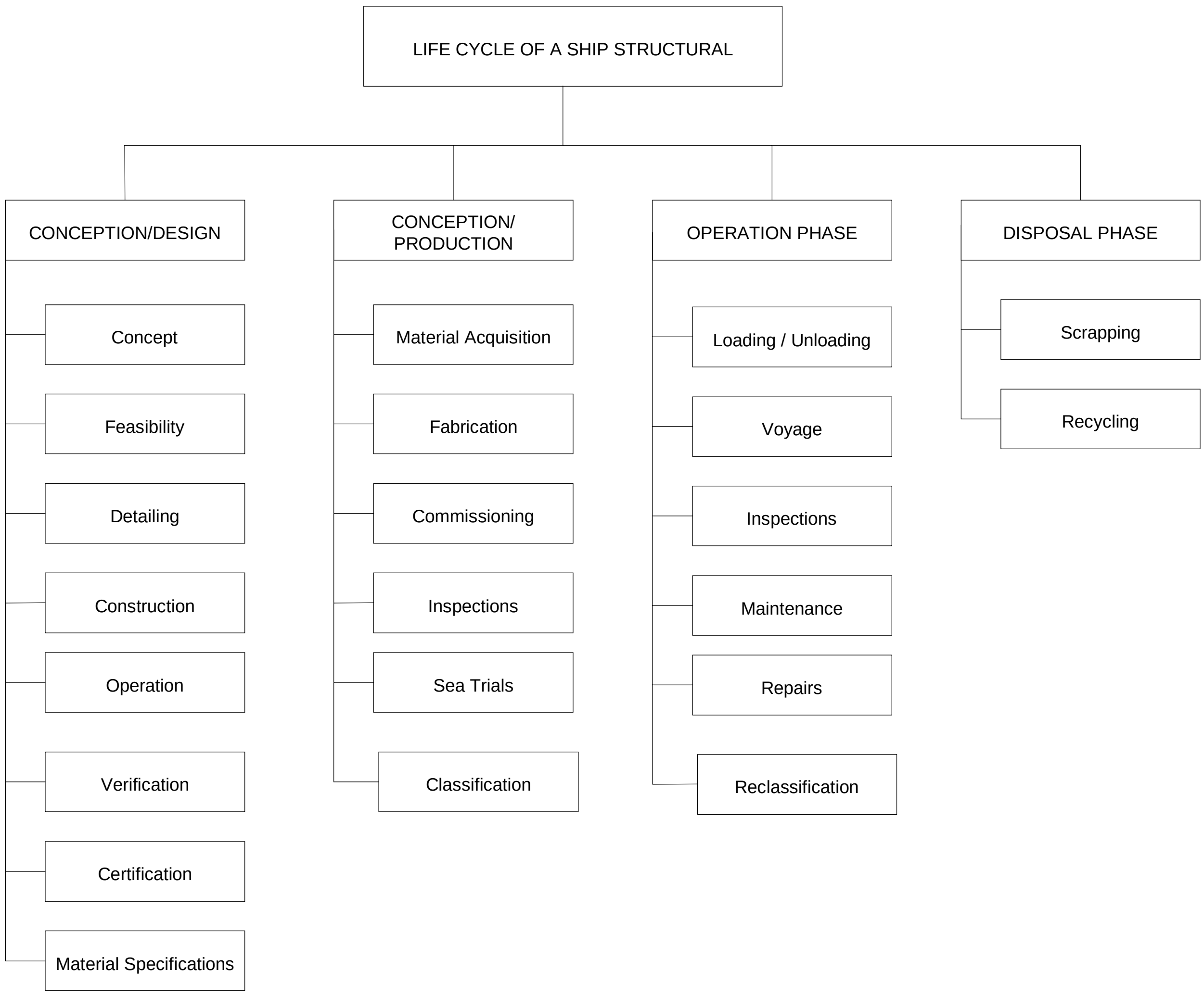


Figure B-4. Life Cycle of a Ship Structural System

B.3.3. Operation and Maintenance (O&M) Phase

This is the service stage of the structure and it can be called the useful or productive phase of a structure's life. This phase forms the main thrust of the current study. Detail discussion on this phase is presented on the topic of life cycle of existing structure, in Section B.4.

B.3.4. Disposal Phase

The disposal phase is concerned with how to end the life of the structure. Issues to be considered in this phase include environmental impact of disposal and recycling of parts.

B.4. Service Life Management of Existing Structures

B.4.1. Introduction

The maintenance of the structural integrity of an existing structure for its intended remaining service life depends on the hazards that are experienced by the structure, the operational conditions, inspection, repair and maintenance history. This section presents an overview of the various issues that are relevant to evaluating the life of existing structures. Specifically, the failure modes, degradation modes, maintenance and repair strategies that have been applied to existing structures, are discussed.

B.4.2. Modes of Structural Failure

One of the first tasks that must be tackled for any type of vessel is identification and classification of potential structural failure modes. A brief review of some previous SSC reports suggests that there is no general consensus on how modes of ship structural failures are classified. Various methods, including, load type, stress type, degradation type, crack sizes and others have been used. A review of some ship structure's failure modes classifications, that have been reported, is the subject of the present section.

Stamburgh and Wood (SSC 337, 1991) grouped failure modes according to crack sizes. Two levels of crack severity, namely, nuisance and fracture cracks were used in the classification. Nuisance cracks are small cracks detected before they propagate into adjacent structural components. Nuisance cracks can usually be repaired by welding. Significant fractures are serious cracks that usually propagate perpendicular to the longitudinal direction and pose a serious threat to structural integrity, including a loss of watertightness or complete failure.

Ma and Bea (SSC 395, 1997) classified ship structural failures according to the type of load that induces the failure mode. Two categories, namely, dynamic and static loading were used in the classification. Dynamic failure mode is due to cyclic loading and includes low cycle fatigue, high cycle fatigue and corrosion fatigue. Low cycle fatigue is due to cyclic loading of 0.5 to 1000 cycles and high cycle fatigue takes place when the cyclic loading is greater or equal to 1000 cycles. Loads generally exceed the yield strength of the material. The endurance limit of a material ("infinite' life) exists when failure cannot occur below a certain stress level. Failure is predicted by the Goodman diagram approach or by Linear Elastic Fracture Mechanics (LEFM) techniques using the Paris equation. Failure occurs by crack initiation and growth. Since cracks already exist in welded structures, in the form of weld imperfections, most dynamic failures are propagated by crack growth. In dynamic failure, the fracture surface is usually flat and contains small lines (beach marks) that radiate out from the crack origin. Corrosion fatigue is the acceleration of crack propagation in the presence of cyclic loads in a corrosive environment such as seawater.

The static failure mode results from static loading and includes, brittle fracture, ductile fracture, buckling failure and stress corrosion cracking. Brittle fracture takes place in materials with yield strengths less than 0.5 percent strain before fracture, such as cast iron, concrete and ceramic and can be predicted fairly accurately by the maximum normal stress theory. Materials that are not normally brittle can become brittle in some environments, such as low temperatures. The fracture surface is usually flat and contains arrow shaped lines known as "Chevron marks" which point to the origin of the failure. Ductile fracture is typical in materials with yield strengths greater than 0.5 percent strain before fracture, such as steel and aluminum and can be predicted by several failure theories, including the maximum shear stress theory and the distortion energy theory (von Mises). The fracture surface is usually distorted due to failure by yielding. Buckling failure results from significant compressive loading that surpass stable equilibrium.

Daidola and Basar (SSC 301, 1980) identified five failure categories for longitudinal strength of a hull girder. These are (i) yield failure due to bending of the ship considered as a beam; (ii) compressive instability buckling; (iii) brittle fracture; (iv) fatigue fracture; and (v) ultimate plastic collapse.

White and Ayyub (1989) categorized failure modes according to the severity of consequences resulting from failure. The failure modes were classified into catastrophic, end of serviceability; serviceability limiting, non-limiting and nuisance failure modes.

Catastrophic failure modes are the ones in which the consequence of failure is the possible loss of the vessel. Such potential failure modes include brittle fracture of the deck or bottom as a result of rapid crack development from a smaller flaw and rupture of bottom plating as a result of impact with the water surface during slamming.

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

(i) Ductile yielding of a gross panel of the deck or bottom such that insignificant plastic deformation has taken place. This can result in misalignment of shafts or gun-mount train rings, excessive vessel hogging or sagging, and areas of extremely large stress concentrations which could lead to catastrophic failure;

(ii) Buckling of deck or bottom panels. This mechanism is not just the buckling of panels of plating between stiffeners, but rather the overall buckling of gross panels between traverse stiffening. Invariably such deformations lead to reduced load carrying capacity among the remaining structural members and are precursors to some types of catastrophic failure; and

(iii) Cracking of multiple structural details in a primary load carrying area. Again, it is not a catastrophic failure by itself, but rather an indication of potential weakness in the structure which might recur even if the symptoms are repaired.

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

(i) Fatigue cracking of local details which run into the skin of the ship and penetrate it;

(ii) Fatigue cracking of engine mounts or other structural supports of machinery or equipment which might cause reduced operational capability; and
(iii) Fracture of major structural components that could possibly lead to more serious consequences.

Non-limiting failure modes are those failure modes which are most likely to cause a major degradation in the vessel's mission, but could possibly affect vessel performance. Some possible failure mechanisms are:
(i) Buckling of local plating between stiffeners in the underwater hull. Local plate buckling is not a reason to take a vessel out of service, but it could have an effect on the hydrodynamic performance of the vessel;
(ii) Yielding of local plating between stiffeners as a result of combined in-plane and out-of-plane loads. The consequences are the same as for buckling of the plating; and
(iii) Bimetallic corrosion at the deckhouse-hull connection in steel ships with aluminum deckhouses.

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

Mansour et al. 1997 (SSC 398), classified ship structure failures into three types: primary, secondary and tertiary. The primary behavior is associated with the ship as a whole. The secondary behavior is associated with a stiffened panel between bulkheads or web frames. The tertiary behavior is associated with plates between stiffeners considered as isotropic plates. Furthermore, Mansour et al. (1997) noted that fatigue of ship details is an important concern and a separate analysis is usually conducted to ensure adequate fatigue life of typical details. Several failure mechanisms are usually associated with primary, secondary and tertiary failures.

Primary (also called global or hull) failure modes consist of the fully plastic moment mode, the initial yield moment mode, and the instability collapse moment mode. The last includes buckling and post-buckling strength of the hull and is always the governing mode of failure. The fully plastic mode gives an upper bound on the ultimate moment. It is never attained in a hull of normal proportions. The initial yield mode assumes that buckling does not occur prior to yielding and is considered here only since it is a function of the standard elastic section modulus of the ship and the yield strength of the material, both normally used in current design practice. This mode provides a point of reference relative to current practice. It should be noted, however, that the initial yield moment is usually higher than the true instability collapse moment.
Secondary mode of failure relates to failure of a stiffened panel of the hull. Two main types of failure are possible, stiffener-induced or plate-induced failure (see Hughes, 1983) and tertiary mode of failure is associated with failure of a plate between stiffeners.

Although, there is no general consensus on how failure modes should be classified, there is a general agreement that, there is interaction between failure modes and, all failures modes are influenced by environment factors. For example, general corrosion reduces plate thickness and increases both the static and dynamic stresses on the plate, possibly leading to a dynamic or static failure mode. Hydrogen embrittlement would also accelerate the advent of brittle fracture. In addition, a single fracture can contain several failure modes. For example, a small crack that exists at a welding imperfection will grow in a stable manner by fatigue. At some crack length, the stress may reach a critical level and cause unstable crack growth by brittle fracture. This brittle fracture may be arrested by load sharing with adjacent structure or an increase in material thickness along the crack front. Majority of ship structural failures are initiated by high cycle fatigue and corrosion effects (Ma et al., 1997).

B.4.3. Degradation of Ship Structures

Steel is the primary material that is used for construction of ship structures. This is because steel provides desirable properties such as strength, stiffness and durability. Also, compared to other materials such as composite, the cost of using steel is very low. However, steel also degrades with time, the primary causes of degradation being:

(i) The continual loading and unloading of the ship structure;
(ii) The sea environment which is extremely corrosive; and
(iii) General wear and tear.

Degradation manifests itself in two main forms; namely, corrosion and fatigue. The two phenomena may also interact. For example, highly corroded steel structures will generally suffer greater stresses than non-corroded structures and hence, are more likely to suffer from fatigue damage. A review of degradation mechanisms is the subject of this section.

B.4.3.1. Fatigue and Corrosion

Fatigue and corrosion are the most pervasive types of structural damage experienced by ship structures (Ma et al., 1997). The problems, if not properly repaired or rectified, can potentially lead to catastrophic failure or unanticipated out-of-service time. Several studies have been undertaken to investigate the nature of degradation in commercial and naval ship structures. Most of the studies indicated that the character of the defect found in ship structures depends on a large number of variables which include the quality of construction, inspection and repair practice, and quality control and assurance.

One such study undertaken by Kirhope et al., 1994 for Canadian naval ships indicated that cracking and deformation defects are always present throughout the ship structure’s life while corrosion defect gradually becomes more frequent as the ship ages beyond eight years. This is an indication of a gradual breakdown of the paint and corrosion protection system after eight years.

Nippon Kaiji Kyokai (NKK), the Japanese classification society, published survey results from the fleet of commercial ships classified by NKK, Ohyaji, 1987. This fleet includes general cargo ships, oil tankers, bulk carriers, general cargo and lumber carriers, ore carriers, LPG tankers, container carriers, car carriers, and other ships with ages from one to 25 years. There are about

519 ships in this fleet. NKK findings are quite informative and detail presentation can be found in SSC 365. A brief overview of the findings is presented in the following section.

Figure B-5 summarizes the types of damage to critical hull members. The damage includes corrosion, structure (cracking), vibration (cracking), and others (e.g. collision caused buckling). Damage was defined as defects or deterioration requiring repairs. Damage due to corrosion accounts for more than half the total damage. Damage due to corrosion starts to take place at about four years, the frequency increased steadily to about 15 years, and then levels off until 25 years. Figure B-6 summarizes the number of corrosion related damage to cargo, ballast, and other spaces in the ships for all structural members as a function of ship age. Figure B-7 summarizes corrosion damage to side shell elements (excluding all other internal components). Figure B-8 summarizes damage to critical frame members in the side shell. Side shell plate damage is relatively few compared with the critical frame members. Corrosion related damage accounts for the majority of damage starting at about the seventh year. Structure cracking can start at the first year, and apparently accounts for little damage after about the 20th year. In oil tankers, 53 percent of damage occurs to bulkhead members, and 57 percent of the damage is due to corrosion. Sixteen percent of the damage occurs in side shell elements and 38 percent of the damage is due to corrosion (62 percent due to cracking). Ten percent of the damage occurs to upper deck members and 90 percent of the damage is due to corrosion (10 percent due to cracking).

Figures B-5 to B-8 provide valuable insight into when, where and how structural damage is occurring in a wide variety of ships operated in a wide variety of services. The results indicate that corrosion is the most common form of defect requiring repairs. Corrosion is often a contributing factor to cracking. The extent of corrosion damage is primarily dependent on the initial protection that is provided and the maintenance history. The results also indicate that cracking is generally associated with welds and stress concentrations and is the second most common source of damage. Further analysis of the results indicated that the use of high strength steels with correspondingly higher general stress levels again makes fatigue cracking more likely (the fatigue strength does not increase in proportion to the yield or ultimate tensile strength).

In a Ship Structure Committee sponsored project (SSC 337) an investigation was conducted to review case studies of ship structure failures and inspect new ship failures. The goal was to determine the modes of serious damage in ship structures. The study represented a cross-section of ship types and operational areas. Fatigue cracking was observed or reported in 11 of the 16 cases examined. Fatigue cracking preceded brittle fracture in nine cases examined. Brittle fracture was observed in 11 of the 16 cases examined. Ductile fracture was located at the point of fracture arrest in two cases examined. All of the fractures investigated originated at a design or fabrication detail. The majority of brittle fractures examined originated in steel Grades A and B. Brittle fracture arrest was attributed to riveted construction in three cases, and structural redundancy in one case. Riveted seams and joints and various forms of structural redundancy appear to be the most effective means of arresting running fractures in ship structures. The main conclusion from these studies is that fatigue and corrosion are the most common and pervasive damage mechanisms in ship structures. Before any maintenance can be carried out, the ship structure has to be inspected for the damage.

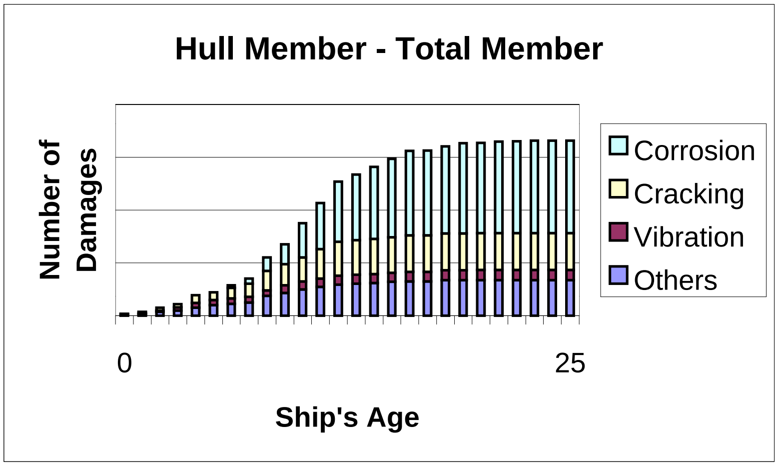


Figure B-5. Relation Between Frequency of Damage to Hull Structural Members for Different Causes and Ship Age for All Ship Types (SSC 365)

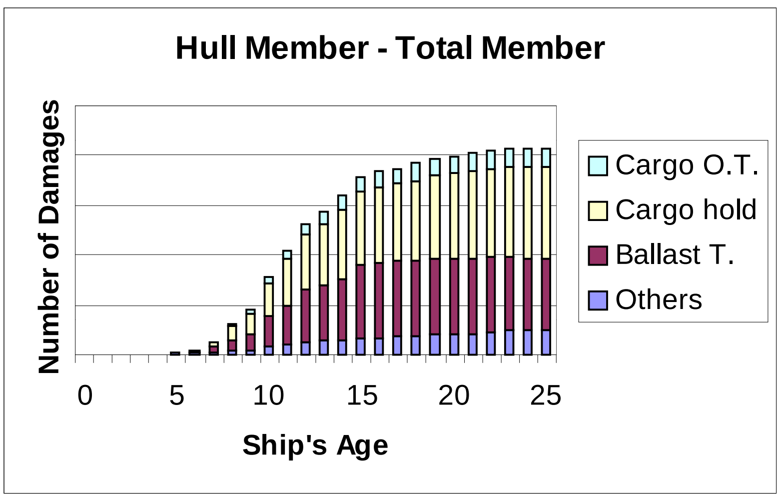


Figure B-6. Relation Between Frequency of Damage Due to Corrosion and Fatigue for All Structural Members, Service Conditions, and Ship Age (SSC 365)

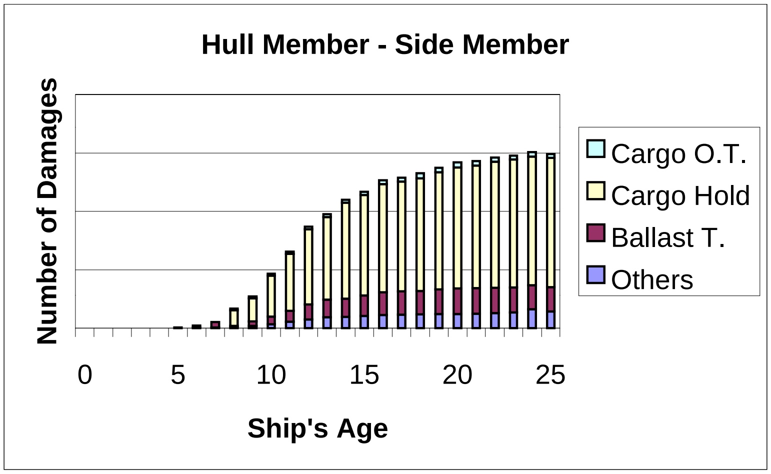


Figure B-7. Relation Between Frequency of Damage Due to Corrosion and Fatigue in Side Shell Members, Service Conditions, and Ship Age (SSC 365)

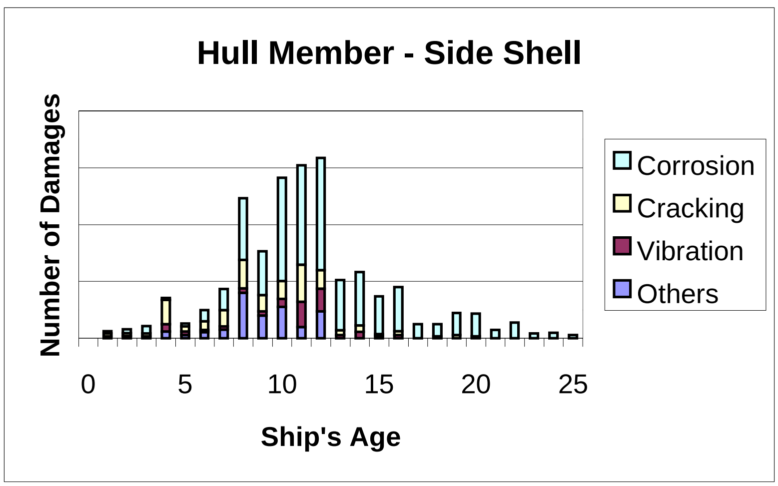


Figure B-8. Relation Between Frequency of Damage to Side Shell Members, Different Causes of Damage, and Ship Age (SSC 365)

B.4.4. Inspection

B.4.4.1. Objectives of Inspection

After a ship enters service, its hull structure is monitored by a series of in-service inspections (surveys after construction) to assess the integrity of the hull structure. The goal of these inspections is to ensure that the ships are structurally sound and able to resist all expected loads in their future operations. In-service inspections have a different role from construction inspections, which are mainly aimed at ensuring that the ship structure is constructed according to the drawings and appropriate standards of fabrication have been followed. In-service inspections provide a means to evaluate the current condition of steel and coatings, to detect unexpected flaw and damage, and permit appropriate maintenance and repair measures to be taken to preserve the integrity of the hull structure. Inspection objectives can be identified as one or more of the following:

(i) Detecting defects including fatigue cracks, buckling, corrosion and pitting;
(ii) Reporting present condition of steel plate thickness reduction due to corrosion;
(iii) Reporting present condition of coating and other corrosion protection systems; and
(iv) Detecting any other problems such as structural deformation, leakage etc.

B.4.4.2. Types of Inspection

Inspections can be categorized into two types:

(i) Mandatory inspections - those required by classification societies or flag administration, and
(ii) Owner's voluntary inspections - those performed by owners for their own purposes.

Mandatory inspections are required by the classification society or flag administration. These inspections are also commonly referred to as surveys. The frequency and extent of surveys are detailed in classification society rules. In terms of frequency, marine vessels generally have to be inspected annually except for small vessels under a certain size. These mandatory inspections required by class society can be further classified into three types: annual surveys, intermediate surveys and special surveys. The requirements for the different types of surveys vary between classification societies. Each type of inspection has specific tasks that have to be performed.

Annual survey is carried out every year within 3 months on each side of the anniversary date of the special survey. Its aim is to ensure that the hull structure and piping are maintained in a satisfactory condition. It typically takes about one to two days to complete. The survey includes an external survey of the hull and piping as far as accessible and practicable. The detailed requirements of annual surveys are listed in classification society rules.

Intermediate survey consists of the requirements of an annual survey and an additional examination, the extent being determined by the vessel's age and condition as reported at the preceding special survey. Intermediate surveys are due at the mid-point of a special survey/certificate cycle. Its aim is to verify that the condition of the hull structures has not deteriorated at a greater rate than assumed during the preceding special survey. In other words, no unexpected conditions have occurred, in particular with regard to corrosion. All intermediate (hull) surveys can be performed at the second or third annual surveys. Thus these surveys have a nine-month window before and after the due date. A "close-up" (which means within reach of a hand) examination of some areas will be carried out. For vessels that are older than ten years, the extent of survey is increased. Thickness measurements may be required. The intermediate surveys take approximately three to four days to complete.

Special surveys are generally required at five-year intervals. They can be commenced on the fourth annual survey up to fifteen months before the due date. Its aim is to provide an in-depth look at the structural condition of the vessel. All compartments are subjected to survey. Dry-docking is also a part of the requirement that ensures that sufficient access and repair facilities are available. Special surveys take about one to two weeks to complete. The extent of the special survey requirement increases with the age of the ship. The detailed scope of special surveys is listed in classification society rules.

A considerable effort has been made since 1980 to improve the minimum standards for surveys required by Classification Societies. These are incorporated in the IACS Unified Requirements and form the basis for new IMO Resolution A744 “Guidelines on the Enhanced Program of Inspections during Survey of Oil Tankers and Bulk Carriers”. The requirements were first prepared by IACS and agreed by its Council in September 1992 and have later been amended and updated. The Unified Requirements cover all three types of surveys, i.e. annual survey, intermediate survey and special survey. They specify the minimum extent of overall and close-up surveys, thickness measurements and tank testing, all grouped according to ship age. The updated Requirements include more specific rules with regard to survey planning and reporting.

In addition to the rules of class societies, the flag administration, such as U.S. Coast Guard (USCG), may have additional requirements for ships servicing on certain routes. For examples, tankers operating on Trans-Alaska Pipeline Service (TAPS) may have to follow more frequent inspections and have Critical Areas Inspection Plans (CAIPs).

Besides mandatory surveys, some owners have owner’s voluntary inspections. These inspections are aimed at prolonging the lives of their fleet and to help repair planning. The frequency of owner’s volunteered inspections varies widely. Programs range from spot checks after each voyage, to general surveys once a year, to complete internal exams every six months (Sipes 1990). Many owners/operators also conduct surveys before scheduled dry-docking, because the cost of repairing cracks found after a ship is already in dock is considerably higher than those listed on a bid specification. Other owners/operators hold to the philosophy that the proper place to find cracks is in the shipyard, and therefore do not conduct pre-dry-dock surveys. An inspections is therefore designed to meet one or more of the following three requirements:

- (i) Classification societies' statutory requirements;
- (ii) Flag administration requirements;
- (iii) Owner inspection requirements.

B.4.4.3. Scope of Inspection

The scope of a mandatory survey follows the IACS Unified Requirements for annual, intermediate and special survey and the scope of an owner’s survey depends on the specific inspection type and objectives. An inspection scope defined prior to each inspection covers issues such as spaces to be inspected and extent of inspection for structural defects, corrosion, pitting and coating.

The following technical information is assembled for each ship in order to plan an effective evaluation of the structural condition, prior to the commencement of every survey (TSCF 1995):

- (i) Main structural plans;
- (ii) Extent of coatings and corrosion protection systems;

(iii) Previous structural survey reports and thickness measurement reports, including both Classification Society and Owner's reports;
(iv) Previous maintenance and repair history;
(v) Classification Society's condition evaluation reports and status, including any outstanding conditions of class;
(vi) Updated information on inspections and actions taken by ship's personal with reference to structure and coatings;
(vii) Critical and high risk areas for corrosion and structural fractures;
(viii) Survey planning documents (optional);
(ix) Cargo and ballast loading history;
(x) Extent of use of inert gas plant and tank cleaning (optional); and
(xi) Trading route history.

B.4.4.4. Preparation for Inspection

After the planning, the structure is prepared to a condition ready for inspection. For tanker structures, three tasks, namely cleaning, ventilation, and general lighting are completed before inspectors enter tanks. The tanks must be cleaned to allow inspectors to inspect effectively. Ventilation facilities are then installed to prevent gas hazard to the inspectors.

The effectiveness of the tank cleaning is an important factor contributing to the success of a structural survey. The water in the ballast tanks must be pumped out. There is typically a layer of mud left on all horizontal surfaces which is usually hard to remove. Also, the surfaces in the cargo tanks of tankers can have a layer of wax or cargo residue (sludge) left after cargo oil is pumped out. All the scales, mud, wax or standing water will hide structural defects. Insufficiently cleaned tanks will not only prevent a good visual and ultrasonic survey but will also increase the hazards faced by the inspectors from hydrocarbon levels and slippery structure. In the case of tankers, tank cleaning can be performed with an existing Crude Oil Washing (COW) system. Sediment and sludge may still be a problem in shadow areas and perhaps on the bottom, and in this case crew assistance in sludge removal by using shovels, scrapers and buckets may be necessary.

Ventilation is critical to the safety of inspectors during an inspection into a tank containing hazardous cargo. The risks of hazardous vapors, suffocation, fire and explosions are controlled by conventional gas freeing, cleaning and ventilating. Before entering tanks, gas testing is conducted to ensure that the air in the tanks will not endanger the inspectors. To get rid of these dangerous gases, continuous forced ventilation is supplied to the tank during the inspection. An adequate number of deck fans are used to supply the fresh air. In the case of tankers, the stated cleaning and gas freeing an entire vessel take about seven days and require taking the vessel out of service.

General lighting is provided by water-turbine lights or air-driven portable lights suspended through deck openings and/or by natural daylight, since all access and tank cleaning holes are opened. Local lighting is provided by the flashlights or cap lights carried by the team members.

B.4.4.5. Methods of Inspection

After preparing for inspection, inspectors can then go into ship structures to search for defects and assess structural conditions. Inspecting a ship is considered a very dangerous task because of the risks associated with injuries from falling, toxicity of certain cargoes and fire/explosion hazards from residual gas. Different aspects of safety of the inspection personnel during inspection are detailed in various references (see TSCF 1986, 1997 for example).

A fundamental problem encountered by inspectors is obtaining satisfactory access to structural details. The most difficult areas to inspect on large vessels are the upper areas and under-deck structure because of difficult access due to their heights. Popular access methods at the present time are "walking & physical climbing" and "rafting", because they are relatively easy and cost effective. It needs to be noted that no matter what access method is used, the best way to detect cracks is to be within an arm’s length and to use visual inspection.

Walking the bottom is commonly used in all types of inspections. This method only allows close-up inspections in the lower region. However, it can be used to assess the overall condition of a tank or a hold. A visual inspection can be performed from the bottom to define suspicious areas such as those containing rust stains or oil leakage patterns. An access method to reach these areas can then be requested by surveyors to further conduct a close-up survey.

Physical climbing is a very common method to inspect critical areas such as side shell longitudinals in tankers. The inspectors use the side longitudinals as a ladder to gain access to upper regions of the tank. Most company policies recommend that the climbing height not exceed 3 meters. In fact, a fall at a height of 3 meters or less could cause serious, if not fatal, injury.

Rafting is one of the more common methods used to survey a tank prior to entering the yard. If conditions and company policy permit, it can be done at sea, with no out-of-service costs, but with pumping and other costs. The method consists of usually two inspectors canvassing the perimeter of a partially ballasted tank in an inflatable rubber raft. An in-depth rafting survey can take 15 to 20 days, resulting in considerable out-of-service costs. If this method is used, the swash bulkheads and centreline girders of the vessels should have large access openings for raft passage. In addition, access to the deck-head is still limited by the depth of the upper portion of the transverse web frames. Although rafting has some risks due to problems with ship motion induced fluid surge in the tank or with unchecked gas condition, it is generally accepted as the best and most cost effective method for surveying the entire tank (Sipes, 1990).

Portable staging is a promising method. It uses a portable staging device which works and looks much the same as a window washer device used on tall skyscrapers. The device is easy to disassemble so that access through a manhole is possible. It can usually carry from one to four people. It is air powered. The main difficulty of this method is the initial rigging. If permanent deck plugs were provided in the new construction period, it would greatly improve the rigging efficiency.

A past study performed by Holzman (1992) summarized 13 inspection access methods for tanker inspections. Each method has its particular advantages and disadvantages. Table B-2 summarizes the advantages and disadvantages of alternative internal tank structure inspection methods and techniques. Also, USCG R&D has been conducting and sponsoring work on evaluating innovative inspection techniques such as remotely controlled lights, video cameras, flat plate inspection techniques, imaging systems, thermography and others (Goodwin & Hansen 1995, and Hansen 1995). Most of these techniques are not yet widely used in ship structure inspection, but some of them may have the potential to provide a more efficient way of inspection in the future.

The effectiveness of an inspection is dependent on the method of inspection and accessibility. Other factors that affect inspection are discussed in Damsetz et al. (1996) (SSC-389). Improving the inspection method, and improving accessibility will increase the percentage of critical structural details that are inspected. Currently most vessels are only fitted with ladders to provide access to the tank bottom. The accessibility to some critical structural details such as side shell longitudinal is poor. It can be greatly improved by simply adding climbing bars, additional horizontal girders, or catwalks with handrails. Accessibility is a key design consideration in current designs.

Table B-2. Summary of Access Methods (Holzman, 1992)

Methods	Advantages	Disadvantages
Tanker design	Safety, increased accessibility	Cost, weight, maintenance, unwanted structural detail
Walking the bottom	Inexpensive	Poor accessibility, only line of sight view
Climbing w/o fall safety device	Increased accessibility, inexpensive	Unsafe, impossible to climb central tanks
Physical climbing with fall safety device	Increased accessibility, inexpensive	Initial rigging difficult, physically demanding
Access to side member with ascender	Increased accessibility, inexpensive	Initial rigging difficult, training required
Fixed Staging	Access available to all members in party	Expensive, labor intensive
Rafting	Can be accomplished underway, inexpensive	Considered unsafe by some, expensive, time consuming
Binocular with high intensity light	Can be accomplished underway	Hands on inspection not possible, only line of sight view
Portable staging	Light repairs possible, relatively safe	Expensive, difficult initial rigging
Mechanical arm	Increased accessibility	Difficult initial rigging
Divers	Can be accomplished underway	Diver inexperienced in ship inspections, time consuming, expensive, unsafe
Remotely Operated Video (ROV)	Can be done underway, gas freeing tank not required if equipment is intrinsically safe	Expensive, easy for operator to become disoriented
Acoustic emission	Can be accomplished while vessel is in service provided equipment is intrinsically safe	Only tank top area currently feasible

B.4.4.6. Recording of Inspection Data

While the inspection is underway, inspectors have to record the defects they find. When conducting an internal structural survey, typically the inspector will carry a small pocket size notepad and pen. The defects will be recorded in the notepad. The location, the affected structural member, the type and the size of the defect, and a recommended repair are recorded.

An alternative way of recording data is to use a small tape recorder. This is easier than writing on a notepad since the inspector does not need to remove his glove. Besides, he/she can keep inspecting while recording. However the difficulty lies in transcribing the information. Some companies are developing rugged equipment for recording gauging data with ability to transfer the data directly to computers for analysis and printouts.

One of the requirements of IMO Resolution A.713 is Documentation Onboard. The owner is required to supply and maintain hull survey related documentation onboard, which is to be kept for the lifetime of the ship. The purpose of the document includes identification critical structural areas; stipulation of the minimum extent, locations, means and access arrangements for close-up survey; gauging of sections and internal structures; and nomination of suspect areas consistent with rule requirements.

In the case of ABS rules, for example, the required onboard document is to contain (ABS 1995):

(i) Reports of structural surveys;
(ii) Condition evaluation report;
(iii) Thickness measurement report;
(iv) Survey planning document.

Inspection report for mandatory survey uses the formats as specified by each individual classification society. Owners/operators sometimes keep track of the ship maintenance condition in a more detailed format. In the case of tankers, many results are presented efficiently on longitudinal elevation drawings of the ship: e.g., Starboard and Port sideshell, longitudinal bulkheads and Centerline (girder or bulkhead as applicable). Supplementary drawings might include horizontal plan views at critical waterlines or girder levels. Usually the least useful drawings are transverse sections at web frames, since comparisons among web frames require tedious flipping through a batch of such drawings (Stanley, 1996). However, it often is useful to have at least one generalized transverse section, to show details of structural designs and how they fail, particularly if the failures are not neatly confined to the longitudinal elements such as shell or bulkhead stiffeners and their connections to transverse structure.

In general, survey reports contains the following:

(i) Structural defects such as crack, buckling and indent;
(ii) Pitting and grooving corrosion including pitting intensity diagram;
(iii) Thickness measurement of steel plates;
(iv) Coating condition including percentage of breakdown, peeling, flaking and blistering;
(v) Condition of corrosion control systems such as sacrificial anode or impressed current cathodic protection systems;
(vi) Effectiveness of previous repairs;
(vii) Crack growth if previously not repaired; and
(viii) Drawings or photographs to supplement the above data.

A graphical format is normally preferable for a surveyor to review before commencing an inspection. The surveyor can add an intangible, his/her own prior experience, to reinforce the trends presented. The data reporting will be enhanced if the results can be presented in a form that is easy and simple for surveyors and analysts to use and keep up-to-date (to expand the database).

With the advent of computerized databases, several systems have been developed to facilitate the large amount of inspection, maintenance and repair (IMR) work. A previous SSC report (SSC-380) has summarized the features of four existing commercial IMR software and some other non-commercial ones (Schulte-Strathaus, 1995). The four software include the CATSIR database systems (developed by CHEVRON in cooperation with OCEANEERING), ARCO's Hull Fracture Database (HFDB), FracTrac (developed by MCA Engineering) and SID (Structural Inspection Database) developed by MIL Systems. All these software have reporting modules to facilitate reporting inspection results.

B.4.4.7. Analysis of Inspection Data

When all the necessary survey data and findings, with respect to overall and local corrosion, fractures, and deformations have been collected, the residual strength of the ship can be evaluated. TSCF (1986 and 1997) give the following guidelines regarding structural integrity in terms of overall hull girder strength, buckling, fracture, general corrosion and local pitting.

The overall hull girder strength is confirmed on the basis of the actual hull girder section modulus, which may be assessed initially using an allowable area at deck and bottom. Any buckling found during the survey is taken as an indication of areas which require stiffening or renewal of material and any fractures found are normally to be repaired by part renewal of material or by welding. Structural modifications may also be advisable to avoid repetition of fractures.

Area of heavy wastage due to general corrosion needs to be analyzed. The integrity of a corroded local structure can be analyzed by applying a percentage reduction in thickness and a buckling criterion. If wastage is in excess of the allowable limit, steel renewal may be needed. Local corrosion or pitting of the shell that can lead to possible hull penetration that needs to be studied. Isolated pits are not believed to significantly influence the strength of plates or other structural members, but may cause a potential pollution or leakage problem. When large areas of structure are affected, however, this will influence the strength and must be considered when assessing the residual mean thickness of material. The bending capacity reduction obtained from testing of plates with uniform machined pits suggests that capacity reduction is roughly proportional to the loss of material. One way of estimating steel reduction is to use the pitting diagrams together with measurements of pitting depths.

The effectiveness of the coating system has to be evaluated as well the remaining coating life is estimated. Coating repair and maintenance plans can then be developed in conjunction with steel maintenance plan.

Guidelines for corrosion wastage have been developed in a tabular format by TSCF (1997). The Table lists wastage allowance for different structural components. When corrosion wastage exceeds a certain percentage, assessment or steel renewals will be required according to the table. Buckling criteria are also given in the same table. Guidelines for pitting repair are provided as well. See the reference (TSCF 1996) for more detailed information.

After the inspection data analysis is done, repair and maintenance plans can be developed.

B.4.5. Maintenance

The main objective of structural maintenance is to prevent unwarranted degradations of the strength and serviceability of the structure. The goal is to preserve the integrity of the structure through judicious renewals of steel and repairs to damaged elements. Maintenance can be preventative or reactive. Both strategies are employed in ship structures. For example, preventive maintenance can be directed at corrosion protection or fatigue damage to rudder bearings and supports. Reactive maintenance can be directed at repair to accidental damage and unanticipated fatigue damage to the ship structure. Maintenance can be continuous and/or periodic.

For existing and aging ship structures that have suffered from lack of long-term preventive maintenance, the most severe damage is corrosion of hull structures. The hull structure is usually provided with coating at the new construction stage. To aid in maintenance decisions, periodic surveys should be done every five years. If not properly maintained, coating will normally break down and lose its preventive effect after 5 to 10 years. Thereafter, an increased rate of corrosion will be experienced. At the time when such vessels come up for their third special periodic survey (12-15 years of age) it will normally be necessary to renew significant amount of steel mainly in the form of internal structures. To prevent expensive steel renewal coating should be maintained constantly.

By maintaining the coating well, the hull structure may last for 25 years and beyond without the need for steel renewals. On the other hand without maintaining the corrosion protection system, the need for significant steel renewals will normally start at around 15 years of age (DNV, 1991). Since steel renewals are expensive, the coating repair is critical for owners. By deferring coating repairs, the owner risks steel renewals at the next overhaul. Roughly speaking, the cost to coat plating is equal to the cost of renewing 10 percent of the same plate assuming a thickness of 12 mm (Tikka, 1991). In addition, steelwork in an existing structure introduces new problems such as residual stresses and possible weld defects. Thus, if corrosion has resulted in critical coating breakdown, it is recommended that the structure be blasted and re-coated.

From both visual and gauging information of a survey, decisions can be taken regarding life continuance and to the extent of maintenance necessary to reinstate the corrosion protection system. In the case of long-term (8 to 10 years) operations, re-coating of the breakdown areas would be regarded as a cost-effective solution instead of any potential steel renewals. For shorter-term (4 to 5 years) operations, temporary protection systems such as soft coatings or sacrificial anodes may be considered. The effective life of soft coatings is usually restricted to about 2 to 4 years only, for this reason this protection system should really be regarded as temporary and should be subject to more regular and comprehensive thickness gauging and close-up surveys than that considered for hard coatings (TSCF, 1992).

