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SSC-386

SHIP MAINTENANCE PROJECT

Volume 3

Repairs and Maintenance

SHIP STRUCTURE COMMITTEE

1995

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SSC-386 SHIP MAINTENANCE PROJECT **Volume 3** **Ship Structure Committee 1995**

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SHIP MAINTENANCE PROJECT

This report summarizes the results of a joint industry-government sponsored cooperative research project that focused on the development of engineering technology that could lead to improvements in structural maintenance for new and existing tankers. The project was a milestone in that it was conducted on behalf of 22 sponsoring and participating organizations representing government regulatory bodies, classification societies, new-build and repair yards, and ship owners and operators. In these times of fiscal austerity, future joint industry projects will continue to be essential for leveraging our industry wide research needs.

The report has been divided into four volumes; Fatigue Damage Evaluation, Corrosion Damage Evaluation, Repairs and Maintenance, and Durability Considerations. These studies developed and verified engineering guidelines for the evaluation of fatigue damage and corrosion to critical structural components of exisiting ships. A Repair Management System is developed to aid in the diagnosis of ship structural failures and the evaluation of repair alternatives. Finally, engineering and maintenance measures to improve the durability of critical structural details in tankers are proposed. A glossary of terms used is provided and recommendations are presented for future research.

JC Card

J. C. CARD
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

This report is one in a series of reports conducted as part of a two year Joint Industry Research Project "Structural Maintenance for New and Existing Ships" initiated in June 1990 by the Department of Naval Architecture and Offshore Engineering of the University of California at Berkeley to both develop practical tools and procedures for the analysis of proposed ship structural repairs and to prepare guidelines for the cost effective design and construction of lower-maintenance ship structures. This project was organized into six studies. This report is based on the results of Study 4 whose objective was to develop and verify engineering guidelines for the evaluation of fatigue and corrosion repairs to critical structural components of existing ships. This report documents a Repair Management System (RMS) to aid in the diagnosis of ship structural failures and the evaluation of repair alternatives.

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METRIC CONVERSION CARD

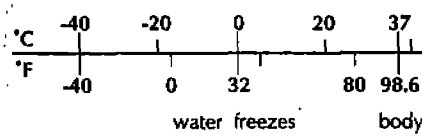
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	metric ton	t
VOLUME				
tsp	teaspoons	5	milliliters	mL
Tbsp	tablespoons	15	milliliters	mL
in^3	cubic inches	16	milliliters	mL
fl oz	fluid ounces	30	milliliters	mL
c	cups	0.24	liters	L
pt	pints	0.47	liters	L
qt	quarts	0.95	liters	L
gal	gallons	3.8	liters	L
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
TEMPERATURE (exact)				
°F	degrees Fahrenheit	subtract 32, multiply by 5/9	degrees Celsius	°C

4

Approximate Conversions fror

Symbol	When You Know	Multiply by
LENGTH		
mm	millimeters	0.04
cm	centimeters	0.4
m	meters	3.3
m	meters	1.1
km	kilometers	0.6
AREA		
cm^2	square centimeters	0.16
m^2	square meters	1.2
km^2	square kilometers	0.4
ha	hectares (10,000 m^2)	2.5
MASS		
g	grams	0.035
kg	kilograms	2.2
t	metric ton (1,000 kg)	1.1
VOLUMI		
mL	milliliters	0.03
mL	milliliters	0.06
L	liters	2.1
L	liters	1.06
L	liters	0.26
m^3	cubic meters	35
m^3	cubic meters	1.3
TEMPERATI		
°C	degrees Celsius	multiply by 9 add 32



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Volume 3 : Repairs and Maintenance

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Cross Reference List for Reports under the Ship Maintenance Project

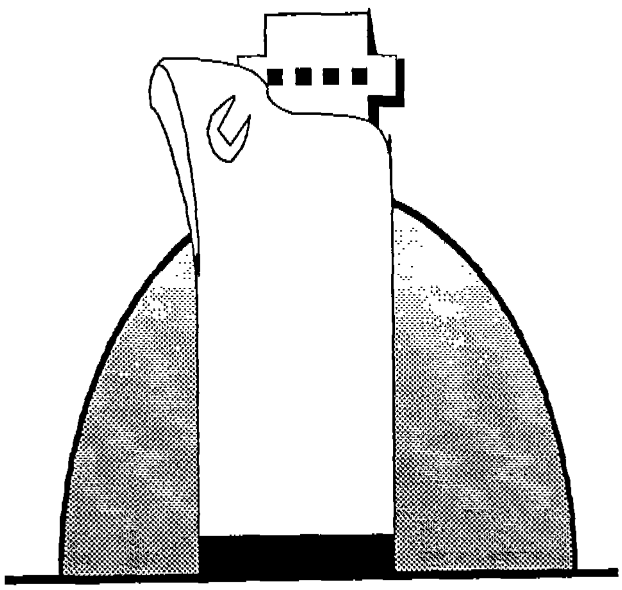
University of California, Berkeley

Number	Title	SSC Report #	NTIS Accession #
	-SSC Published Reports		
SMP 1-3	Fatigue Reliability of Welded Joints in Tanker Structures	SSC-386-Vol 1	PB96-113683
SMP 1-5	Fatigue Damage Evaluation Software : Theory Documentation	SSC-386-Vol 1	PB96-113683
SMP 1-8	Fatigue Damage Evaluation Software : Verification Analysis	SSC-386-Vol 1	PB96-113683
SMP II-1	The Development of a Rational Basis for Defining Corrosion Limits in Tankers	SSC-386-Vol 2	PB96-113691
SMP 4-1	RMS – Repair Management System	SSC-386-Vol 3	PB96-113709
SMP 5-1	Durability Considerations for New and Existing Ships	SSC-386-Vol 4	PB96-113717
SMP 5-2	Advancements in Tankship Internal Strucutral Inspection Techniques	SSC-386-Vol 4	PB96-113717
-The below reports are available from NTIS but were not published by the SSC			
SMP 1-6	Fatigue Damage Evaluations: User Manual	SSC-386-1-6	PB95-261608
SMP 1-7	Fatigue Damage Evaluations: Program Documentation	SSC-386-1-7	PB95-261780
SMP 1-9	Fatigue Damage Evaluations: Structural Maintenance Project Tanker Database	SSC-386-1-9	PB95-261772
SMP 1-10	Fatigue Damage Evaluations: PROSHIP- User Manual	SSC-386-1-10	PB95-261590
SMP 1-11	Fatigue Damage Evaluations: PROSHIP- Program Documentation	SSC-386-1-11	PB95-261582
SMP 2-1	Evaluation of Corrosion Damage in Crude and Product Carriers	SSC-386-2-1	PB95-261798
SMP 2-2	Corrosion Margins for Oil Tankers	SSC-386-2-2	PB95-261806
SMP 2-3	Ship Maintenance Information System	SSC-386-2-3	PB95-264016
SMP 2-4	Corrosion Damage Evaluations	SSC-386-2-4	PB95-264024
SMP 3-1	Structural Analysis and Loadings: Modeling & Analysis Strategy Development	SSC-386-3-1	PB95-264057
SMP 3-1A	Structural Analysis and Loadings: Loadings Strategy Development	SSC-386-3-1A	PB95-264065
SMP 3-2	Study of Critical Structural Details	SSC-386-3-2	PB95-264032

STRUCTURAL MAINTENANCE FOR NEW AND EXISTING SHIPS

RMS--Repair Management System

A System to Aid in the Diagnosis of Ship Structural Failures and the Evaluation of Repair Alternatives



by
Keith A. Gallion

Supervised by
Professor Robert G. Bea

Report No. SMP-4-1
May, 1992

Department of Naval Architecture & Offshore Engineering
University of California, Berkeley