Various maintenance management philosophies have been advocated for ship structural systems. The three most common approaches are: Reliability, Availability, Maintainability and Supportability (RAMS); Reliability Centered Maintenance (RCM) and Risk Management (RM). The key differences among the three maintenance management approaches (RAMS, RCM and

RM) are the method by which the vessel or component condition is represented, and the trigger for vessel maintenance actions.

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 is 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.

RCM employs current vessel structural condition information and vessel operational profile descriptions to estimate a theoretical 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.

A structural RM technique employs structural risk as a yard stick 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 failure probability estimates are used to define the likelihood of component of 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 required for either the RCM or RM approaches cannot be practicably implemented. In addition, statistically significant amounts of relevant component degradation data required for a RAMS approach and used in 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.

B.4.6. Repairs

B.4.6.1. Crack and Corrosion Repairs

The repair of a ship structural system, especially critical internal structural details, is 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 repairs and maintenance makes repair and maintenance tracking very difficult. Take crack repair for an example. Many crack repairs appear to be ineffective. Veeing and welding cracks that have occurred early in the life of the ship seems to be ineffective; they quickly develop again. If one replaces the cracked plate and modify design by adding a bracket, or a lug, the repair can usually last longer than veeing and welding. However, this repair may not be cost effective if the ship will be scrapped in the near future. Three types of repairs namely, crack repair, steel renewal and pitting/grooving repairs among others are possible.

Repair strategies for cracks vary widely. Repairs of cracks can range from temporary cold patches to stop leaks to complete re-design of the structural detail and replacement of steel nearby the detail. Welding cracks is a popular repair, but it frequently failed again within a short time, as stated above. Drilling the ends of the cracks is a frequently used temporary repair measure that is used until the ship can be taken into dry-dock. Repairs of these cracks can range from simple welding to addition of reinforcing elements. Experience indicates that many of these repairs must be repeated in subsequent dry-docking (Bea, 1992).

Selecting crack repair method can also depend on the location of the crack. Cracks in primary structures require more serious repair than those in secondary structures. A primary structure is a structure that contributes significantly to the main structural strength of the ship. Examples of primary structures are hull plates, stiffeners, principal decks and main transverses. A secondary structure is a structure that neither contributes to the structural strength nor the watertight integrity of the ship structure. Examples include partition bulkheads and platforms.

Cracks in a primary structure may be temporarily repaired by fitting double plates over the affected area or gouging out the crack and filling in with weld metal. Gouging and re-welding is an easy and common method of repair. However, the strength of a gouged and re-welded crack is almost invariably less than the original material. The repaired weld will create new crack potentials and thus fail even earlier. Such repairs are sometimes considered in attempting to get the ship to a facility where full repairs can be made. The better and formal methods of repair are to crop and renew the cracked plate or to modify the local geometry to reduce the stress concentration. If a longer life continuance is expected for the ship, a more robust repair such as geometry modification should be considered. On the other hand, cracks in a secondary structure may be arrested temporarily by drilling a hole of diameter equal to the plate thickness at a distance of two times the plate thickness in front of the visible crack tip and on a line with the direction of anticipated crack propagation (Ma et al., 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 continuance of the ship. A summary of possible crack repair methods is presented in Table B-3.

In the event of steel renewals being required to compensate for either local corrosion wastage or buckling, it is important that the extent of this new material be sufficient to maintain structural continuity and avoid any potential discontinuities (SSC, 395). From the repair point of view, the replacement of complete panels of structure may prove most cost effective and ultimately more reliable than merely renewing individual members especially if a longer life span has been projected for the vessel. For instance, in the case of the removal and re-welding of bulkhead stiffening to bulkhead plating, the chances of penetrations of the remaining corroded plating is usually very high and the future watertight integrity of this division remains in question. Also, the combination of steel renewal and coating could be the most cost-effective method for a longer life span.

In some cases, generally corroded areas of tank structures are found to be below the minimum section modulus requirements. It may be possible, at the discretion of the relevant Classification Society, to install additional steelworks in conjunction with an effective corrosion protection system (painting), rather than carry out extensive steel renewals. This form of repair should aim at re-establishing the required minimum section modulus of the overall defective areas, while dealing directly with local defects or fractures as found 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 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 penetration with subsequent pollution danger. A minimum thickness should be established for pitting repair (Ma and Bea, 1992). Pitting repairs can be classified into three levels according to the remaining plate thickness. While the remaining plate thickness is more than the defined thickness, the pitting is recommended to be grit blasted and brush coated with two coats of coal tar epoxy or to be vacuum blasted and filled with pour-able pit filler. While the remaining thickness is between the defined thickness and 6 mm, it is recommended weld up the pitting. If the pitting is so severe that the remaining thickness is less than 6 mm, it should be cropped and renewed with a new plate. A summary of possible corrosion repair methods is presented in Table B-4.

Table B-3. 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, 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 section and butt weld 3. Apply 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. Apply post weld improvement techniques

Table B-4. Corrosion Repair Options

Severity of Corrosion	Type of Corrosion	Corrosion Repair Options
Minor coating breakdown	General corrosion	• No repair and monitor • Spot blast and patch coat • Add/maintain anodes
	Pitting corrosion – small shallow pits less than 50 percent plate thickness in depth	• No repair and monitor • Spot blast, epoxy pit fill and patch coat • Add/maintain anodes
Major coating breakdown	General corrosion	• No repair and monitor • Spot blast and patch coat • Re-blast and recoat • Add/maintain anodes
	Pitting corrosion – large, deep pits greater than 50 percent plate thickness in depth, small number	• No repair and monitor • Spot blast, weld fill, patch coat • Add/maintain anodes
	Pitting corrosion – large, deep pits greater than 50 percent plate thickness in depth, large number	• No repair and monitor • Spot blast, weld cover plate, patch coat (temporary repair) • Cut out, weld new plate, blast, coat (permanent repair) • Add/maintain anodes

B.4.6.2. Repair Management Strategy

A four-step repair management strategy for a ship structural system repair was developed in a previous SSC study (Bea et al., 1995). The goal of the management strategy is to determine the best repair strategy. The suggested steps include:

Step 1: Inspection of structural failure;
Step 2: Determination of mode of structural failure;
Step 3: Determination of cause of structural failure; and
Step 4: Evaluation of repair alternatives and selection.

Structural inspection is performed to locate structural failures and describe the basic properties of the failure. These properties include crack location, crack orientation, crack length, percentage wastage or other information necessary to analyze failure. After the inspection, the failure mode has to be determined. This can range from fatigue damage, corrosion fatigue damage, fracture buckling, to stress corrosion cracking. However, it is well known that the majority of ship structural failures are due to high cycle fatigue and corrosion so effort should be concentrated in these areas.

In order to evaluate repair alternatives, the cause of failure has to be determined. There are at least five basic causes of a ship structural failure. These include are design problems, insufficient quality control, overloading, environmental factors and combined effects.

The design problems could arise from insufficient static, fatigue and/or buckling strength in the design. This insufficiency could arise from poor analysis procedures, poor material selections for service conditions. Thus this problem arises from the design and conception phase of the life cycle. Insufficient quality control could arise during construction from faulty material selection or fabrication. Examples include poor or incorrect welding procedures, incomplete welding, material defects and tolerance problems. Overloading includes situations that cannot be foreseen in initial design. Examples include collision, poor tug operations, and poor seamanship in extreme weather. Environmental factors cause corrosion of the ship structure due to inadequate maintenance.

In reality, structural failures usually result from combined effects. Two or more factors usually contribute to the cause of damage in varying degrees. For example, the environmental factor of corrosion exists in some form for most ship structural failures but is not always the primary cause of damage. The Ship Structural Committee has categorized the causes of fracture in a similar manner. These categories include abnormal forces, presence of flaws or notches, inadequate physical properties at service temperature, and combination of causes (Stambaugh, 1990).

Once the mode and cause of failure have been determined with a degree of certainty, alternative repairs can be evaluated. This step is one of the most difficult due to the large number of factors that should be considered. The repair that best satisfies the life continuance, economic, location, time and other considerations is the one that should be chosen. These repair considerations are discussed in the following section.

Life continuance consideration can be the most important factor in repair decisions. For example, if a ship is going to be kept in service for another five years and then retired or sold, the ship owner may select a repair that can last for more than five years. Supposing the repair works well, the failed critical structural detail will be out of trouble for the rest of five years with a high reliability. This consideration is related to the economic consideration. However, the difficult part is the life estimation of a particular repair method.

Economic considerations can also play a dominant role in repair decisions. Economic factors include the future plans for the ship, age of the ship, total cost and time to complete repairs, cargo transport obligations, money available, current steel costs, repair rates, wage rates, etc. Decision is usually based on the certain initial repair costs and the possible future costs of maintenance. This is mainly due to the complexity of the repair decision, which makes future costs difficult to evaluate. However, future costs for inadequate, non-durable repairs may dominate the decision. A complete economic analysis should take into account the trade off between initial and future costs. In the same way that a more durable ship has lower maintenance costs, more durable repairs will have lower future repair costs.

Repair location must also be taken into consideration. This factor falls into two categories – voyage repairs and shipyard repairs. Voyage repairs are made at sea mostly in emergency situations. Voyage repairs are often very difficult since “hot work” (welding) is usually prohibited in critical hull structure due to the presence of flammable materials. As a result, cold patching is a popular temporary remedy. Shipyard repairs are made either at dockside or in a dry dock environment after the tanks is ventilated and washed to accommodate hot work. This is the most ideal repair environment especially for big vessels.

Time considerations must also be addressed in repair decisions. Time factors, such as, the time available to complete repairs and the time until the next inspection and repairs are important issues that cannot be ignored. More thorough repairs are required if there is a long time before the next inspection or overhaul period.

Several additional considerations must be taken into account in repair alternative evaluations. These considerations include the following: Classification societies like American Bureau of Shipping (ABS), Bureau Veritas, Det Norske Veritas, Germanischer Lloyd, Lloyd’s Register of Shipping and others dictate the minimum structural requirements for compliance with class rules. Also Regulating authorities, such as the United States Coast Guard, dictate the minimum requirements for ship operation within their jurisdiction. Environmental safety has become a major consideration in the repair of ships. Environmental disasters can produce both ecological damage and serious financial damage to the owner and operations of the ship as illustrated by the grounding of the Exxon Valdez in Prince William Sound (Davidson, 1990). The goal of repairs is to minimize the chance that such an incident is caused by poor repair and maintenance of the structure. Accessibility for monitoring by crew will determine whether monitoring of minor structural problems is feasible. If a structural failure cannot be monitored effectively it must be repaired.

B.5. Life Extension and Replacement

The aging process leads to degradation of a ship structure and this can undermine the structural integrity of the vessel. Thus, the structural integrity of the vessel must be assessed from time to time during the service life to determine the economics of keeping the vessel in service.

For commercial vessels, the total cost of operating and maintaining the vessel must be compared with the expected revenue to be generated by the vessel. The total cost of operation must include inspection, maintenance and repair, and the financial cost of meeting classification society requirements. It is expected that classification society requirements will become more stringent with age and the financial cost of maintenance and repair will increase. Furthermore, the time spent on maintenance, the labor and material required for maintaining the serviceability of the vessel have to be evaluated. Revenue loss when the vessel is not available due to maintenance must also be added to the operational cost. The risk of environmental disaster that can lead to ecological damage, resulting in high financial cost to the owners and operators of the vessel increase with age and should also be taken into account in the analysis. These costs and others must be compared with the expected revenue. When the expected costs outweigh the expected revenue then it might no longer be economical to keep the vessel in service, the vessel should be retired. If the expected revenue is greater than the expected cost, the vessel can still be kept in service but life extension procedures, which have been discussed in Section B.4, namely, inspection, repair and maintenance have to be rigorously implemented.

Similar considerations have to be made for navy vessels. The cost of operation must be weighed against the vessel's availability and operational readiness. If the vessel has to be out of service for long periods of time or cannot effectively perform its operational duties, a decision has to be made as to the viability of continuing to incur financial cost for maintenance and life extension of the vessel. If this is considered to be a viable option, then the life extension procedures discussed in Section B.4 have to be implemented, otherwise, the vessel should be retired.

TABLE OF CONTENTS

Table of Contents .... C-ii
C. Guidelines Detailed Using a Naval Vessel C-1
C.1. Introduction C-1
C.2. Development of Failure Scenarios for a Containership C-5
C.2.1. Buckling of an Unstiffened Side Shell Panel, in the Cargo Space C-5
C.2.2. Buckling of an Unstiffened Outer Side Shell Panel, in the Cargo Space C-7
C.2.3. Fatigue of an Inner Side Shell Longitudinal Stiffener, in the Cargo Space C-8
C.2.4. Fatigue of an Outer Side Shell Longitudinal Stiffener, in the Cargo Space C-9
C.2.5. Fatigue of an Outer Bottom Panel Longitudinal Stiffener, in the Cargo Space C-10
C.2.6. Fatigue of a Double Bottom Panel Longitudinal Stiffener, in the Cargo Space C-11
C.2.7. Buckling of an Unstiffened Panel, in the Main Deck of the Machinery Room C-12
C.2.8. Fatigue of a Main Engine Foundation Stiffener C-14
C.2.9. Buckling of an Unstiffened Side Shell Panel, in the Machinery Room C-16
C.2.10. Fatigue of a Side Shell Longitudinal Stiffener, in the Machine Room C-16
C.3. Demonstration of the Development of Cause-Consequence Diagrams for Some Initiating Events C-17
C.3.1. Buckling of an Unstiffened Inner Side Shell Panel, in the Cargo Space C-18
C.3.2. Fatigue of an Outer Side Shell Longitudinal Stiffener, in the Cargo Space C-36
C.3.3. Buckling of an Unstiffened Panel, in the Main Deck of the Machinery Room C-58
C.3.4. Fatigue of a Main Engine Foundation Stiffener, in the Machinery Room C-76
C.4. Development of Risk Profiles and Risk Management C-99
C.5. Risk-based Management of System Integrity: Selection of Inspection and Repair Strategy C-104
C.5.1. Inspection and Repair Program and Strategy Development C-104
C.5.2. Example Structural Failure C-105
C.5.3. Example Inspection Methods C-106
C.5.4. Example Repair Methods C-106
C.5.5. Example Decision Trees C-107
C.5.6. Inspection and Repair Risk Profiles C-113
C.6. References C-114

C. GUIDELINES DETAILED USING A NAVAL VESSEL

C.1. Introduction

In this appendix, a risk-based methodology for managing the life cycle of ship structures is detailed and demonstrated using examples on as needed basis. For example, the development of cause-consequence diagrams and risk profiles is detailed following their description in Chapter 2 of the report.

As presented in this report, the risk analysis of a ship structure requires detailed information about the characteristics of the ship under consideration, such as structural configuration, including data about structural details geometry and construction practice, material properties, loads acting on the structure, inspection data, … etc. In order to define the critical structural events and their associated occurrence probabilities these data need to be collected and examined. The consequences of a structural failure or a failure scenario need also to be evaluated and inputted in risk profiles, therefore allowing the execution of the risk analysis and management. As for any commercial or naval vessel the needed data are property of the ship owner, the objective of this appendix is to detail and demonstrate the methodology of risk profiling by performing cause-consequence analysis based on the data presented in the reviewed literature about ship analysis and operation as provided in the bibliography.

A containership that can be naval or commercial is selected in this appendix for the purpose of performing a cause-consequence analysis of structural failures. The selection of the containership is based on its massive use for the transportation of general cargo, not only in the United States, but all over the world. The great advantage of the containership over the general cargo ship, that makes it is very popular among marine transportation companies, is its capacity of carrying all of its cargo in unitized standard containers that take part in an inter-modal transportation system. Although the methodology was detailed and demonstrated for a containership, the developed cause-consequence diagrams and risk profiles can be adapted easily for other ship types such as tankers or naval vessels.

The full containership general arrangement, as presented in Figure C-1, embodies the concept of cellular stowage within the holds, plumbing directly down through a multiple array of hatches, in a guided arrangement necessary to secure the containers without damage against motions at sea. Additionally, most containerships are designed to carry containers on deck, stacked three to four units high and secured by systems of lashing (Tagart 1980). In order to optimize container-storage-space utilization, the machinery space is usually located well aft with generally not more than one cargo hold between the machinery space and the stern.

Containership requires a careful consideration of structural requirements as it is desirable from a cargo-space point of view to have a ship bottom and shell, with no decks or internal structures. However, a certain amount of longitudinal structure is required for longitudinal strength, transverse structure for transverse wracking and torsional strength. A typical structural arrangement of a containership is presented in Figure C-2. Hatches occupy almost the entire deck space, usually only one in the breadth of the ship, leaving only a narrow strip of deck plating outboard. This necessitates a double-side-shell structural construction to provide longitudinal strength, also stiffening against lateral and torsional loads from the sea. Some stringers are used to provide resistance to buckling in compression when the ship is in sagging condition. The containers are stacked as many as six high, with resulting loads on the inner bottom applied entirely through the four corner posts of the containers. Extra stiffening within the double bottom has to be provided at the points where these high, concentrated loads are taken. Transverse bulkheads are spaced according to multiples of the length of the containers, plus the bulkhead structure itself with a strip of deck above.

Similar to most ship structures, a containership structure has the following potential, primary modes of failure that can degrade the ship structural integrity:

1. Failure due to yielding or plastic flow of deck or bottom materials,
2. Failure due to elastic-plastic buckling of deck or bottom panels, and
3. Failure in a fatigue and fracture mode for weld details.

Taking in view an extension of the ship structure affected by a given or specified failure, it is convenient to classify the failures into two classes:

1. Ultimate failures that represent the loss of the ship, and
2. Serviceability failures that decrease the operational performance the ship structure, perhaps making it unsuitable for service.

Table C-1 provides a suggested classification of ultimate and serviceability failures that are suitable for reliability and risk analyses. According to this table, the ultimate failure modes include flexural strength and buckling, and the serviceability failure modes include permanent deformation and first yield. The fatigue failure is included in both modes, depending on the extent of fatigue damage.

The importance of a failure is classified according to the degree of deterioration of ship safety or extension of the ship structure affected by a given failure mode as provided in Figures 2-6 and 2-7. For this purpose, failures are classified as follows:

1. <u>Primary failure mode</u> that may affect a significant portion of the structure and cause the loss or major degradation of the vessel's performance,
2. <u>Secondary failure mode</u> that may affect a part of the structure and cause damage or degradation of the structure or a vessel's performance, and
3. <u>Tertiary failure mode</u> that may affect a small part of the structure and cause minor damage or degradation of the structure or a vessel's performance.

The ship structure is designed according to standard rules provided by Classification Societies. These standards result in structural designs with acceptable safety levels for the primary failure modes, avoiding the loss of the ship. These failure modes should have a very low probability of occurrence. The secondary and tertiary failure modes do not represent a catastrophic failure potential to the vessel as they cause minor effects on the structure and the vessel's performance, and if detected and repaired do not represent any danger to the ship. However, if these small damages are not repaired, during the ship life they can degrade the structure and the vessel's performance, and in association with other degradation mechanism, such as corrosion, they can precipitate the occurrence of a major structural failure, that can lead to the loss of the ship.

Failure classification and the potential implications of these failures can justify the use of these failures as initiating events in the risk assessment and management methodology. Initiating events are viewed as failures or bad beginnings that can, with time or operation or cycles, degrade the ship structure and lead to significant consequences. Therefore, initiating events should include failures such as buckling of an unstiffened panel and the fatigue of a structural part. Specifically for a containership, the Ship Structure Committee report SSC-405 (1999) presents some locations where the fatigue failure is very common and some of them are used in the subsequent sections of this appendix.

This appendix presents the details of the methodology to ship owners or operators so that with access to their particular data they can readily apply the methodology to their specific vessel.

Table C-1. Classification of Structural failures as a Function of the Damage to the Ship Structure

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

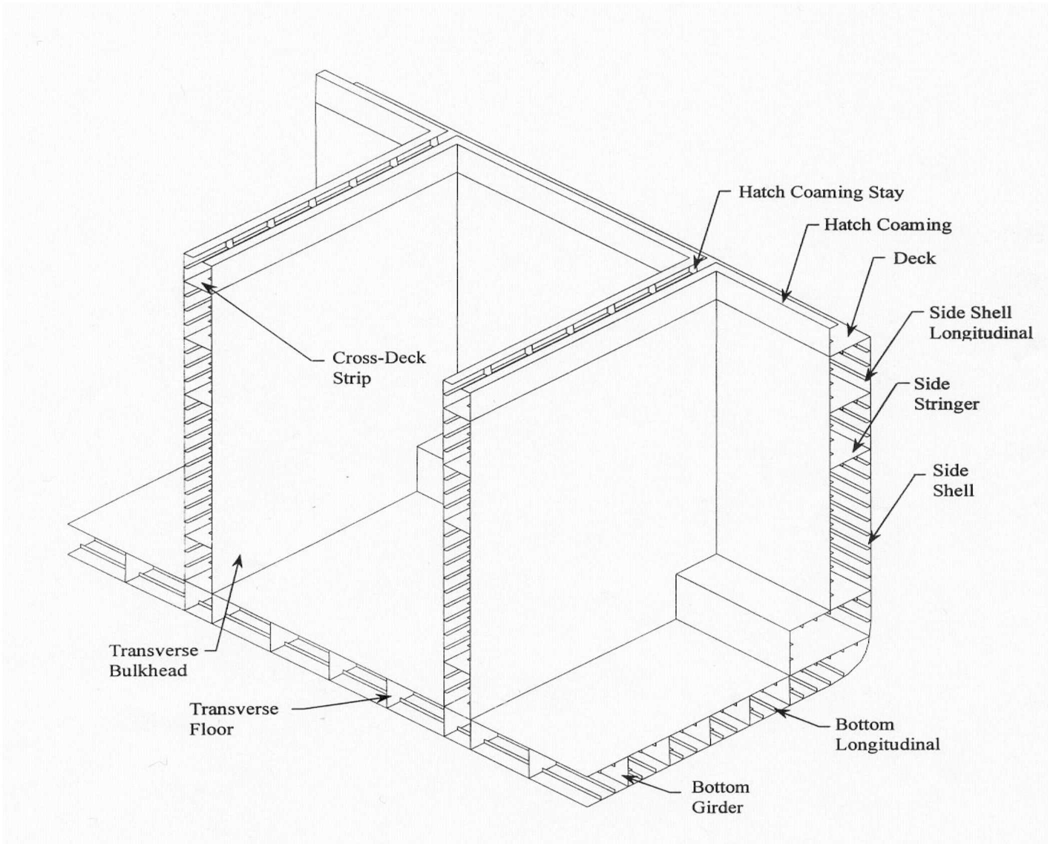


Figure C-1. General Arrangement of a Containership (Tagart 1980)

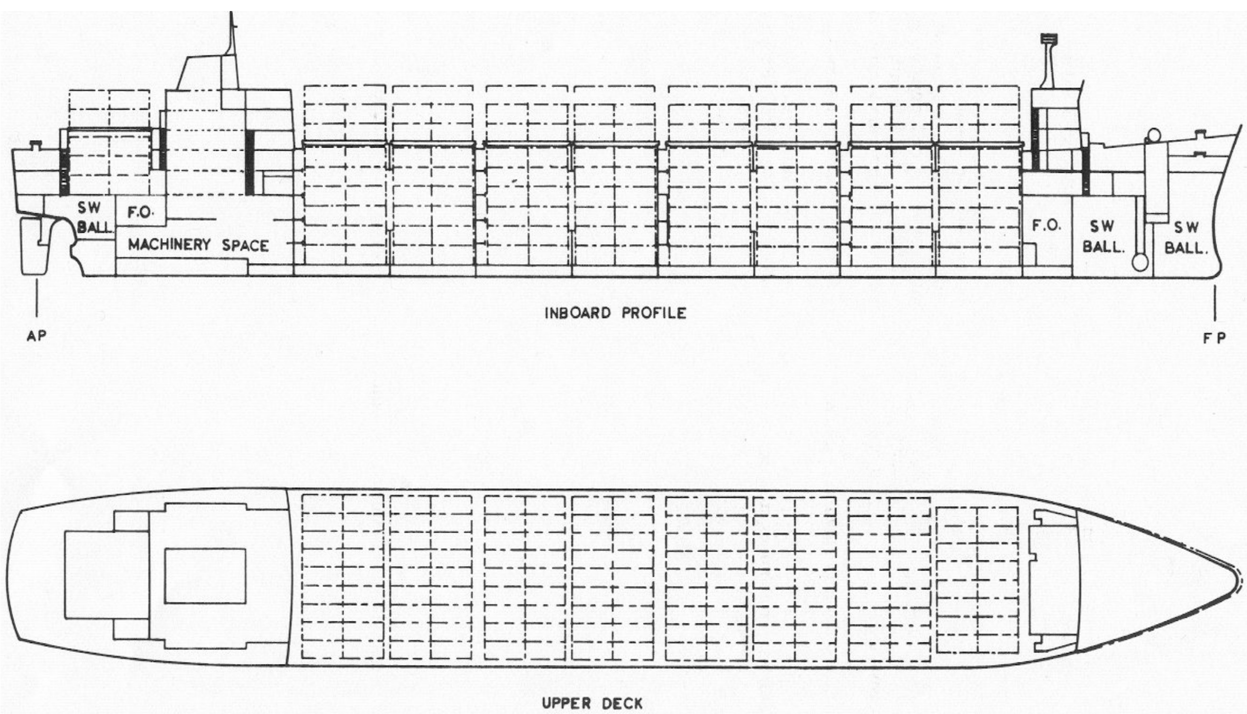


Figure C-2. Structural Arrangement of the Midship Section of a Containership (SSC-405, 1999)

C.2. Development of Failure Scenarios for a Containership

This section of Appendix A describes possible failure scenarios for a containership that have as an initiating event a structural failure. The following initiating events are analyzed in this appendix for the purpose of demonstration:

1. Buckling of an unstiffened inner side shell panel, in the cargo space;
2. Buckling of an unstiffened outer side shell panel, in the cargo space;
3. Fatigue of an inner side shell longitudinal stiffener, in the cargo space;
4. Fatigue of an outer side shell longitudinal stiffener, in the cargo space;
5. Fatigue of an outer bottom panel longitudinal stiffener, in the cargo space;
6. Fatigue of a double bottom panel longitudinal stiffener, in the cargo space;
7. Buckling of an unstiffened panel, in the main deck of the machinery room;
8. Fatigue of a main engine foundation stiffener, in the machinery room;
9. Buckling of an unstiffened side shell panel, in the machinery room; and
10. Fatigue of a side shell longitudinal stiffener, in the machinery room.

In subsequent sections of this appendix, the failure scenarios corresponding to each of these initiating events are developed. The analysis kept track of all potential consequences in terms of the following metrics:

1. Ship crew;
2. Cargo onboard ship;
3. Environment;
4. Non-crew humans, corresponding to a population that is not part of the ship crew, but can suffer consequences of the accident with the ship;
5. Ship machinery; and
6. Ship structure.

The consequence analysis for each initiating event was developed to the extent needed to detail and demonstrate the methodology; therefore, the consequence analysis was not fully developed and presented only the general consequences associated with the presented failure scenarios.

Subsequent sections detail the bases behind developing the cause-consequence diagrams for the above 10 initiating events.

C.2.1. Buckling of an Unstiffened Side Shell Panel, in the Cargo Space

The failure scenarios the initiating event “Buckling of an Unstiffened Side Shell Panel, in the Cargo Space” are provided in this section. The failure scenarios can be classified in two groups: (1) scenarios related to the failure of ship systems other than structural systems, i.e., nonstructural systems, such as engine, propulsion, ship stability, …, etc., and (2) scenarios involving the failure of the ship structural system.

C.2.1.1. Failure of Nonstructural Ship Systems

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-3, which presents the sequence of events that should be considered for the development of the cause-consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: possible injuries;
2. Cargo: possible damage to containers;
3. Environment: none;
4. Non-crew: none;
5. Structure: possible hull fatigue and corrosion; and
6. Cost of inspection, and possible cost of repair, in case of buckling detection.

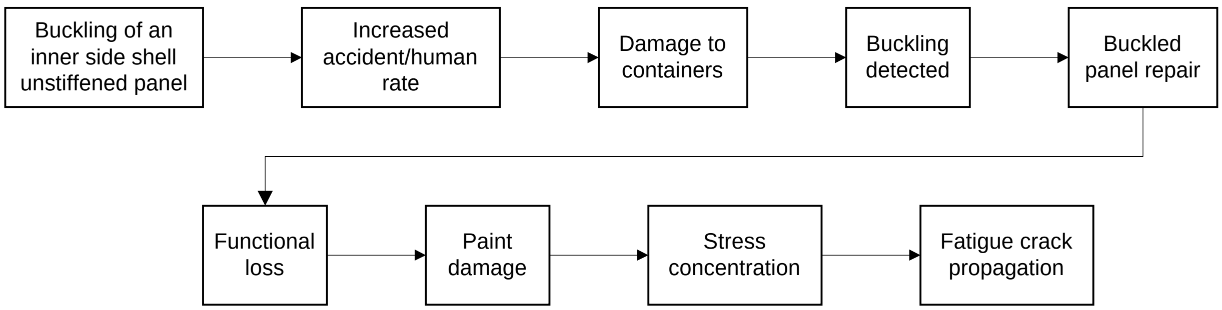


Figure C-3. Buckling of an Unstiffened Side Shell Panel – Consequences for the Cargo Hold

C.2.1.2. Failure of the Ship Structural System

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-4, which presents the sequence of events that should be considered for the development of the cause-consequence diagram in this case. The consequences associated with the failure scenarios are:

1. Crew: possible injuries and deaths, considering the hull collapse;
2. Cargo: possible loss of cargo, in case of hull failure;
3. Environment: possible contamination with fuel and lubricant oil, and cargo, in case of hull collapse;
4. Non-crew: none;
5. Structure: extensive hull damage, considering the failure of a primary structural member;
6. Ship: possible loss of ship in case of hull failure; and
7. Cost of inspection, and possible cost of repair, in case of buckling detection.

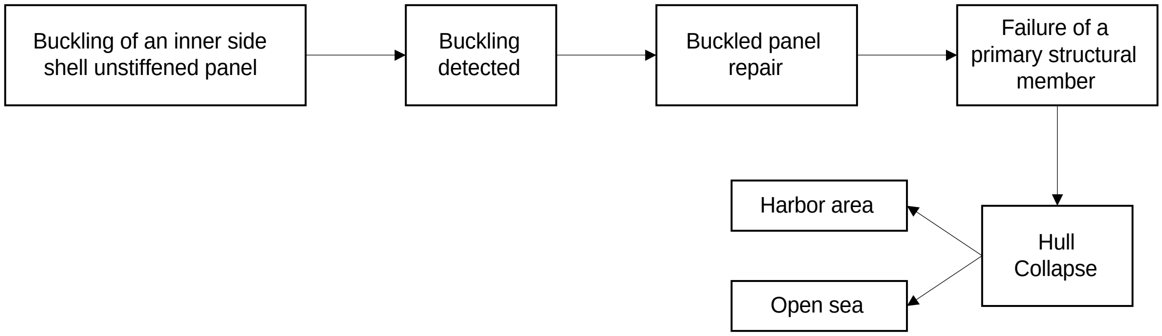


Figure C-4. Buckling of an Unstiffened Side Shell Panel – Consequences for the Ship Structure

C.2.2. Buckling of an Unstiffened Outer Side Shell Panel, in the Cargo Space

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-5, which presents the sequence of events that should be considered for the development of the cause-consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: possible injuries and deaths, considering the hull collapse or fracture;
2. Cargo: possible loss of cargo, in case of hull failure;
3. Environment: possible contamination with fuel and lubricant oil, and cargo, in case of hull collapse;
4. Non-crew: none;
5. Structure: extensive hull damage, considering the failure of a primary structural member;
6. Ship: possible loss of ship in case of hull failure; and
7. Cost of inspection, and possible cost of repair, in case of buckling detection.

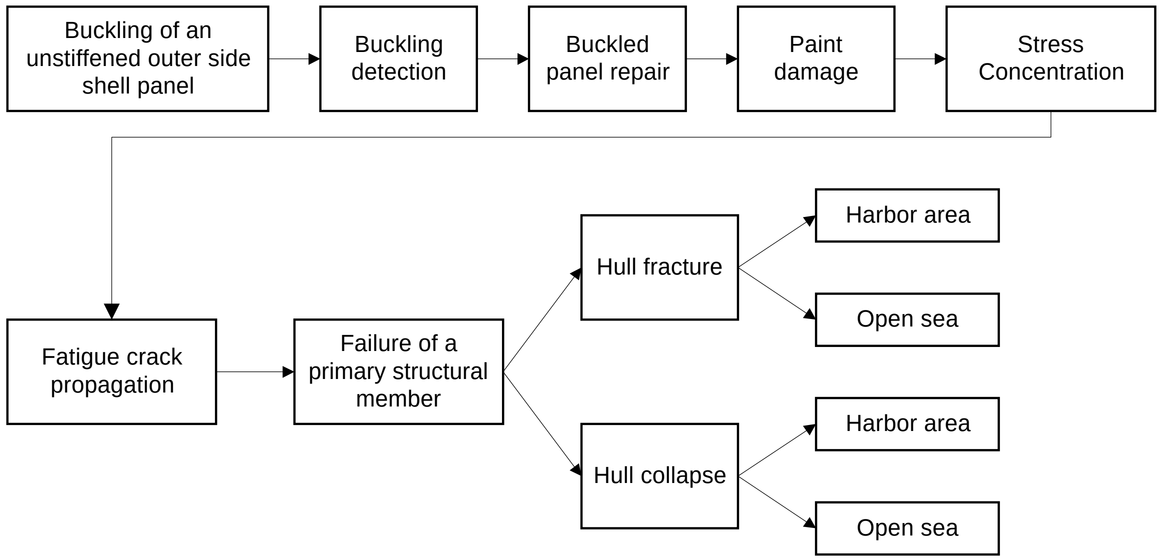


Figure C-5. Buckling of an Unstiffened Outer Side Shell Panel, in the Cargo Space

C.2.3. Fatigue of an Inner Side Shell Longitudinal Stiffener, in the Cargo Space

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-6, which presents the events that should be considered for the development of the consequence diagram. The consequence analysis for this initiating event is not fully developed herein as it presents only the consequences associated with selected possible failure scenarios. The consequences can include the following:

1. Crew: possible injuries and death, considering the hull collapse or fracture;
2. Cargo: possible damage to containers, in case of a failure of a primary structural member, or even loss of cargo, in case of hull failure;
3. Environment: contamination with fuel and lubricant oil, and cargo; the marine life can be affect if the hull failure occurs in harbor area;
4. Non-crew: financial and health problems for the population living close to the harbor area, if the hull failure occurs in harbor area;
5. Structure: extensive damage, considering the failure of a primary structural member;
6. Ship: possible loss of ship in case of hull failure; and
7. Cost of inspection, and possible cost of repair, in case of crack detection.

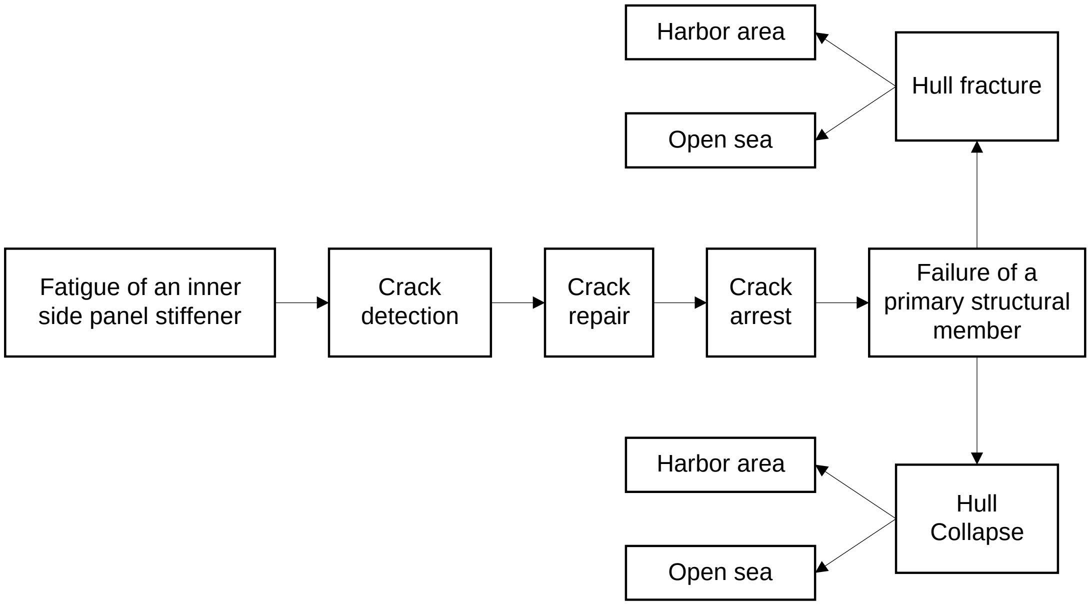


Figure C-6. Fatigue of an Inner Side Shell Longitudinal Stiffener, in the Cargo Space

C.2.4. Fatigue of an Outer Side Shell Longitudinal Stiffener, in the Cargo Space

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-7, which presents the sequence of events that should be considered for the development of the cause-consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: possible injuries and deaths, considering the hull collapse or fracture;
2. Cargo: possible loss of cargo, in case of hull failure;
3. Environment: possible contamination with fuel and lubricant oil, and cargo, in case of hull failure; the marine life can be affect if the failure occurs in harbor area;
4. Non-crew: financial and health problems for the population living close to the harbor area, if the hull failure occurs in harbor area;
5. Structure: extensive hull damage, considering the failure of a primary structural member;
6. Ship: possible loss of ship in case of hull failure;
7. Cost of inspection, and possible cost of repair, in case of crack detection.

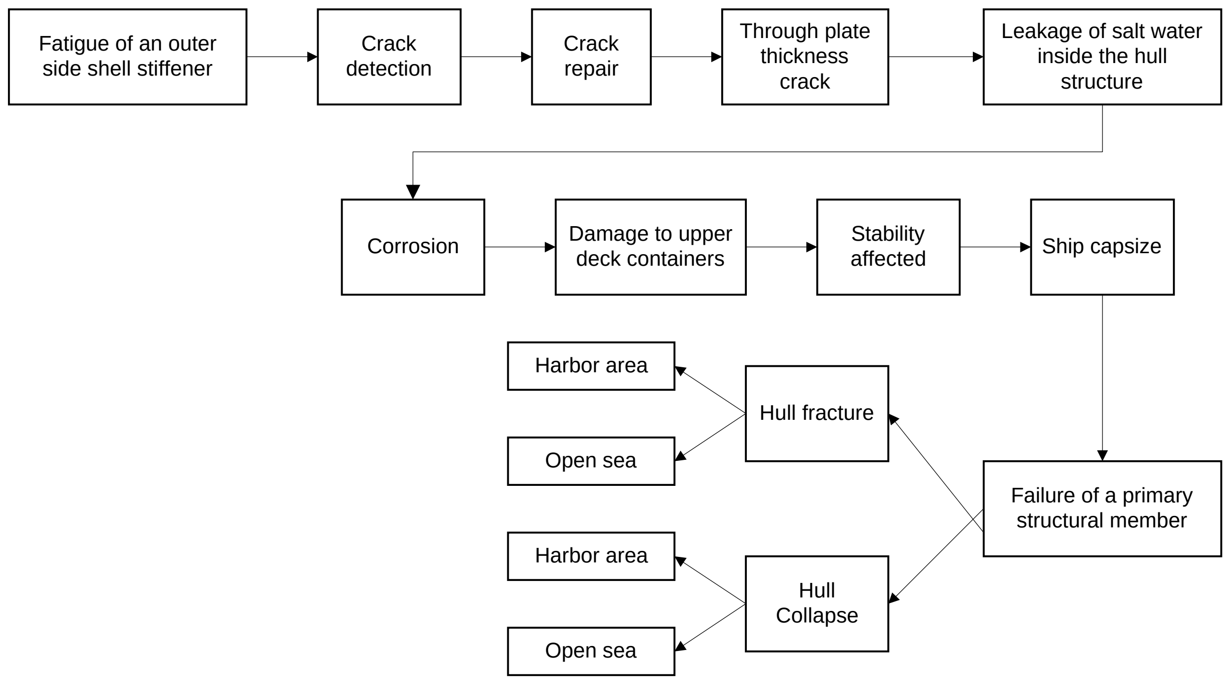


Figure C-7. Fatigue of an Inner Side Shell Longitudinal Stiffener, in the Cargo Space

C.2.5. Fatigue of an Outer Bottom Panel Longitudinal Stiffener, in the Cargo Space

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-8, which presents the sequence of events that should be considered for the development of the cause-consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: possible injuries and deaths, considering the hull collapse or fracture;
2. Cargo: possible loss of cargo, in case of hull failure;
3. Environment: possible contamination of with fuel, in case of leakage from the bottom tanks; possible contamination with fuel and lubricant oil, and cargo, in case of hull failure; the marine life can be affect if the failure occurs in harbor area;
4. Non-crew: financial and health problems for the population living close to the harbor area, if the hull failure occurs in harbor area;
5. Structure: extensive hull damage, considering the failure of a primary structural member;
6. Ship: possible loss of ship in case of hull failure; and
7. Cost of inspection, and possible cost of repair, in case of crack detection.

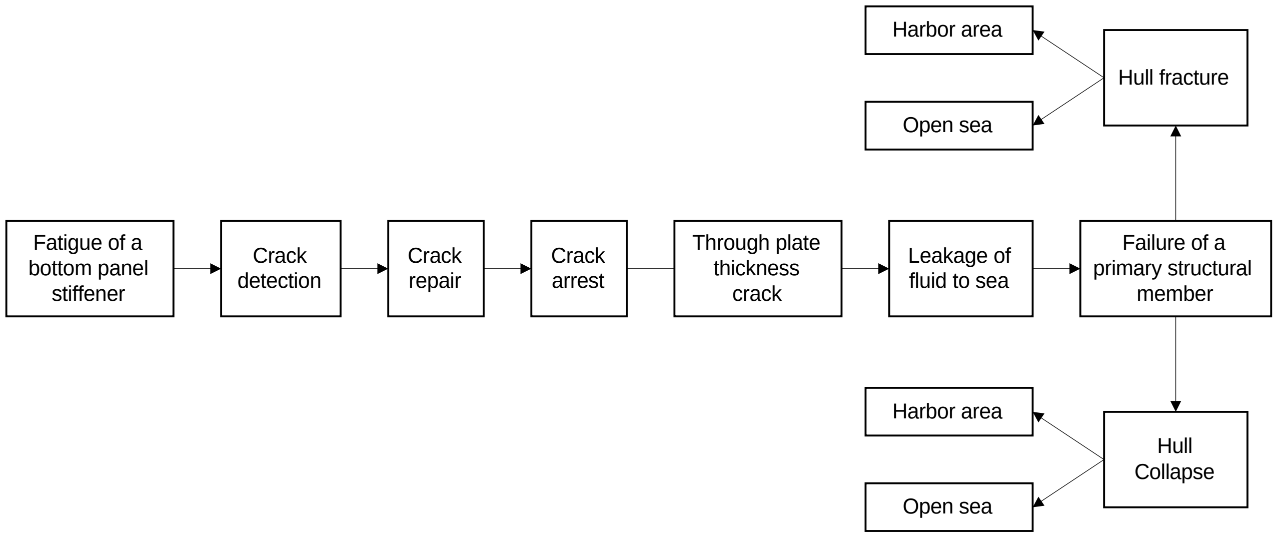


Figure C-8. Fatigue of an Outer Bottom Panel Longitudinal Stiffener, in the Cargo Space

C.2.6. Fatigue of a Double Bottom Panel Longitudinal Stiffener, in the Cargo Space

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-9, which presents the sequence of events that should be considered for the development of the cause-consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: possible injuries and deaths, considering the hull collapse or fracture;
2. Cargo: possible damage to the containers, in case of leakage of fluid from the bottom tank; possible loss of cargo, in case of hull failure;
3. Environment: possible contamination with fuel and lubricant oil, and cargo, in case of hull failure; the marine life can be affect if the failure occurs in harbor area;
4. Non-crew: financial and health problems for the population living close to the harbor area, if the hull failure occurs in harbor area;
5. Structure: extensive hull damage, considering the failure of a primary structural member;
6. Ship: possible loss of ship in case of hull failure;
7. Cost of inspection, and possible cost of repair, in case of crack detection.

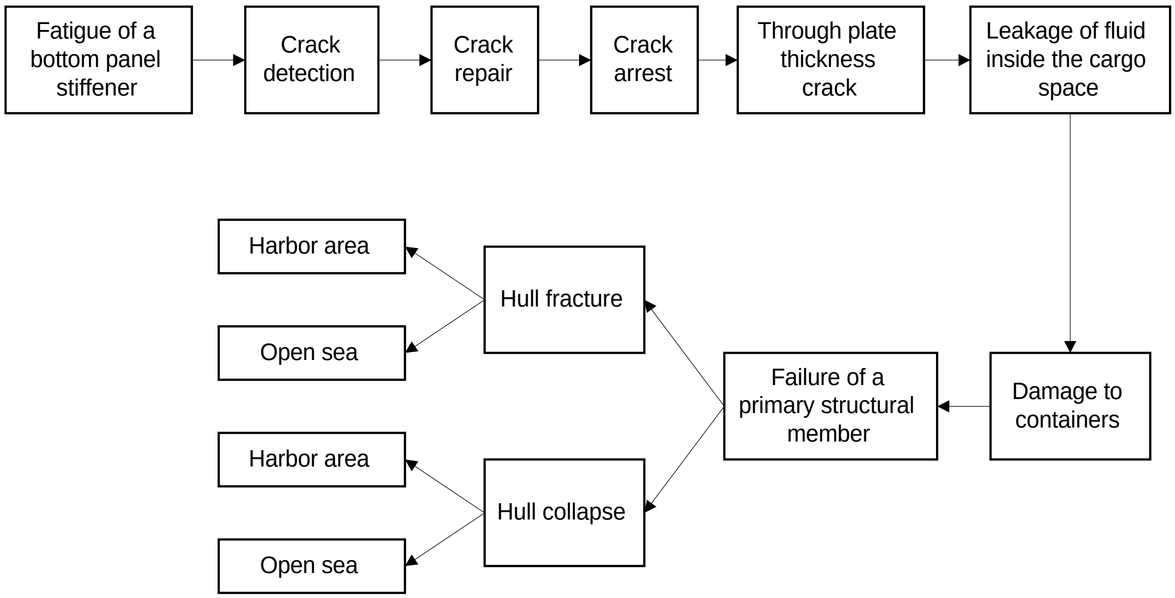


Figure C-9. Fatigue of a Double Bottom Panel Longitudinal Stiffener, in the Cargo Space

C.2.7. Buckling of an Unstiffened Panel, in the Main Deck of the Machinery Room

The failure scenarios developed based on this initiating event are classified in two groups: (1) failure scenarios that could lead to the failure of the machinery system, and (2) failure scenarios that could lead to the failure of the ship structural system.

C.2.7.1. Failure of the Ship Machinery System

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-10, which presents the events that should be considered for the development of the consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: possible injuries and deaths, in case of fire in the machinery room;
2. Cargo: none;
3. Environment: none;
4. Non-crew: none;
5. Machinery: moderate to serious damage, in case of fire in the machinery room;
6. Structure: strength affected by heat, in case of fire in the machinery room;
7. Ship: decrease in propulsion performance; and
8. Cost of inspection, and possible cost of repair, in case of buckling detection.

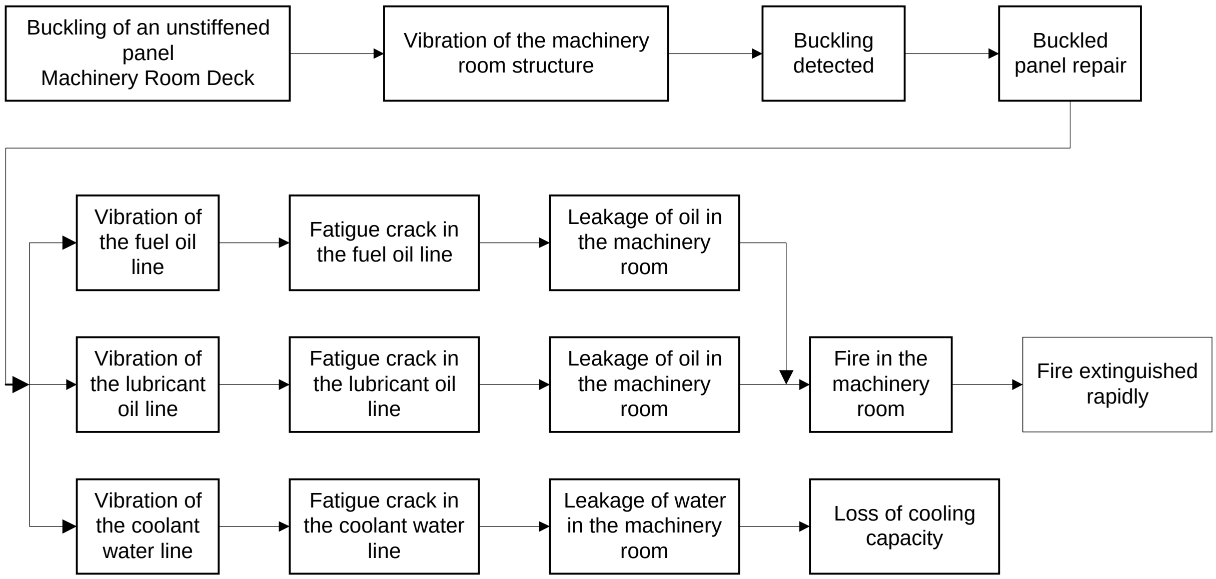


Figure C-10. Buckling of an Unstiffened Panel, in the Main Deck of the Machinery Room – Failure of Ship Machinery

C.2.7.2. Failure of the Ship Structural System

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-11, which presents the events that should be considered for the development of the consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: discomfort due to vibration;
2. Cargo: none;
3. Environment: none;
4. Non-crew: none;
5. Machinery: decrease of propulsion system performance, in case of vibration and misalignment; moderate to serious damage, in case of failure of a primary member;
6. Structure: increase of dynamic stress due to vibration; extensive damage in case of failure of a primary member;
7. Ship: decrease in propulsion performance; and
8. Cost of inspection, and possible cost of repair, in case of buckling detection.

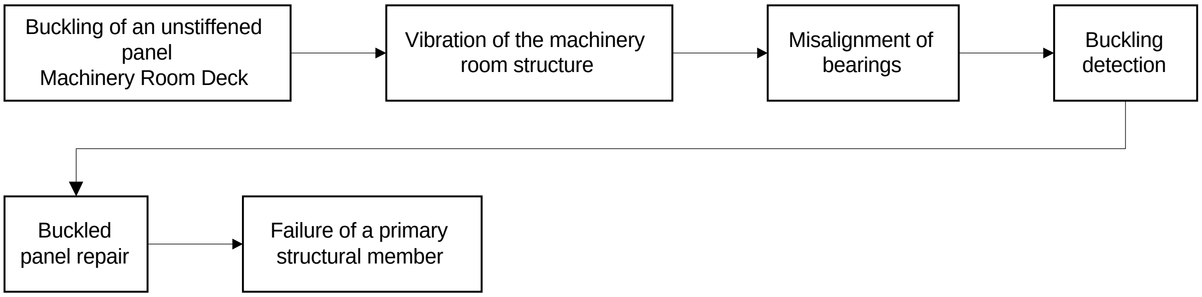


Figure C-11. Buckling of an Unstiffened Panel, in the Main Deck of the Machinery Room – Failure of Ship Structure

C.2.8. Fatigue of a Main Engine Foundation Stiffener

The failure scenarios developed based on this initiating event are classified in two groups: (1) failure scenarios that could lead to the failure of the machinery system, and (2) failure scenarios could lead to the ship structural system failure.

C.2.8.1. Failure of the Ship Machinery System

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-12, which presents the events that should be considered for the development of the consequence diagram. The consequences associated with the failure scenarios are:

i) Crew: possible injuries and deaths, in case of fire in the machinery room;
ii) Cargo: none;
iii) Environment: none;
iv) Non-crew: none;
v) Machinery: moderate to serious damage, in case of fire in the machinery room;
vi) Structure: strength affected by heat, in case of fire in the machinery room;
vii) Ship: decrease in propulsion performance; and
viii) Cost of inspection, and possible cost of repair, in case of crack detection.

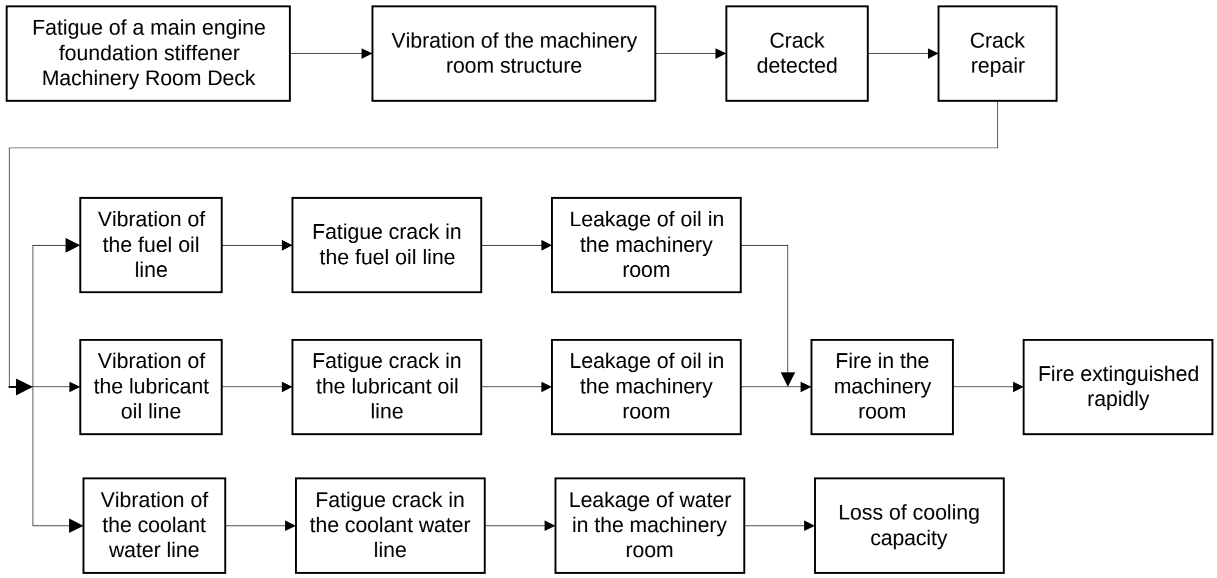


Figure C-12. Fatigue of a Main Engine Foundation Stiffener – Failure of Ship Machinery

C.2.8.2. Failure of the Ship Structural System

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-13, which presents the events that should be considered for the development of the consequence diagram. The consequences associated with the failure scenarios are:

i) Crew: discomfort due to vibration; possible deaths in case of fire in the machine room;
ii) Cargo: none;
iii) Environment: none;
iv) Non-crew: none;
v) Machinery: decrease of propulsion system performance, in case of vibration and misalignment; moderate to serious damage, in case of failure of a primary member or fire in the machine room;
vi) Structure: increase of dynamic stress due to vibration; extensive damage in case of failure of a primary member; Strength affected by heat in case of failure in the machine room;
vii) Ship: decrease in propulsion performance; and
viii) Cost of inspection, and possible cost of repair, in case of crack detection.

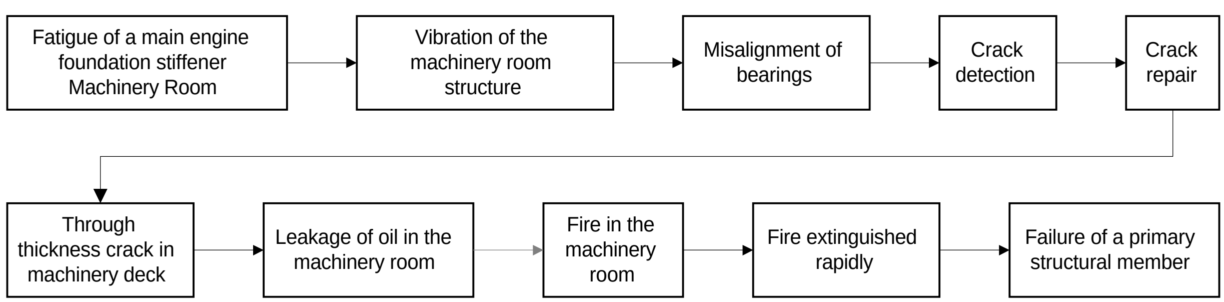


Figure C-13. Fatigue of a Main Engine Foundation Stiffener – Failure of Ship Structure

C.2.9. Buckling of an Unstiffened Side Shell Panel, in the Machinery Room

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-14, which presents the events that should be considered for the development of the consequence diagram. The consequences associated with the failure scenarios are:

1. Crew: possible discomfort related to the loss of some support functions, such as air-conditioning, due to reduction of auxiliary power or other auxiliary function, as a function of the damage to auxiliary machinery;
2. Cargo: none;
3. Environment: none;
4. Non-crew: none;
5. Machinery: moderate damage, considering the possible damage to the auxiliary machinery;
6. Structure: extensive damage, considering the failure of a primary structural member;
7. Ship: may face some decrease in auxiliary functions performance; and
8. Cost of inspection, and possible cost of repair, in case of buckling detection.

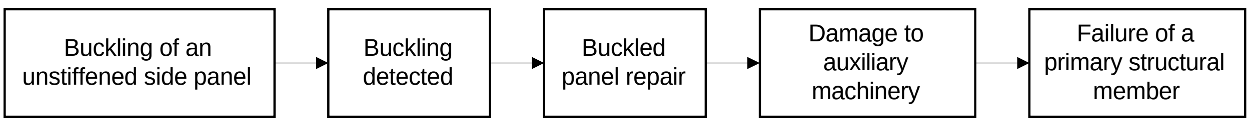


Figure C-14. Buckling of an Unstiffened Side Panel, in the Machinery Room

C.2.10. Fatigue of a Side Shell Longitudinal Stiffener, in the Machine Room

The failure scenarios associated with this initiating event can be developed based on the diagram shown in Figure C-15, which presents the events that should be considered for the development of the consequence diagram. The consequences associated with the failure scenarios are:

i) Crew: possible injuries and deaths, due to the flooding of the machinery room;
ii) Cargo: none;
iii) Environment: none;
iv) Non-crew: none;
v) Machinery: serious damage, considering the possible flooding of the machinery room;
vi) Structure: extensive damage, considering the failure of a primary structural member;
vii) Ship: loss of propulsion, considering the flooding of the machinery room; and
viii) Cost of inspection, and possible cost of repair, in case of fatigue crack repair.

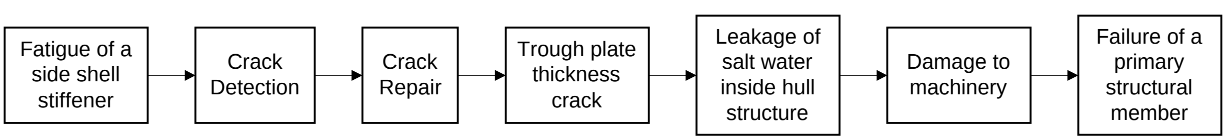


Figure C-15. Fatigue of a Side Panel Longitudinal Stiffener, in the Machinery Room

C.3. Demonstration of the Development of Cause-Consequence Diagrams for Some Initiating Events

This section presents the development of the cause-consequence diagrams for four initiating events for the purpose of demonstrating the methodology of Chapter 2 of this report.

The following initiating events, already presented in Section C.2 as cases 1, 4, 7 and 8, respectively, have their cause-consequence diagram developed in details in subsequent subsections:

1. Buckling of an unstiffened inner side panel, in the cargo space;
2. Fatigue of an outer side shell longitudinal stiffener, in the cargo space;
3. Buckling of an unstiffened panel, in the main deck of the machinery room;
4. Fatigue of a main engine foundation stiffener, in the machinery room.

The consequences associated with the failure scenarios for each initiating event are presented in the form of tables. Each failure scenario was given a nomenclature that is composed of a group of characters corresponding to the underlying events that define failure scenario. For each of these events, the following characters are used to provide and define its status:
Y = yes, corresponding to the occurrence of the event;
N = no, corresponding to the non-occurrence of the event;
U = unused, indicating that the event is not part of the scenario under analysis.

In the subsequent subsections, the failure scenarios corresponding to each of those initiating events are developed, and the consequences are provides for the following significance metrics:

1. Ship crew;
2. Ship cargo;
3. Environment;
4. Non-crew humans, corresponding to a population that is not part of the ship crew, but can suffer consequences of the accident with the ship;
5. Ship machinery; and
6. Ship structural system.

The failure scenarios are classified according to severity of the consequences associated with their occurrence. For the development of this example, five severity categories are used for the purpose of demonstration, according to the following definition:

1. <u>Consequence Rating 1:</u> trivial consequences expected as part of normal operation;
2. <u>Consequence Rating 2:</u> minor repairable faults with small cargo damage, without consequences for ship systems other than structural, for the crew and non-crew members, and for the environment;
3. <u>Consequence Rating 3:</u> major repairable faults, with moderate damage to ship system other than structural, possible injuries or death of crew and without consequences for the non-crew members and for the environment;
4. <u>Consequence Rating 4:</u> major repairable faults, with serious damage, that cause loss of serviceability of ship systems other than structural, with possible injuries and deaths in the crew, without consequence for the non-crew members and for the environment; and

5. Consequence Rating 5: non-repairable faults, with serious damage to ship systems other than structural, with possible injuries and death of crew members, and with consequences for the non-crew or for the environment.

C.3.1. Buckling of an Unstiffened Inner Side Shell Panel, in the Cargo Space

As presented in section C.2, the failure scenarios developed based on this initiating event are classified in two groups: (1) scenarios related to the failure of ship systems other than structural systems, i.e., nonstructural systems, such as engine, propulsion, ship stability, …, etc., and (2) scenarios involving the failure of the ship structural system.

C.3.1.1. Failure of Other Ship Systems

Eight characters, with the following meaning and sequence compose the definition of the failure scenarios:

_ XXXXXXX = the first character corresponds to the increase in the rate of accidents involving crew members inside the cargo space;
X _ XXXXXX = the second character corresponds to the occurrence of damage to containers;
XX _ XXXXX = the third character corresponds to the detection of the buckling;
XXX _ XXXX = the fourth character corresponds to the repair of the buckled panel;
XXXX _ XXX = the fifth character corresponds to a functional loss, meaning the loss of cargo space in the cargo hold;
XXXXX _ XX = the sixth character corresponds to the damage in the paint of the buckled panel;
XXXXXX _ X = the seventh character corresponds to the occurrence of stress concentration in the structural components near the buckled panel; and
XXXXXXX _ = the eighth character corresponds to the fatigue crack propagation in the structure.

A code composed of three numerical characters identifies each of failure scenarios. The meaning of these characters is:

_ XX = the first digit is equal to 1, corresponding to the Section 3.1 of appendix A;
X _ X = the second digit is equal to 1, corresponding to the Section 3.1.1 of appendix A; and
XX _ = the third digit corresponds to the number of failure scenario associated with the initiating event.

The cause-consequence diagram associated with this initiating event is presented in Figure C-16. The consequences of the possible failure scenarios associated with the buckling of an inner side shell unstiffened panel, in the cargo space, are presented in Table C-2.

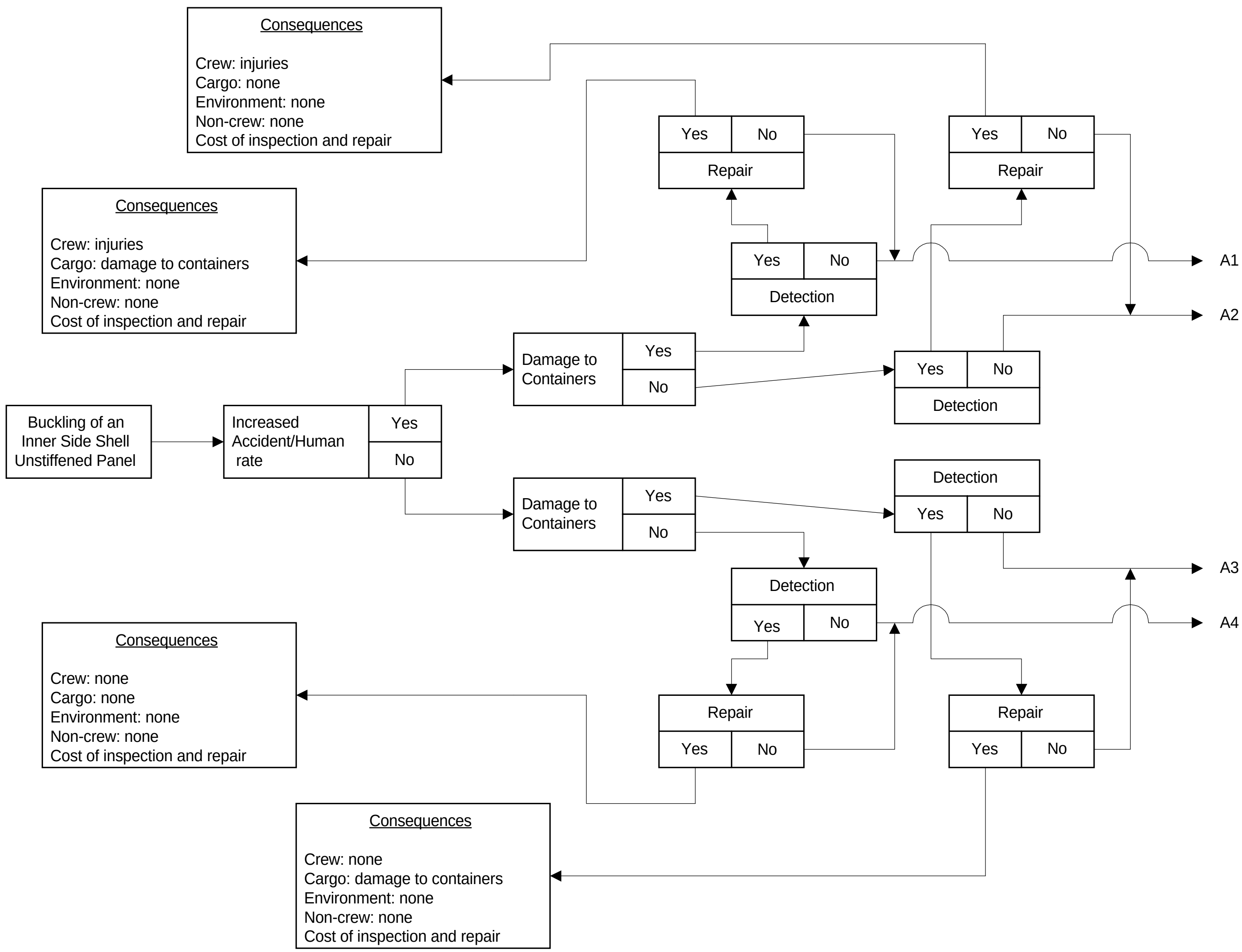


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 01/09)

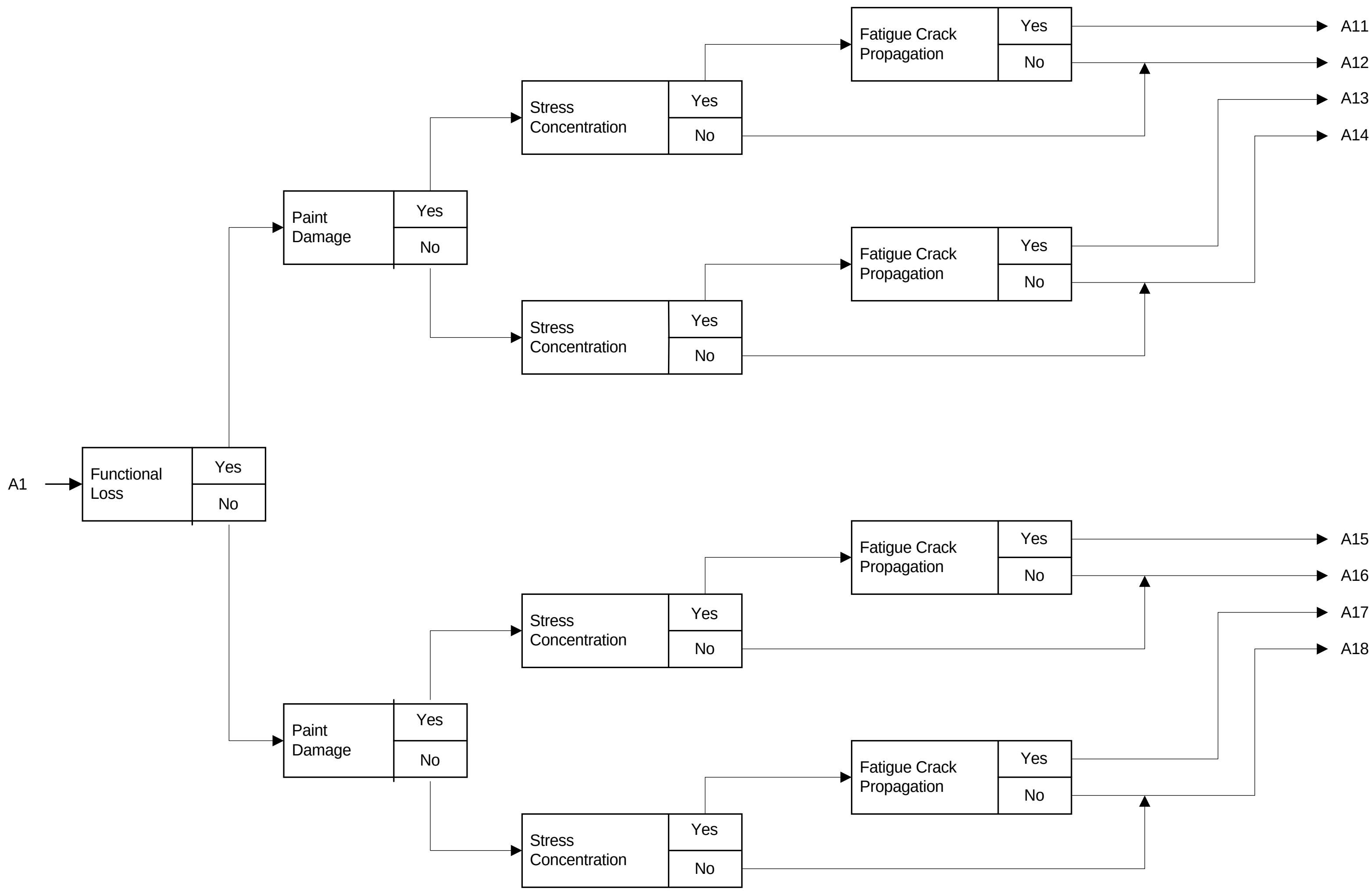


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 02/09)

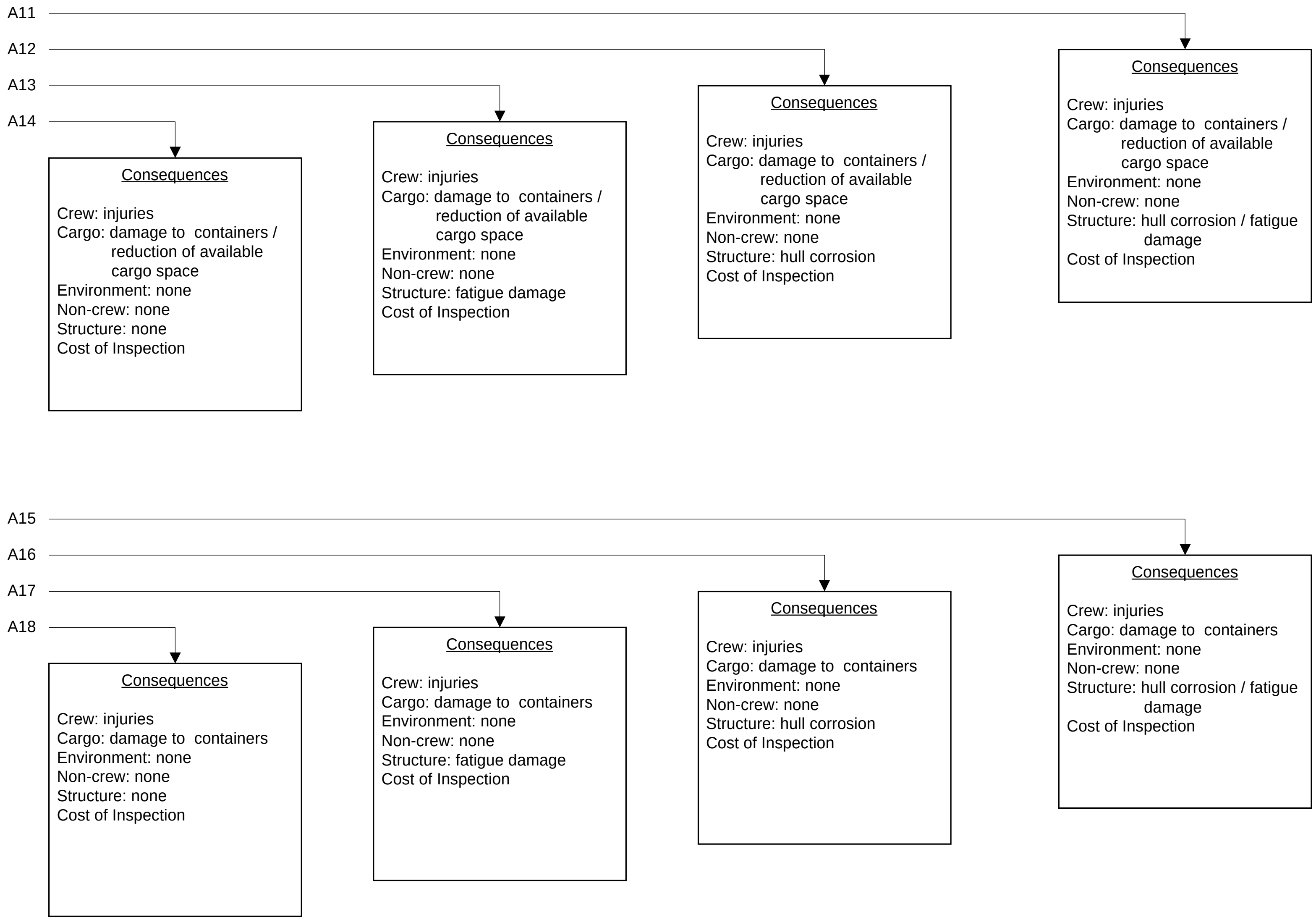


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 03/09)

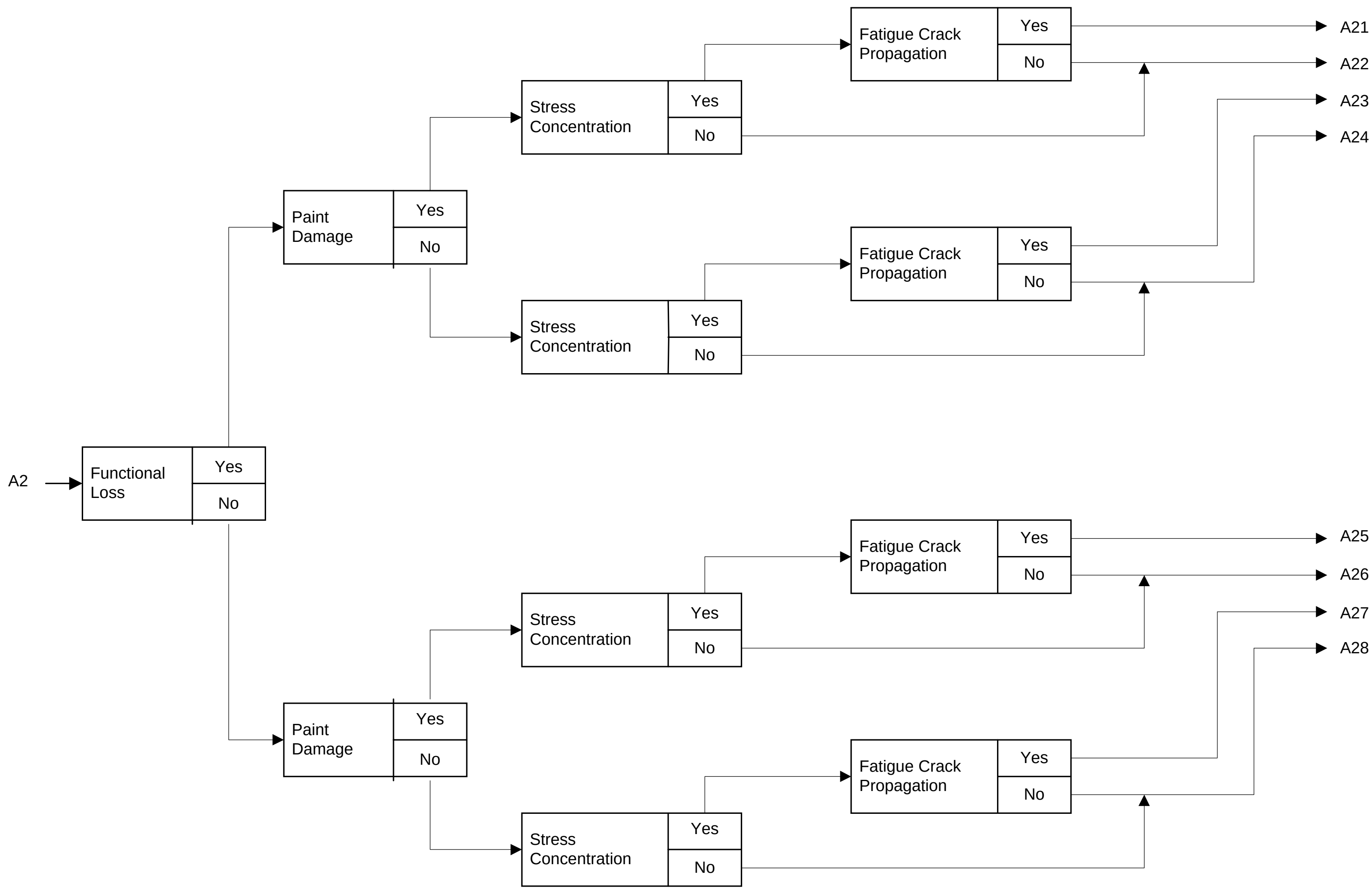


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 04/09)

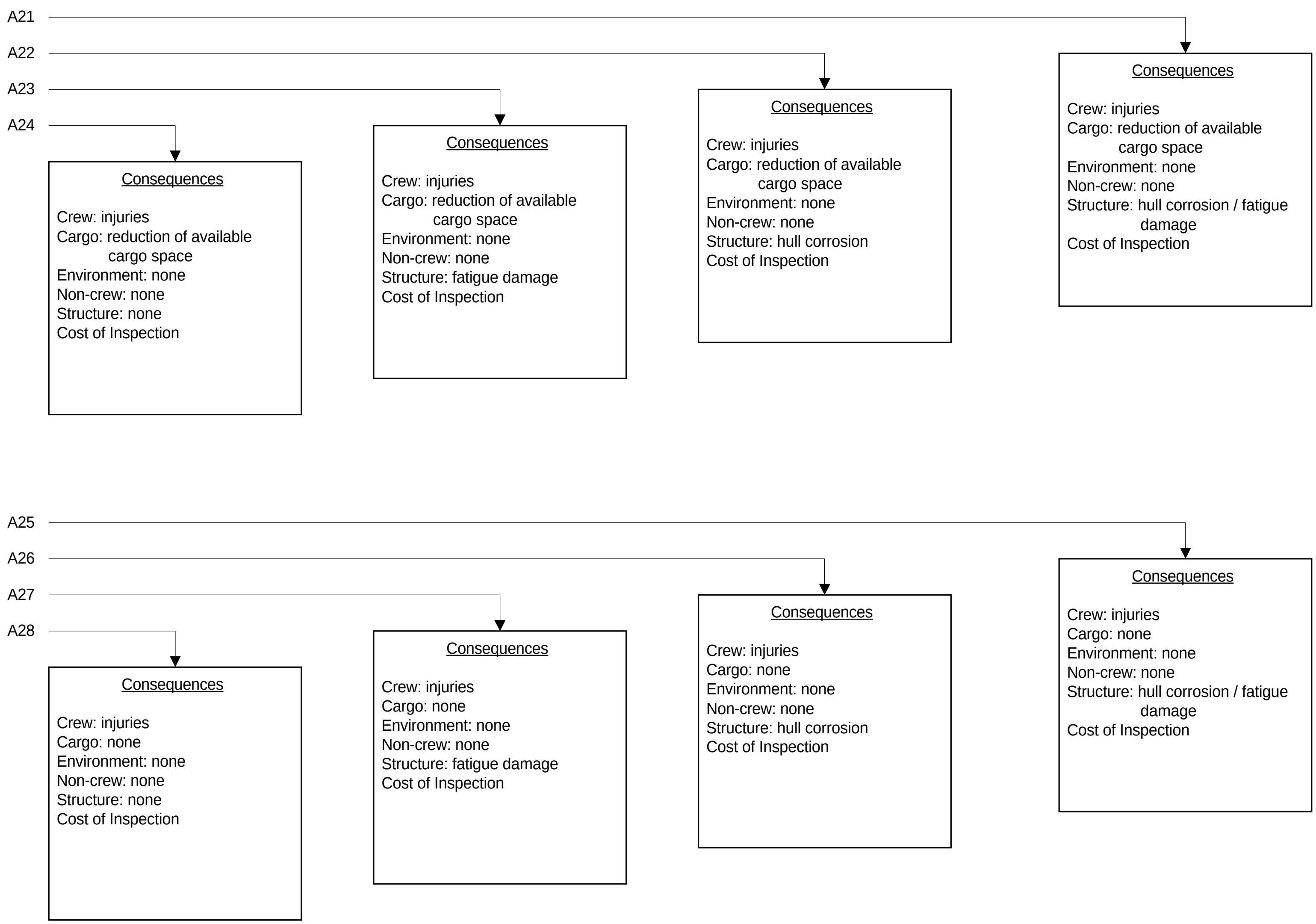


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 05/09)