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RMS--Repair Management System

A System to Aid in the Diagnosis of Ship Structural Failures and the Evaluation of Repair Alternatives

by

Keith A. Gallion

ABSTRACT

Due to the complexity of the engineering task and the limited time available, structural repair decisions for crude oil carriers and other large ships often lack sufficient evaluation. To minimize the risk of future structural failures due to poor repair, a new approach is required to provide a more thorough and consistent approach to repair decisions. The goal of this research is to review the process of ship structural repair and to investigate a computerized method to help manage the information required to make intelligent repair decisions. The proposed system, the Repair Management System (RMS), consists of several modules to help the user step through the repair process. These steps include determining the mode and cause of failure (Failure Diagnosis Module), generating a list of repair alternatives (Repair Alternatives Selection Module), analyzing the alternatives and the associated uncertainties (Repair Analysis Module), and selecting the best alternative using decision analysis (Decision Analysis Module). To limit the scope of the research, concentration is placed on the fatigue mode of failure for the side shell structure of crude oil carriers. To demonstrate the feasibility of the RMS concept, an initial version has been programmed using FORTRAN for the fatigue mode of failure. A case study is performed on the repair of a transverse cutout failure using this initial version to illustrate the usefulness of this simple code. The initial version of the RMS could be developed into a powerful tool to aid repair engineers in fatigue repair analysis. However, significant effort is required to fully implement the complete RMS for all modes of failure in a more appropriate programming environment such as C or an expert system shell.

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RMS--Repair Management System

A System to Aid in the Diagnosis of Ship Structural Failures and the Evaluation of Repair Alternatives

by

Keith A. Gallion

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LIST OF SYMBOLS

β	Safety index
A	Life intercept of the SN curve
B	Uncertainty factor (bias) in estimation of fatigue stress component Ω
CF	Confidence or certainty factor related to an expert system rule
C_i, C_f	Initial and future repair costs in present dollars
COV= C	Coefficient of variation
D	Linear cumulative damage
δ	Weibull scale parameter
Δ_f	Linear cumulative damage at failure
ε	Weibull shape parameter
EMV	Expected monetary value
erf(x)	Error function of x
F(t)	Cumulative distribution of t
f(t)	Probability density of t
$\Phi(x)$	Standard normal cumulative distribution function
f_0	Average number of cycles of alternating stress per year
FS	Factor of safety
$\Gamma(x)$	Gamma function of x
K	Stress concentration factor
K_{ij}	Stress concentration factor for load case i at detail location j
m	Inverse slope of SN curve
MNR	Mean number of repairs required for a repair option
MTBR	Mean time between repairs for a repair option
N	Number of cycles of alternating stress
$n(S_i)$	Number of cycles alternating stress Si applied
N_f	Predicted number of cycles to failure under stress range
$N_f(S_i)$	Number of cycles to failure at stress Si
N_0	Weibull maximum number of exceedances in cycles
P_f	Probability of failure of a repair option
PVF	Present value factor to convert the future costs of failure to present value
r	Rate of return on money
R_i	Load ratio for load case j at the ship location under study.
σ	Actual stress
$\sigma_{\ln Tf}$	Standard deviation in natural log of the time to failure
σ_n	Nominal stress
S_0	Weibull extreme alternating stress range
σ_{sd}	Standard deviation

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t	Plate thickness
$\mathbf{T_f}$	Time to failure
$\mathbf{T_{f50}}$	Time to failure, mean
$\mathbf{T_s}$	Desired service life of a repair or ship
U(x)	Utility function of x for decision analysis of repair options
Ω	Stress parameter calculated by wave exceedance diagrams, spectral methods, Weibull model or the Nolte-Hansford model

PREFACE

The two year Joint Industry Research Project "**Structural Maintenance for New and Existing Ships**" was initiated in 1990 by the Department of Naval Architecture and Offshore Engineering, University of California at Berkeley. The objective of this project was to develop practical tools and procedures for the analysis of proposed ship structural repairs and to prepare guidelines for the cost-effective design and construction of lower-maintenance ship structures.

This project was made possible by the following sponsoring organizations:

-American Bureau of Shipping
-Amoco Transport Company
-Arco Marine Incorporated
-BP Marine
-Bureau Veritas
-Chevron Shipping Company
-Daewoo Shipbuilding & Heavy Machinery Ltd.
-Exxon Company International
-Ishikawajima-Harima Heavy Industries Ltd.
-Jurong Shipyard Ltd.
-Lisnave - Estaleiros Navais de Lisboa, SA
-Maritime Administration
-Military Sealift Command
-Mitsubishi Heavy Industries Inc.
-Mobile Ship and Transport Co.
-National Defense Headquarters (Canada)
-Naval Sea Systems Command
-Newport News Shipbuilding & Dry Dock Co.
-United States Coast Guard

In addition, the following organizations contributed to the project as observers:

-Germanischer Lloyd
-Lloyd's Register of Shipping
-West State Inc.

The project was organized into six studies:

Study 1 -- Fatigue Damage Evaluations
Study 2 -- Corrosion Damage Evaluations
Study 3 -- Interaction of Details with Adjacent Structure
Study 4 -- Fatigue and Corrosion Repair Assessments
Study 5 -- Durability Guidelines for New Ships
Study 6 -- Development of Software and Applications Examples

This report documents results from Study 4. The objective of Study 4 was to develop and verify engineering guidelines for the evaluation of fatigue and corrosion repairs to critical structural components of existing ships. This report documents a Repair Management System (RMS) to aid in the diagnosis of ship structural failures and the evaluation of repair alternatives.

CHAPTER 1. INTRODUCTION AND OVERVIEW

1.1. Problem Definition

The dynamic, uncertain and harsh nature of the environment in which a ship operates makes the design and maintenance of a ship a challenging process. Through experience, more advanced design procedures, and tougher materials the catastrophic failures experienced by the Liberty ships in World War II are not a problem for today's ships. Modern ships are now plagued with the less dramatic problem of localized structural failures. When the ship under consideration is a crude oil carrier (tanker) that can carry as much as 200,000 tons of crude oil, these local failures can have very serious safety, financial and environmental implications.

To minimize the risk of structural failure, ship design, operations, human factors, maintenance and repairs must all be addressed. It is the goal of this research is to review the process of structural repairs of crude oil carriers and to investigate a new approach to help manage the information used to make good decisions on the repair of these structural failures.

1.2. Overview of Ship Design Process

To understand the complexities of ship structural repair, a review of the basic process of ship design is required. Until recently, ship design was governed by empirical and technical rules developed from decades of shipbuilding experience. Today the ship designer has the power (and burden) of finite element analysis. Using the finite element approach, the designer develops a new ship structure by completing the following steps:

1. determine the preliminary design using experience, design rules, classification society rules, and other sources;
2. create finite element models of the structure;

3. analyze the overall structure for maximum lo
and ballast conditions;
4. analyze the structural details for dynamic loa
and ballast conditions;
5. inspect analysis results to ensure proper saf
failure, local fracture and fatigue, and bucklin
6. modify the structure and repeat the above step

Considering the size of a typical ship, the large number associated with the loadings and modeling process, consuming and complex process.

The result of this design process is a ship structu structural durability if properly constructed, operated a current levels of durability in commercial crude oil carrie to develop as the ship ages toward its intended design fatigue, cracking, and corrosion of the primary structure.

1.3. Scope of Work

The severity of fatigue, fracture and corrosion pr factors--initial design, construction, operational factors, and the owner and operators. The initial design governs the intended environment and is based on various assumptio maintenance of the ship. Construction includes the use fit-up and alignment of components, proper welding ar proper coating applications so that the design objectives Operational factors such as ballasting, cargo loading ar trading routes govern the actual loads the structure is su The maintenance philosophy of the owner, including ins

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and steel renewals, governs the life-cycle condition of the structure. Inadequate initial design, poor construction, unwise operational practices, and inadequate maintenance all accelerate the advent of structural failures.