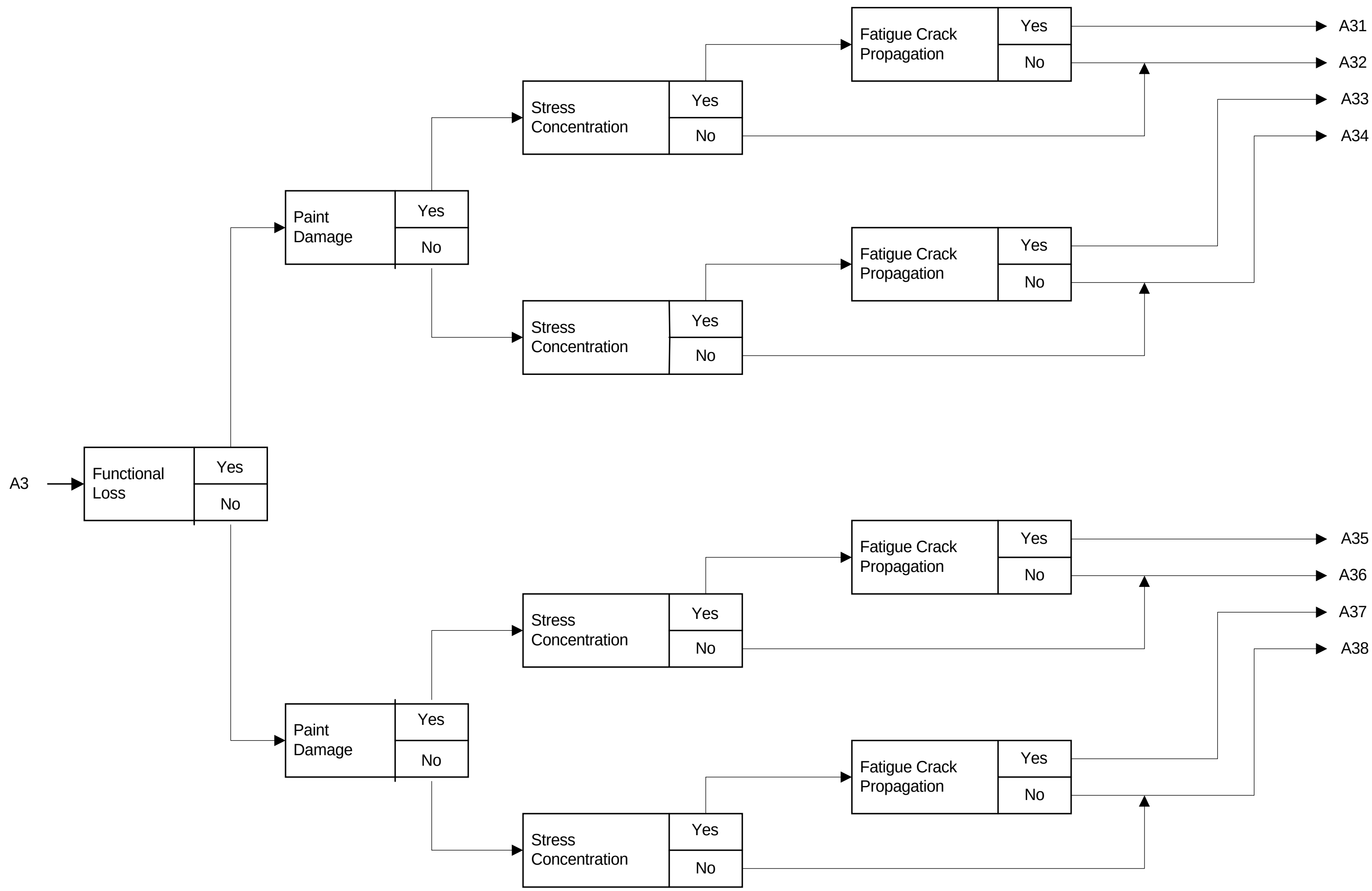


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 06/09)

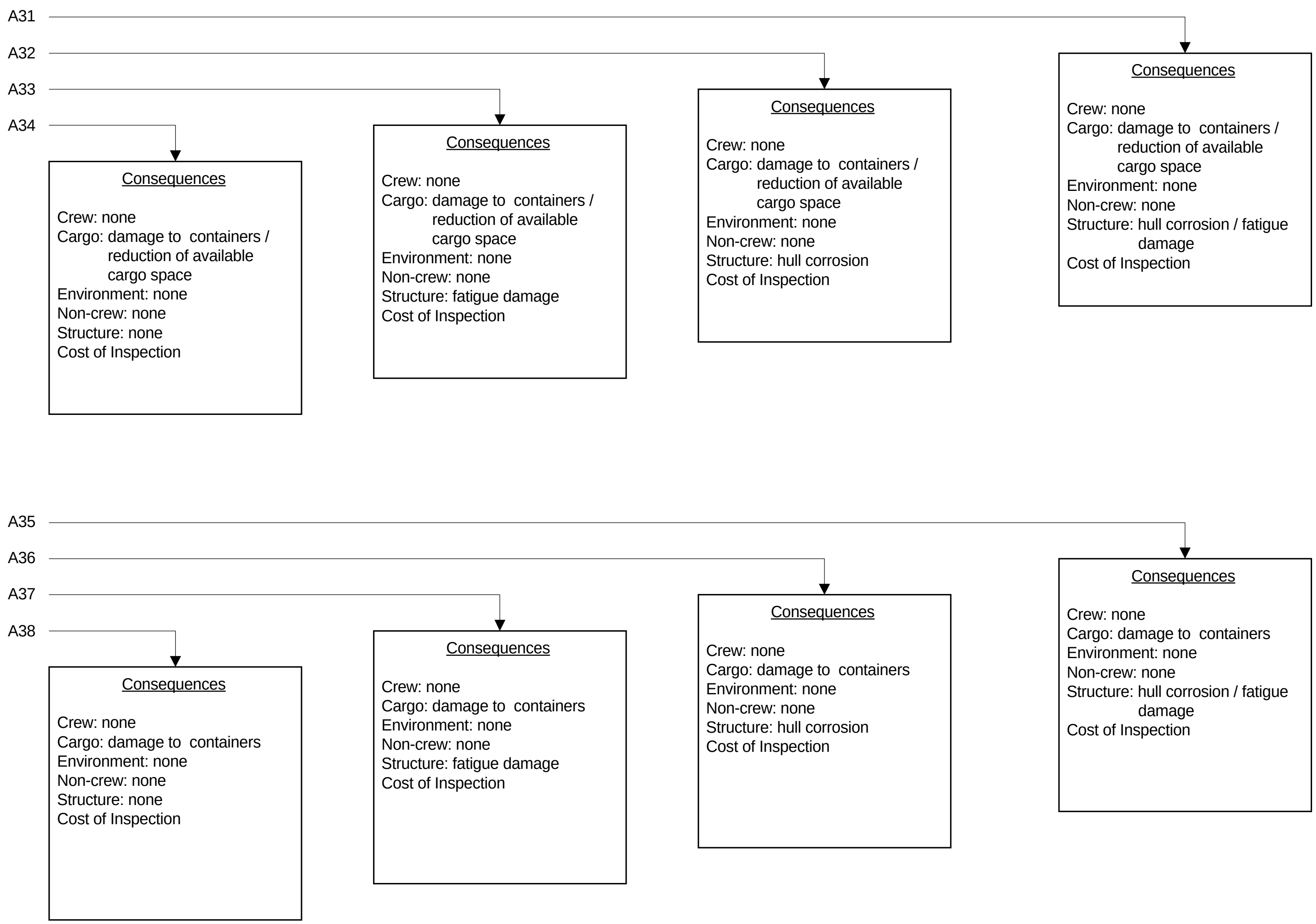


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 07/09)

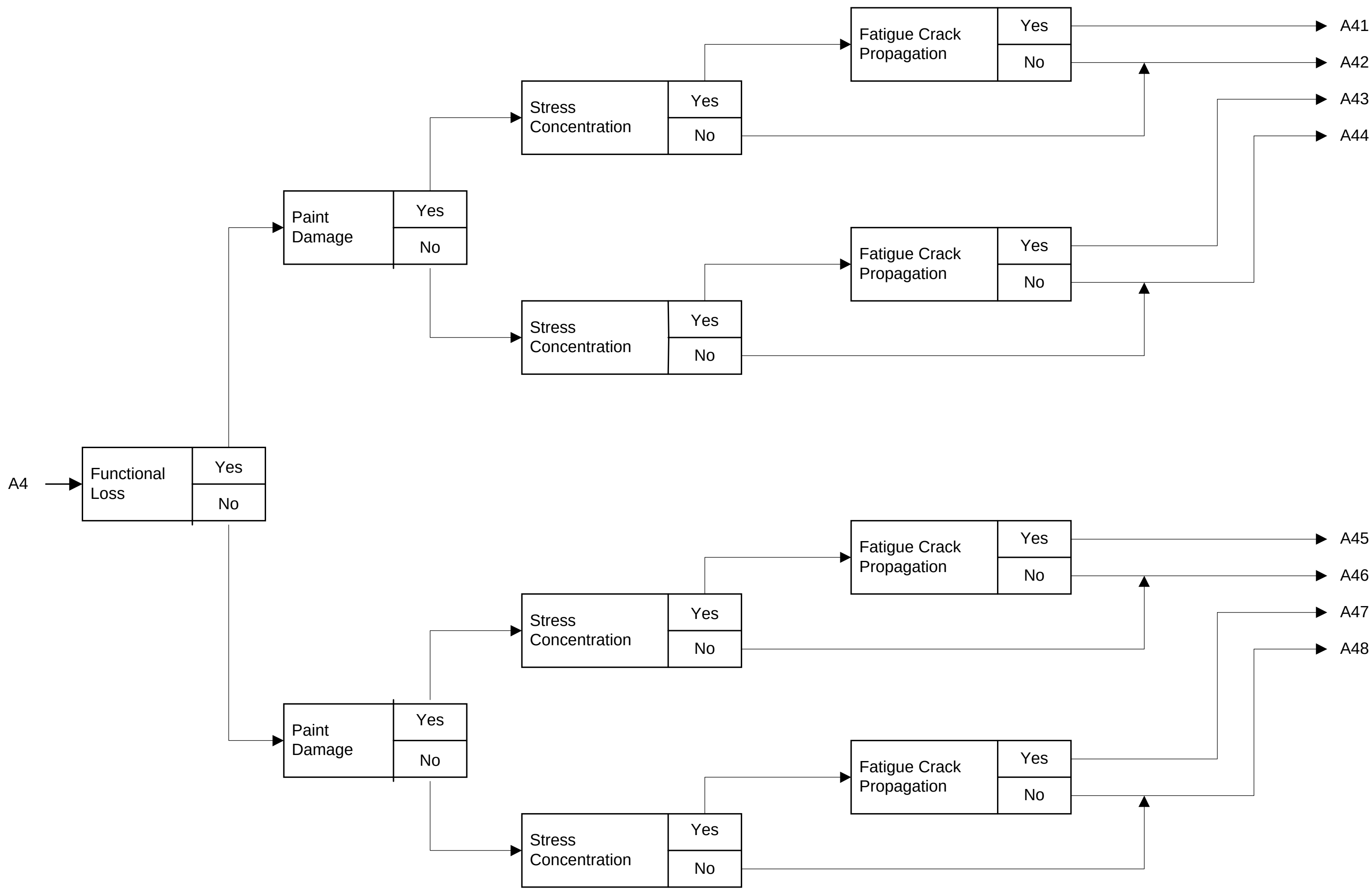


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 08/09)

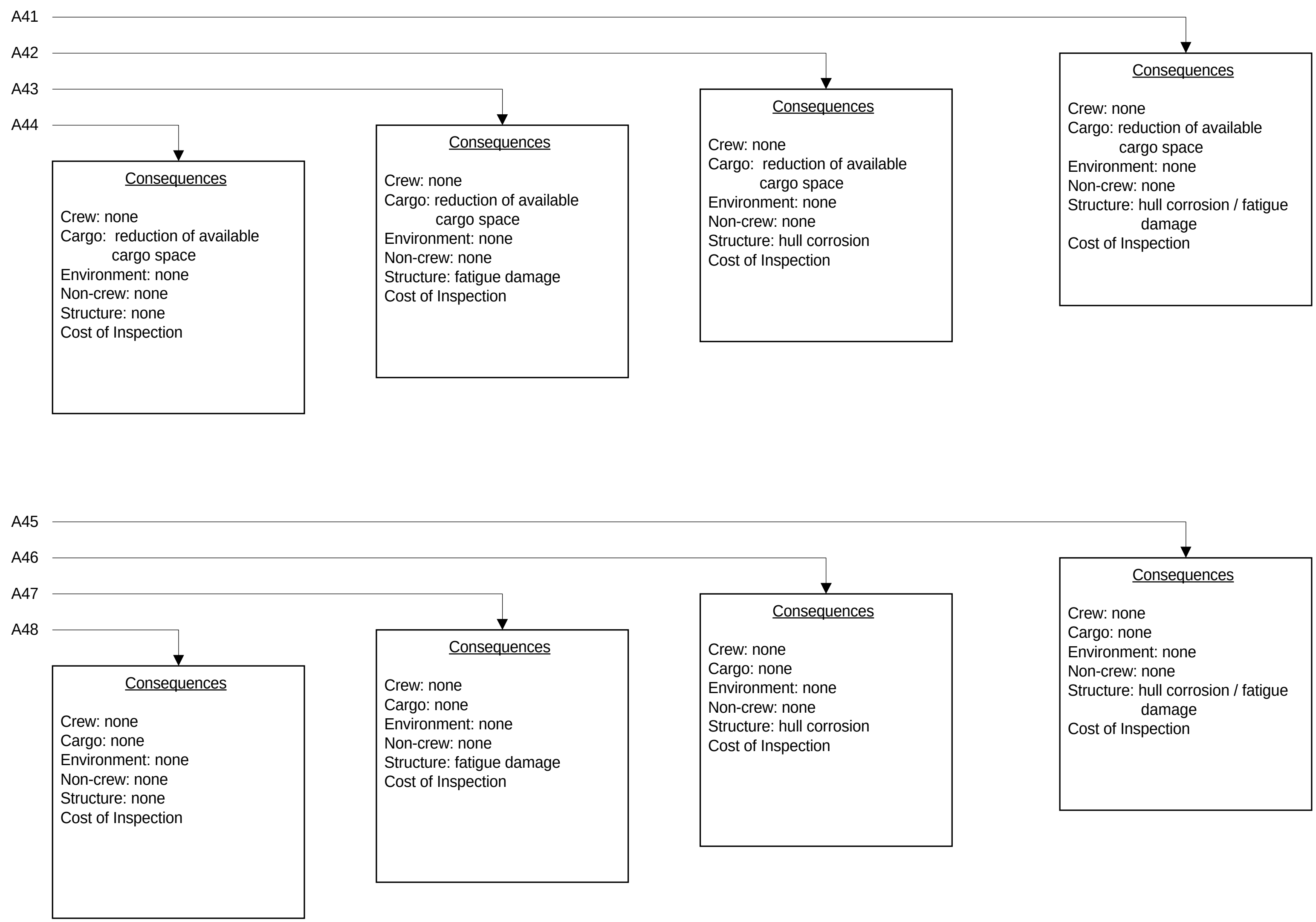


Figure C-16. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Failure on Systems other than the Structural System (Page 09/09)

Table C-2. General Consequences Associated with the Buckling of a Inner Side Shell Unstiffened Panel (Page 01/05)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
111	YYYYUUUU	Injuries	Damage to containers	None	None	None	Cost of Inspection and Repair	3
112	YYYNYYYY YYNUYYYY	Injuries	Damage to containers; Reduction of available cargo space	None	None	Hull corrosion; Fatigue damage	Cost of inspection	4
113	YYYNYYYN YYNUYYYN	Injuries	Damage to containers; Reduction of available cargo space	None	None	Hull corrosion	Cost of inspection	3
114	YYYNYYNU YYNUYYNU	Injuries	Damage to containers; Reduction of available cargo space	None	None	Hull corrosion	Cost of inspection	3
115	YYYNYNYY YYNUYNYY	Injuries	Damage to containers; Reduction of available cargo space	None	None	Fatigue damage	Cost of inspection	3
116	YYYNYNYN YYNUYNYN	Injuries	Damage to containers; Reduction of available cargo space	None	None	None	Cost of inspection	3
117	YYYNYNNU YYNUYNNU	Injuries	Damage to containers; Reduction of available cargo space	None	None	None	Cost of inspection	3
118	YYYNNYYY YYNUNYYY	Injuries	Damage to containers	None	None	Hull corrosion; Fatigue damage	Cost of Inspection	4
119	YYYNNYYN YYNUNYYN	Injuries	Damage to containers	None	None	Hull corrosion	Cost of inspection	3
1110	YYYNNYNU YYNUNYNU	Injuries	Damage to containers	None	None	Hull corrosion	Cost of inspection	3
1111	YYYNNNYY YYNUNNYY	Injuries	Damage to containers	None	None	Fatigue damage	Cost of inspection	3

Table C-2. General Consequences Associated with the Buckling of a Inner Side Shell Unstiffened Panel (Page 02/05)

Failure Scenario		**Consequence**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
1112	YYYNNNYN YYNUNNYN	Injuries	Damage to containers	None	None	None	Cost of inspection	3
1113	YYYNNNNU YYNUNNNU	Injuries	Damage to containers	None	None	None	Cost of inspection	3
1114	YNYYUUUU	Injuries	None	None	None	None	Cost of inspection and repair	3
1115	YNYNYYYY YNNUYYYY	Injuries	Reduction of available cargo space	None	None	Hull corrosion; Fatigue damage	Cost of inspection	4
1116	YNYNYYYN YNNUYYYN	Injuries	Reduction of available cargo space	None	None	Hull corrosion	Cost of inspection	3
1117	YNYNYYNU YNNUYYNU	Injuries	Reduction of available cargo space	None	None	Hull corrosion	Cost of inspection	3
1118	YNYNYNYY YNNUYNYY	Injuries	Reduction of available cargo space	None	None	Fatigue Damage	Cost of inspection	3
1119	YNYNYNYN YNNUYNYN	Injuries	Reduction of available cargo space	None	None	None	Cost of inspection	3
1120	YNYNYNNU YNNUYNNU	Injuries	Reduction of available cargo space	None	None	None	Cost of inspection	3
1121	YNYNNYYY YNNUNYYY	Injuries	None	None	None	Hull corrosion; Fatigue damage	Cost of Inspection	3
1122	YNYNNYYN YNNUNYYN	Injuries	None	None	None	Hull corrosion	Cost of inspection	3
1123	YNYNNYNU YNNUNYNU	Injuries	None	None	None	Hull corrosion	Cost of inspection	3
1124	YNYNNNYY YNNUNNYY	Injuries	None	None	None	Fatigue damage	Cost of inspection	3

Table C-2. General Consequences Associated with the Buckling of a Inner Side Shell Unstiffened Panel (Page 03/05)

Failure Scenario		**Consequence**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
1125	YNYNNNYN YYNUNNYN	Injuries	None	None	None	None	Cost of inspection	3
1126	YNYNNNNU YNNUNNNU	Injuries	None	None	None	None	Cost of inspection	3
1127	NYYYUUUU	None	Damage to containers	None	None	None	Cost of inspection and repair	2
1128	NYYNYYYY NYNUYYYY	None	Damage to containers; Reduction of available cargo space	None	None	Hull corrosion; Fatigue damage	Cost of inspection	3
1129	NYYNYYYN NYNUYYYN	None	Damage to containers; Reduction of available cargo space	None	None	Hull corrosion	Cost of inspection	3
1130	NYYNYYNU NYNUYYNU	None	Damage to containers; Reduction of available cargo space	None	None	Hull corrosion;	Cost of inspection	3
1131	NYYNYNYY NYNUYNYY	None	Damage to containers; Reduction of available cargo space	None	None	Fatigue damage	Cost of inspection	3
1132	NYYNYNYN NYNUYNYN	None	Damage to containers; Reduction of available cargo space	None	None	None	Cost of inspection	3
1133	NYYNYNNU NYNUYNNU	None	Damage to containers; Reduction of available cargo space	None	None	None	Cost of inspection	3
1134	NYYNNYYY NYNUNYYY	None	Damage to containers	None	None	Hull corrosion; Fatigue damage	Cost of inspection	3
1135	NYYNNYYN NYNUNYYN	None	Damage to containers	None	None	Hull corrosion;	Cost of inspection	2

Table C-2. General Consequences Associated with the Buckling of a Inner Side Shell Unstiffened Panel (Page 04/05)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
1136	NYYNNYNU NYNUNYNU	None	Damage to containers	None	None	Hull corrosion;	Cost of inspection	2
1137	NYYNNNYY NYNUNNYY	None	Damage to containers	None	None	Fatigue damage	Cost of inspection	2
1138	NYYNNNYN NYNUNNYN	None	Damage to containers	None	None	None	Cost of inspection	2
1139	NYYNNNNU NYNUNNNU	None	Damage to containers	None	None	None	Cost of inspection	2
1140	NNYYUUUU	None	None	None	None	None	Cost of inspection and repair	1
1141	NNYNYYYY NNNUYYYY	None	Reduction of available cargo space	None	None	Hull corrosion; Fatigue damage	Cost of inspection	3
1142	NNYNYYYN NNNUYYYN	None	Reduction of available cargo space	None	None	Hull corrosion;	Cost of inspection	3
1143	NNYNYYNU NNNUYYNU	None	Reduction of available cargo space	None	None	Hull corrosion;	Cost of inspection	3
1144	NNYNYNYY NNNUYNYY	None	Reduction of available cargo space	None	None	Fatigue damage	Cost of inspection	3
1145	NNYNYNYN NNNUYNYN	None	Reduction of available cargo space	None	None	None	Cost of inspection	3
1146	NNYNYNNU NNNUYNNU	None	Reduction of available cargo space	None	None	None	Cost of inspection	3
1147	NNYNNYYY NNNUNYYY	None	None	None	None	Hull corrosion; Fatigue damage	Cost of inspection	3
1148	NNYNNYYN NNNUNYYN	None	None	None	None	Hull corrosion	Cost of inspection	1

Table C-2. General Consequences Associated with the Buckling of a Inner Side Shell Unstiffened Panel (Page 05/05)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
1149	NNYNNYNU NNNUNYNU	None	None	None	None	Hull corrosion	Cost of inspection	1
1150	NNYNNNYY NNNUNNYY	None	None	None	None	Fatigue damage	Cost of inspection	1
1151	NNYNNNYN NNNUNNYN	None	None	None	None	None	Cost of inspection	1
1152	NNYNNNNU NNNUNNNU	None	None	None	None	None	Cost of inspection	1

C.3.1.2. Failure of the Ship Structural System

Five characters, with the following meaning and sequence compose the definition of the failure scenarios:

_ XXXX = the first character corresponds to the detection of the buckling;
X _ XXX = the second character corresponds to the repair of the buckled panel;
XX _ XX = the third character corresponds to the failure of a primary structural member;
XXX _ X = the fourth character corresponds to the hull collapse; and
XXXX _ = the fifth character corresponds to the geographical location of the hull failure, where the letter “O” means open sea, and the letter “H” means area near the harbor.

A code composed of three numerical characters identifies each of failure scenarios. The meaning of these characters is:

_ XX = the first digit is equal to 1, corresponding to the sub-section 3.1 of appendix A;
X _ X = the second digit is equal to 2, corresponding to the sub-section 3.1.2 of appendix A; and
XX _ = the third digit corresponds to the number of failure scenario associated with the initiating event.

The cause-consequence diagram associated with this initiating event is presented in Figure C-17. The consequences of the possible failure scenarios associated with the buckling of an inner side shell unstiffened panel, in the cargo space, are presented in Table C-3.

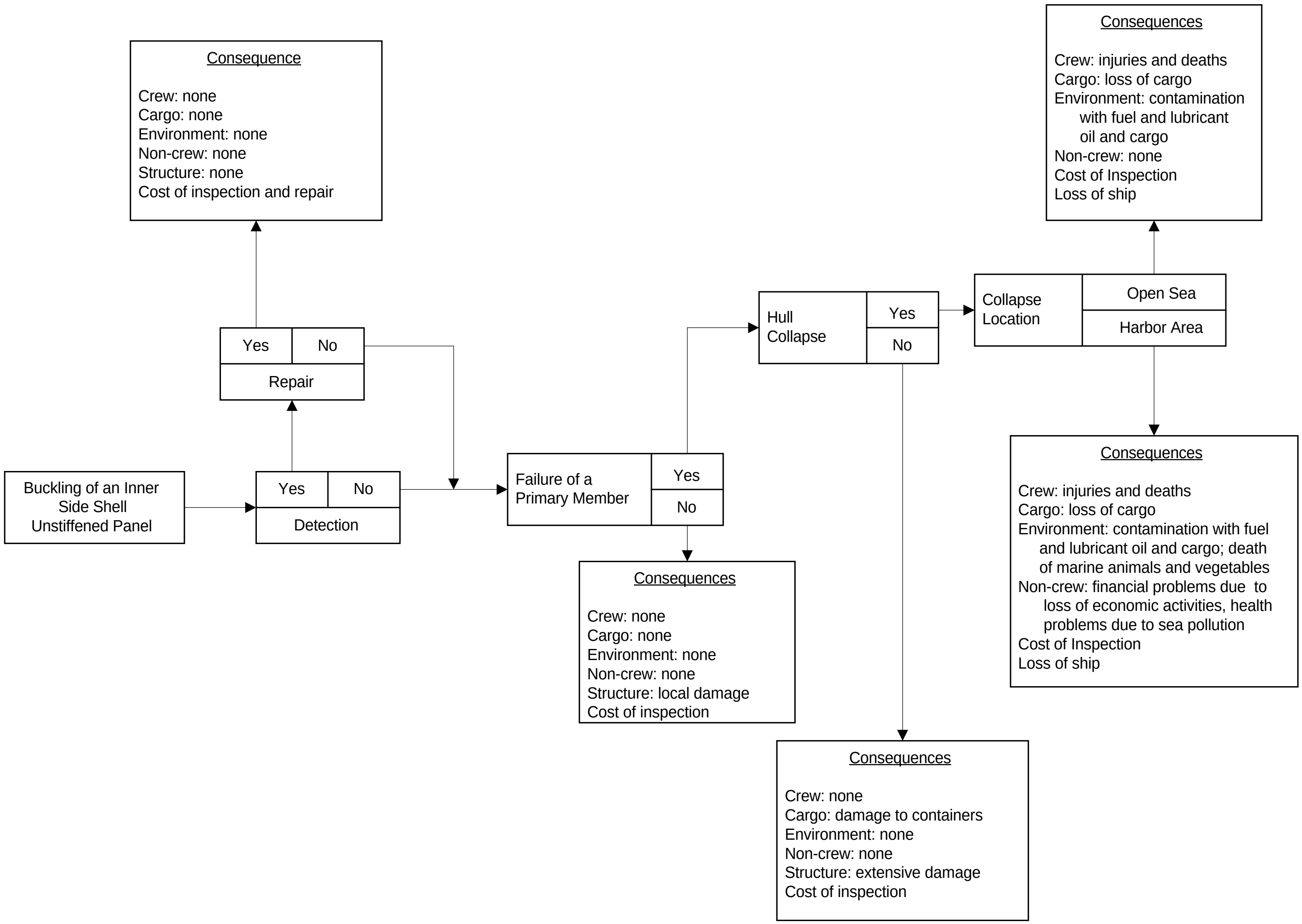


Figure C-17. Cause-Consequence Diagram for the Buckling of an Unstiffened Inner Side Shell Panel in the Cargo Space Structural System Failure

Table C-3. Structural Consequences Associated with the Buckling of a Inner Side Shell Unstiffened Panel (Page 01/01)

Failure Scenario		**Consequence**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
121	YYUUU	None	None	None	None	None	Cost of inspection and repair	1
122	YNYYO NUYYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
1223	YNYYH NUYYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
1224	YNYNU NUYNU	None	Damage to containers	None	None	Extensive damage	Cost of inspection	3
1225	YNNUU NUNUU	None	None	None	None	Local damage		2

C.3.2. Fatigue of an Outer Side Shell Longitudinal Stiffener, in the Cargo Space

Thirteen characters, with the following meaning and sequence compose the definition of the failure scenarios:

_ XXXXXXXXXXXX = the first character corresponds to the crack detection;
X _ XXXXXXXXXXX = the second character corresponds to the repair of the cracked stiffener;
XX _ XXXXXXXXXX = the third character corresponds to the crack arrest;
XXX _ XXXXXXXXX = the fourth character corresponds to the presence of a through thickness crack in the plate of the outer shell panel;
XXXX _ XXXXXXXX = the fifth character corresponds to the leakage of salt water inside the hull structure, flooding the space between outer and inner side shell;
XXXXX _ XXXXXXX = the sixth character corresponds to the corrosion os structural components due to the presence of salt water;
XXXXXX _ XXXXXX = the seventh character corresponds to damage to containers located above the upper deck, due to reduction of ship free board caused by the leakage of salt water;
XXXXXXX _ XXXXX = the eighth character corresponds to the dynamic stability of the ship that may be affected by the flooding of the space between the inner and outer shell;
XXXXXXXX _ XXXX = the ninth character corresponds to the ship capsize;
XXXXXXXXX _ XXX = the tenth character corresponds to the failure of a primary structural member;
XXXXXXXXXX _ XX = the eleventh character corresponds to the hull collapse or fracture;
XXXXXXXXXXX _ X = the twelfth character corresponds to the hull fracture; and
XXXXXXXXXXXX _ = the thirteenth character corresponds to the geographical location of the hull failure, where the letter “O” means open sea, and the letter “H” means area near the harbor.

A code composed of two numerical characters identifies each of failure scenarios. The meaning of these characters is:

_ X = the first digit is equal to 2, corresponding to the sub-section 3.2 of appendix A; and
X _ = the second digit corresponds to the number of failure scenario associated with the initiating event.

The cause-consequence diagram associated with this initiating event is presented in Figure C-18. The consequences of the possible failure scenarios associated with the fatigue of an outer side shell longitudinal stiffener, in the cargo space, are presented in Table C-4.

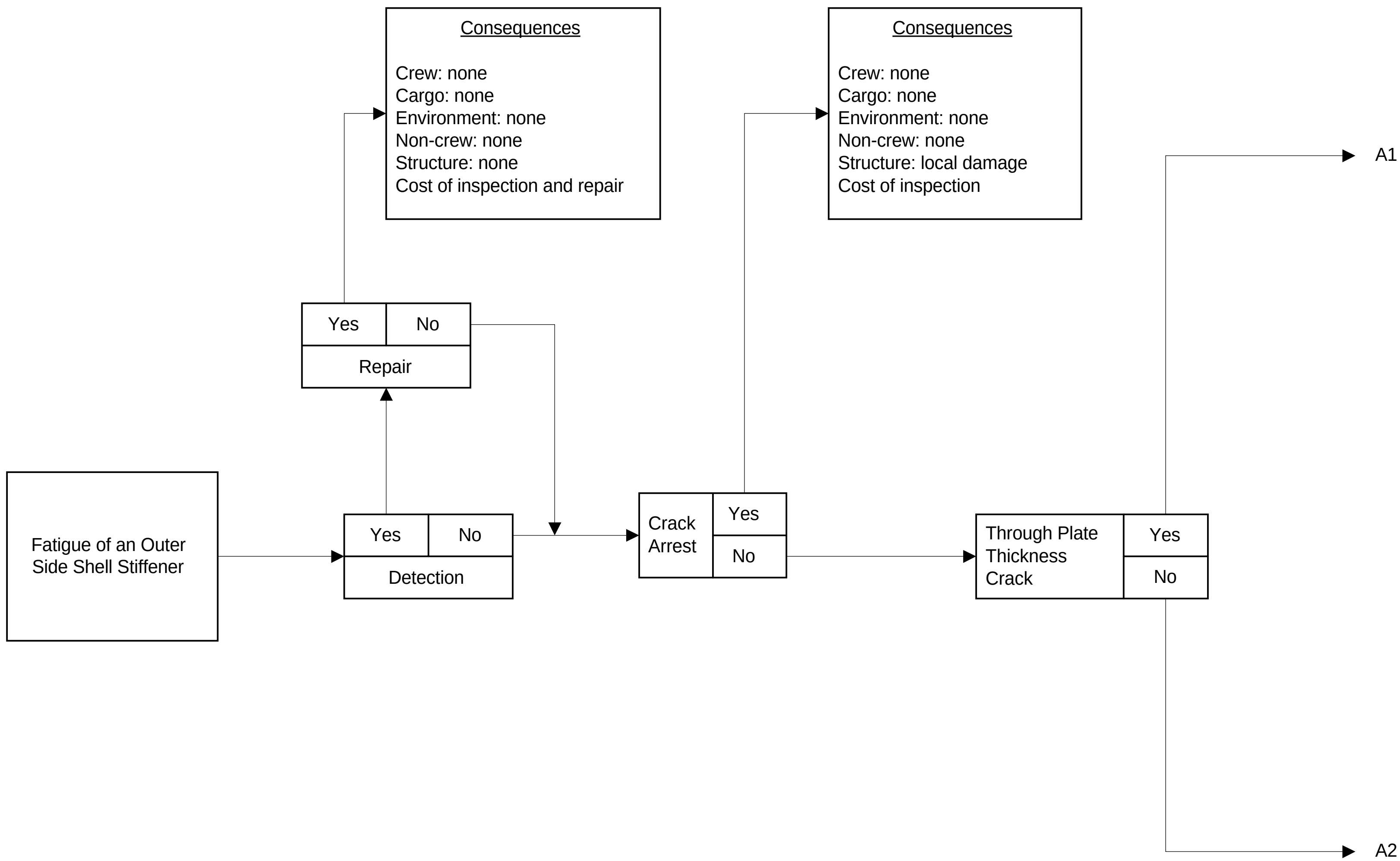


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 01/12)

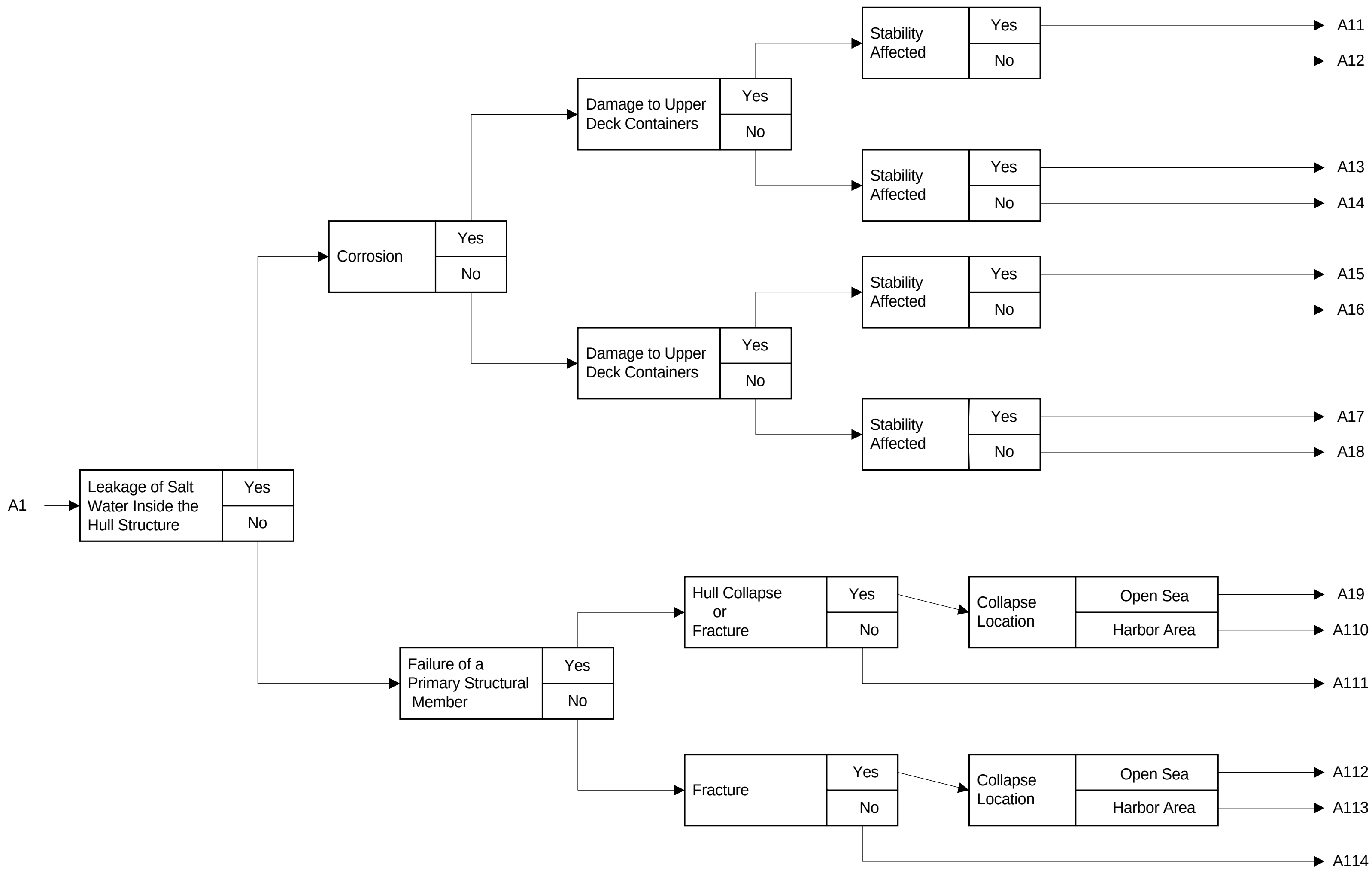


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 02/12)

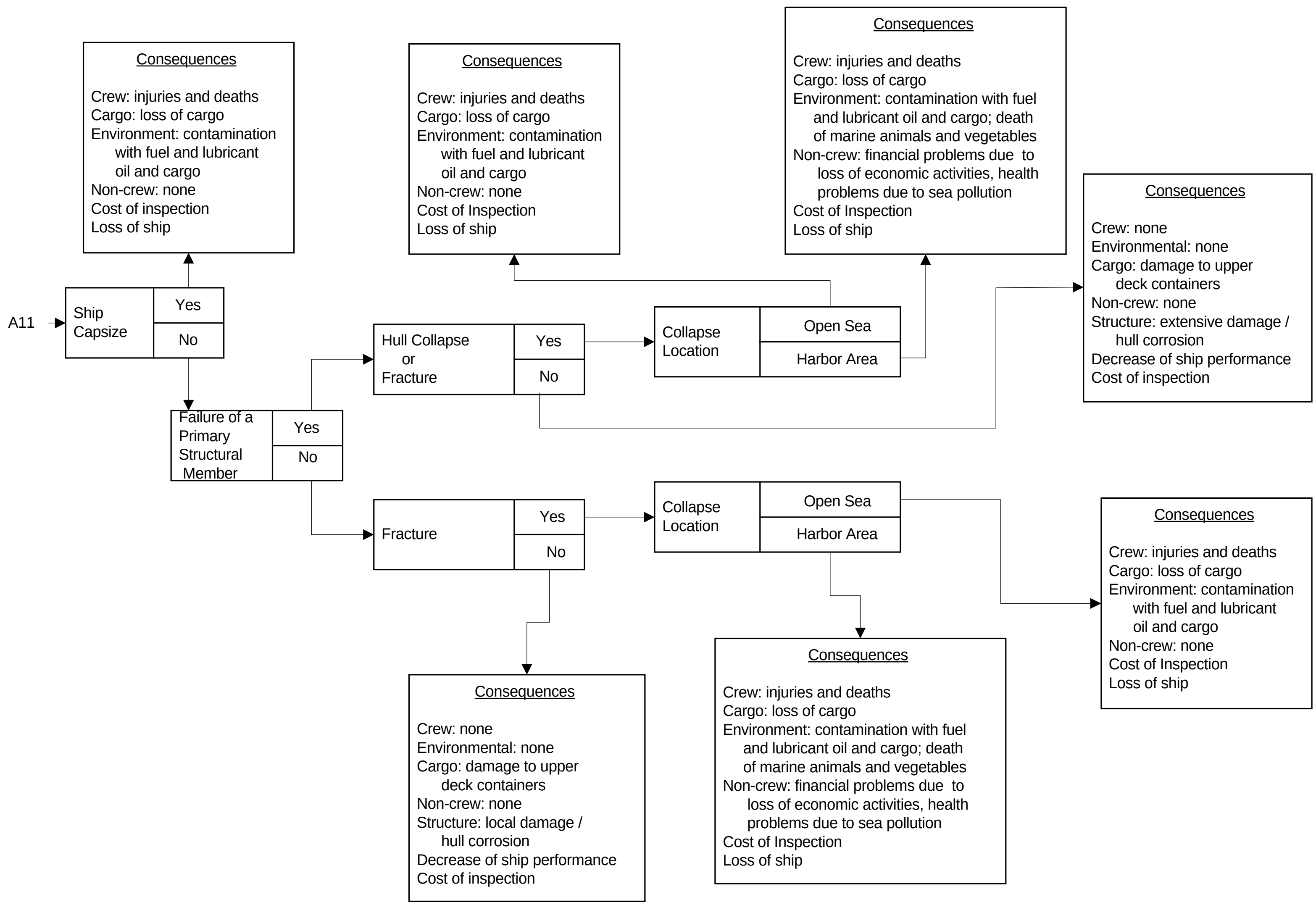


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 03/12)

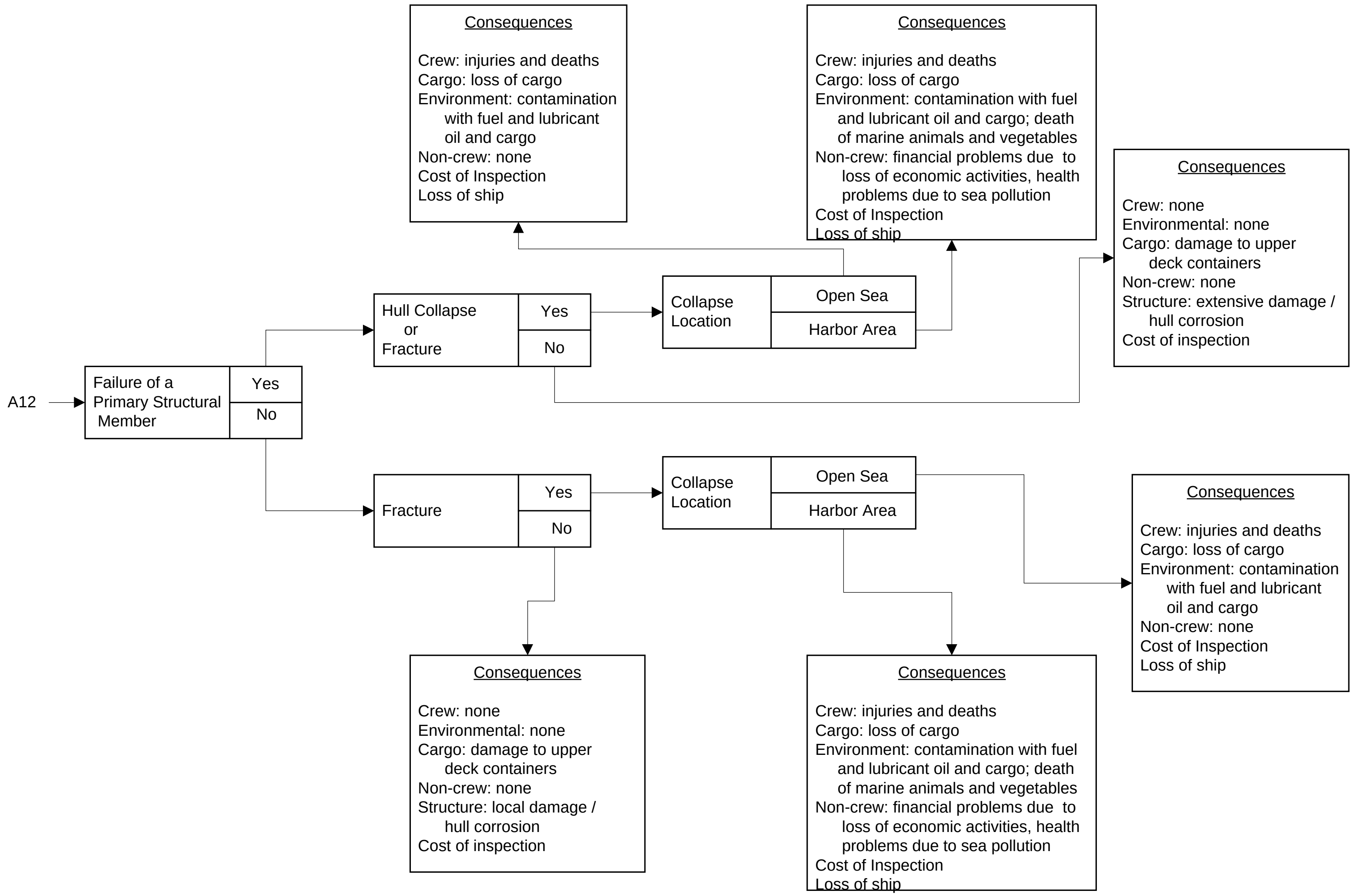


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 04/12)

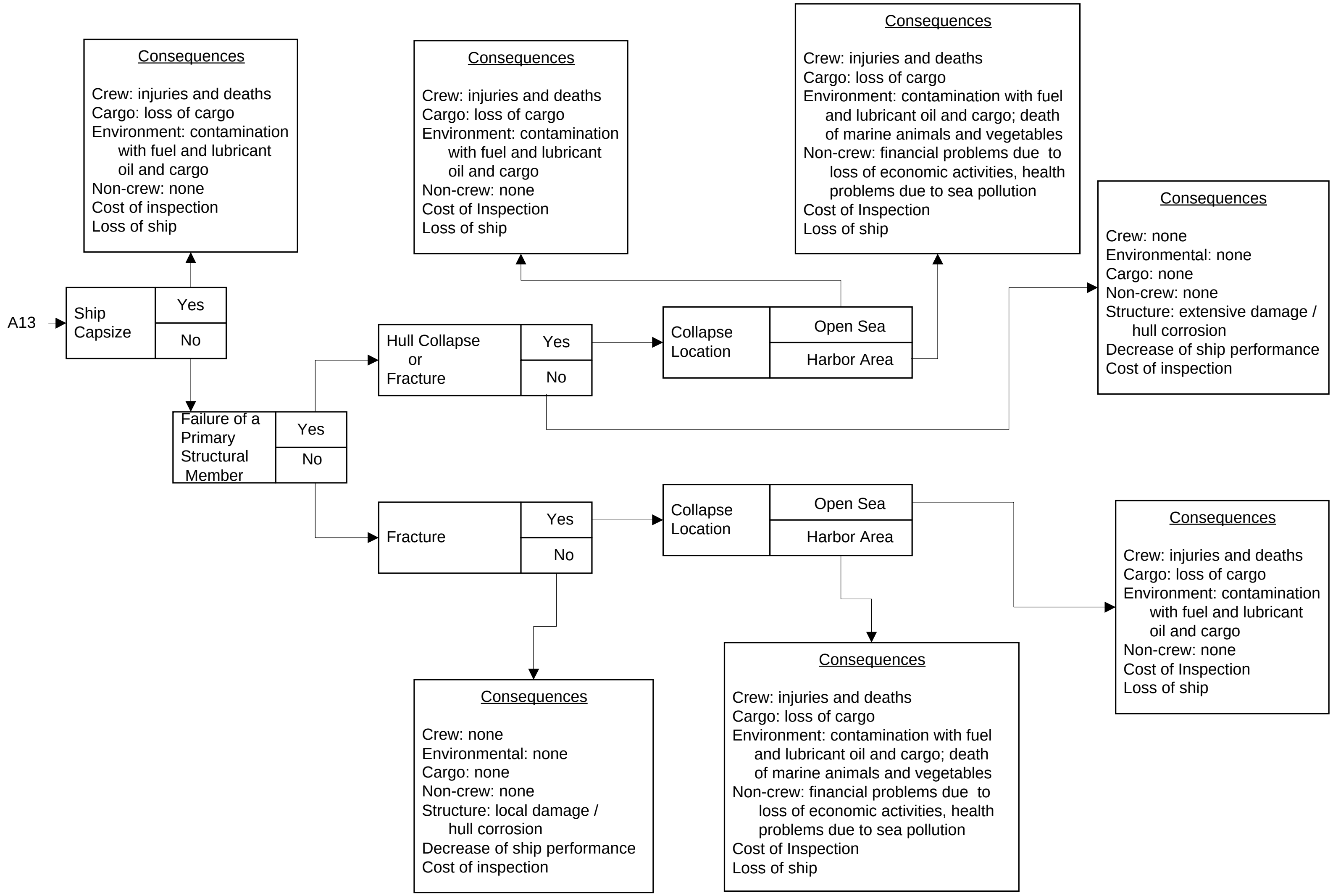


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 05/12)

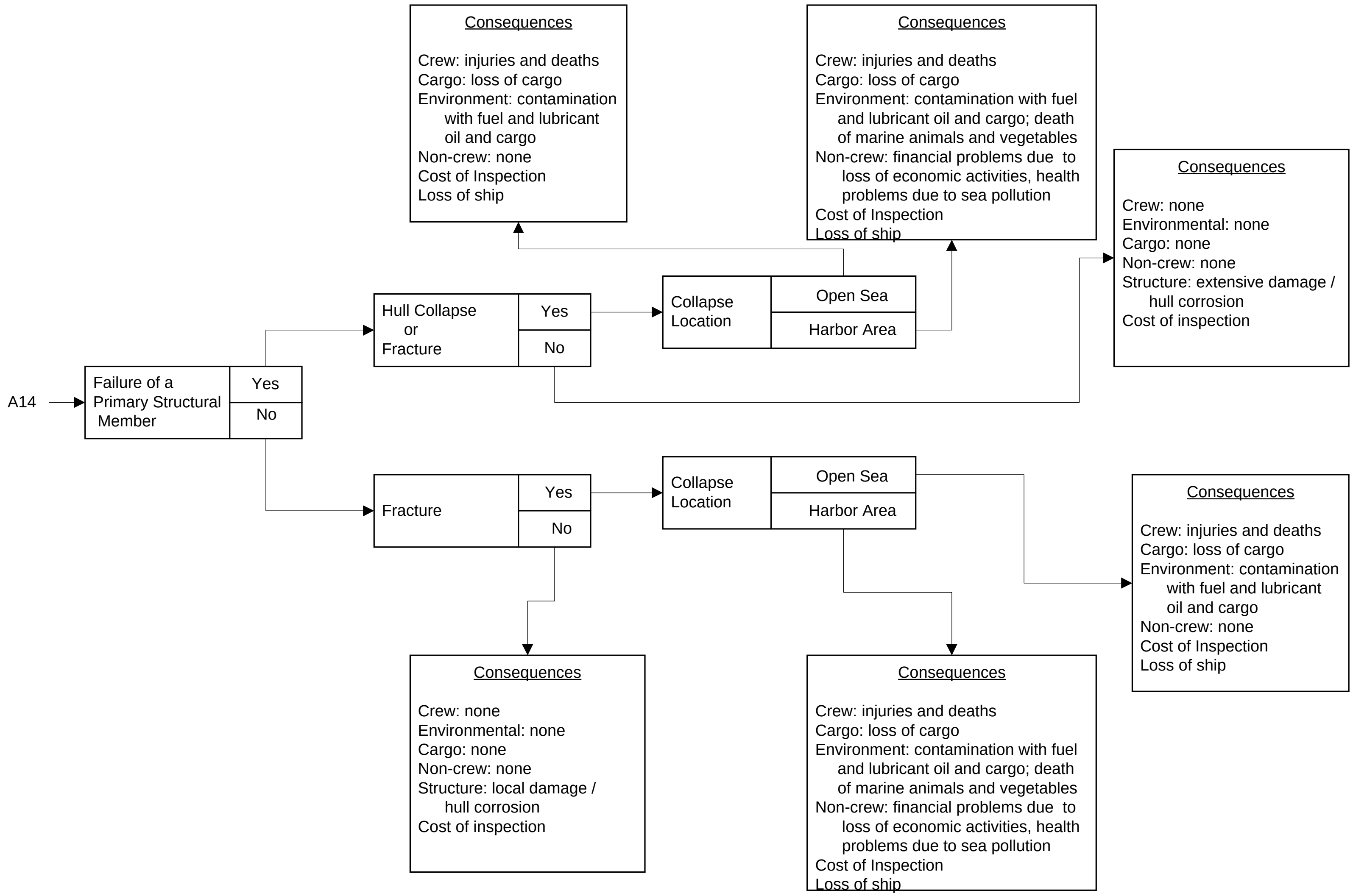


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 06/12)

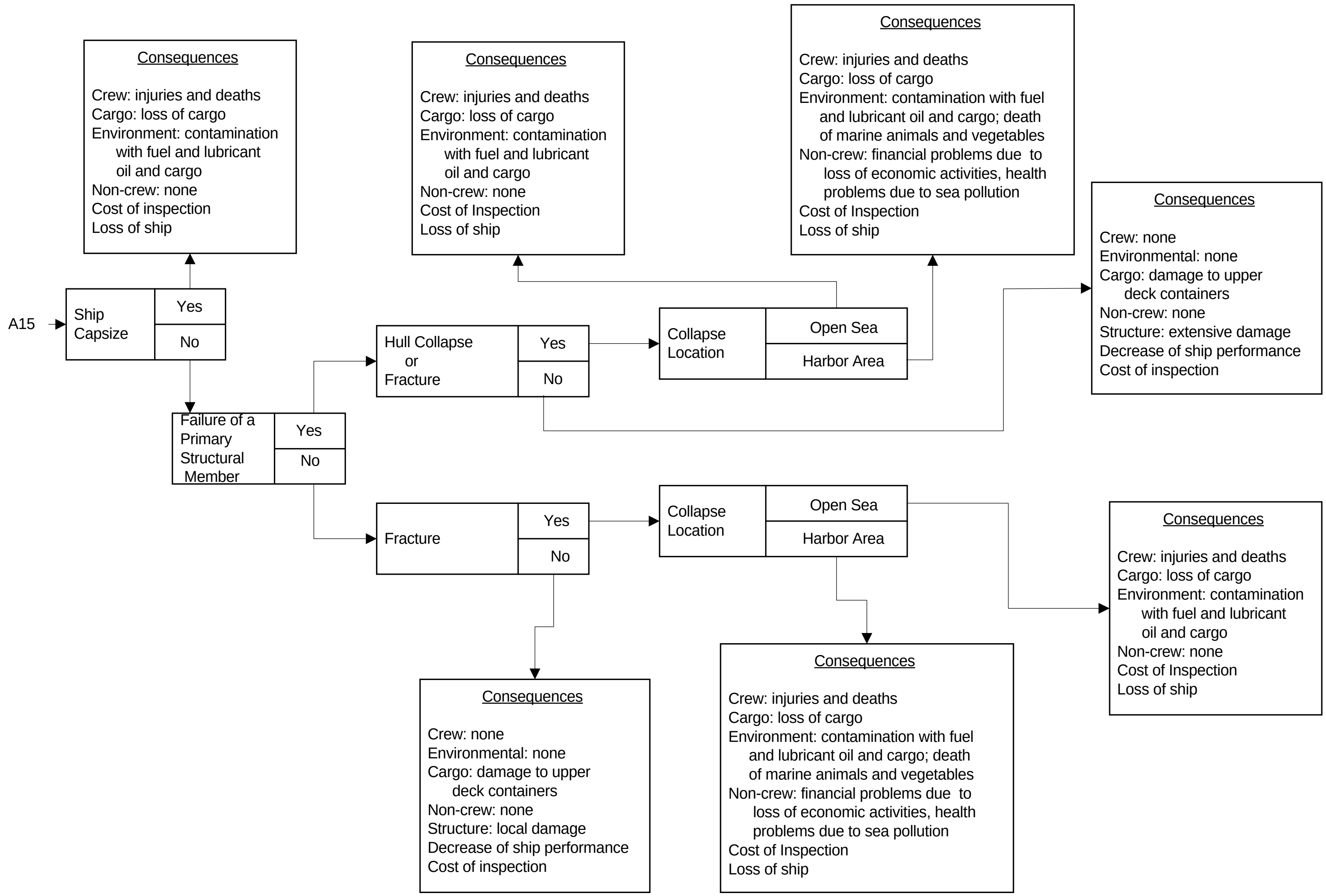


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 07/12)

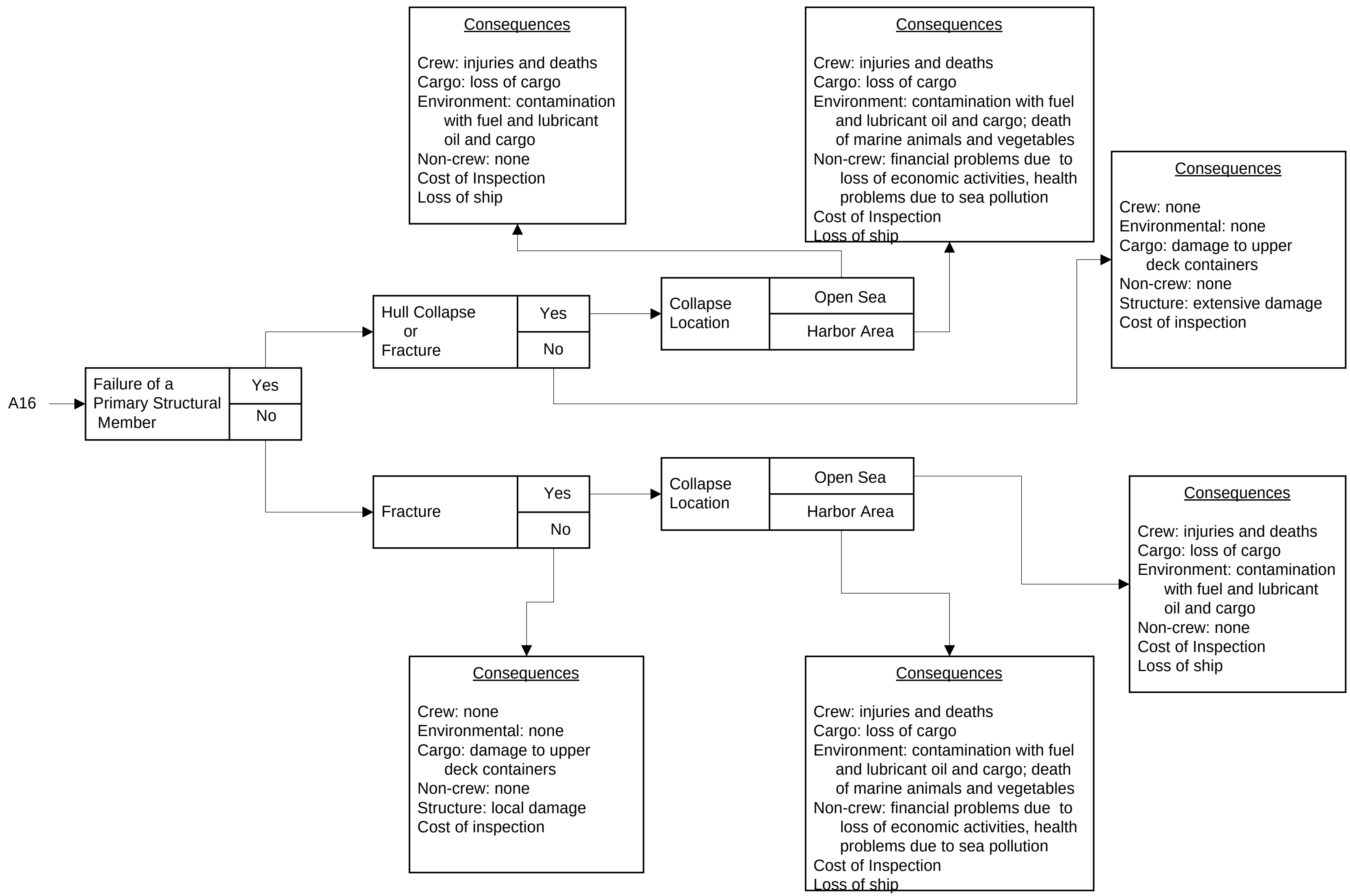


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 08/12)

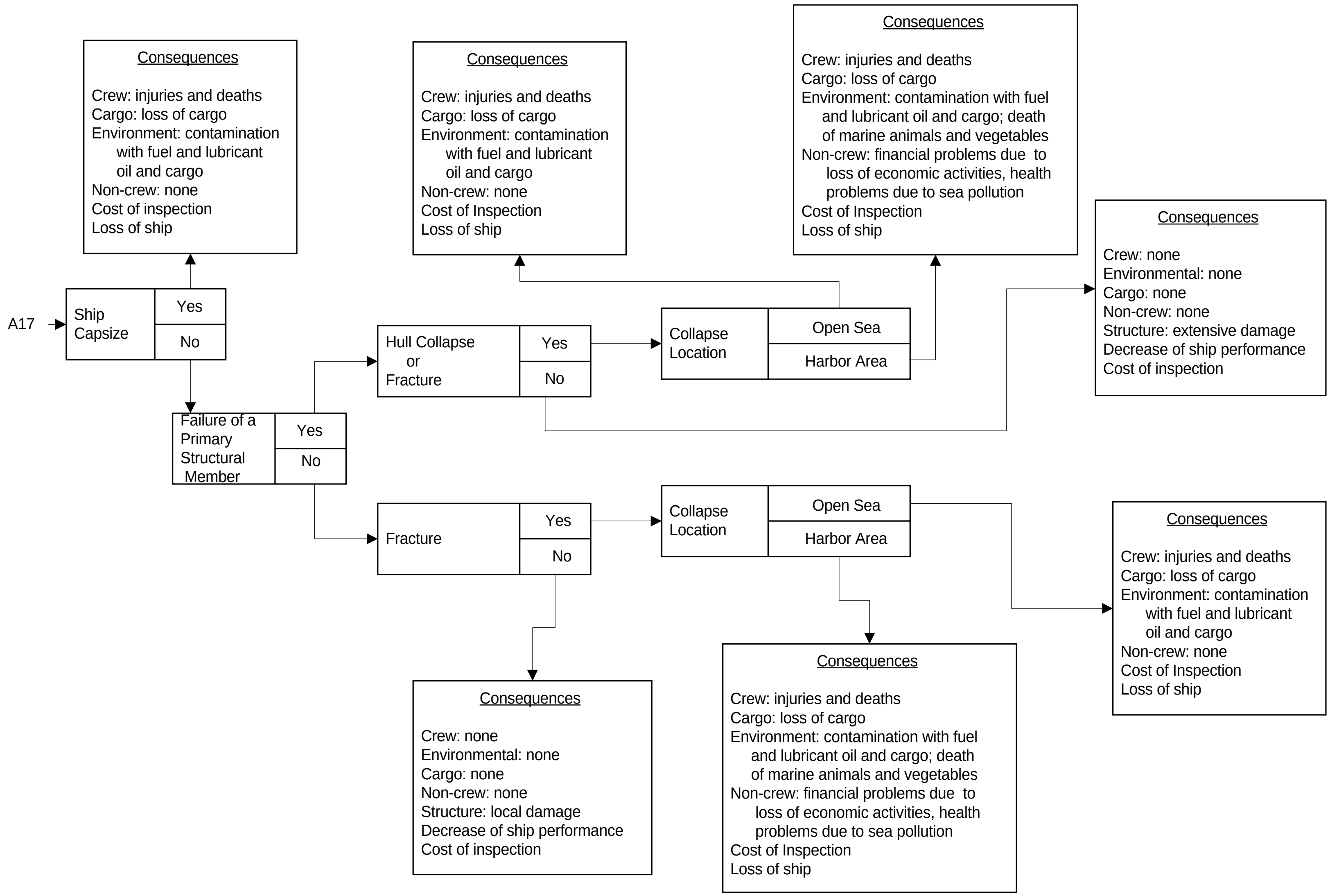


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 09/12)

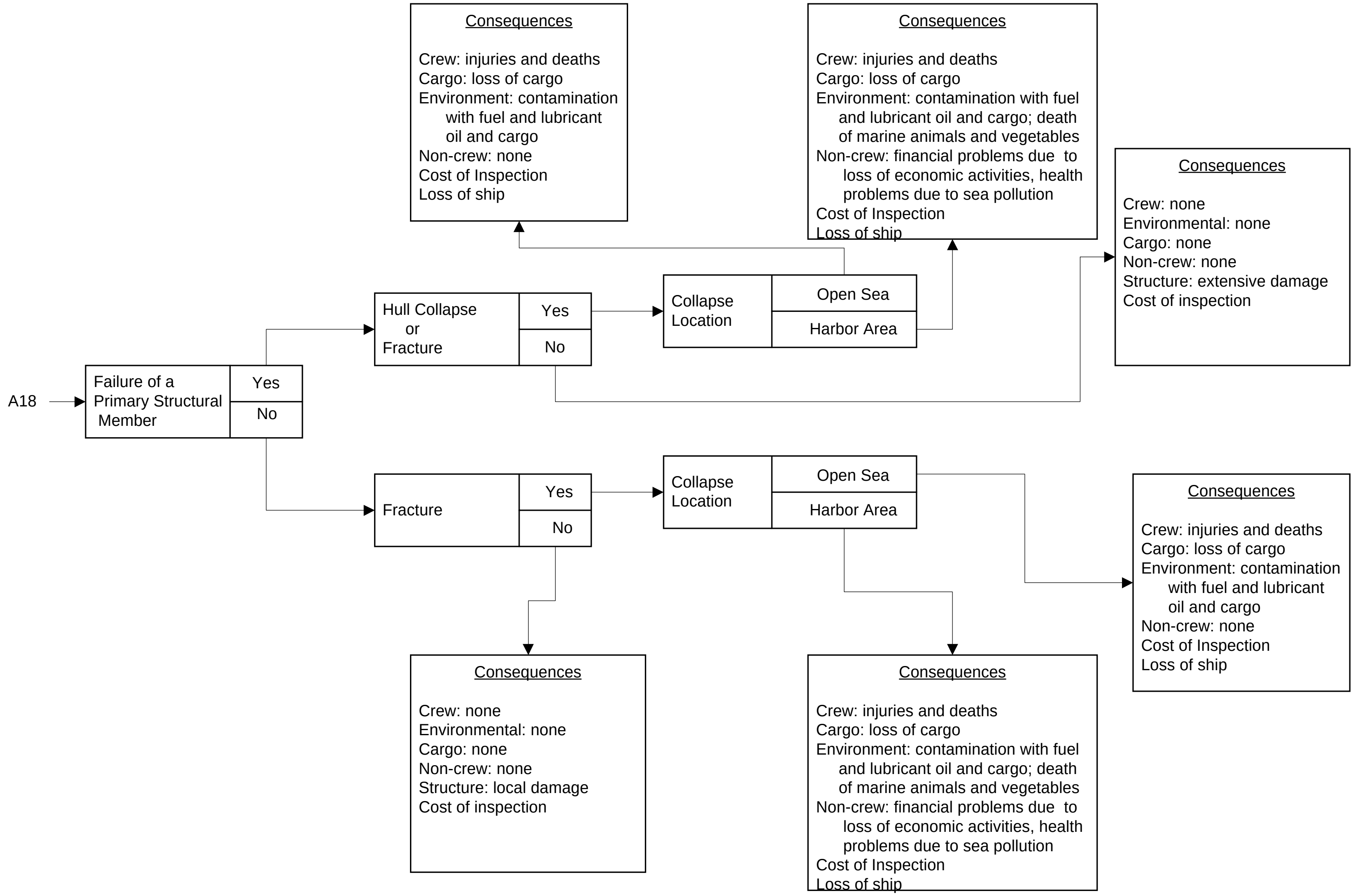


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 10/12)

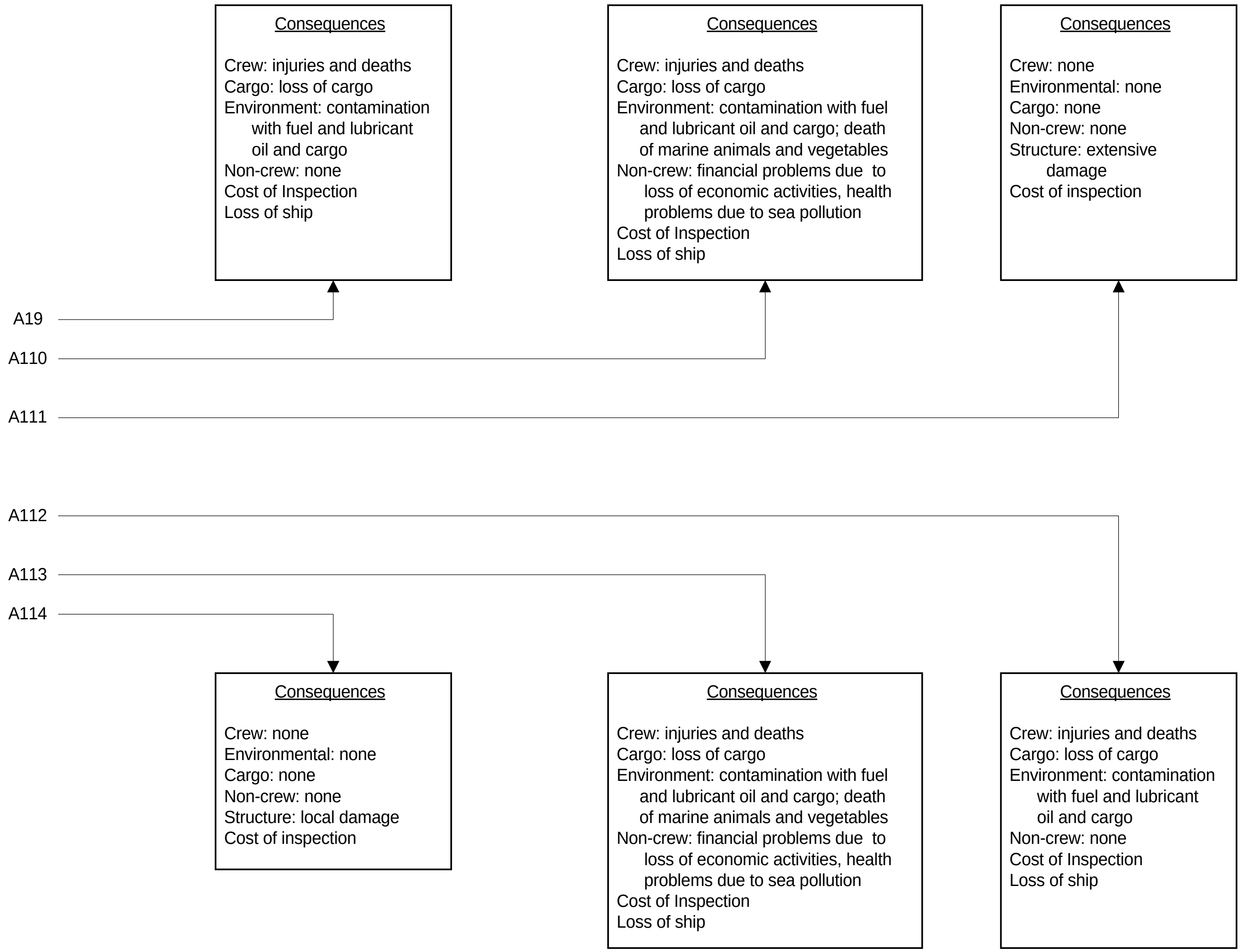


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 11/12)

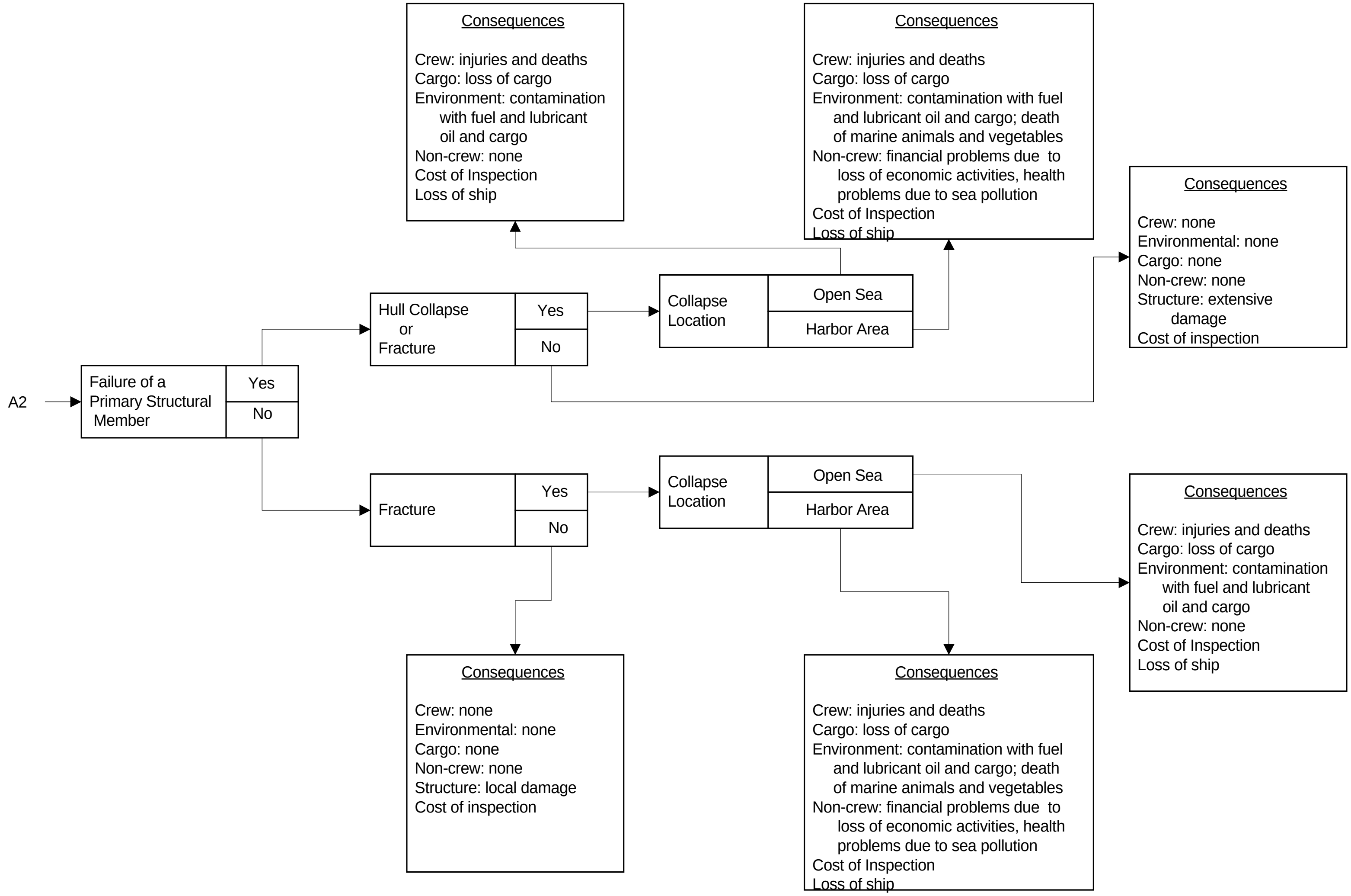


Figure C-18. Cause-Consequence Diagram for the Fatigue of an Outer Side Shell Panel in the Cargo Space (Page 12/12)

Table C-4. Consequences Associated with the Fatigue of an Outer Side Shell Longitudinal Stiffener (Page 01/09)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
21	YYUUUUUUUUUUU	None	None	None	None	None	Cost of inspection and repair	1
22	YNYUUUUUUUUUU NUYUUUUUUUUUU	None	None	None	None	Local damage	Cost of inspection	2
23	YNNYYYYYYUUUU NUNYYYYYYUUUU	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
24	YNNYYYYYNYYUO NUNYYYYYNYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
25	YNNYYYYYNYYUH NUNYYYYYNYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
26	YNNYYYYYNYNUU NUNYYYYYNYNUU	None	Damage to upper deck containers	None	None	Hull corrosion; Extensive damage	Cost of inspection	3
27	YNNYYYYYNNUYO NUNYYYYYNNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
28	YNNYYYYYNNUYH NUNYYYYYNNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5

Table C-4. Consequences Associated with the Fatigue of an Outer Side Shell Longitudinal Stiffener (Page 02/09)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
29	YNNYYYYYNNUNU NUNYYYYYNNUNU	None	Damage to upper deck containers	None	None	Hull corrosion; Local damage	Cost of inspection	2
210	YNNYYYYNUYYUO NUNYYYYNUYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
211	YNNYYYYNUYNUU NUNYYYYNUUNUU	None	Damage to upper deck containers	None	None	Hull corrosion; Extensive damage	Cost of inspection	3
212	YNNYYYYNUYYUH NUNYYYYNUYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
213	YNNYYYYNUNUYO NUNYYYYNUNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
214	YNNYYYYNUNUYH NUNYYYYNUNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
215	YNNYYYYNUNUNU NUNYYYYNUNUNU	None	Damage to upper deck containers	None	None	Hull corrosion Local damage	Cost of inspection	3
216	YNNYYYNYYUUUU NUNYYYNYYUUUU	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5

Table C-4. Consequences Associated with the Fatigue of an Outer Side Shell Longitudinal Stiffener (Page 03/09)

Failure Scenario		Consequences						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
217	YNNYYYNYNYYUO NUNYYYNYNYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
218	YNNYYYNYNYYUH NUNYYYNYNYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
219	YNNYYYNYNYNUU NUNYYYNYNYNUU	None	None	None	None	Hull corrosion; Extensive damage	Cost of inspection	3
220	YNNYYYNYNNUYO NUNYYYNYNNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
221	YNNYYYNYNNUYH NUNYYYNYNNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
222	YNNYYYNYNNUNU NUNYYYNYNNUNU	None	None	None	None	Hull corrosion; Local damage	Cost of inspection	2
223	YNNYYYNNUYYUO NUNYYYNNUYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship		5
224	YNNYYYNNUYNUU NUNYYYNNUUNUU	None	None	None	None	Hull corrosion; Extensive damage	Cost of inspection	3

Table C-4. Consequences Associated with the Fatigue of an Outer Side Shell Longitudinal Stiffener (Page 04/09)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
225	YNNYYYNNUYYUH NUNYYYNNUYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
226	YNNYYYNNUNUYO NUNYYYNNUNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
227	YNNYYYNNUNUYH NUNYYYNNUNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
228	YNNYYYNNUNUNU NUNYYYNNUNUNU	None	None	None	None	Hull corrosion Local damage	Cost of inspection	2
229	YNNYYNYYYUUUU NUNYYNYYYUUUU	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
230	YNNYYNYYNYYUO NUNYYNYYNYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
231	YNNYYNYYNYYUH NUNYYNYYNYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5

Table C-4. Consequences Associated with the Fatigue of an Outer Side Shell Longitudinal Stiffener (Page 05/09)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
232	YNNYYNYYNYNUU NUNYYNYYNYNUU	None	Damage to upper deck containers	None	None	Extensive damage	Cost of inspection	3
233	YNNYYNYYNNUYO NUNYYNYYNNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
234	YNNYYNYYNNUYH NUNYYNYYNNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
235	YNNYYNYYNNUNU NUNYYNYYNNUNU	None	Damage to upper deck containers	None	None	Local damage	Cost of inspection	2
236	YNNYYNYNUYYUO NUNYYNYNUYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
237	YNNYYNYNUYNUU NUNYYNYNUUNUU	None	Damage to upper deck containers	None	None	Extensive damage	Cost of inspection	3
238	YNNYYNYNUYYUH NUNYYNYNUYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5

Table C-4. Consequences Associated with the Fatigue of an Outer Side Shell Longitudinal Stiffener (Page 06/09)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
239	YNNYYNYNUNUYO NUNYYNYNUNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
240	YNNYYNYNUNUYH NUNYYNYNUNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
241	YNNYYNYNUNUNU NUNYYNYNUNUNU	None	Damage to upper deck containers	None	None	Local damage	Cost of inspection	2
242	YNNYYNNYYUUUU NUNYYNNYYUUUU	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
243	YNNYYNNYNYYUO NUNYYNNYNYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
244	YNNYYNNYNYYUH NUNYYNNYNYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
245	YNNYYNNYNYNUU NUNYYNNYNYNUU	None	None	None	None	Extensive damage	Cost of inspection	3
246	YNNYYNNYNNUYO NUNYYNNYNNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5

Table C-4. Consequences Associated with the Fatigue of a Outer Side Shell Longitudinal Stiffener (Page 07/09)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
247	YNNYYNNYNNUYH NUNYYNNYNNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
248	YNNYYNNYNNUNU NUNYYNNYNNUNU	None	None	None	None	Local damage	Cost of inspection	2
249	YNNYYNNNUYYUO NUNYYNNNUYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
250	YNNYYNNNUYNUU NUNYYNNNUUNUU	None	None	None	None	Extensive damage	Cost of inspection	3
251	YNNYYNNNUYYUH NUNYYNNNUYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
252	YNNYYNNNUNUYO NUNYYNNNUNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
253	YNNYYNNNUNUYH NUNYYNNNUNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
254	YNNYYNNNUNUNU NUNYYNNNUNUNU	None	None	None	None	Local damage	Cost of inspection	2

Table C-4. Consequences Associated with the Fatigue of a Outer Side Shell Longitudinal Stiffener (Page 08/09)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
255	YNNYNUUUUYYUO NUNYNUUUUYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of Inspection	5
256	YNNYNUUUUYYUH NUNYNUUUUYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
257	YNNYNUUUUYNUU NUNYNUUUUYNUU	None	None	None	None	Extensive damage	Cost of inspection	3
258	YNNYNUUUUNUYO NUNYNUUUUNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
259	YNNYNUUUUNUNU NUNYNUUUUNUNU	None	None	None	None	Local damage	Cost of inspection	2
260	YNNYNUUUUNUYH NUNYNUUUUNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
261	YNNNUUUUUYYUO NUNNUUUUUYYUO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
262	YNNNUUUUUYYUH NUNNUUUUUYYUH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5

Table C-4. Consequences Associated with the Fatigue of a Outer Side Shell Longitudinal Stiffener (Page 09/09)

Failure Scenario		**Consequences**						
Code	Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
263	YNNNUUUUUYNUU NUNNUUUUUYNUU	None	None	None	None	Extensive damage	Cost of inspection	3
264	YNNNUUUUUNUYO NUNNUUUUUNUYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of Inspection	5
265	YNNNUUUUUNUYH NUNNUUUUUNUYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
266	YNNNUUUUUNUNU NUNNUUUUUNUNU	None	None	None	None	Local damage	Cost of inspection	2

C.3.3. Buckling of an Unstiffened Panel, in the Main Deck of the Machinery Room

The failure scenarios developed based on this initiating event are classified in two groups: (1) failure scenarios involving the failure of ship machinery system, and (2) failure scenarios involving the ship structural system failure.