For a ship already in service, initial design is complete and the operation of the ship is largely controlled by the economic goals of the owner. As a result, maintenance of the structure is critical. Maintenance involves three levels:

- Inspections to uncover structural problems.
- Preventative maintenance to address problems before they occur. This can include programs such as "just in time" coating maintenance to ensure wastage limits of plating are not exceeded.
- Repair of structural problems following discovery by inspection.

The emphasis of this research is on the proper repair of critical structural detail (CSD) failures in crude oil carriers.

1.4. Repair Decisions

When a structural failure in the form of cracking or excessive corrosion is discovered by inspection, a decision must be made as to the most effective repair. This decision is difficult due to the vast array of engineering, construction and repair knowledge that must be assimilated to make a good repair decision. The same technical issues as in the design of a new ship should be considered. However, many additional factors--both technical and otherwise--must also be considered in a much shorter time. These factors, which will be discussed in more detail in Chapter 2, include technical, economic, and logistic factors.

As a result of the complexity and the short time allowed, the proper repair of ships currently relies heavily on the experience of repair engineers and repair yard personnel. There is simply not enough time to take into account all possible factors and perform detailed analyses. Repair decisions often lack thorough technical and economic evaluation, but serve to get ships back into service quickly.

1.5. RMS Approach

Recently, considerable effort has been put into understanding the effectiveness of specific repairs, especially those associated with fatigue of CSDs. This effort has resulted both from an aging fleet of existing ships and a heightened public interest in environmental issues and is reflected in many papers on the subject (e.g., [USCG,1990], [Jordon,1978,1980], [TSCF,1991]). In addition, records of ship condition are shifting from paper-based systems to computerized systems that contain inspection and repair information in database format. This computerized information can be sorted by an experienced repair engineer to help evaluate the effectiveness of past repairs and assess the overall condition of the ship.

This poses the key question addressed in this research: **How do we properly manage the computerized inspection and repair data, the existing knowledge of both successful and unsuccessful repairs, the complex analysis tools and additional knowledge to make intelligent and timely repair decisions?**

The answer proposed by this research is the **Repair Management System (RMS)**. The RMS is a computerized framework to help repair engineers make good repair decisions by assisting engineers with structural failure diagnosis and repair alternative evaluation, Figure 1.2. The RMS is the first known attempt to handle the complexities of ship structural repair analysis in a framework that provides both elements critical to good repair--quick decisions and thorough evaluations.

The goals of the RMS approach are to: (1) provide a consistent and structured repair strategy; (2) ensure complete and prompt repair evaluations; (3) increase the level of expertise in the shipyard and office; (4) promote a sharing of repair information among ship owners, operators and shipyards; and (5) utilize analytical and historical ship data. To reach these goals, the ability to use both numerical analysis information and symbolic knowledge is required. As a result, an expert system approach to programming is explored.

To limit the scope of this research, concentration is placed on side shell CSDs of crude oil carriers. To further define the scope, a questionnaire was sent to all the participants in the Structural Maintenance Project (SMP) requesting information on the most desirable features of computer software associated with repairs. The highest priorities of participants that responded were the expected life analysis of repairs and a database of repair alternatives, Table 1.1. As a result, concentration in this research is placed on the development of these features within the RMS.

The primary objectives of the RMS research are therefore to: (1) develop a framework for the development of a complete RMS; (2) develop a prototype version of the software for side shell structure, concentrating on repair life estimation and repair alternative selection; and (3) perform a case study using the developed tool for a side shell CSD.

1.6. Overview of Report

In Chapter 2 the basics of ship structural repairs are discussed. These basics include a discussion of the knowledge used in making repair decisions, the steps involved in making a repair decision (gather data, determine mode of failure, determine cause of failure, evaluate and select repair alternative), the considerations involved in making the decision (technical, logistical, and economic), and the general repair options available.

In Chapter 3 the various approaches to repair are discussed with concentration on the proposed RMS. These approaches include the experience-based approach, the detailed analysis approach, and the RMS approach. Details of a computer implementation of a complete RMS to analyze the mode and cause of failure, select repair alternatives, evaluated the life of the alternatives, and perform a decision analysis on these alternatives are discussed.

In Chapter 4 possible methods of failure mode analysis for the RMS are evaluated. These methods include experience evaluation by experts, rule-based systems based on expert knowledge, and a probabilistic approach.

In Chapter 5 the RMS repair alternative selection is discussed in detail for the fatigue mode of structural failure, with concentration on crude oil carrier side shell CSDs. In addition, the specifics of side shell CSD repair are discussed.

In Chapter 6 the RMS repair alternative evaluation for the fatigue mode of structural failure is outlined. A method for simplified comparative analysis is proposed to estimate the fatigue lives of the repair alternatives.

Chapter 7 the RMS repair alternative decision analysis is outlined. The uncertainty in the analysis and decision process is discussed followed by the application of a structured decision analysis involving expected monetary value of repair alternatives and utility theory.

In Chapter 8 the RMS approach is used in the development of a FORTRAN computer routine to illustrate the evaluation of repair alternatives for fatigue failure of crude oil carrier side shell CSDs. A case study analysis is conducted to verify the code and illustrate its effectiveness as a repair tool.

Finally, in Chapter 9 the research is summarized with some concluding remarks and recommendations for future developments.

In the appendices the following are provided: a brief introduction to the basics of expert systems (Appendix A); a listing of the initial version of the RMS and the associated input and output files (Appendix B); and a review of previous repair study work (Appendix C).

Rank (1=most desirable feature)

Feature	A	B	C	D	E	F	G	H	Avg.
Expected life analysis of repair alternatives	1	5	3	1	1	1	2	3	2.1
Economic tradeoff analysis of repair alternatives	4	6	5	5	3	2	3	1	3.6
Graphical database of possible repairs	2	4	1	3	2	4	1	2	2.4
Extendibility to allow updating with new repair data	5	2	4	4	6	3	5	6	4.4
Repair database analysis capabilities (statistical)	3	3	6	6	5	5	4	4	4.5
Reliability-based information	6	1	2	2	4	6	6	5	4.0