C.3.3.1. Failure of the Ship Machinery System

Fifteen characters, with the following meaning and sequence compose the definition of the failure scenarios:

_ XXXXXXXXXXXXXX = the first character corresponds to the occurrence of vibration of the machinery room structure;
X _ XXXXXXXXXXXXX = the second character corresponds to the detection of the buckling;
XX _ XXXXXXXXXXXX = the third character corresponds to the repair of the buckled panel;
XXX _ XXXXXXXXXXX = the forth character corresponds to the vibration of the fuel oil line;
XXXX _ XXXXXXXXXX = the fifth character corresponds to the presence of fatigue crack in the fuel oil line;
XXXXX _ XXXXXXXXX = the sixth character corresponds to the occurrence of leakage of fuel oil in the machinery room;
XXXXXX _ XXXXXXXX = the seventh character corresponds to the vibration of the lubricant oil line;
XXXXXXX _ XXXXXXX = the eighth character corresponds to the presence of a fatigue crack in the lubricant oil line;
XXXXXXXX _ XXXXXX = the ninth character corresponds to the occurrence of leakage of lubricant oil in the machinery room;
XXXXXXXXX _ XXXXX = the tenth character corresponds to the vibration of the coolant water line;
XXXXXXXXXX _ XXXX = the eleventh character corresponds to the presence of a fatigue crack in the coolant water line;
XXXXXXXXXXX _ XXX = the twelfth character corresponds to the leakage of coolant water in the machinery room;
XXXXXXXXXXXX _ XX = the thirteenth character corresponds to the occurrence of fire in the machine room;
XXXXXXXXXXXXX _ X = the fourteenth character corresponds to the rapidly extinguish of fire; and
XXXXXXXXXXXXXX _ = the fifteenth character corresponds to the loss of cooling capacity.

A code composed of three numerical characters identifies each of failure scenarios. The meaning of these characters is:

_ XX = the first digit is equal to 3, corresponding to the sub-section 3.3 of appendix A;
X _ X = the second digit is equal to 1, corresponding to the sub-section 3.3.1 of appendix A; and
XX _ = the third digit corresponds to the number of failure scenario associated with the initiating event.

The cause-consequence diagram associated with this initiating event is presented in Figure C-19. The consequences of the possible failure scenarios associated with the buckling of an unstiffened panel in main deck of the machinery room are presented in Table C-5. As the consequences of these failure scenarios do not affect the cargo, the environment or the non-crew, these items are not presented in Table C-5.

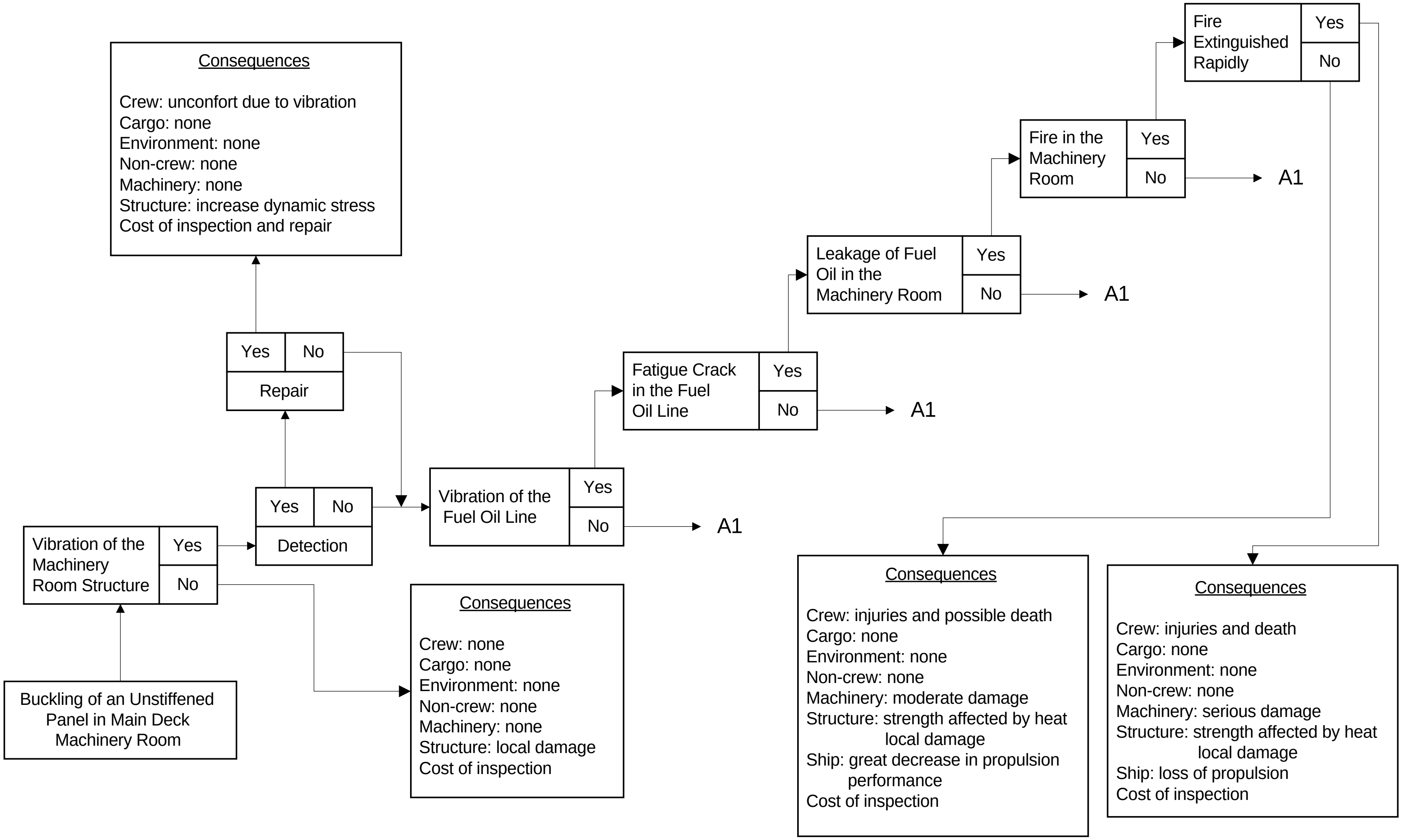


Figure C-19. Cause Consequence Diagram for the Buckling of an Unstiffened Panel in the Main Deck of Machinery Room Machinery System Failure (Page 01/02)

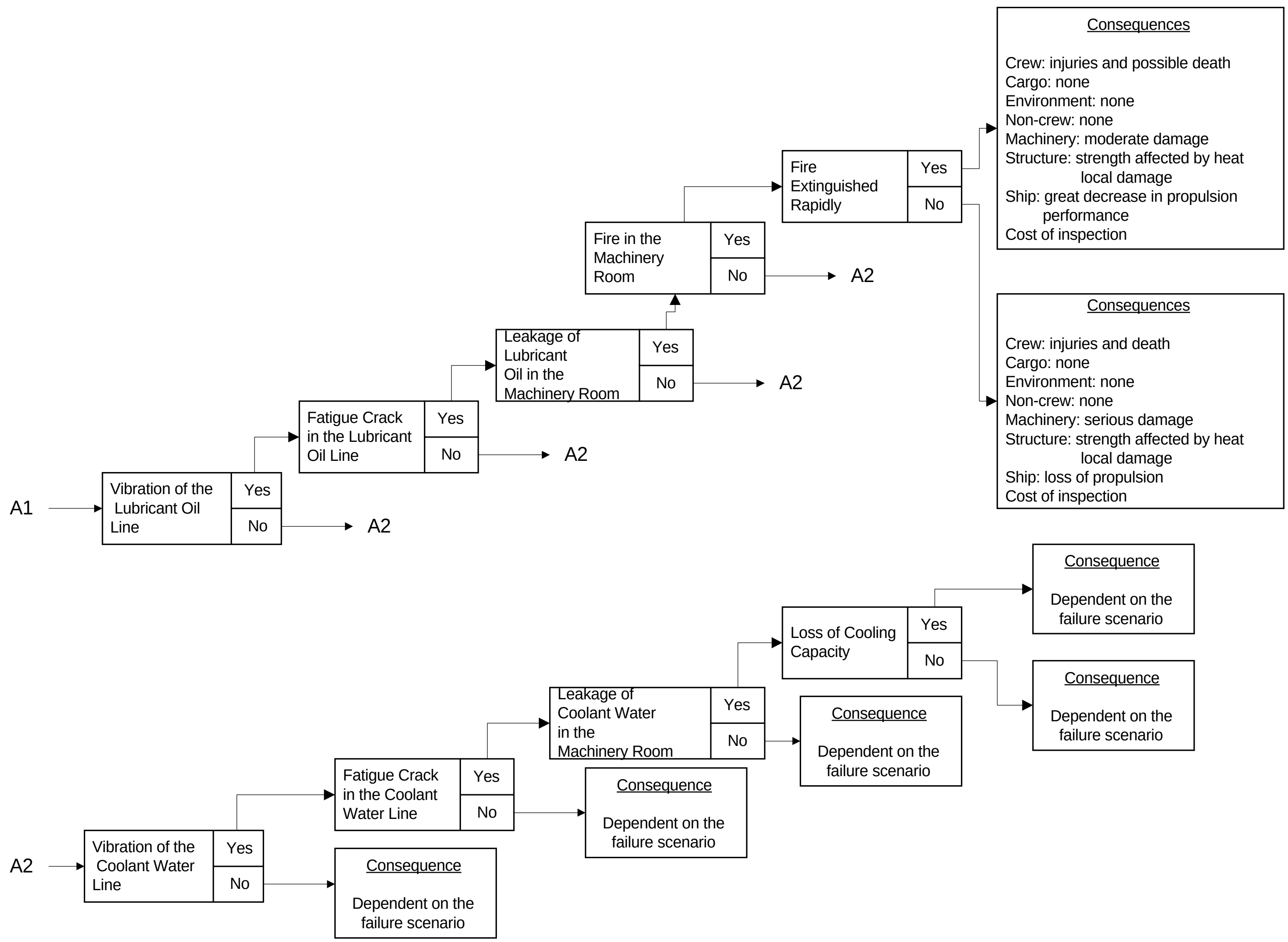


Figure C-19. Cause-Consequence Diagram for the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery System Failure (Page 02/02)

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 01/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
311	YYYUUUUUUUUUUUU	Discomfort due to vibration	None	Increase the dynamic stress	None	Cost of inspection and repair	2
312	YYNYYYUUUUUUYYU YNUYYYUUUUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
313	YYNYYYUUUUUUYNU YNUYYYUUUUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
314	YYNYYYYYYUUUYYU YNUYYYYYYUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
315	YYNYYYYYYUUUYNU YNUYYYYYYUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
316	YYNYYYYYYYYYNUY YNUYYYYYYYYYNUY	Discomfort due to vibration	Leakage of fuel and lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
317	YYNYYYYYYYYYNUN YNUYYYYYYYYYNUN	Discomfort due to vibration	Leakage of fuel and lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
318	YYNYYYYYYYYNNUU YNUYYYYYYYYNNUU	Discomfort due to vibration	Leakage of fuel oil and lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
319	YYNYYYYYYYNUNUU YNUYYYYYYYNUNUU	Discomfort due to vibration	Leakage of fuel oil and lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3110	YYNYYYYYYNUUNUU YNUYYYYYYNUUNUU	Discomfort due to vibration	Leakage of fuel oil and lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3111	YYNYYYYYNYYYNUY YNUYYYYYNYYYNUY	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 02/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
3112	YYNYYYYYNYYYNUN YNUYYYYYNYYYNUN	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
3113	YYNYYYYYNYYNNUU YNUYYYYYNYYNNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
3114	YYNYYYYYNYNUNUU YNUYYYYYNYNUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
3115	YYNYYYYYNNUUNUU YNUYYYYYNNUUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
3116	YYNYYYYNUYYYNUY YNUYYYYNUYYYNUY	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3117	YYNYYYYNUYYYNUN YNUYYYYNUYYYNUN	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
3118	YYNYYYYNUYYNNUU YNUYYYYNUYYNNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
3119	YYNYYYYNUYNUNUU YNUYYYYNUYNUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
3120	YYNYYYYNUNUUNUU YNUYYYYNUNUUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
3121	YYNYYYNUUYYYNUY YNUYYYNUUYYYNUY	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 03/09)

Failure Scenarios		Consequences					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
3122	YYNYYYNUUYYYNUN YNUYYYNUUYYYNUN	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3123	YYNYYYNUUYYNNUU YNUYYYNUUYYNNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3124	YYNYYYNUUYNUNUU YNUYYYNUUYNUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3125	YYNYYYNUUNUUNUU YNUYYYNUUNUUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3126	YYNYYNYYYUUUYYU YNUYYNYYYUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
3127	YYNYYNYYYUUUYNU YNUYYNYYYUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
3128	YYNYYNYYYYYYNUY YNUYYNYYYYYYNUY	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3129	YYNYYNYYYYYYNUN YNUYYNYYYYYYNUN	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3130	YYNYYNYYYYYNNUU YNUYYNYYYYYNNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3131	YYNYYNYYYYNUNUU YNUYYNYYYYNUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 04/09)

Failure Scenarios		Consequences					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
3132	YYNYYNYYYNUUNUU YNUYYNYYYNUUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3133	YYNYYNYYNYYYUUY YNUYYNYYNYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3134	YYNYYNYYNYYYUUN YNUYYNYYNYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3134	YYNYYNYYNYYNUUU YNUYYNYYNYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3135	YYNYYNYNUYYYUUY YNUYYNYNUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3136	YYNYYNYNUYYYUUN YNUYYNYNUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3137	YYNYYNYNUYYNUUU YNUYYNYNUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3138	YYNYYNYNUYNUUUU YNUYYNYNUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3139	YYNYYNYNUNUUUUU YNUYYNYNUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3140	YYNYYNNUUYYYUUY YNUYYNNUUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 05/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
3141	YYNYYNNUUYYYUUN YNUYYNNUUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3142	YYNYYNNUUYYNUUU YNUYYNNUUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3143	YYNYYNNUUYNUUUU YNUYYNNUUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3144	YYNYYNNUUNUUUUU YNUYYNNUUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3145	YYNYNUYYYUUUYYU YNUYNUYYYUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
3146	YYNYNUYYYUUUYNU YNUYNUYYYUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
3147	YYNYNUYYYYYYNUY YNUYNUYYYYYYNUY	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3148	YYNYNUYYYYYYNUN YNUYNUYYYYYYNUN	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3149	YYNYNUYYYYYNNUU YNUYNUYYYYYNNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3150	YYNYNUYYYYNUNUU YNUYNUYYYYNUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 06/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
3151	YYNYNUYYYNUUNUU YNUYNUYYYNUUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3152	YYNYNUYYNYYYUUY YNUYNUYYNYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3153	YYNYNUYYNYYYUUN YNUYNUYYNYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3154	YYNYNUYYNYYNUUU YNUYNUYYNYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3155	YYNYNUYYNYNUUUU YNUYNUYYNYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3156	YYNYNUYYNNUUUUU YNUYNUYYNNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3157	YYNYNUYNUYYYUUY YNUYNUYNUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3158	YYNYNUYNUYYYUUN YNUYNUYNUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3159	YYNYNUYNUYYNUUU YNUYNUYNUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3160	YYNYNUYNUYNUUUU YNUYNUYNUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 07/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
3161	YYNYNUYNUNUUUUU YNUYNUYNUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3162	YYNYNUNUUYYYUUY YNUYNUNUUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3163	YYNYNUNUUYYYUUN YNUYNUNUUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3164	YYNYNUNUUYYNUUU YNUYNUNUUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3165	YYNYNUNUUYNUUUU YNUYNUNUUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3166	YYNYNUNUUNUUUUU YNUYNUNUUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3167	YYNNUUYYYUUUYYU YNUNUUYYYUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
3168	YYNNUUYYYUUUYNU YNUNUUYYYUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
3169	YYNNUUYYYYYYNUY YNUNUUYYYYYYNUY	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3170	YYNNUUYYYYYYNUN YNUNUUYYYYYYNUN	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 08/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
3171	YYNNUUYYYYYNNUU YNUNUUYYYYYNNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3172	YYNNUUYYYYNUNUU YNUNUUYYYYNUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3173	YYNNUUYYYNUUNUU YNUNUUYYYNUUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3174	YYNNUUYYNYYYUUY YNUNUUYYNYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3175	YYNNUUYYNYYYUUN YNUNUUYYNYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3176	YYNNUUYYNYYNUUU YNUNUUYYNYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3177	YYNNUUYYNYNUUUU YNUNUUYYNYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3178	YYNNUUYYNNUUUUU YNUNUUYYNNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3179	YYNNUUYNUYYYUUY YNUNUUYNUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3180	YYNNUUYNUYYYUUN YNUNUUYNUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3

Table C-5. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Machinery Failure (Page 09/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
3181	YYNNUUYNUYYNUUU YNUNUUYNUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3182	YYNNUUYNUYNUUUU YNUNUUYNUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3183	YYNNUUYNUNUUUUU YNUNUUYNUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3184	YYNNUUNUUYYYUUY YNUNUUNUUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
3185	YYNNUUNUUYYYUUN YNUNUUNUUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
3186	YYNNUUNUUYYNUUU YNUNUUNUUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3187	YYNNUUNUUYNUUUU YNUNUUNUUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3188	YYNNUUNUUNUUUUU YNUNUUNUUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
3189	NYNUUUUUUUUUUUU NNUUUUUUUUUUUUU	None	None	None	None	Cost of inspection	2

C.3.3.2. Failure of the Ship Structural System

Five characters, with the following meaning and sequence compose the definition of the failure scenarios:

_ XXXX = the first character corresponds to the ocurrence of vibration of the machinery room structure;
X _ XXX = the second character corresponds to the occurrence of misalignment of the propulsion shaft bearings;
XX _ XX = the third character corresponds to the detection of the buckling;
XXX _ X = the fourth character corresponds to the repair of the buckled panel; and
XXXX _ = the fifth character corresponds to the failure of a primary structural member.

A code composed of three numerical characters identifies each of failure scenarios. The meaning of these characters is:

_ XX = the first digit is equal to 3, corresponding to the sub-section 3.3 of appendix A;
X _ X = the second digit is equal to 2, corresponding to the sub-section 3.3.2 of appendix A; and
XX _ = the third digit corresponds to the number of failure scenario associated with the initiating event.

The cause-consequence diagram associated with this initiating event is presented in Figure C-20. The consequences of the possible failure scenarios associated with the buckling of an unstiffened panel in main deck of the machinery room are presented in Table C-6. As the consequences of these failure scenarios do not affect the cargo, the environment or the non-crew, these items are not presented in Table C-6.

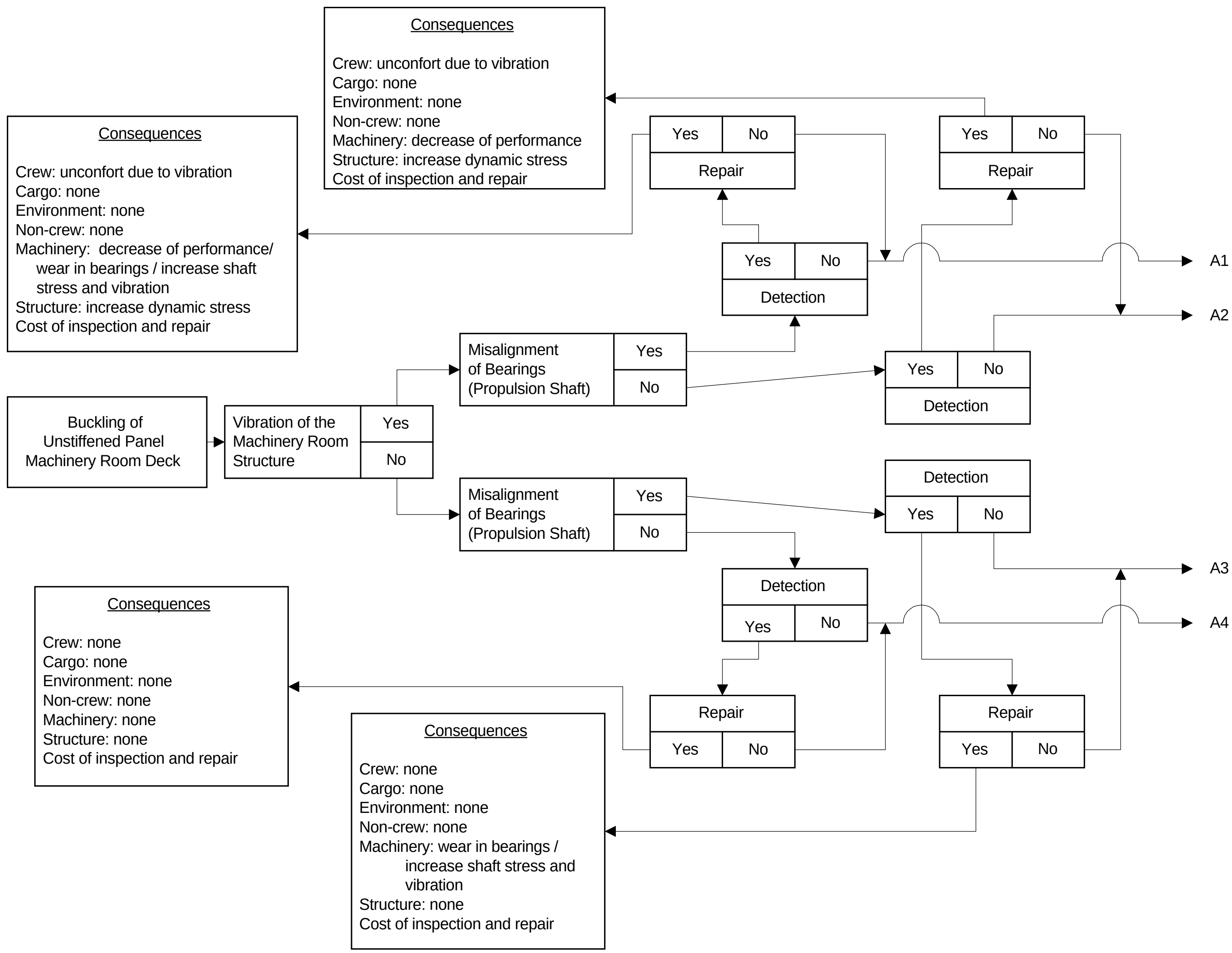


Figure C-20. Cause Consequence Diagram for the Buckling of an Unstiffened Panel in the Main Deck of Machinery Room Structural System Failure (Page 01/02)

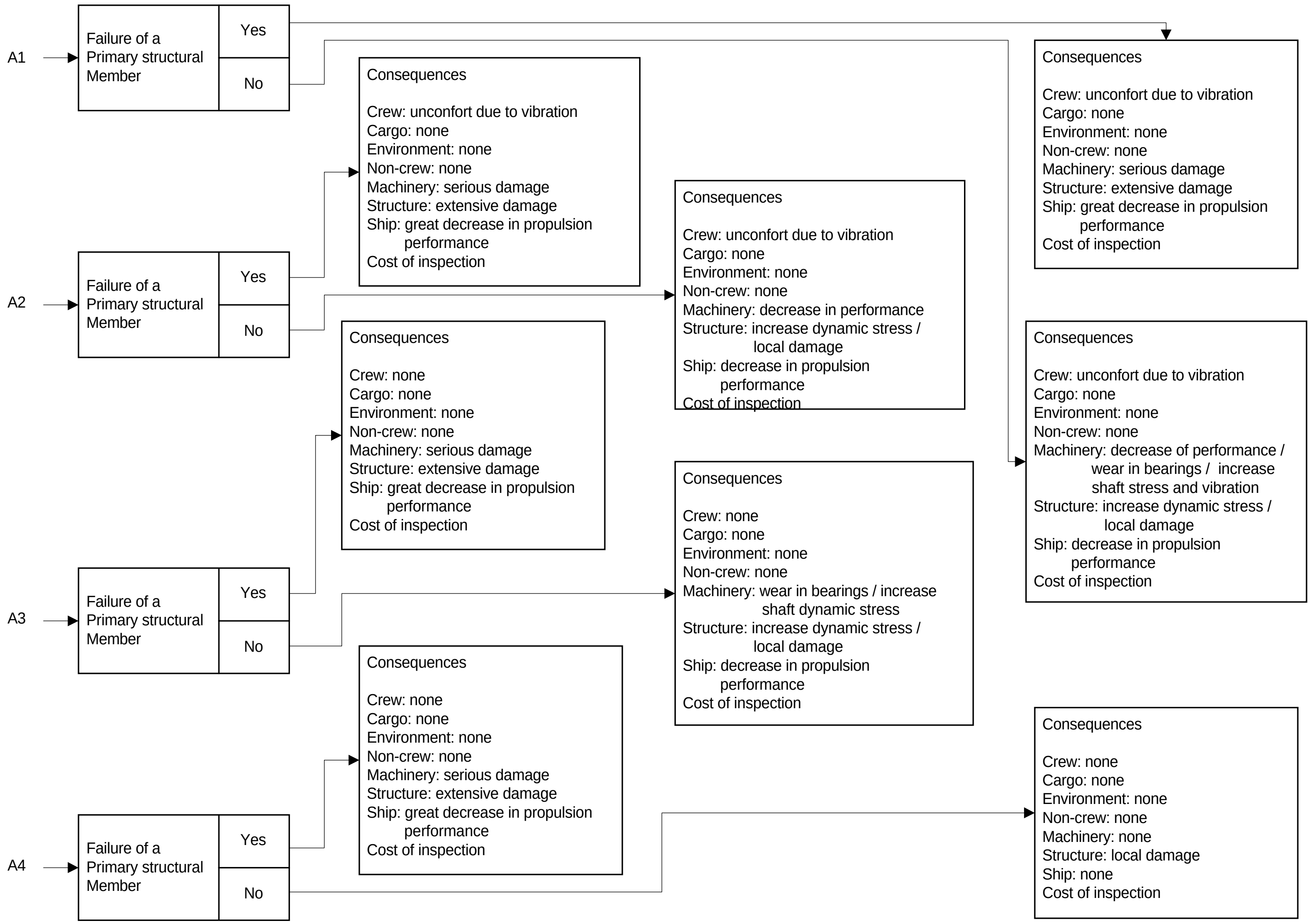


Figure C-20. Cause Consequence Diagram for the Buckling of an Unstiffened Panel in the Main Deck of Machinery Room Structural System Failure (Page 02/02)

Table C-6. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Structural Failure (Page 01/02)

Failure Scenario		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
321	YYYYU	Discomfort due to vibration	Decrease of performance; Wear in bearings; Increase shaft stress and vibration	Increase dynamic stress;	Decrease of propulsion performance	Cost of inspection and repair	3
322	YYYNY YYNUY	Discomfort due to vibration	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
323	YYYNN YYNUN	Discomfort due to vibration	Decrease of performance; Wear in bearings; Increase shaft stress and vibration	Increase in dynamic stress; Local damage	Decrease of propulsion performance	Cost of inspection	3
324	YNYYU	Discomfort due to vibration	Decrease of performance	Increase dynamic stress	Decrease of propulsion performance	Cost of inspection and repair	3
325	YNYNY YNNUY	Discomfort due to vibration	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
326	YNYNN YNNUN	Discomfort due to vibration	Decrease of performance;	Increase in dynamic stress; Local damage	Decrease of propulsion performance	Cost of inspection	3
327	NYYYY	None	Wear in bearings; Increase shaft stress and vibration	None	Decrease of propulsion performance	Cost of inspection and repair	3
328	NYYNY NYNUY	None	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3

Table C-6. Consequences Associated with the Buckling of an Unstiffened Panel in the Main Deck of the Machinery Room Structural Failure (Page 02/02)

Failure Scenario		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
329	NYYNN NYNUN	None	Wear in bearings; Increase shaft stress and vibration	Local damage	Decrease of propulsion performance	Cost of inspection	3
3210	NNYYU	None	None	None	None	Cost of inspection and repair	1
3211	NNYNY NNNUY	None	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
3212	NNYNN NNNUN	None	None	Local damage	None	Cost of inspection	2

C.3.4. Fatigue of a Main Engine Foundation Stiffener, in the Machinery Room

The failure scenarios developed based on this initiating event are classified in two groups: (1) failure scenarios involving failure of ship machinery system, and (2) failure scenarios involving the ship structural system failure.

C.3.4.1. Failure of the Ship Machinery System

Fifteen characters, with the following meaning and sequence compose the definition of the failure scenarios:

_ XXXXXXXXXXXXXX = the first character corresponds to the occurrence of vibration of the machinery room structure;
X _ XXXXXXXXXXXXX = the second character corresponds to the crack detection;
XX _ XXXXXXXXXXXX = the third character corresponds to the repair of the crack;
XXX _ XXXXXXXXXXX = the forth character corresponds to the vibration of the fuel oil line;
XXXX _ XXXXXXXXXX = the fifth character corresponds to the presence of fatigue crack in the fuel oil line;
XXXXX _ XXXXXXXXX = the sixth character corresponds to the occurrence of leakage of fuel oil in the machinery room;
XXXXXX _ XXXXXXXX = the seventh character corresponds to the vibration of the lubricant oil line;
XXXXXXX _ XXXXXXX = the eighth character corresponds to the presence of a fatigue crack in the lubricant oil line;
XXXXXXXX _ XXXXXX = the ninth character corresponds to the occurrence of leakage of lubricant oil in the machinery room;
XXXXXXXXX _ XXXXX = the tenth character corresponds to the vibration of the coolant water line;
XXXXXXXXXX _ XXXX = the eleventh character corresponds to the presence of a fatigue crack in the coolant water line;
XXXXXXXXXXX _ XXX = the twelfth character corresponds to the leakage of coolant water in the machinery room;
XXXXXXXXXXXX _ XX = the thirteenth character corresponds to the occurrence of fire in the machine room;
XXXXXXXXXXXXX _ X = the fourteenth character corresponds to the rapidly extinguish of fire; and
XXXXXXXXXXXXXX _ = the fifteenth character corresponds to the loss of cooling capacity.

A code composed of three numerical characters identifies each of failure scenarios. The meaning of these characters is:

_ XX = the first digit is equal to 4, corresponding to the sub-section 3.4 of appendix A;
X _ X = the second digit is equal to 1, corresponding to the sub-section 3.4.1 of appendix A; and
XX _ = the third digit corresponds to the number of failure scenario associated with the initiating event.

The cause-consequence diagram associated with this initiating event is presented in Figure C-21. The consequences of the possible failure scenarios associated with the buckling of an unstiffened panel in main deck of the machinery room are presented in Table C-7. As the consequences of these failure scenarios do not affect the cargo, the environment or the non-crew, these items are not presented in Table C-7.

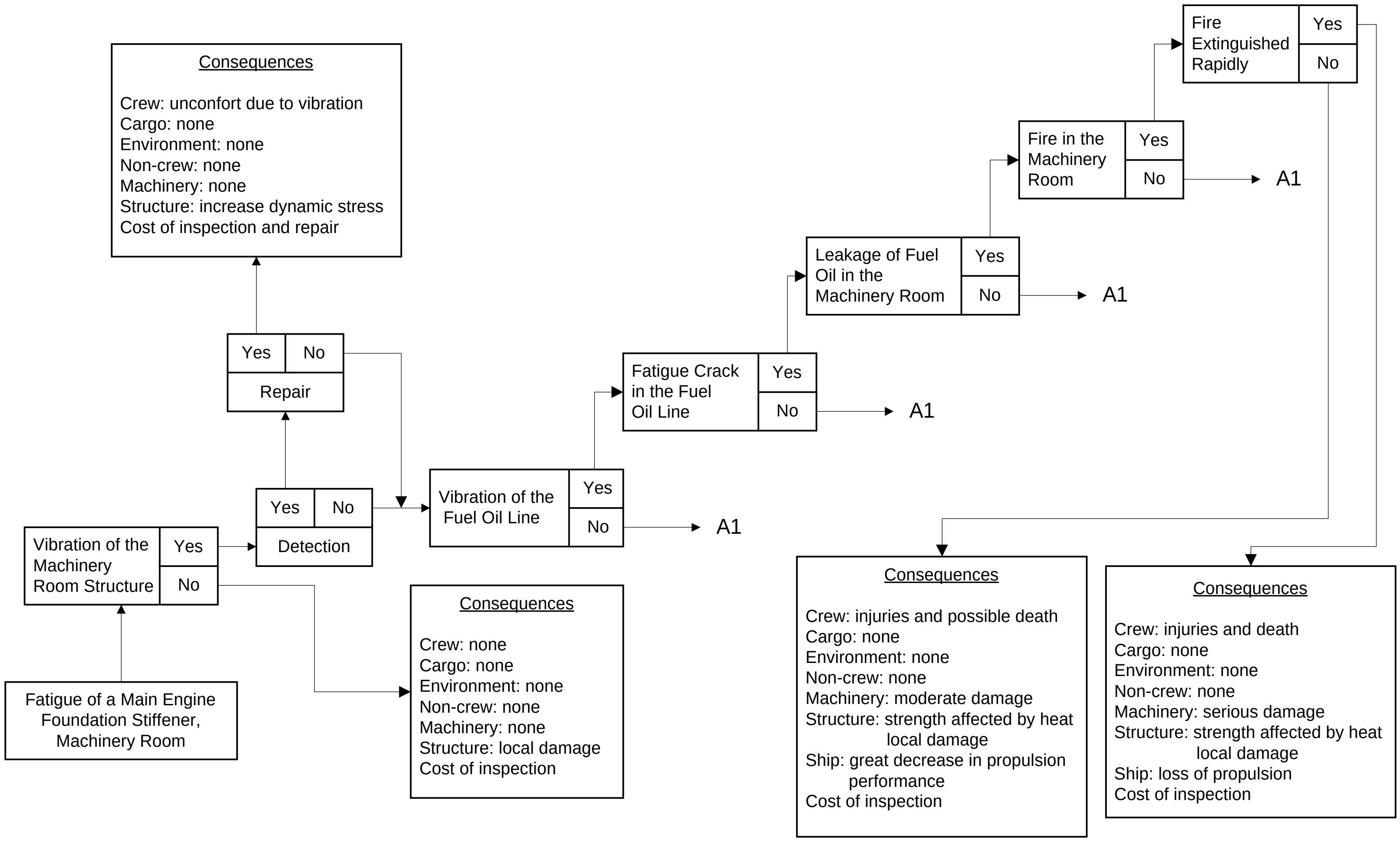


Figure C-21. Cause-Consequence Diagram for the Fatigue of a Main Engine Foundation Stiffener Machinery System Failure (Page 01/02)

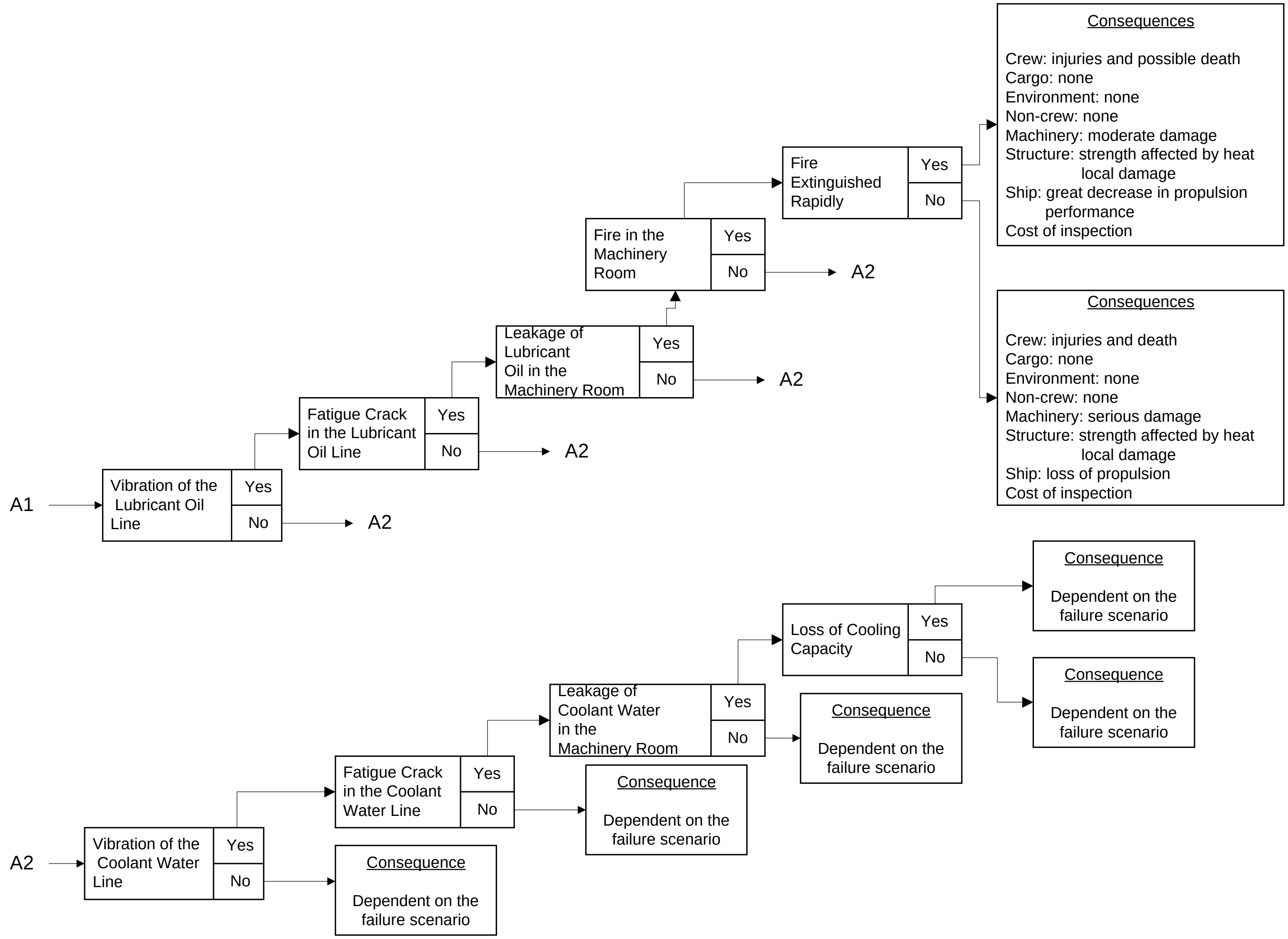


Figure C-21. Cause-Consequence Diagram for the Fatigue of a Main Engine Foundation Stiffener Machinery System Failure (Page 02/02)

Table C-7. Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Machinery Failure (Page 01/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
411	YYYUUUUUUUUUUUU	Discomfort due to vibration	None	Increase the dynamic stress	None	Cost of inspection and repair	2
412	YYNYYYUUUUUUYYU YNUYYYUUUUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
413	YYNYYYUUUUUUYNU YNUYYYUUUUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
414	YYNYYYYYYUUUYYU YNUYYYYYYUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
415	YYNYYYYYYUUUYNU YNUYYYYYYUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
416	YYNYYYYYYYYYNUY YNUYYYYYYYYYNUY	Discomfort due to vibration	Leakage of fuel and lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
417	YYNYYYYYYYYYNUN YNUYYYYYYYYYNUN	Discomfort due to vibration	Leakage of fuel and lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
418	YYNYYYYYYYYNNUU YNUYYYYYYYYNNUU	Discomfort due to vibration	Leakage of fuel oil and lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
419	YYNYYYYYYYNUNUU YNUYYYYYYYNUNUU	Discomfort due to vibration	Leakage of fuel oil and lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4110	YYNYYYYYYNUUNUU YNUYYYYYYNUUNUU	Discomfort due to vibration	Leakage of fuel oil and lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4111	YYNYYYYYNYYYNUY YNUYYYYYNYYYNUY	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4

Table C-7. Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Machinery Failure (Page 02/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4112	YYNYYYYYNYYYNUN YNUYYYYYNYYYNUN	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
4113	YYNYYYYYNYYNNUU YNUYYYYYNYYNNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
4114	YYNYYYYYNYNUNUU YNUYYYYYNYNUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
4115	YYNYYYYYNNUUNUU YNUYYYYYNNUUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
4116	YYNYYYYNUYYYNUY YNUYYYYNUYYYNUY	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4117	YYNYYYYNUYYYNUN YNUYYYYNUYYYNUN	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
4118	YYNYYYYNUYYNNUU YNUYYYYNUYYNNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
4119	YYNYYYYNUYNUNUU YNUYYYYNUYNUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
4120	YYNYYYYNUNUUNUU YNUYYYYNUNUUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion capacity	Cost of inspection	3
4121	YYNYYYNUUYYYNUY YNUYYYNUUYYYNUY	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4

Table C-7. Consequences Associated with the Fatigue of a Main Engine Room Foundation – Machinery Failure (Page 03/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4122	YYNYYYNUUYYYNUN YNUYYYNUUYYYNUN	Discomfort due to vibration	Leakage of fuel oil and coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4123	YYNYYYNUUYYNNUU YNUYYYNUUYYNNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4124	YYNYYYNUUYNUNUU YNUYYYNUUYNUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4125	YYNYYYNUUNUUNUU YNUYYYNUUNUUNUU	Discomfort due to vibration	Leakage of fuel oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4126	YYNYYNYYYUUUYYU YNUYYNYYYUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
4127	YYNYYNYYYUUUYNU YNUYYNYYYUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
4128	YYNYYNYYYYYYNUY YNUYYNYYYYYYNUY	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4129	YYNYYNYYYYYYNUN YNUYYNYYYYYYNUN	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4130	YYNYYNYYYYYNNUU YNUYYNYYYYYNNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4131	YYNYYNYYYYNUNUU YNUYYNYYYYNUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3

Table C-7. Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Machinery Failure (Page 04/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4132	YYNYYNYYYNUUNUU YNUYYNYYYNUUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4133	YYNYYNYYNYYYUUY YNUYYNYYNYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4134	YYNYYNYYNYYYUUN YNUYYNYYNYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4134	YYNYYNYYNYYNUUU YNUYYNYYNYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4135	YYNYYNYNUYYYUUY YNUYYNYNUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4136	YYNYYNYNUYYYUUN YNUYYNYNUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4137	YYNYYNYNUYYNUUU YNUYYNYNUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4138	YYNYYNYNUYNUUUU YNUYYNYNUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4139	YYNYYNYNUNUUUUU YNUYYNYNUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4140	YYNYYNNUUYYYUUY YNUYYNNUUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4

Table C-7. Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Machinery Failure (Page 05/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4141	YYNYYNNUUYYYUUN YNUYYNNUUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4142	YYNYYNNUUYYNUUU YNUYYNNUUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4143	YYNYYNNUUYNUUUU YNUYYNNUUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4144	YYNYYNNUUNUUUUU YNUYYNNUUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4145	YYNYNUYYYUUUYYU YNUYNUYYYUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
4146	YYNYNUYYYUUUYNU YNUYNUYYYUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
4147	YYNYNUYYYYYYNUY YNUYNUYYYYYYNUY	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4148	YYNYNUYYYYYYNUN YNUYNUYYYYYYNUN	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4149	YYNYNUYYYYYNNUU YNUYNUYYYYYNNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4150	YYNYNUYYYYNUNUU YNUYNUYYYYNUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3

Table C-7. Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Machinery Failure (Page 06/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4151	YYNYNUYYYNUUNUU YNUYNUYYYNUUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4152	YYNYNUYYNYYYUUY YNUYNUYYNYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4153	YYNYNUYYNYYYUUN YNUYNUYYNYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4154	YYNYNUYYNYYNUUU YNUYNUYYNYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4155	YYNYNUYYNYNUUUU YNUYNUYYNYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4156	YYNYNUYYNNUUUUU YNUYNUYYNNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4157	YYNYNUYNUYYYUUY YNUYNUYNUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4158	YYNYNUYNUYYYUUN YNUYNUYNUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4159	YYNYNUYNUYYNUUU YNUYNUYNUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4160	YYNYNUYNUYNUUUU YNUYNUYNUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3

Table C-7. Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Machinery Failure (Page 07/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4161	YYNYNUYNUNUUUUU YNUYNUYNUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4162	YYNYNUNUUYYYUUY YNUYNUNUUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4163	YYNYNUNUUYYYUUN YNUYNUNUUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4164	YYNYNUNUUYYNUUU YNUYNUNUUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4165	YYNYNUNUUYNUUUU YNUYNUNUUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4166	YYNYNUNUUNUUUUU YNUYNUNUUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4167	YYNNUUYYYUUUYYU YNUNUUYYYUUUYYU	Injuries and death	Moderate damage	Strength affected by heat, Local damage	Great decrease of propulsion performance	Cost of inspection	3
4168	YYNNUUYYYUUUYNU YNUNUUYYYUUUYNU	Injuries and death	Serious damage	Strength affected by heat, Local damage	Loss of propulsion	Cost of inspection	4
4169	YYNNUUYYYYYYNUY YNUNUUYYYYYYNUY	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4170	YYNNUUYYYYYYNUN YNUNUUYYYYYYNUN	Discomfort due to vibration	Leakage of lubricant oil, leakage of coolant water	Increase the dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3

Table C-7. Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Machinery Failure (Page 08/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4171	YYNNUUYYYYYNNUU YNUNUUYYYYYNNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4172	YYNNUUYYYYNUNUU YNUNUUYYYYNUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4173	YYNNUUYYYNUUNUU YNUNUUYYYNUUNUU	Discomfort due to vibration	Leakage of lubricant oil	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4174	YYNNUUYYNYYYUUY YNUNUUYYNYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4175	YYNNUUYYNYYYUUN YNUNUUYYNYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4176	YYNNUUYYNYYNUUU YNUNUUYYNYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4177	YYNNUUYYNYNUUUU YNUNUUYYNYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4178	YYNNUUYYNNUUUUU YNUNUUYYNNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4179	YYNNUUYNUYYYUUY YNUNUUYNUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4180	YYNNUUYNUYYYUUN YNUNUUYNUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3

Table C-7. Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Machinery Failure (Page 09/09)

Failure Scenarios		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4181	YYNNUUYNUYYNUUU YNUNUUYNUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4182	YYNNUUYNUYNUUUU YNUNUUYNUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4183	YYNNUUYNUNUUUUU YNUNUUYNUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4184	YYNNUUNUUYYYUUY YNUNUUNUUYYYUUY	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Loss of propulsion	Cost of inspection	4
4185	YYNNUUNUUYYYUUN YNUNUUNUUYYYUUN	Discomfort due to vibration	Leakage of coolant water	Increase dynamic stress, Local damage	Moderate decrease of propulsion performance	Cost of inspection	3
4186	YYNNUUNUUYYNUUU YNUNUUNUUYYNUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4187	YYNNUUNUUYNUUUU YNUNUUNUUYNUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4188	YYNNUUNUUNUUUUU YNUNUUNUUNUUUUU	Discomfort due to vibration	Decrease of performance due to vibration	Increase dynamic stress, Local damage	Decrease of propulsion performance	Cost of inspection	3
4189	NYNUUUUUUUUUUUU NNUUUUUUUUUUUUU	None	None	Local damage	None	Cost of inspection	2

C.3.4.2. Failure of the Ship Structural System

Nine characters, with the following meaning and sequence compose the definition of the failure scenarios:

_ XXXXXXXX = the first character corresponds to the occurrence of vibration of the machine room structure;
X _ XXXXXXX = the second character corresponds to the occurrence of misalignment of the propulsion shaft bearings;
XX _ XXXXXX = the third character corresponds to the crack detection;
XXX _ XXXXX = the fourth character corresponds to the crack repair;
XXXX _ XXXX = the fifth character corresponds to the presence of a through thickness crack in the machinery deck plate;
XXXXX _ XXX = the sixth character corresponds to the leakage of oil in the machinery room, due to the presence of fuel or lubricant oil in tanks below the machinery deck;
XXXXXX _ XX = the seventh character corresponds to the occurrence of fire in the machinery room;
XXXXXXX _ X = the eighth character corresponds to the rapidly extinguish of fire; and
XXXXXXXX _ = the ninth character corresponds to the failure of a primary structural member.

A code composed of three numerical characters identifies each of failure scenarios. The meaning of these characters is:

_ XX = the first digit is equal to 4, corresponding to the sub-section 3.4 of appendix A;
X _ X = the second digit is equal to 2, corresponding to the sub-section 3.4.2 of appendix A; and
XX _ = the third digit corresponds to the number of failure scenario associated with the initiating event.

The cause-consequence diagram associated with this initiating event is presented in Figure C-22. The consequences of the possible failure scenarios associated with the fatigue of a main engine foundation stiffener are presented in Table C-8. As the consequences of these failure scenarios do not affect the cargo, the environment or the non-crew, these items are not presented in Table C-8.

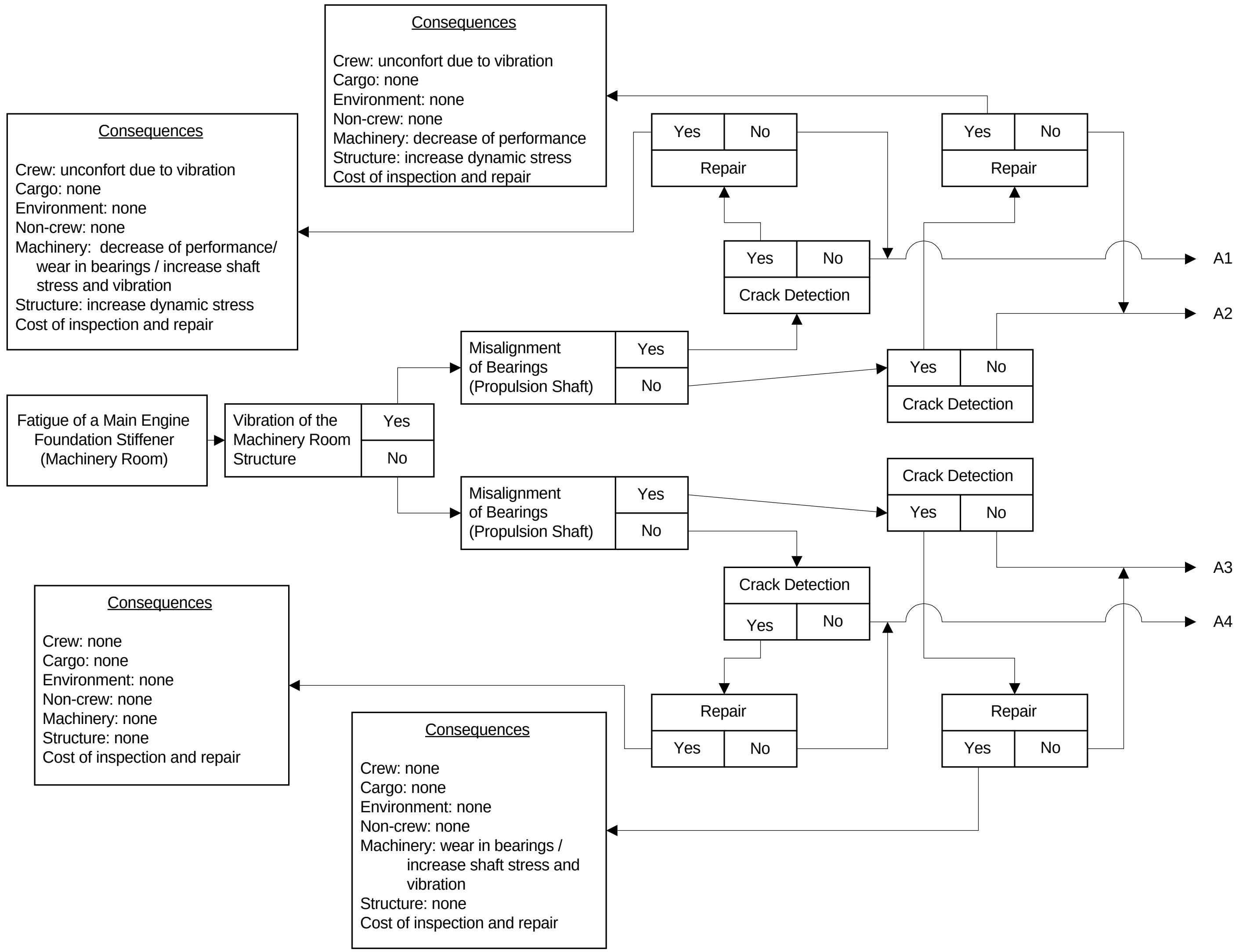


Figure C-22. Cause-Consequence Diagram for the Fatigue of a Main Engine Foundation Stiffener Structural System Failure (Page 01/05)

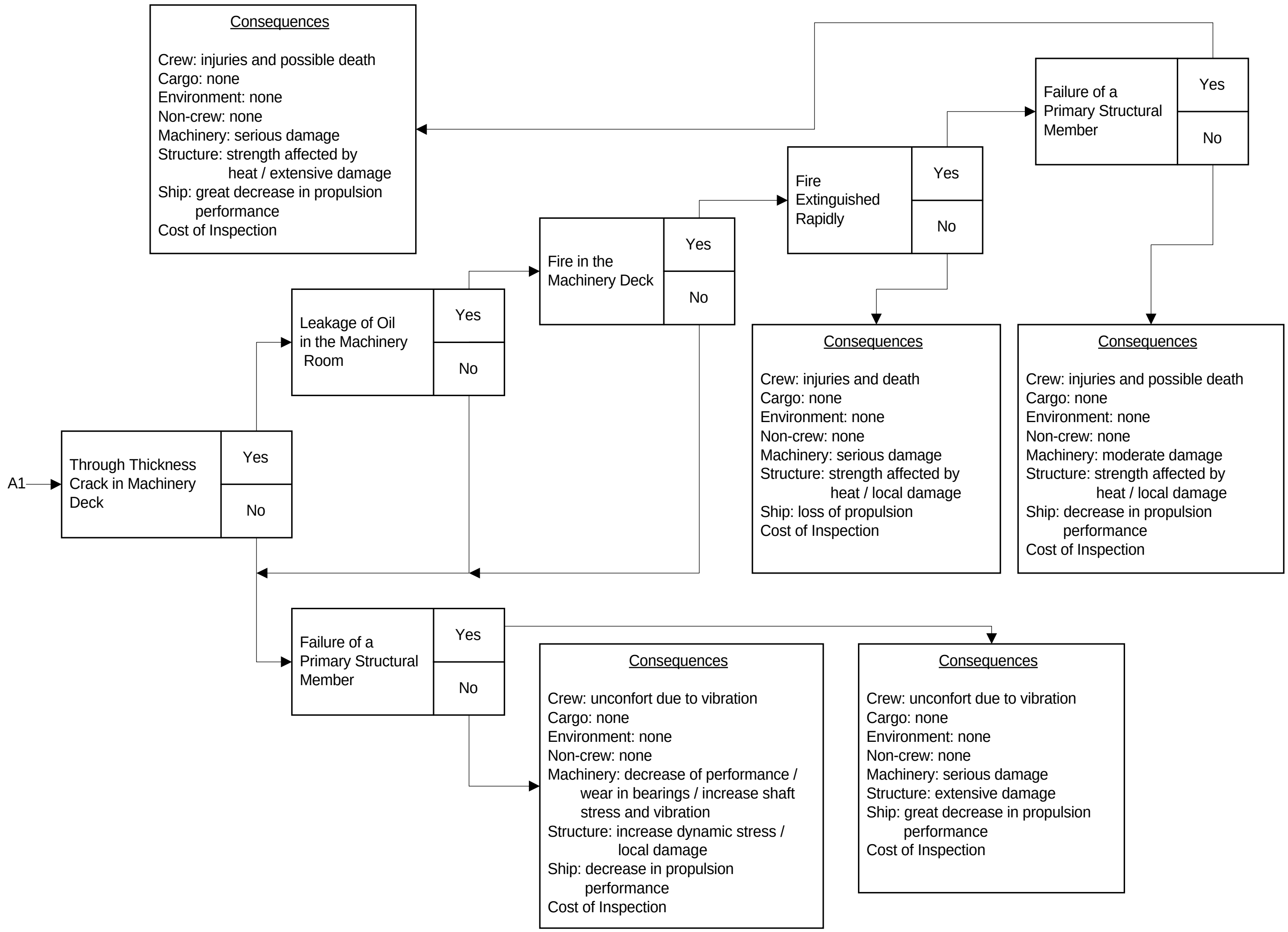


Figure C-22. Cause-Consequence Diagram for the Fatigue of a Main Engine Foundation Stiffener Structural System Failure (Page 02/05)

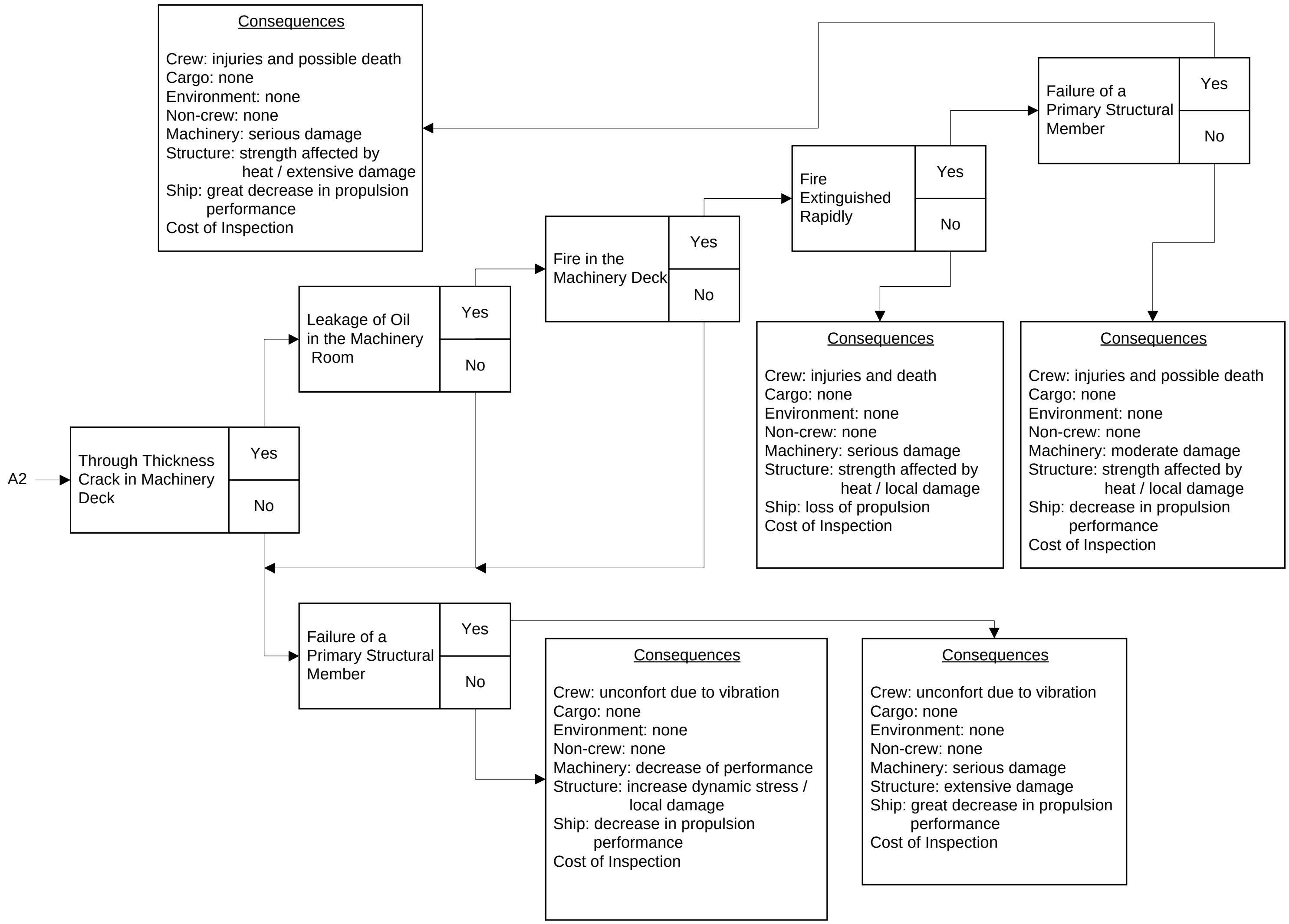


Figure C-22. Cause-Consequence Diagram for the Fatigue of a Main Engine Foundation Stiffener Structural System Failure (Page 03/05)

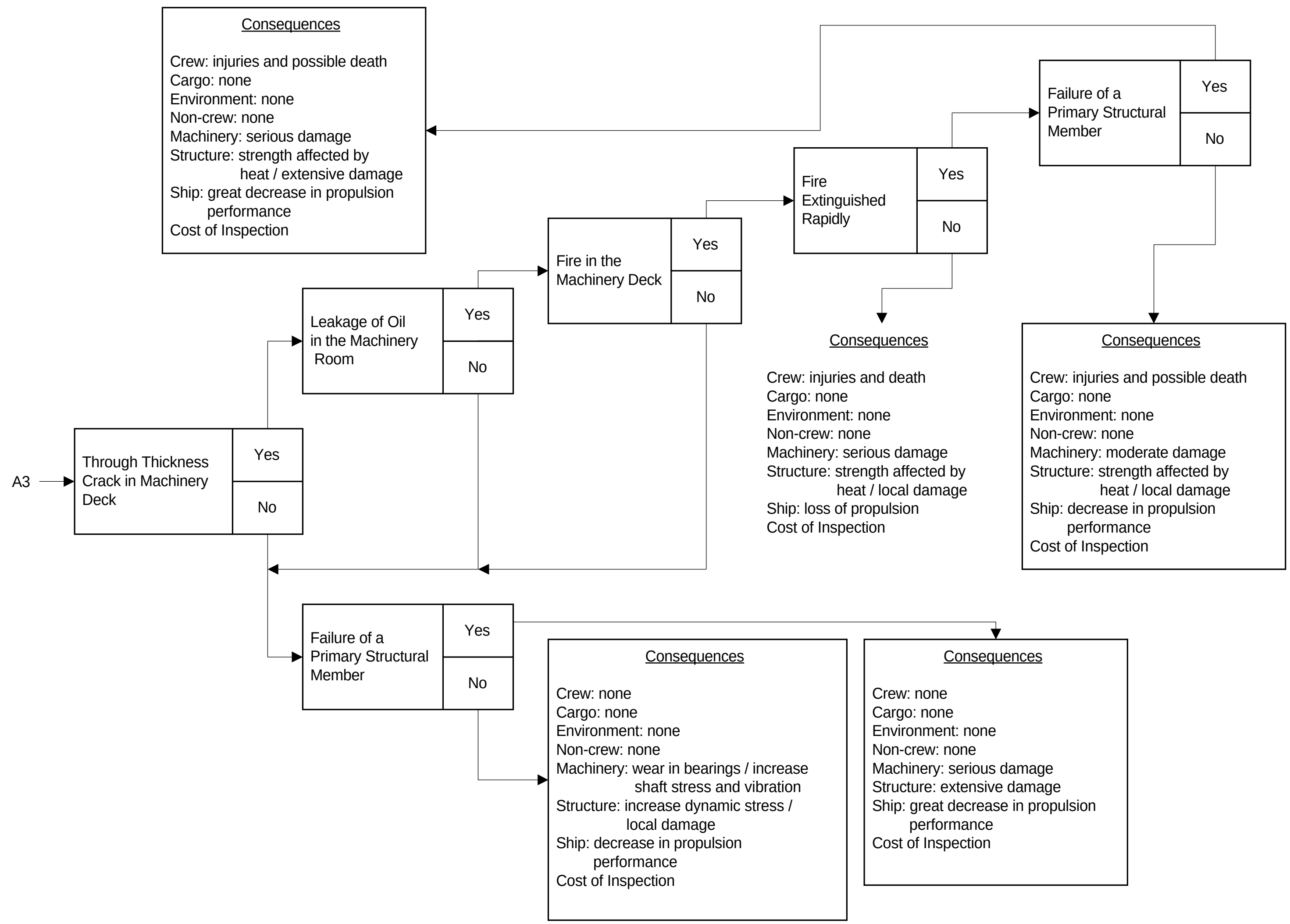


Figure C-22. Cause-Consequence Diagram for the Fatigue of a Main Engine Foundation Stiffener Structural System Failure (Page 04/05)

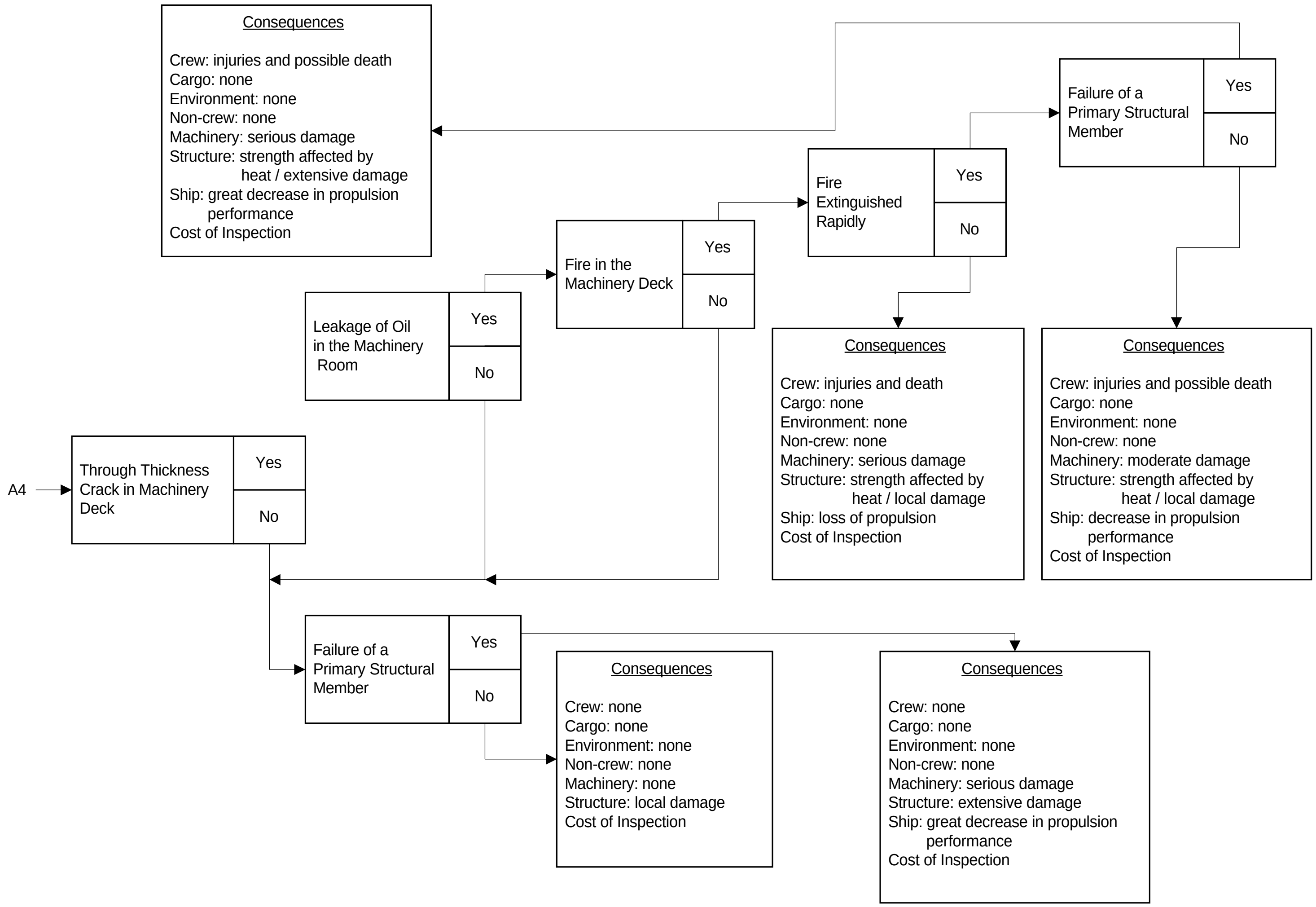


Figure C-22. Cause-Consequence Diagram for the Fatigue of a Main Engine Foundation Stiffener Structural System Failure (Page 05/05)

Table C-8. Structural Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Structural Failure (Page 01/04)

Failure Scenario		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
421	YYYYUUUUU	Discomfort due to vibration	Decrease of performance; Wear in bearings; Increase shaft stress and vibration	Increase dynamic stress;	Decrease of propulsion performance	Cost of inspection and repair	2
422	YYYNYYYYY YYNUYYYYY	Injuries and death	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
423	YYYNYYYYN YYNUYYYYN	Injuries and death	Moderate damage	Strength affected by heat; Local damage	Decrease of propulsion performance	Cost of inspection	3
424	YYYNYYYNU YYNUYYYNU	Injuries and death	Serious damage	Strength affected by heat; Local damage	Loss of propulsion	Cost of inspection	4
425	YYYNYYNUY YYNUYYNUY	Discomfort due to vibration	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
426	YYYNYYNUN YYNUYYNUN	Discomfort due to vibration	Decrease of performance; Wear in bearings; Increase shaft stress and vibration	Increase in dynamic stress; Local damage	Decrease of propulsion performance	Cost of inspection	2
427	YYYNYNUUY YYNUYNUUY	Discomfort due to vibration	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
428	YYYNYNUUN YYNUYNUUN	Discomfort due to vibration	Decrease of performance; Wear in bearings; Increase shaft stress and vibration	Increase in dynamic stress; Local damage	Decrease of propulsion performance	Cost of inspection	2
429	YYYNNUUUY YYYNNUUUY	Discomfort due to vibration	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4210	YYYNNUUUN YYYNNUUUN	Discomfort due to vibration	Decrease of performance; Wear in bearings; Increase shaft stress and vibration	Increase in dynamic stress; Local damage	Decrease of propulsion performance	Cost of inspection	2

Table C-8. Structural Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Structural Failure (Page 02/04)

Failure Scenario		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4211	YNYYUUUUU	Discomfort due to vibration	Decrease of performance	Increase dynamic stress	Decrease of propulsion performance	Cost of inspection and repair	2
4212	YNYNYYYYY YNNUYYYYY	Injuries and death	Serious damage	Extensive damage	Great decrease in propulsion performance	Cost of inspection	3
4213	YNYNYYYYN YNNUYYYYN	Injuries and death	Moderate damage	Strength affected by heat; Local damage	Decrease of propulsion performance	Cost of inspection	3
4214	YNYNYYYNU YNNUYYYNU	Injuries and death	Serious damage	Strength affected by heat; Local damage	Loss of propulsion	Cost of inspection	4
4215	YNYNYYNUY YNNUYYNUY	Discomfort due to vibration	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4216	YYYNYYNUN YYNUYYNUN	Discomfort due to vibration	Decrease of performance	Increase in dynamic stress; Local damage	Decrease of propulsion performance	Cost of inspection	2
4217	YNYNYNUUY YNNUYNUUY	Discomfort due to vibration	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4218	YNYNYNUUN YNNUYNUUN	Discomfort due to vibration	Decrease of performance;	Increase in dynamic stress; Local damage	Decrease of propulsion performance	Cost of inspection	2
4219	YNYNNUUUY YNNUNUUUY	Discomfort due to vibration	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4220	YNYNNUUUN YNNUNUUUN	Discomfort due to vibration	Decrease of performance;	Increase in dynamic stress; Local damage	Decrease of propulsion performance	Cost of inspection	2
4221	NYYYUUUUU	None	Wear in bearings; Increase shaft stress and vibration	None	Decrease of propulsion performance	Cost of inspection and repair	2

Table C-8. Structural Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Structural Failure (Page 03/04)

Failure Scenario		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4222	NYYYYYYYY NYNUYYYYY	Injuries and death	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4223	NYYYYYYYN NYNUYYYYN	Injuries and death	Moderate damage	Strength affected by heat; Local damage	Decrease of propulsion performance	Cost of inspection	3
4224	NYYYYYYNU	Injuries and death	Serious damage	Strength affected by heat; Local damage	Loss of propulsion	Cost of inspection	3
4225	NYYNYYNUY NYNUYYNUY	None	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4226	NYYNYYNUN NYNUYYNUN	None	Wear in bearings; Increase shaft stress and vibration	Local damage	Decrease of propulsion performance	Cost of inspection	2
4227	NYYNYNUUY NYNUYNUUY	None	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4228	NYYNYNUUN NYNUYNUUN	None	Wear in bearings; Increase shaft stress and vibration	Local damage	Decrease of propulsion performance	Cost of inspection	3
4229	NYYNNUUUY NYNUNUUUY	None	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4230	NYYNNUUUN NYNUNUUUN	None	Wear in bearings; Increase shaft stress and vibration	Local damage	Decrease of propulsion performance	Cost of inspection	2
4231	NNYYUUUUU	None	None	None	None	Cost of inspection and repair	1
4232	NNYNYYYYY NNNUYYYYY	Injuries and death	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3

Table C-8. Structural Consequences Associated with the Fatigue of a Main Engine Foundation Stiffener – Structural Failure (Page 04/04)

Failure Scenario		**Consequences**					
Code	Definition	Crew	Machinery System	Structural System	Other Ship Systems	Inspection and Repair	Rating
4233	NNYNYYYYN NNNUYYYYN	Injuries and death	Moderate damage	Strength affected by heat; Local damage	Decrease of propulsion performance	Cost of inspection	3
4234	NNYNYYYNU NNNUYYYNU	Injuries and death	Serious damage	Strength affected by heat; Local damage	Loss of propulsion	Cost of inspection	4
4235	NNYNYYNUY NNNUYYNUY	None	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4236	NNYNYYNUN NNNUYYNUN	None	None	Local damage	None	Cost of inspection	2
4237	NNYNYNUUY NNNUYNUUY	None	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4238	NNYNYNUUN NNNUYNUUN	None	None	Local damage	None	Cost of inspection	2
4239	NNYNNUUUY NNNUNUUUY	None	Serious damage	Extensive damage	Great decrease of propulsion performance	Cost of inspection	3
4240	NNYNNUUUN NNNUNUUUN	None	None	Local damage	None	Cost of inspection	2

C.4. Development of Risk Profiles and Risk Management

Based on the cause-consequence analysis presented in Sections C.2 and C.3, a risk profile analysis can be performed in order to define the critical scenarios for ship safety that could stem from structural failures as initiating events.

The probability of occurrence of a given failure scenario can be defined considering the conditional probabilities of occurrence of underlying events that define the scenario. The probabilities of occurrence of the failure scenarios and the consequence ratings associated with the scenario can be used to plot a risk profile (i.e., the Farmer curve) related to a given initiating event.

For the containership presented in Section C.1 and considering for demonstration purposes an initiating event of fatigue at a main engine foundation stiffener, the risk profile associated with this event can be developed based on the failure scenarios presented in Table C-8. The failure probabilities associated with the failure scenarios that are based on the detection of fatigue crack without repair performance are presented in Table C-9. The failure probabilities presented in Table C-9 are *assumed* conditional failure probabilities for the purpose of developing this demonstrative example. The application of this methodology to real ships would require evaluating the needed conditional failure probabilities. Based on the data presented in Table C-9, the risk profile can be developed as shown in Figure C-23.

Considering the data presented in Table C-9, the risk associated with the failure scenarios can be classified into the following four categories:

1. Risk Level 1: failure scenarios with low probability of occurrence and low consequences;
2. Risk Level 2: failure scenarios with low probability of occurrence and high consequences;
3. Risk Level 3: failure scenarios with high probability of occurrence and low consequences;
4. Risk Level 4: failure scenarios with high probability of occurrence and high consequences.

From these categories, the failure scenarios that would require the most attention by designers and/or operators are those classified in the Risk Levels 2 and 4 as the consequences associated with their failure are high. However, the remaining two categories should be considered for risk management. Based on the data presented in Figure C-23, and considering that the consequences are classified as high for consequence rating equal to or higher than 3, there are some scenarios that must be carefully evaluated by the designers and operators, such as those identified by the codes 424, 4214 e 4234 on the figure and corresponding table. These three scenarios involve the occurrence of fire in the machinery room, and based on not rapidly extinguishing it. In order to prevent failure and/or mitigate the risk associated with these failure scenarios, some actions my be taken by the designers or operators to modify the risk level. The risk modification process can be performed using a decision framework that include identification of alternatives for actions, construction of a decision tress and selecting the best alternative based on optimizing an objective function. Example risk modification actions include the following:

1. Modify the fire detection and protection system in the machinery room, in order to increase the probability of fire extinguish;

2. Strengthen the structure in the main engine foundation, in order to reduce the probability of fatigue crack propagation;
3. Modify the structural inspection and repair requirements, in order to increase the probability of crack inspection and repair;
4. Consider the use of crack arrestors to prevent the fatigue crack propagation;
5. Install sensors to detect the vibration in the shaft, in order to detect the occurrence of the crack propagation before the total development of the scenario;
6. Install sensors to detect vibration in the hull structure, with the same objective presented in v;
7. Isolate hot surfaces in the areas close to the fuel tank, in the machinery room; and
8. Training for ship fire brigade and training for rapid machinery room evacuation in case of fire.

The failure scenario associated with code 4231 although have a high probability of occurrence has low consequences. This scenario must also be analyzed as it can disturb the normal operation of the vessel. The constant need for inspection and repair in order to prevent the scenario occurrence reduces the operational efficiency of the vessel. The strengthening of the structure is a possible way to avoid the fatigue crack initiation.

Another possible way of analyzing the risk profile is through the definition of maximum limits for acceptable probability of occurrence and consequences, such as presented in Figure C-24. The likelihood limit is related with a constant occurrence of a given failure scenario, that disturbs the normal operation of the ship. The consequence limit is related to the amount of consequences that can be tolerated in case of a structural failure. Between these limits, the risk limit expresses how much risk can be tolerated in case of an accident, once the consequence and likelihood limit are not reached. The risk limit can vary from one user to another depending on their risk aversion, insurance coverage, and other political and public-relation considerations. This limit is a function of the behavior of the ship owner or operator when facing some risk. The failure scenarios inside the region A can be tolerated, but the failure scenarios in region B should be evaluated due to their high probability of occurrence or high consequences.

Considering a likelihood limit equal to 1.0E-04 and the consequence limit equal to 3.5, as shown in Figure C-24, the critical scenarios that should be evaluated by the ship designer are 424, 4214, 434, all of them with high consequence rating, and scenario 4231, with a high probability of occurrence. These failure scenarios should be targeted for risk modification.