Table 1.1. Results of Repair PC Code Questionnaire

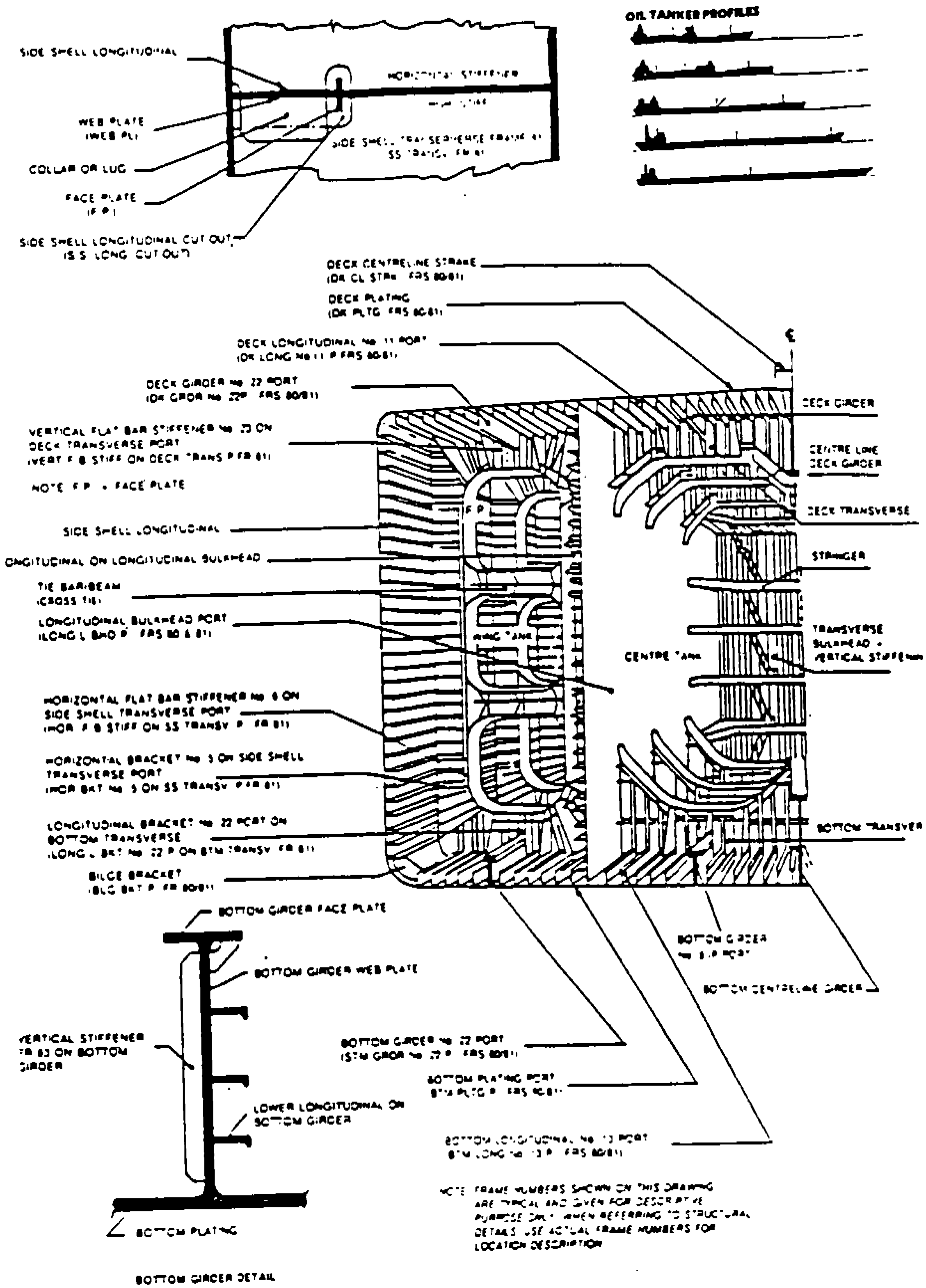

Figure 1.1. Typical Crude Oil Carrier Structure

[TSCF,1991,page 13]

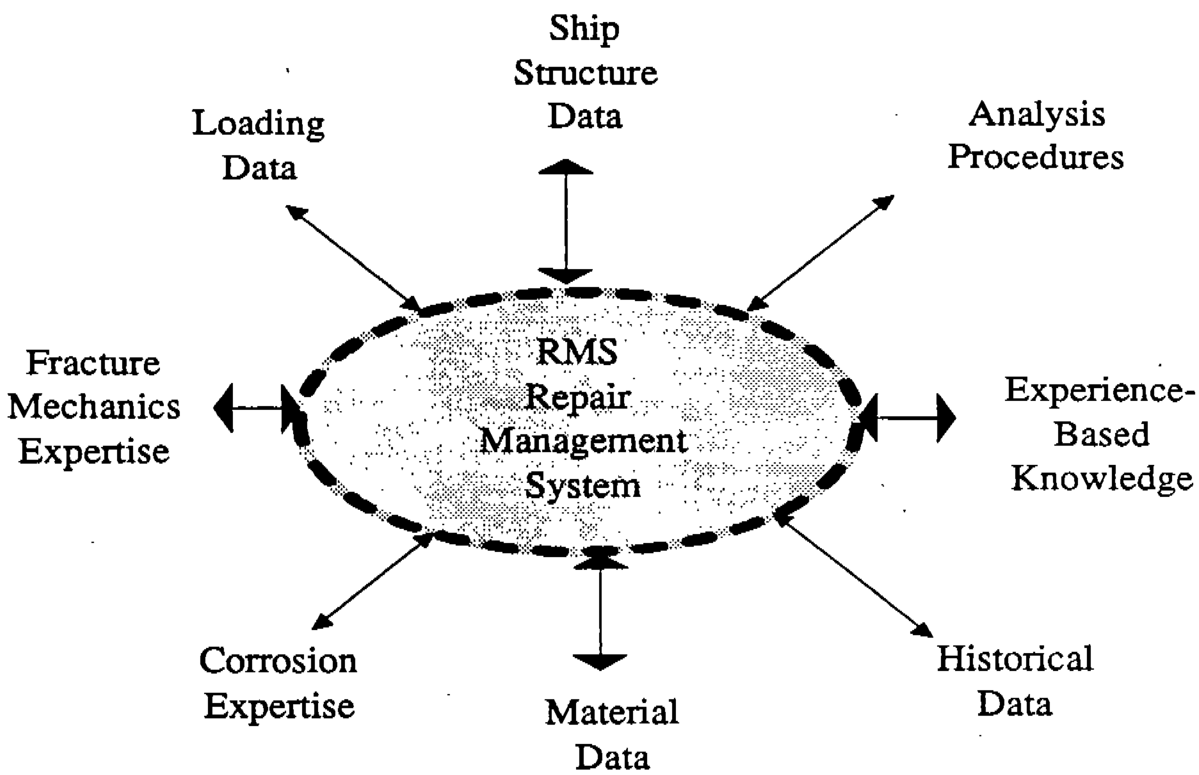

Figure 1.2. RMS Sources of Information

CHAPTER 2. BASICS OF SHIP STRUCTURAL REPAIRS

2.1. Introduction

The purpose of this chapter is to look at all the factors that go into an intelligent repair decision to demonstrate the complexity of the process. Chapter 3 will discuss the approach used by the Repair Management System (RMS) to handle this complexity.

2.2. Repair Decision Steps

In any structural repair situation, there are four basic steps to determining the "best" repair. These steps are summarized below.

Step 1: Gather Data on Structural Failure

Visual structural inspection of tanks on crude oil carriers is performed at regular intervals to locate structural failures and describe the basic properties of the failures. These properties include crack location, crack orientation, crack length, percentage plate wastage and other information necessary to analyze the failure. Due to the enormous size, poor lighting, and dirtiness of the tanks, visual inspection is considered a "heroic" task that cannot locate all structural failures. The probability of crack detection governs the probability that a certain size crack will be detected during an inspection.

Step 2: Determine Mode of Structural Failure

Various ways have been proposed to categorize modes of failure, including by loading type, stress type and others. The Ship Structures Committee categorizes cracks into two levels of crack severity [Stambaugh,1990]:

- <u>Nuisance cracks</u> are small cracks detected before they propagate into adjacent structure. Nuisance cracks are usually repaired by welding.

- Significant fractures are serious cracks that usually propagate perpendicular to the longitudinal and pose a serious threat to structural integrity, including a loss of watertight integrity or complete failure.

For this research, both nuisance cracks and significant fractures are arranged into two load categories of ship structural failure--dynamic and static loading failure. The **dynamic failure mode** occurs under the condition of cyclic loading and includes the following specific modes of failure:

- Low cycle fatigue failure occurs under cyclic loading of 0.5 to 1000 cycles. Loads generally exceed the yield strength of the material. Failure occurs by rapid crack initiation and growth.
- High cycle fatigue failure occurs under cyclic loading of 1000 cycles or more. 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. Cracks already exist in welded structure in the form of weld imperfections and failure occurs by crack growth only. 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 sea water.