Table C-9. Probability of Occurrence of Failure Scenarios Associated with the Fatigue of a Main Engine Foundation Stiffener (Page 01/02)

Code	Conditional Probabilities									Branch Probability	Rating
	1	2	3	4	5	6	7	8	9		
421	1.0E-02	5.0E-03	0.95	0.99	1	1	1	1	1	4.70E-08	2
422	1.0E-02	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.0E-06	1.0E-07	2.38E-34	3
423	1.0E-02	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.0E-06	1.-1.E-7	2.38E-27	3
424	1.0E-02	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.-1.E-6	1.0E+00	2.38E-21	4
425	1.0E-02	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.-1.E-05	1.0E+00	1.0E-07	2.38E-23	3
426	1.0E-02	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.-1.E-05	1.0E+00	1.-1.E-07	2.38E-16	2
427	1.0E-02	5.0E-03	0.95	0.01	1.0E-03	1.-0.5E-03	1.0E+00	1.0E+00	1.0E-07	4.75E-20	3
428	1.0E-02	5.0E-03	0.95	0.01	1.0E-03	1.-0.5E-03	1.0E+00	1.0E+00	1.-1.E-07	4.75E-13	2
429	1.0E-02	5.0E-03	0.95	0.01	1.-1.E-03	1.0E+00	1.0E+00	1.0E+00	1.0E-07	4.75E-17	3
4210	1.0E-02	5.0E-03	0.95	0.01	1.-1.E-03	1.0E+00	1.0E+00	1.0E+00	1.-1.E-07	4.75E-10	2
4211	1.0E-02	1.-5.E-03	0.95	0.99	1	1	1	1	1	9.41E-06	2
4212	1.0E-02	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.0E-06	1.0E-07	4.75E-32	3
4213	1.0E-02	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.0E-06	1.-1.E-7	4.75E-25	3
4214	1.0E-02	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.-1.E-6	1.0E+00	4.75E-19	4
4215	1.0E-02	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.-1.E-05	1.0E+00	1.0E-07	4.75E-21	3
4216	1.0E-02	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.-1.E-05	1.0E+00	1.-1.E-07	4.75E-14	2
4217	1.0E-02	1.-5.E-03	0.95	0.01	1.0E-03	1.-0.5E-03	1.0E+00	1.0E+00	1.0E-07	9.50E-18	3
4218	1.0E-02	1.-5.E-03	0.95	0.01	1.0E-03	1.-0.5E-03	1.0E+00	1.0E+00	1.-1.E-07	9.50E-11	2
4219	1.0E-02	1.-5.E-03	0.95	0.01	1.-1.E-03	1.0E+00	1.0E+00	1.0E+00	1.0E-07	9.50E-15	3
4220	1.0E-02	1.-5.E-03	0.95	0.01	1.-1.E-03	1.0E+00	1.0E+00	1.0E+00	1.-1.E-07	9.50E-08	2

Note: (1) Probability of the Fatigue of a Main Engine Room Foundation = 1.E-03

Table C-9. Probability of Occurrence of Failure Scenarios Associated with the Fatigue of a Main Engine Foundation Stiffener (Page 02/02)

Code	Conditional Probabilities									Branch Probability	Rating
	1	2	3	4	5	6	7	8	9		
4221	1-1.E-2	5.0E-03	0.95	0.99	1	1	1	1	1	4.70E-06	2
4222	1-1.E-2	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.0E-06	1.0E-07	2.38E-32	3
4223	1-1.E-2	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.0E-06	1.-1.E-7	2.38E-25	3
4224	1-1.E-2	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.-1.E-6	1.0E+00	2.38E-19	3
4225	1-1.E-2	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.-1.E-05	1.0E+00	1.0E-07	2.38E-21	3
4226	1-1.E-2	5.0E-03	0.95	0.01	1.0E-03	5.0E-04	1.-1.E-05	1.0E+00	1.-1.E-07	2.38E-14	2
4227	1-1.E-2	5.0E-03	0.95	0.01	1.0E-03	1.-0.5E-03	1.0E+00	1.0E+00	1.0E-07	4.75E-18	3
4228	1-1.E-2	5.0E-03	0.95	0.01	1.0E-03	1.-0.5E-03	1.0E+00	1.0E+00	1.-1.E-07	4.75E-11	3
4229	1-1.E-2	5.0E-03	0.95	0.01	1.-1.E-03	1.0E+00	1.0E+00	1.0E+00	1.0E-07	4.75E-15	3
4230	1-1.E-2	5.0E-03	0.95	0.01	1.-1.E-03	1.0E+00	1.0E+00	1.0E+00	1.-1.E-07	4.75E-08	2
4231	1-1.E-2	1.-5.E-03	0.95	0.99	1	1	1	1	1	9.41E-04	1
4232	1-1.E-2	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.0E-06	1.0E-07	4.75E-30	3
4233	1-1.E-2	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.0E-06	1.-1.E-7	4.75E-23	3
4234	1-1.E-2	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.0E-05	1.-1.E-6	1.0E+00	4.75E-17	4
4235	1-1.E-2	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.-1.E-05	1.0E+00	1.0E-07	4.75E-19	3
4236	1-1.E-2	1.-5.E-03	0.95	0.01	1.0E-03	5.0E-04	1.-1.E-05	1.0E+00	1.-1.E-07	4.75E-12	2
4237	1-1.E-2	1.-5.E-03	0.95	0.01	1.0E-03	1.-0.5E-03	1.0E+00	1.0E+00	1.0E-07	9.50E-16	3
4238	1-1.E-2	1.-5.E-03	0.95	0.01	1.0E-03	1.-0.5E-03	1.0E+00	1.0E+00	1.-1.E-07	9.50E-09	2
4239	1-1.E-2	1.-5.E-03	0.95	0.01	1.-1.E-03	1.0E+00	1.0E+00	1.0E+00	1.0E-07	9.50E-13	3
4240	1-1.E-2	1.-5.E-03	0.95	0.01	1.-1.E-03	1.0E+00	1.0E+00	1.0E+00	1.-1.E-07	9.50E-06	2

Note: (1) Probability of the Fatigue of a Main Engine Room Foundation = 1.E-03

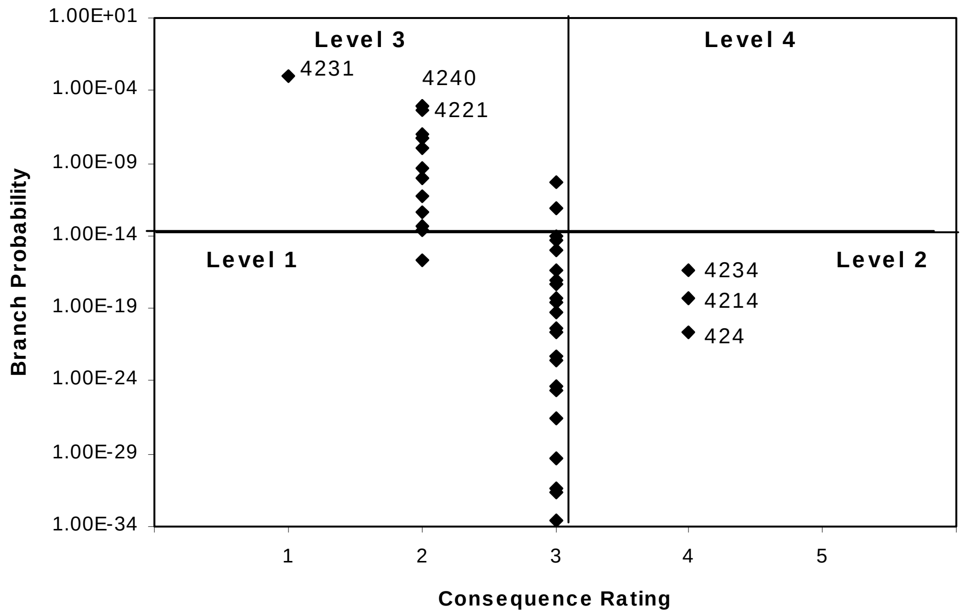


Figure C-23. Risk Profile Associated with the Occurrence of the Fatigue of a Main Engine Foundation Stiffener

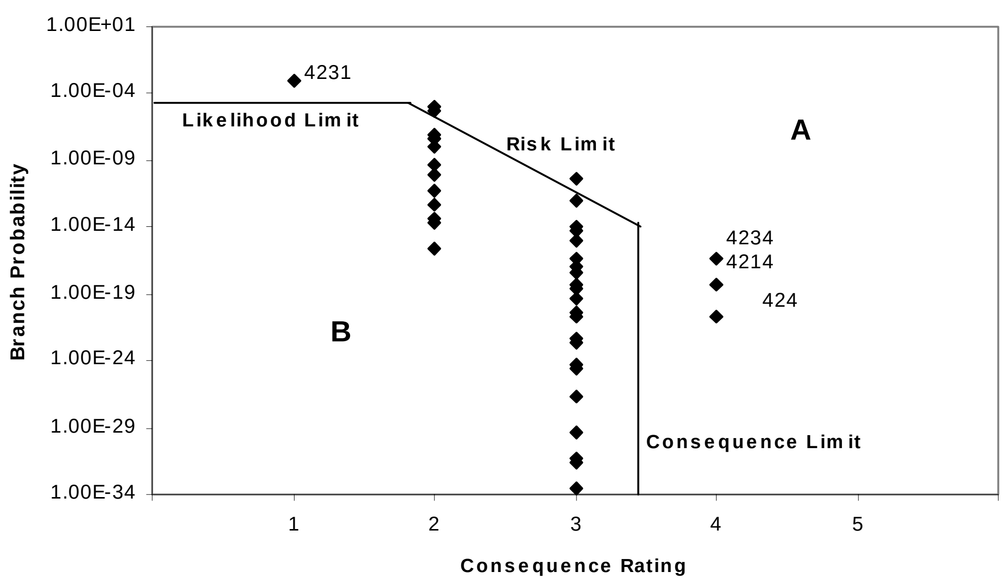


Figure C-24. Risk Profile Associated with the Occurrence of the Fatigue of a Main Engine Foundation Stiffener –
Analysis Based on Acceptable and Non-Acceptable Risk

C.5. Risk-based Management of System Integrity: Selection of Inspection and Repair Strategy

C.5.1. Inspection and Repair Program and Strategy Development

In Section C.4, cause-consequence diagrams were used to develop risk profiles, critical failure scenarios for the safety of the ship were defined, ranked and categorized. The next step is to manage the integrity of the system using a risk methodology. The development of inspection and repair programs can be viewed as a part of the risk-based management of system integrity. This process is schematically shown in Figure C-25.

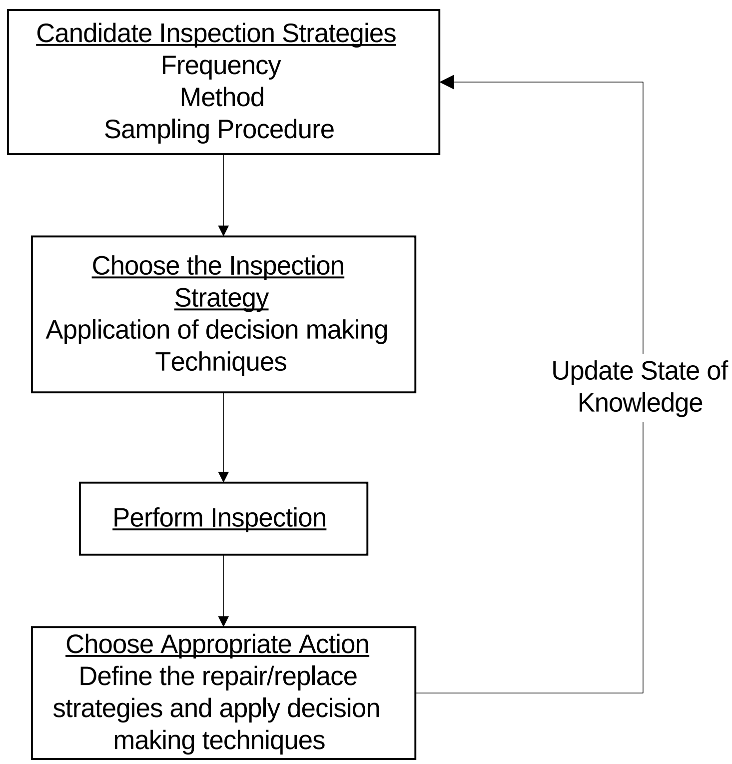


Figure C-25. Inspection and Repair Program and Strategy Development

The recommended process is divided into three basic steps (Vo and Balkey 1995):

1. Choose candidate inspection strategies, defining the frequency, method and sampling procedure for inspection. The method of inspection includes the procedure, equipment, and level of personnel qualification to perform the inspection. The inspection strategy may also take advantage of monitoring systems and maintenance programs already defined for the structural detail. Critical uncertainties associated with this step are the potential for degradation or failure associated with the structural detail, the potential for inspection damage, including the potential for danger to the inspector, and the reliability of the inspection method. Appendix B includes details on inspection strategies.
2. Choose an inspection strategy and perform inspection. From the candidate inspection strategies, defined in the above step, the effect of each of these strategies on the failure probability of the structural detail is estimated. Inspections cost and costs related to the

structural failure, in case of no defect detection, are also estimated for each strategy. The costs associated with the structural failure can be assessed with the cause-consequence diagram. An inspection strategy is chosen on the basis of these results, with the use of Decision Tree technique. Once the inspection strategy is chosen, the inspection is performed.

3. Choose appropriate action and update state of knowledge. Following the performance of the inspection, another critical decision is faced, that is, should the component be repaired or replaced if defects are detected, or should nothing be done? Furthermore, if a repair or replacement is required, another decision faced is whether to take the action: now or later? The decision depends on whether this action can indeed keep the structural detail in a normal state for the intended period of operation, or whether the potential exists for new damage to be introduced during the repair action, due to imperfect or inadequate repair? The current practice in shipyards is to define the repair method either on-site or slightly later in repair office. Specifically for fatigue cracks, the most common defect found in hull structures of ships undergoing repair, the repair methods varies widely (Ma and Bea, 1995). They can range from temporary drilling a stopping-hole in front of the crack tip to completely re-designing the structural detail and replacing steel near the detail, although the most frequently selected method is to re-weld the crack. When a structural failure is discovered by inspection, a decision must be made as to the most effective repair. These factors include technical, economic, schedule and logistic factors. The technical factor involves mainly the expected life of the repair, in comparison with the expected life of the hull structure. The economic, schedule and logistic factors include considerations related to the future plans for the ship, age of the ship, total costs and time to complete repair, etc, as presented in Appendix B. Structural reliability analysis can be used to determine the effects of the inspection findings and potential corrective actions on the failure probabilities. Decision trees can be used to define the best repair strategy for the structural detail, considering the technical aspects related to the hull structural performance in addition to the economical aspects involving not only repair but also the costs related to a possible structural failure. In any case, all of the results related to the inspection should be used to update the risk-based knowledge database on a periodic basis to re-rank the structural details on the basis of risk and to redefine the inspection program, starting with step *i* of the overall procedure, providing a living process as long as the ship is in service.

An example of the decision-making process as for inspection and repair analysis is presented in this section.

C.5.2. Example Structural Failure

The structural failure under analysis is the fatigue of a main engine room foundation stiffener, which has already been analyzed in Section C.4 of this appendix. The crack is assumed to initiate and propagate in the manner shown in Figure C-26. The fatigue crack grows in the stiffener, in an area of stress concentration induced by the part geometry. The crack length is taken to be equal to 6.5 mm.

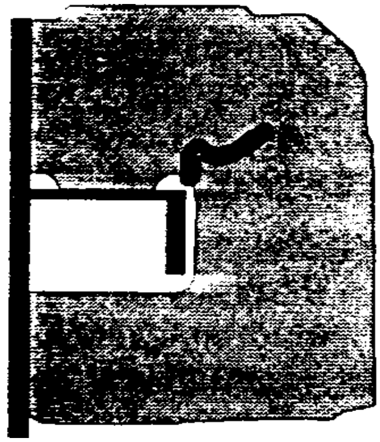


Figure C-26. Geometry of the fatigue Crack in the Main Engine Foundation Stiffener

C.5.3. Example Inspection Methods

According to Soares and Garbatov (1996), two non-destructive inspection techniques are usually applied to inspect hull structures and are used herein for demonstration purposes. These inspection techniques are visual inspection and magnetic particle inspection. For both inspection techniques, Soares and Garbatov (1996) used of the exponential distribution to represent the probability of detection (POD) curve, which is written as:

$$POD(a) = 1.0 - \exp\left(-\frac{a - a_{do}}{\lambda_d}\right),\ a \leq a_{d0} \qquad \text{(C-1)}$$

where a = the crack length, a_{d0} = the crack length threshold, and λ_d = the density function parameter. Soares and Garbatov (1996) suggested the following data for the *POD* distribution:

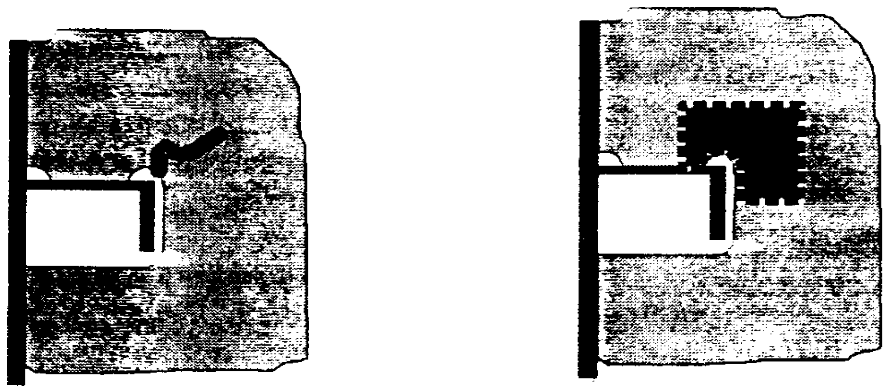
- Magnetic Inspection: a_{d0} = 1.0 mm, λ_d = 2.50 mm, and
- Visual Inspection: a_{d0} = 5.0 mm, λ_d = 1.0 mm.

Both techniques are considered as possible inspection strategies for the inspection of the main engine foundation.

C.5.4. Example Repair Methods

As for repair alternatives, Ma and Bea (1995) list some possible repair alternatives for this failure. For this example, three repair alternatives can be considered as shown in Figure C-27:

i) Repair 1: grind out crack and re-weld;
ii) Repair 2: grind out crack and re-weld, plus post weld treatment, such as the grinding of the weld line to improve its fatigue strength;
iii) Repair 3: replace the cracked plate, cutting out the cracked section and welding a new piece.



(a) Repair 1 and 2 (re-weld) b) Repair 3 (replace the cracked plate)

Figure C-27. Alternatives for the Repair of the Fatigue Crack

According to Ma and Bea (1995), repair 3 costs three times the monetary cost of repair 1, and repair 2 costs two times the monetary cost of repair 1. According to those authors, repair 3 has the highest expected life, followed by repair 2. Therefore, the reliability of the structural detail is higher, if repaired with the third repair alternative in comparison with the reliability provided by the other two repair alternatives.

C.5.5. Example Decision Trees

The decision-tree technique is used to select the most suitable inspection and repair strategy for the structural detail under analysis. The decision tree used in this example is presented in Figure C-28. This tree illustrates the sequence of decisions and uncertainties involved in the choice between three possible alternatives for the structural detail repair, including the visual inspection (Inspection Method 1), the magnetic particle inspection (Inspection Method 2), and no inspection. The tree also considers the three repair alternatives, in case of crack detection, plus the choice of no repair.

Starting from the left end of the tree and following any particular path through the tree leads to a single value of the decision criterion, in this case the total cost. The probabilities attached to the branches at each chance node represent the likelihood of following the path. By starting at the left end of the tree and following a process of taking expected values at chance nodes, the tree is averaged out to yield an expected cost for each alternative. As an example, the numerical calculations are shown to the right of the tree along with the path scenario.

The first choice node defines the possible structural inspection methods to be used in the inspection of the main engine room stiffener. The first decision node involves the possibility of fatigue crack detection in the inspection. The probabilities associated with this node are defined using the probability of detection curve for each inspection method, considering the crack length equal to 6.5 mm.

After the detection node, considering the crack detection case, there is a choice node, corresponding to the decision about crack repair. Once the repair decision is made, there is another decision node that represents the choice about what type of repair should be executed. This tree considers only repair alternatives already presented in this section.

After the decision about the possible repair execution, a second decision node must be considered. The second decision node involves the estimation of the structure failure probability if the fatigue crack is detected and repaired, considering the future operation of the ship. This probability must be estimated based on structural reliability analysis. The values presented on the decision tree are illustrative, aiming the development of this example. The probabilities of failure associated with each type of repair indicate that the repair 3 is better than repair 2, which is better than repair 1, in accordance with the analysis presented by Ma and Bea (1995).

A third decision node is presented on the tree, representing the uncertainties in the failure consequences associated with the fatigue failure of the stiffener. As presented in Section C.4 of this appendix, the risk associated with the failure scenarios can be classified in four categories. According to the data presented in Figure C-23, the failure scenarios associated with the fatigue of a main engine room foundation stiffener can be classified in three categories, Level 1, Level 2 and Level 3, with Level 4 having no failure scenarios. The failure consequences associated with this third decision node are classified according to those three categories defined in the risk profile assessment. The failure probability associated with each of these levels corresponds to the sum of the probability of occurrence of each scenario classified in the level under analysis.

The following failure scenarios compose the three levels of risk:

<u>Level 1:</u> 422, 423, 425, 426, 427, 429, 4212, 4213, 4215, 4217, 4222, 4223, 4224, 4225, 4227, 4232, 4233, 4235, and 4237;
<u>Level 2:</u> 424, 4214, and 4234; and
<u>Level 3:</u> 421, 428, 4210, 4211, 4216, 4218, 4219, 4220, 4221, 4226, 4228, 4229, 4230, 4231, 4236, 4238, 4239, and 4240.

Using the data presented in Table C-9, the following probabilities are associated with the occurrence of the risk levels:

<u>Level 1:</u> 1.25E-12;
<u>Level 2:</u> 4.80E-14; and
<u>Level 3:</u> 9.99E-01.

These failure probabilities corresponds to the probability of occurrence of a failure scenario, corresponding to a given risk level, given the occurrence of the main engine foundation stiffener fatigue failure.

The costs presented on the decision tree are adopted for the example, and do not correspond to any real case. An important point is the adoption of different costs of inspection for the inspection methods, since the greater the detection capacity of the method, the greater are the costs associated with its use.

The consequence costs presented on the decision tree are for the purpose of demonstration. The higher the consequences associated with a given risk level, the higher are the consequence costs. Finally, the costs associated with the repair execution are illustrative, but their relation is defined according to the costs presented by Ma and Bea (1995), where the repair 3 methods costs three times the cost of repair 1 method, and repair 3 method costs twice the cost of repair 1 method.

In order to analyze the results of the decision tree, the branches related to a given inspection method must be grouped, in order to form a strategy pair. Each pair is composed of one decision branch corresponding and associated consequences based on the detection of the fatigue crack and second branch corresponding to consequences associated with the non-detection of the fatigue crack. The following pairs were considered for demonstration purposes:

Strategy 1-1. Inspection Method 1, Repair 1 and Non-detection;
Strategy 1-2. Inspection Method 1, Repair 2 and Non-detection;
Strategy 1-3. Inspection Method 1, Repair 3 and Non-detection;
Strategy 1-4. Inspection Method 1, No repair and Non-detection;
Strategy 2-1. Inspection Method 2, Repair 1 and Non-detection;
Strategy 2-2. Inspection Method 2, Repair 2 and Non-detection;
Strategy 2-3. Inspection Method 2, Repair 3 and Non-detection;
Strategy 2-4. Inspection Method 2, No repair and Non-detection;
Strategy 3-1. No inspection.

The expected costs associated with each of these strategy pairs, based on the data presented on the Figure C-28, are:

Strategy 1-1: 28.00 k$ (thousands of dollars);
Strategy 1-2: 35.67 k$;
Strategy 1-3: 43.44 k$;
Strategy 1-4: 20.59 k$;
Strategy 2-1: 49.10 k$;
Strategy 2-2: 57.87 k$;
Strategy 2-3: 66.75 k$;
Strategy 2-4: 40.69 k$;
Strategy 3-1: 0.50 k$.

These expected values show that based on the data presented on the decision tree, the most adequate inspection strategy for the fatigue failure of the main engine stiffener foundation is no inspection, which has an expected value of cost of 0.5 k$ (thousands of dollars). This result can be explained based on the low probabilities associated with the occurrence of the failure scenarios classified according to the most serious risk levels, such as level 2. The weighted costs related to these levels are very low, and do not influence the results of the expected costs associated with the pairs previously defined.

Examination of the tree reveals that the probability of crack detection defined by the better inspection method is not high enough to reduce the weighted consequential costs related to the structure failure in comparison to its higher inspection costs.

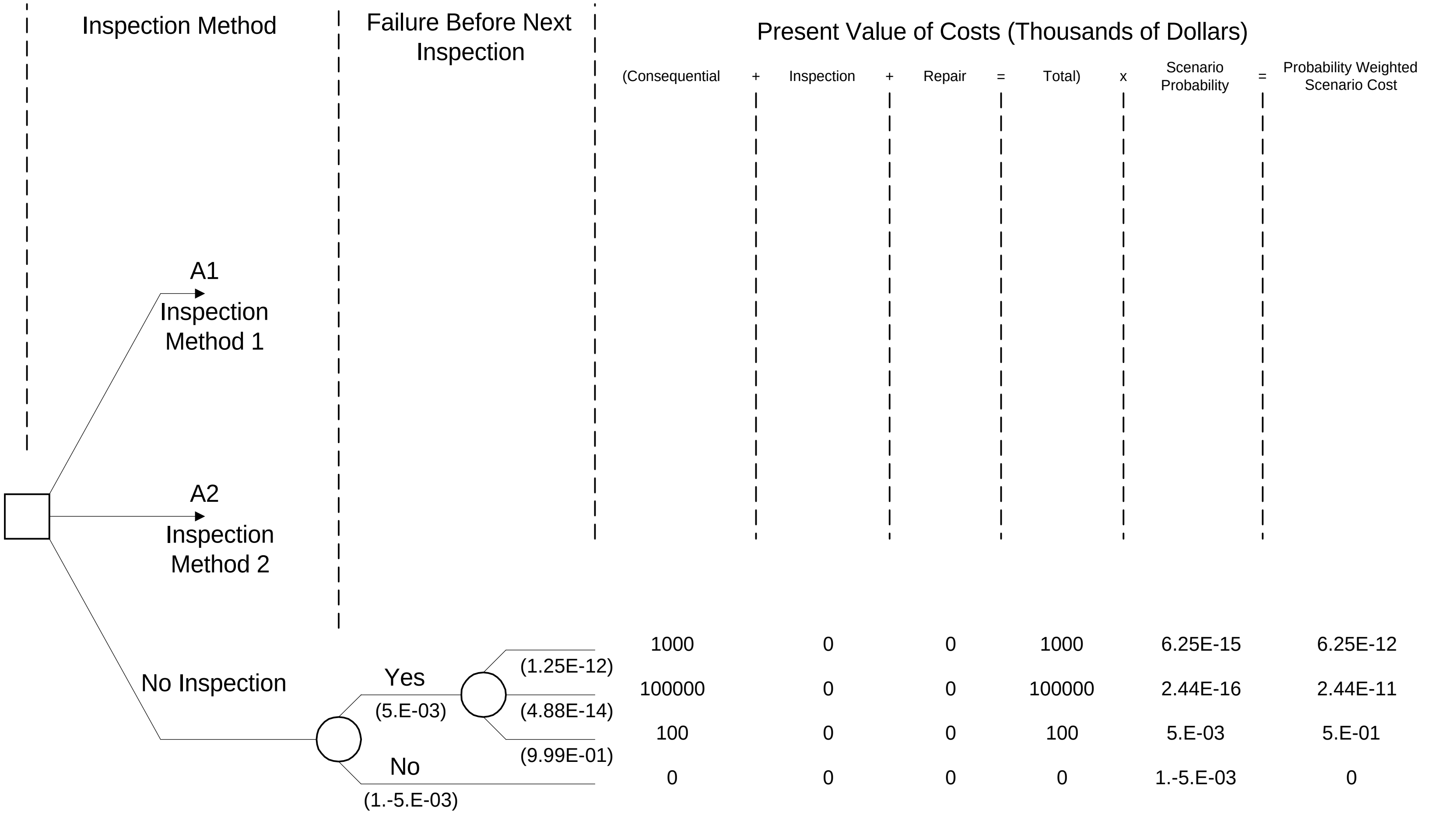
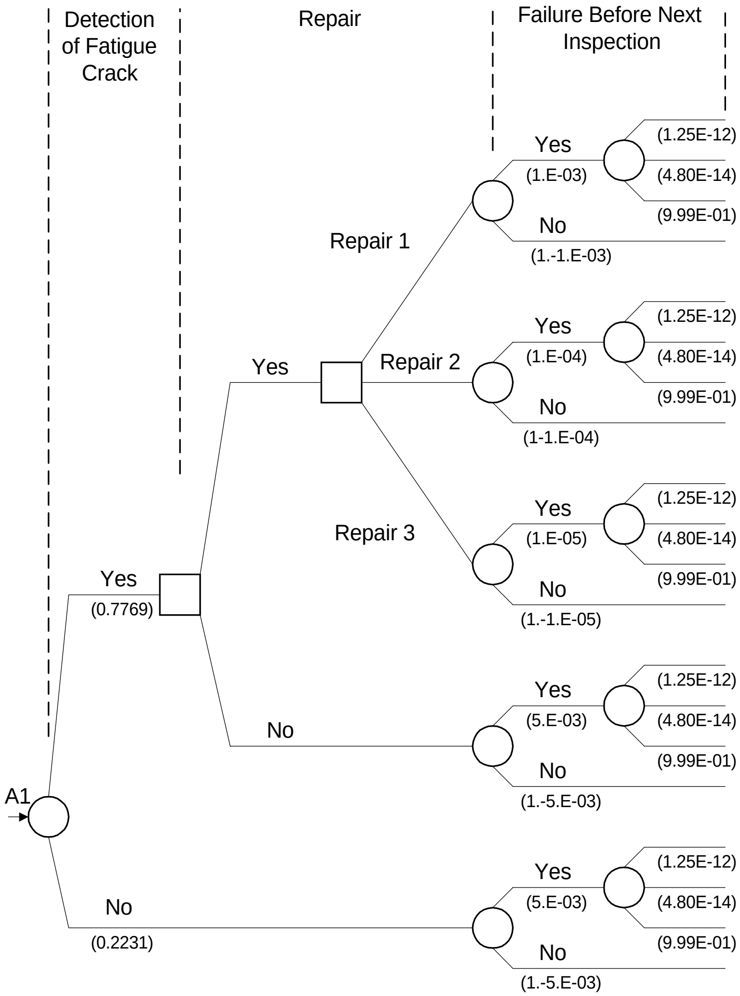


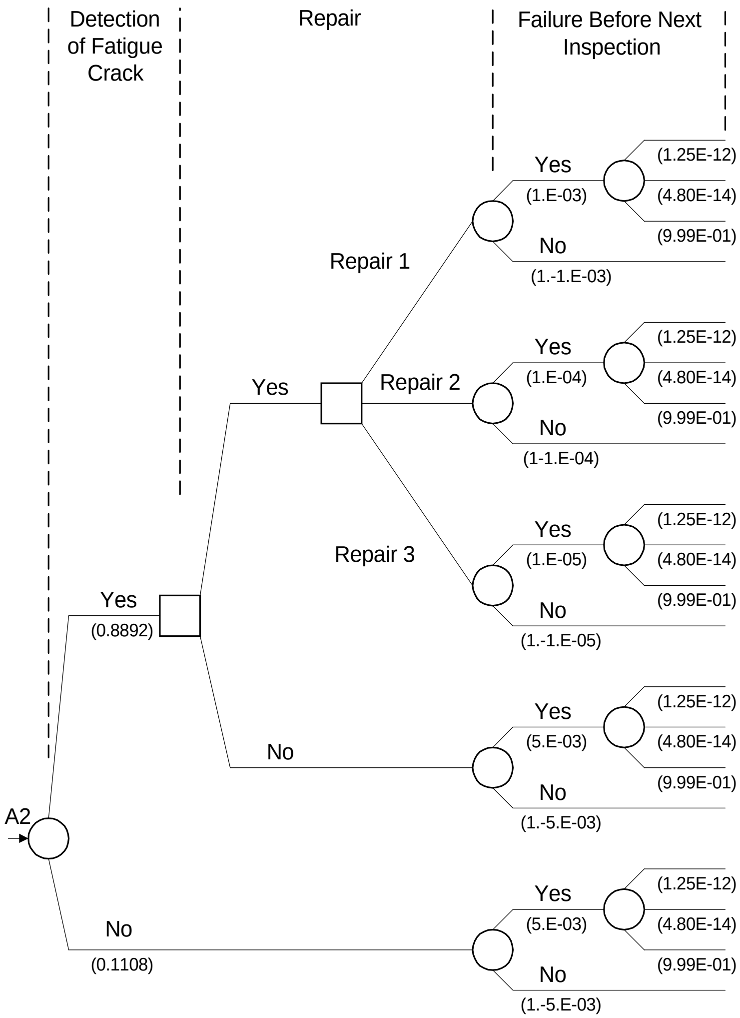
Figure C-28. Decision Tree for Choosing Inspection and Repair Strategy - Page 01/03



Present Value of Costs (Thousands of Dollars)

(Consequential	+ Inspection	+ Repair	= Total)	x Scenario Probability	= Probability Weighted Scenario Cost
1000	20	10	1030	9.71E-16	1.00E-12
100000	20	10	100030	3.73E-17	3.73E-12
100	20	10	130	7.77E-04	1.01E-01
0	20	10	30	7.77E-01	23.31
1000	20	20	1040	9.71E-17	1.00E-13
100000	20	20	100040	3.73E-18	3.73E-13
10	20	20	140	7.77E-05	1.09E-02
0	20	20	40	7.77E-01	31.07
1000	20	30	1050	9.71E-18	1.02E-14
100000	20	30	100050	3.73E-19	3.73E-14
100	20	30	150	7.77E-06	1.16E-03
0	20	30	50	7.77E-01	38.84
1000	20	0	1020	4.85E-15	4.95E-12
100000	20	0	100020	1.86E-16	1.86E-11
100	20	0	120	3.88E-03	4.66E-01
0	20	0	20	7.77E-01	15.53
1000	20	0	1020	1.39E-15	1.42E-12
100000	20	0	100020	5.35E-17	5.36E-12
100	20	0	120	1.11E-03	1.33E-01
0	20	0	20	2.23E-01	4.46

Figure C-28. Decision Tree for Choosing Inspection and Repair Strategy – Page 02/03



Present Value of Costs (Thousands of Dollars)

(Consequential	+ Inspection	+ Repair	= Total)	x Scenario Probability	= Probability Weighted Scenario Cost
1000	40	10	1050	1.11E-15	1.17E-12
100000	40	10	100050	4.27E-17	4.27E-12
100	40	10	150	8.88E-04	1.33E-01
0	40	10	50	8.89E-01	44.46
1000	40	20	1060	1.11E-16	1.18E-13
100000	40	20	100060	4.27E-18	4.27E-13
10	40	20	160	8.88E-05	1.42E-02
0	40	20	60	8.89E-01	53.35
1000	40	30	1070	1.11E-17	1.19E-14
100000	40	30	100070	4.27E-19	4.27E-14
100	40	30	170	8.88E-06	1.51E-03
0	40	30	70	8.89E-01	62.24
1000	40	0	1040	5.56E-15	5.78E-12
100000	40	0	100040	2.13E-16	2.13E-11
100	40	0	140	4.44E-03	6.21E-01
0	40	0	40	8.89E-01	35.56
1000	40	0	1040	6.93E-16	7.20E-13
100000	40	0	100040	2.66E-17	2.66E-12
100	40	0	140	5.53E-04	7.75E-02
0	40	0	40	1.11E-01	4.43

Figure C-28. Decision Tree for Choosing Inspection and Repair Strategy – Page 03/03

C.5.6. Inspection and Repair Risk Profiles

In addition to the analysis of the expected costs as provided in Section C.5.5, the risk profiles of the three inspection strategies can also be studied. The risk profile is a graph that shows the chances associated with possible consequences of the inspection presented in terms of costs. The risk profile is presented as a cumulative distribution function of the costs associated with each strategy.

The risk profile is defined based on the analysis of the risk profile associated with each of branch pairs defined for the inspection strategies. The risk profile is presented in Figure C-29, limiting the costs to the value of 120 thousand dollars, once that beyond this value, all pairs presented a very high probability, close to one.

The risk profile indicates that the strategy “no inspection” presents higher probabilities associated with lower costs, followed by the strategy corresponding to the use of visual inspection without repair. The results support the use of the “no inspection” strategy for the structural inspection.

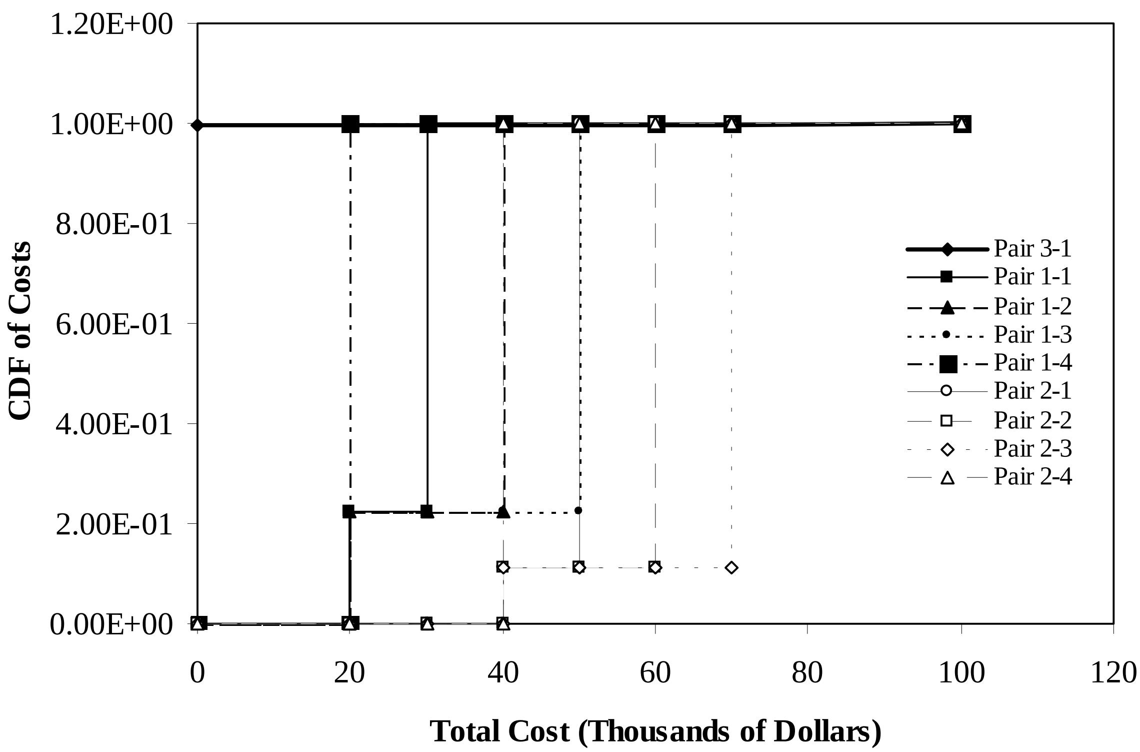


Figure C-29. Risk Profiles for Inspection Strategies

C.6. References

1. Ma, K-T., and Bea, R.G. (1995) “A Repair Management System for Fatigue Crack in Ships.” Society of Naval architects and Marine Engineers, Transactions, 103, 343-369.
2. Vo, T. V., and Balkey, K.R. (1995) “Chapter 17:Risk-Based Inspection and Maintenance.” In Probabilistic Structural Mechanics Handbook, edited by C. Sundararajan, Chapman and Hall, 388-415.
3. Soares, C.G., and Garbatov, Y. (1996) “Influence of Inspection and Repair on The Fatigue Reliability of Oil Tankers.” Proceedings, 15th Conference on Offshore Mechanics and Artic Engineering, C. G. Soares, R.G. Bea, B.J. Leira, N.K. Shetty, W.S. Atkins, and J.E. Vinnem, eds., ASME, New York, 245-254.

PROJECT TECHNICAL COMMITTEE MEMBERS

The following persons were members of the Project Technical Committee that represented the Ship Structure Committee to the Contractor as the resident subject matter experts. As such they performed technical review of the initial project 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.

Project Technical Committee Chairperson

Dr. Roger Basu	American Bureau of Shipping

Project Technical Committee Members

Cdr. Mark Cruder	United States Coast Guard
LT Joe Dufresne	United States Coast Guard
LT Lee Boone	United States Coast Guard
Mr. David Kihl	NSWCD
Mr. Chao Lin	Maritime Administration.
Mr. David Wood	Gibbs & Cox
LT David Martyn	United States Coast Guard
Mr. Harold Reemsnyder	Bethlehem Steel
Mr. Steve Sharpe	American Bureau of Shipping

Executive Director

Lieutenant David J. Martyn	United States Coast Guard

Administrative Assistant

Ms. Jeannette Delaney	Q Systems, INC

Ship Structure Committee Partners and Liaison Members

Partners

The Society of Naval Architects and Marine Engineers

Mr. Jose Femenia
President,
Society of Naval Architects and Marine Engineers

Dr. John Daidola
Chairman,
SNAME Technical & Research Steering Committee

The Gulf Coast Region Maritime Technology Center

Dr. John Crisp
Executive Director,
Gulf Coast Maritime Technology Center

Dr. Bill Vorus
Site Director,
Gulf Coast Maritime Technology Center

Liaison Members

American Iron and Steel Institute	Mr. Alexander Wilson
American Society for Testing & Materials	Captain Charles Piersall (Ret.)
American Society of Naval Engineers	Captain Dennis K. Kruse (USN Ret.)
American Welding Society	Mr. Richard Frank
Bethlehem Steel Corporation	Dr. Harold Reemsnyder
Canada Center for Minerals & Energy Technology	Dr. William R. Tyson
Colorado School of Mines	Dr. Stephen Liu
Edison Welding Institute	Mr. Dave Edmonds
International Maritime Organization	Mr. Tom Allen
International Ship and Offshore Structure Congress	Dr. Alaa Mansour
INTERTANKO	Mr. Dragos Rauta
Massachusetts Institute of Technology	Mr. Dave Burke / Captain Chip McCord
Memorial University of Newfoundland	Dr. M. R. Haddara
National Cargo Bureau	Captain Jim McNamara
Office of Naval Research	Dr. Yapa Rajapaksie
Oil Companies International Maritime Forum	Mr. Phillip Murphy
Tanker Structure Cooperative Forum	Mr. Rong Huang
Technical University of Nova Scotia	Dr. C. Hsiung
United States Coast Guard Academy	Commander Kurt Colella
United States Merchant Marine Academy	Dr. C. B. Kim
United States Naval Academy	Dr. Ramswar Bhattacharyya
University of British Columbia	Dr. S. Calisal
University of California Berkeley	Dr. Robert Bea
University of Houston - Composites Eng & Appl.	Dr. Jerry Williams
University of Maryland	Dr. Bilal Ayyub
University of Michigan	Dr. Michael Bernitsas
University of Waterloo	Dr. J. Roorda
Virginia Polytechnic and State Institute	Dr. Alan Brown
Webb Institute	Dr. Kirsi Tikka
Welding Research Council	Dr. Martin Prager
Worchester Polytechnic Institute	Dr. Nick Dembsey
World Maritime Consulting, INC	VADM Gene Henn, USCG Ret.

RECENT SHIP STRUCTURE COMMITTEE PUBLICATIONS

Ship Structure Committee Publications on the Web - All reports from SSC 392 and forward are available to be downloaded from the Ship Structure Committee Web Site at URL: http://www.shipstructure.org

SSC 391 and below are available on the SSC CD-ROM Library. Visit the National Technical Information Service (NTIS) Web Site for ordering information at URL: http://www.ntis.gov/fcpc/cpn7833.htm

SSC Report Number	Report Bibliography
SSC 415	**Crack Arrest Toughness of Steel Weldments** Dr. L.N. Pussegoda, Dr. L. Malik, B.A. Graville, Y. Han, and Dr. S. J. Kennedy, 2000
SSC 414	**Probability Based Design (Phase 4) Synthesis of the Reliability Thrust Area** P.A. Frieze 2000
SSC-413	**Effect of Welded Stiffeners on Crack Growth Rate** R. J. Dexter, P. J. Pilarski 2000
SSC 412	**Interactive Nature of Cathodic Polarization and Fatigue** C. Jaske 2000
SSC 411	**Evaluation of Effect of Construction Tolerances on Vessel Strength** D. Bruchman, D. Kihl, J. Adamchak 2000
SSC 410	**Fatigue of Aluminum Structural Weldments** R. K. Kramer, B. Rampolla, and A. Magnusson 2000
SSC 409	**Guide to Damage Tolerance Analysis of Marine Structures** I.F. Glen, A. Dinovitzer, L. Malik, R. Basu, and R. Yee 2000
SSC 408	**Detection Probability Assessment of Visual Inspection of Ships,** L .A. Demsetz, J. Cabrera 1999
SSC 407	**Optimal Strategies for Inspection of Ships for Fatigue and Corrosion Damage,** K. Ma, I. R. Orisamolu, R. G. Bea, 1999
SSC 406	**Sea Operational Profile for Structural Reliability Assessments,** I. F. Glenn, R. B. Paterson, L. Luznik, 1999
SSC 405	**Fatigue Resistant Detail Design Guide for Ship Structures,** I. F. Glenn, A. Dinovitzer, R. B. Paterson, L. Luznik, C. Bayley, 1999
SSC 404	**Ship Structural Integrity Information System (SSIS) Phase III: Ship Quality Information System**, H. P. Reeve, R. G. Bea, 1998
SSC 403	**Design Guide for Marine Applications of Composites**, E. Greene, 1997