The **static failure mode** occurs under the condition of static loading and includes the following specific modes of failure:

- Brittle fracture occurs under static loading and is typical in materials with yield strengths less than 0.5 percent strain before fracture, such as cast iron, concrete and ceramic. Failure is predicted fairly accurately by the maximum normal stress theory and occurs by fracture (not yielding). 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 occurs under static loading and is typical in materials with yield strengths greater than 0.5 percent strain before fracture, such as steel and aluminum. Failure is 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 occurs under compressive loading under sufficient load to surpass unstable equilibrium. Standard solutions exist for bucking of a simple column under compression with various end constraints. More complicated structure, such as the plate structure of a ship, is a difficult analytical problem that requires finite element techniques.
- Stress corrosion cracking can occur in parts subjected to continuous static loads in a corrosive environment. The degradation of strength is represented by the reduction of fracture toughness with time.

All the above modes are influenced by environmental 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. As another example, hydrogen embrittlement would accelerate the advent of brittle fracture.

In addition, a single fracture can contain several 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.

Since a majority of ship structural failures are initiated by high cycle fatigue and corrosion effects, the RMS will concentrate in these areas. However, it is important to keep in mind these other possible modes. The mode of failure dictates the analysis procedures required to evaluate a failure.

Step 3: Determine Cause of Structural Failure

There are five basic causes of a ship structural failure. These causes are the following:

- Design Problem. This cause includes insufficient static, fatigue and/or buckling strength in the design. This insufficiency could result from poor analysis procedures, poor material selection for the service conditions, underestimation of loadings and/or incorrect or insufficient structural modeling.
- Insufficient Quality Control. This cause occurs during construction and results in faulty material processing or fabrication. Examples include poor or incorrect welding procedures, incomplete welding, material defects and tolerance problems.
- Overloading. This cause includes situations that cannot be foreseen in initial design. Examples include collisions, poor tug operations and poor seamanship in extreme weather.
- Environmental Factors. The primary environmental factor is corrosion of the ship structure due to inadequate maintenance.
- Combined Effects.

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].

Step 4: Evaluate Repair Alternatives and Select

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 technical, logistical, economic and other considerations is the one that should be chosen. These repair considerations are discussed in the following section.

2.3. Repair Considerations

Technical Considerations

A complete technical evaluation should determine the primary factors that influence structural failure. The appropriate repair solution can be determined only after these factors are known with some degree of confidence. The following is a partial list of these factors:

- mode of failure;
- cause of failure;
- expected life of repair;
- type of structure (primary, secondary, or minor);
- location of structure in ship (amidships, side shell, etc.);
- trading route of ship; and
- type tank environment which may influence failure, including
    - tank type (cargo, dirty or segregated ballast),
    - COW (crude oil washing),
    - IGS (inert gas system),
    - steel coatings information,

- cathodic protection, and
- temperature of cargo.

In addition, if the approximate time of a significant fracture is known, factors at the time of fracture may be significant [Stambaugh,1990]:

- ship speed and heading;
- ship heading relative to prevailing sea conditions;
- wind speed and direction;
- Beaufort number or wave height and length;
- sea and air temperatures;
- distribution and weight of cargo, ballast and other variable loads;
- displacement and drafts forward and aft; and
- unusual circumstances (e.g., freak waves, bottom slamming, green water on deck).

Unfortunately, for the more common problem of nuisance cracks and even significant fractures on large crude oil carriers, failures may go undetected for some time so that the conditions at the time of fracture are often unknown.

Logistic Considerations

Even if the technically best repair is determined, logistic factors may limit what type of repairs may be done. These factors include the location of the repairs and time considerations.

The location of repairs falls into two categories. 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 are ventilated and washed to accommodate hot work in the tanks. This is the most ideal repair environment although it still presents problems due to the enormous size of crude oil carriers.

Time considerations include factors such as the time available to complete repairs and the time until the next inspection and repairs. More thorough repairs are required if there is a long time before the next inspection or overhaul period.

Economic Considerations

Economic considerations can play a dominate role in repair decisions. These 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..

The economic decision is usually based on the certain initial repair costs and not 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 tradeoff 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.

Additional Considerations

Several additional considerations must be taken into account in repair alternative evaluations. These considerations include the following:

- <u>Ship classification societies</u> dictate the minimum structural requirements for compliance with class rules. These societies include the American Bureau of Shipping (ABS), Bureau Veritas, Det Norske Veritas (DNV), Germanischer Lloyd, Lloyd's Register of Shipping and others.
- <u>Regulating authorities</u>, 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 operators 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.
- Personnel safety is always a primary concern and is closely tied to environmental safety.
- 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.

2.4. General Repair Options

There are several fixed repair options available when a structural failure is discovered. Basic options for both cracks and corrosion are discussed in the following sections. The specifics of the crack repair options for crude oil carrier side shell structure are further elaborated in Chapter 5.

For both cracks and corrosion one option is to not repair and monitor the failure. This option is usually only chosen for minor cracks in non-critical structure and may not be allowed under classification society or regulatory guidelines.

Crack Repair Options

When a crack or series of cracks is discovered, there are a limited number of repair options that could be selected. These options are summarized in Table 2.1.

As shown in Table 2.1, post-weld improvement techniques are always an option in the repair of cracks, although they are usually cost prohibitive. These methods serve to increase the fatigue life of a part at the weld and include both geometric and residual stress methods. Geometric methods increase fatigue life primarily by reducing the geometric stress concentration at the weld location. Geometric methods include grinding (full profile burr grinding or disc grinding), weld toe remelting (TIG dressing or plasma dressing) and weld profiling. Residual methods increase fatigue life through the mechanical addition of residual compressive stresses on the surface of the weld to decrease the magnitude of the resultant tensile alternating stresses when the part is in service. Residual methods include shot peening and hammer peening.

Tests have shown an increase in fatigue life by as much as a factor of two by post-weld improvement methods; however, the increased cost of these procedures must be considered. For more detailed information on the effects of post-weld techniques, good references include the following: [Almar-Naess,85], [ISSC,1988], [ISSC,1991].

Corrosion Repair Options

When corrosion is discovered, there are also a limited number of repair options that could be selected. These options are summarized in Table 2.2. In all cases of recoating, the specific type of coating must be determined. The life of a coating is dependent on many factors [Pollard,1991], including quality of surface preparation, tank and structure type, number of coats applied, type of coating and thickness of coating. The allowable corrosion margins vary among classification societies and are based on various approaches [Chen,1991].

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 2.1. Crack Repair Options

Severity of Corrosion	Type of Corrosion	Corrosion Repair Options
minor coating breakdown	general corrosion	1. no repair and monitor 2. spot blast and patch coat 3. add/maintain anodes
	pitting corrosion--small, shallow pits less than 50% plate thickness in depth	1. no repair and monitor 2. spot blast, epoxy pit fill and patch coat 3. add/maintain anodes
major coating breakdown	general corrosion	1. no repair and monitor 2. spot blast and patch coat 3. reblast and recoat 4. add/maintain anodes
	pitting corrosion--large, deep pits greater than 50% plate thickness in depth, small number	1. no repair and monitor 2. spot blast, weld fill, patch coat 3. add/maintain anodes
	pitting corrosion--large, deep pits greater than 50% plate thickness in depth, large number	1. no repair and monitor 2. spot blast, weld cover plate, patch coat (temporary repair) 3. cut out, weld new plate, blast, coat (permanent repair) 4. add/maintain anodes

Table 2.2. Corrosion Repair Options

CHAPTER 3. APPROACHES TO REPAIR AND THE RMS APPROACH

3.1. Introduction

Several possible approaches to the repair of CSDs in ships are presented, including the experience-based approach, the detailed analysis approach, and the recommended Repair Management System (RMS) approach.

3.2. Traditional Approach to Repair

Currently, an experience-based approach to repair decisions is primarily used. Sometimes referred to as the "black magic" approach by those in the repair business, the traditional approach handles the complexity of the repair problem by using a general set of guidelines for the repair of structural failures. Decisions can be made quickly, but many important technical factors such as the cause of failure are not considered. No detailed analysis to estimate the life of a repair is performed.

3.3. Detailed Analysis Approach to Repair

In special situations, a detailed analysis approach is applied to particularly troublesome structural problems. This involves lengthy detailed ship motion analysis, global and local finite element models, and fatigue analysis such as the analyses by classification societies [ABS,1988] and consulting firms [MCA,1987,1991]. This approach produces repair decisions that are based on the best available analysis techniques and results in technically superior repair decisions. However, significant time and money are spent on this approach, making it inappropriate for most day-to-day decision requirements for repairs.

3.4. RMS Approach to Repair

Clearly, the traditional approach lacks adequate technical evaluation and the detailed approach, although necessary at times, is inadequate to make on-the-spot repair decisions. The goal of the RMS is to provide a computerized system to allow for a sufficiently complete evaluation of repair alternatives in a reasonable time. Thus, the RMS is a compromise between the traditional and detailed repair analysis approaches, Figure 3.1.

To accomplish this goal, the approach taken by the RMS is to provide efficient and effective access to the information required to make repair decisions. Since the information involved in making a repair decision is both numeric (analysis procedures) and symbolic (experience-based knowledge, etc.) in nature, an expert system approach to programming is suggested. The basic concepts behind expert systems are discussed in Appendix A.

The specific roles of the RMS system are to help determine the mode and cause of failure, list the corresponding repair alternatives and estimate the expected repair life based on a technical evaluation. Once the expected life of the repair is known with some degree of confidence, a repair alternative may be selected based on the logistics and economics of the situation or by a structured decision analysis.

3.5. Brief Review of Expert System Applications

Several diagnosis and structural assessment expert system applications are briefly reviewed to illustrate the successful application of expert systems. The requirements of the RMS are compared to these applications.

Application 1: MYCIN

MYCIN is probably the best known diagnosis expert system application developed. MYCIN was developed at Stanford University to help in the diagnosis and treatment of infectious blood diseases. MYCIN is a rule based expert system that contains over 400 rules for its knowledge-base. IF-THEN rules are described with certainty factors to represent the confidence that each rule is accurate. Because expert options of numerous specialists are embedded in the expert system, MYCIN's performance in diagnosis has proven to be equal to or better than any single infectious blood disease specialist.

Because the RMS requires various forms of knowledge including analytical results, the purely heuristic approach used by MYCIN is inappropriate.

Application 2: SPERIL

SPERIL (Structural Peril) has been under development since 1980 at Purdue University to aid in the damage assessment and safety evaluation of existing structures. The damage assessment of structures due to earthquake and other situations is a very complex process which contains a high degree of uncertainty and human judgment. By encoding expert opinions, a consistent and accurate assessment of damage can be made by any inspector [Adeli,1988].

The approaches used by SPERIL are applicable to global failure analysis. Since the RMS is presently concerned only with local failures, details of the SPERIL system do not fit in the RMS framework. However, the goal of a consistent and accurate assessment are the goal of both SPERIL and the RMS.

Application 3: CRACK

CRACK is an expert system under development at the University of Kansas to aid in the evaluation of fatigue and fracture in steel highway bridges. Due to an increasing population of bridges at or beyond their design lives, the evaluation of fatigue and fracture a very important problem. To aid in the difficult problem of fracture evaluation, CRACK seeks to link the quantitative steps associated with numerical fracture mechanics analysis with the heuristic knowledge about how to gather data, structure the data into a model, and interpret the analysis results [Roddis,1988,1992].

As discussed in Chapter 6, the concentration of RMS is on the fatigue mode of failure using a simplified SN curve approach. Roddis uses a fracture mechanics approach that is required to determine if and when cracks require repair. Presently, regulating authorities require that all cracks discovered on crude oil carries be repaired, independent of length.

Application 4: FALCON

FALCON is a Failure Analysis Consultant developed by Duke University to help determine the mode and cause of structural failures. This approach uses a probabilistic approach to determine the mode and cause of failure [Morrill&Wright,1988]. This approach to failure diagnosis is directly applicable to ship structural failure and is explored further in Chapter 4.

3.6. RMS Proposed System

For the RMS, knowledge can take heuristic (rule-based), probabilistic and numerical forms. These forms include: (1) heuristic/probabilistic knowledge about mode and cause of failure; (2) heuristic knowledge about valid repair alternatives; (3) numerical routines for alternative evaluation; and (4) heuristic or probabilistic decision analysis. Since this knowledge is not simply heuristic, the RMS is a "coupled" expert system that requires both symbolic and numeric processing. The RMS uses the same basic steps to evaluate repairs as discussed in Chapter 2. The type of information required to evaluate these steps is summarized in Table 3.1.

The overall architecture of an ideal RMS would consist of the standard expert system components--the user interface, knowledge-base, database, analysis procedures and inference engine--as detailed in Figure 3.2. To organize the wide array of knowledge required for repair analysis, the knowledge in the RMS is grouped together into several module, each of which require different knowledge representation schemes. These modules include the following:

- control module;
- failure diagnosis module;
- repair alternatives selection module;
- repair analysis module; and
- decision analysis module.

Unlike FALCON and CRACK, the RMS must address all aspects of structural failure. FALCON only addresses failure diagnosis and CRACK concentrates on failure analysis. Conceptually, SPERIL is closest to the RMS since it addresses the diagnosis and evaluation required in damage assessment.

Control Module

The control module is a guide to lead the user through the initial steps of making a repair decision. These steps include:

1. inspect the ship and input structural problems to database;
2. identify specific structural detail and failure to evaluate;
3. search ship condition database to determine if similar problems encountered and if past repairs successful or unsuccessful; and
4. search repair guidance database for specific information about structural problems.

This module would combine heuristics with database search procedures.

Failure Diagnosis Module

The failure diagnosis module would be a guide to evaluate the mode and cause of the structural failure based on the physical appearance of the failure, location of the initial failure, the orientation of the failure, the location in the ship, the type of structural detail, and other factors. The result of this module would be a list of possible modes and causes with their associated levels of certainty.

This could include heuristic or probabilistic knowledge based on the opinions of experts in the field of ship structural mechanics and the ship condition and repair guidance database information. For example, a heuristic for determining if a fracture mode is fatigue based on the appearance of the fracture surface might be:

Rule: **IF** the fracture surface is flat and contains beach marks
THEN mode of failure at this crack location is fatigue with
a confidence factor (CF) of 0.9.

As shown, confidence factors may be assigned to each rule depending on the confidence in the knowledge. Using this heuristic approach, the proper knowledge representation is critical to a successful application. A thorough evaluation of rule syntax, organization, use of metarules, and conflict resolution are required.

A probabilistic approach as used by FALCON is probably the most appropriate for the RMS. Details this approach to failure mode and cause analysis are discussed in Chapter 4.

Repair Alternatives Selection Module

The Repair alternatives selection module serves to select the viable repair alternatives based on the mode and cause of failure, the detail configuration and other considerations.

Details of repair alternative selection with concentration on crude oil carrier side shell CSDs discussed in Chapter 5.

Numerical Analysis Modules

Analysis is conducted by the analysis modules. The type of analysis required is determined by the results of the failure diagnosis. For example, if the failure mode is high cycle fatigue with a high degree of certainty, then a fatigue analysis would be required. Various types of analyses might be required, including:

- fatigue analysis;
- corrosion analysis;
- buckling analysis;
- global failure analysis; and
- structural reliability and condition assessment analysis.

These modules serve to link symbolic information concerning analysis steps, numerical procedures and interpretation of numerical results to conduct analysis. Knowledge representation is a key issue in this module, and Roddis' three level approach linking the heuristic, qualitative, and quantitative levels is required [Roddis,1992].

Since ship repair engineers are often unfamiliar with the details of fatigue, fracture, corrosion, and other analyses as applied to the complex case of a ship structure, the modules associated with these analyses could also serve to educate the users through an extensive explanation facility.

To account for the different structural configurations, a library of standard structural details is required in the general database. New details must be added as required.

A probabilistic approach to the calculations in which the historical database is used to establish a prior probability of failure for a particular structural detail could be incorporated into these modules.

Details of repair life estimation for the fatigue mode of failure are discussed in Chapter 6.

Decision Analysis Module

A final module, the decision analysis module, is required to select the most appropriate repair alternative. A structured procedure is required due to the high level of uncertainty involved in the various stages of the analysis. These uncertainties are associated mainly with the following:

- mode and cause of failure;
- repair life analysis procedure;
- cost estimates; and
- economic variables.

Depending on the repair option selected, the expected life of the repair and the uncertainty in life will vary. By accounting for the various economic factors discussed in Chapter 2 and the uncertainties in the life estimation process, this module could help a repair engineer evaluate alternatives based on both initial and expected future costs, including the cost of failure.

Details of decision analysis applied to fatigue mode of failure are discussed in Chapter 7.

Step	Description	Computational Requirements
1	Gather Data	Data
2	Determine Mode of Failure	Knowledge
3	Determine Cause of Failure	Knowledge
4	a. Determine Repair Alternatives	Data+Knowledge
	b. Evaluate Repair Alternatives	Data+Knowledge+Numerical
	c. Select Repair Alternative	Knowledge

Table 3.1. RMS Computational Requirements

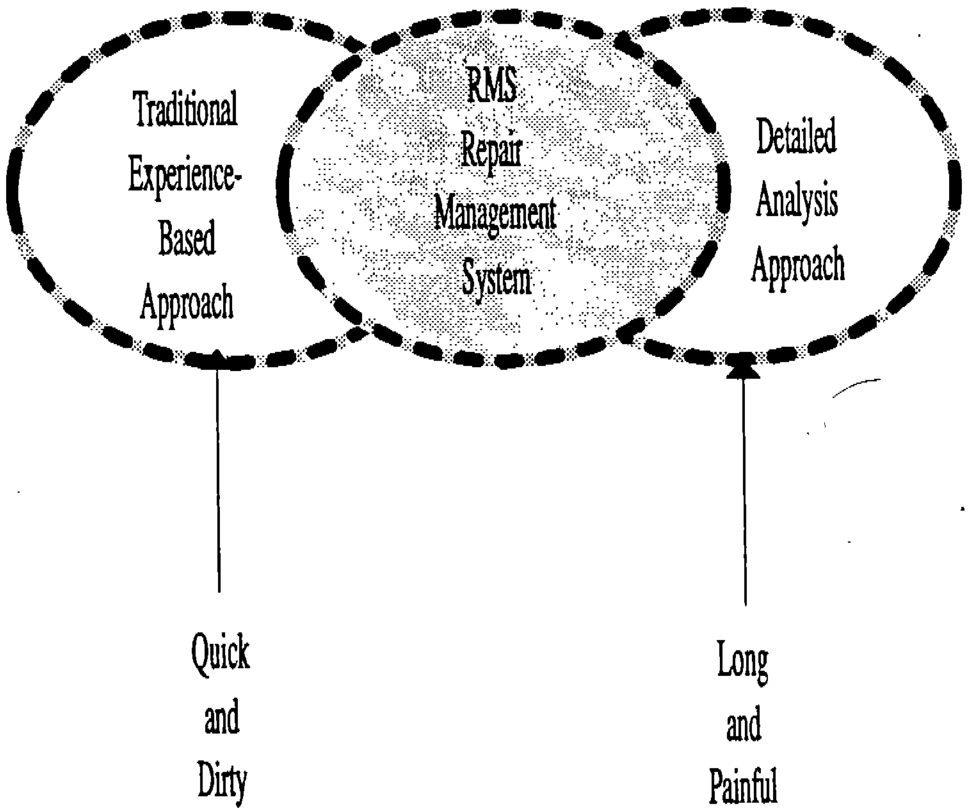

Figure 3.1. RMS Analysis Level

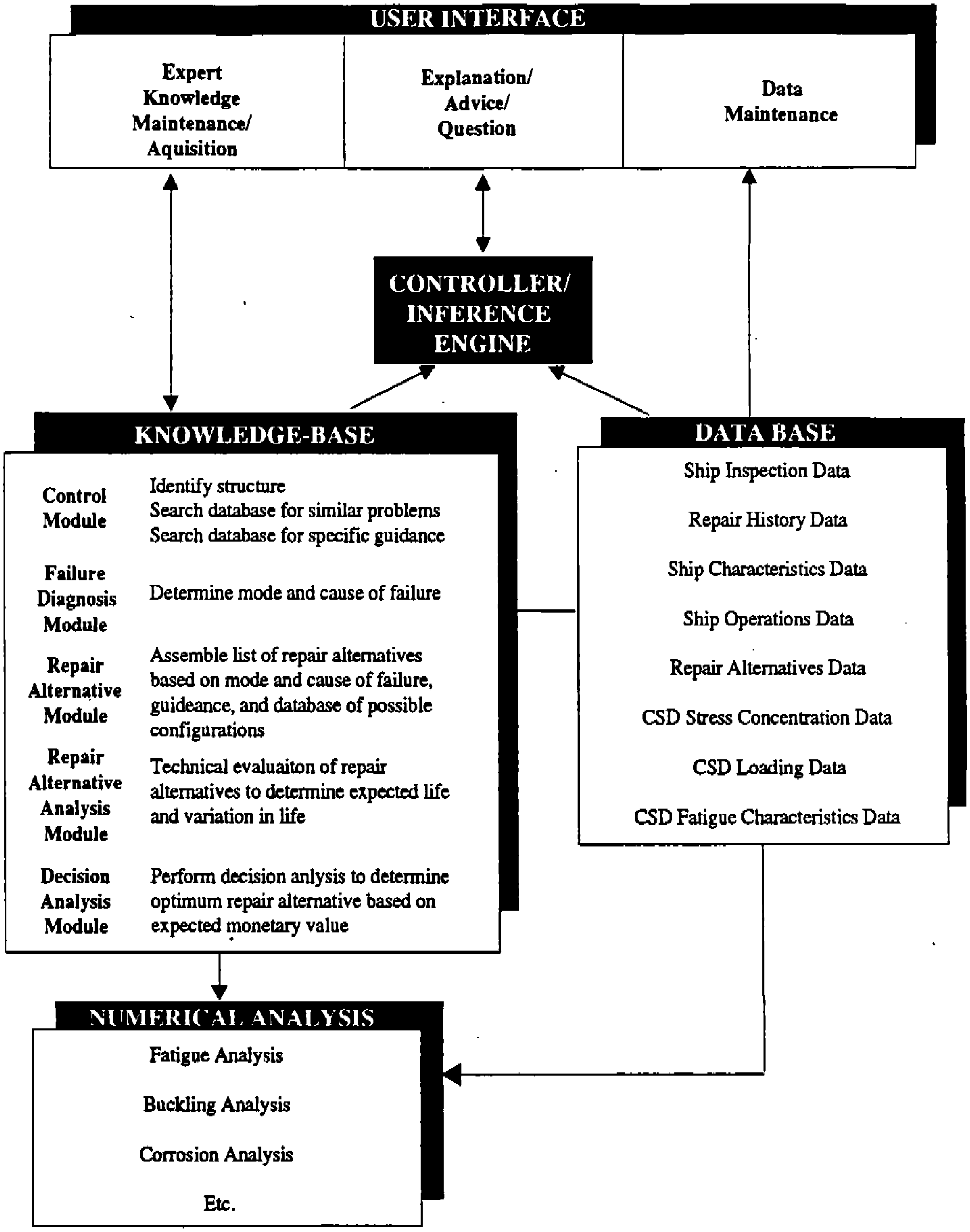

Figure 3.2. RMS System Architecture

CHAPTER 4. RMS FAILURE DIAGNOSIS

4.1. Introduction

Failure diagnosis consists of determining the mode of failure and the cause of failure. Since repair action is generally a function of the mode and cause of a structural failure, the proper determination of the mode and cause is critical to accurate repair analysis in the Repair Management System (RMS). This discussion will concentrate on modes involving metal fracture--the predominant mode of ship structural failure. For a complete discussion of failure analysis for all modes of metal failure, refer to the American Society of Material Engineer's Metals Handbook [ASME].

The mode of ship structural fracture (either fatigue, brittle fracture, or ductile fracture) can usually be determined by experts through inspection of the fracture surface, but repair engineers are generally not experts in fracture inspection. The exact cause of failure cannot usually be determined due to the many factors that contribute to the cause of failure as discussed in Chapter 2. As a result, failure diagnosis should concentrate on two problems:

- increasing the expertise of repair engineers in the field of failure mode analysis; and
- assist in the determination of the contributing causes of failure.

Two basic approaches are to be considered in the following sections--a rule-based approach and a probabilistic approach.

4.2. Rule-Based Approach

Applying rules for the specific case of ship structural metal fracture is fairly straight-forward. Sample rules to help determine the mode of failure at the origin of cracking are:

Rule 1: **IF** the fracture surface is flat and contains beach marks or appears smooth
THEN mode of failure is fatigue.

Rule 2: **IF** the fracture surface is flat and contains chevron marks and appears bright and granular
THEN mode of failure is brittle fracture.

Rule 3: **IF** the fracture surface is not flat (shear lips) and appears dull gray and non-granular
THEN mode of failure is ductile fracture.

This set of rules, which was developed based on a ship fracture investigation guidance manual [Stambaugh,1990,Part 2], could be easily programmed in a rule-based expert system format for use by repair engineers.

Unfortunately, this set of rules is only useful if the fracture surface is visible. A much more extensive set of rules is required to determine the mode of failure based on other attributes. In addition, it is much more difficult to develop a concise set of rules for the determination of the cause of failure due to a large number of possible contributing causes. This difficulty leads to the categorization approach discussed in the following section.

4.3 Categorization Approach

An alternate to the rule-based approach was developed by Duke University through their work on the Failure Analysis Consultant (FALCON) [Morrill&Wright,1988]. This approach uses a probabilistic approach to determine the mode and cause of failure and is probably most appropriate for the RMS. Morrill and Wright illustrate how the determination of the mode and cause of material failure can be viewed as a categorization problem. A table of modes of failure and associated possible causes of failure was developed by questioning experts in failure analysis, Table 4.1. The entrees in Table 4.1 represent $Pr(E_j \mid M_i)$--the probability that, given the mode of

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failure associated with the row, the evidence associated with the column will exist. For example, for the brittle fracture mode and evidence concerning loading:

Pr (LOAD=static | MODE=brittle fracture)	= 0.28
Pr (LOAD=dynamic | MODE=brittle fracture)	= 0.20
Pr (LOAD=impact | MODE=brittle fracture)	= 0.52

Assuming this a collectively exhaustive and mutually exclusive list of loadings, the sum of the probabilities associated with an evidence category must be 1.00. In addition, each category of evidence must be independent of all other evidence categories.

To determine the mode of failure, a series of questions is asked. Initially, the probability of each failure mode is equal to the inverse of the total number of possible modes (0.1 for Table 4.1). For example, the first question might be:

Question: What was the mode of the loading that caused failure?

Answer: Static

After this answer is given, the probability of all failure modes may be updated by applying Bayes' rule. Bayes' rule states that the conditional probability that the failure mode is M_i given that the new evidence E_j is calculated based on the prior probability of mode i by:

$$\Pr(M_i \mid E_j) = \frac{\Pr(M_i)\Pr(E_j \mid M_i)}{\Pr(E_j)} \tag{4.1}$$

Given m possible modes of failure, the probability of evidence Ej is given by:

$$\Pr(Ej) = \sum_{i=1}^{m} \Pr(M_i)\Pr(E_j \mid M_i) \tag{4.2}$$

Therefore, after the first question is asked, the new probability of, for example, brittle mode of failure is:

$$
\begin{aligned}
\Pr(Ej) &= \sum_{i=1}^{10} \Pr(M_i)\Pr(E_j \mid M_i) \\
&= .1(.28)+.1(.63)+.1(.005)+.1(.005)+.1(.005)+ \\
&\quad .1(.73)+.1(.77)+.1(.94)+.1(.80)+.1(.80) \\
&= 0.496
\end{aligned}
$$

$$
\begin{aligned}
\Pr(M_i \mid E_j) &= \frac{\Pr(M_i)\Pr(E_j \mid M_i)}{\Pr(E_j)} \\
&= \frac{0.10\ (0.28)}{0.496} = 0.056 \\
&\Rightarrow \text{probabilty of brittle fracture before next question}
\end{aligned}
$$

This process is continued for each mode after each question until there is a relatively high probability of a single mode of failure.

There are several possible sources of error in this procedure. These sources include the following [Morrill&Wright,1988] [Wood, 1990]:

- probabilities in table (evidential attributes) not accurately accessed;
- evidential attributes not independent and exhaustive;
- competing failure modes are not mutually exclusive or exhaustive; and
- lack of knowledge (not known answer) results in equal probabilities among the possible evidences (same as when evidence known with certainty but also equiprobable).

The magnitude of all these errors can be reduced by careful construction of the table of conditional probabilities.

Additional investigation into failure mode and cause analysis was conducted at Duke. Methods investigated include reasoning by analogy [Morrill&Wright,1989] and pattern recognition techniques [Wood,1989]. These investigations explored solutions to some of the weaknesses of FALCON, including the use of case study data to determine the mode and cause of failure. Detailed evaluation of these approaches will be reserved for future work.

Of current interest is the significant attributes of failure presented by Morrill and Wright. These thirteen attributes are:

1. microscopic fracture appearance (striations, cleavage, etc.);
2. macroscopic fracture appearance (beachmarks, chevron marks, etc.);
3. operating Temperature (low/medium/high);
4. corrosion (true/false);
5. crack is branched (true/false);
6. stress rate (plane strain/plane stress);
7. material strength (low/medium/high);
8. loading mode (static/cyclic/impact);
9. stress type (tension/compression/shear);
10. crack propagation (intergranular/transgranular);
11. crack speed (stable/unstable);
12. point of crack initiation (fillet, scratch, weld, etc.); and
13. alloy type (1020 steel, 7075 aluminum, etc.).

4.4. Categorization Approach Applied to Ship Structure

The FALCON technique is now applied to ship structural failures. The first step in application is the development of a list of significant evidential attributes and significant failure modes for ship structural failure. These attributes must conform as close as possible to the rules discussed above. Based on the discussion in Chapter 2, the following failure modes are proposed for ship structure:

1. high cycle fatigue;
2. corrosion fatigue;

3. brittle fracture;
4. ductile fracture;
5. buckling failure; and
6. stress corrosion cracking.

Also based on the discussion in Chapter 2 and on the work of Morrill and Wright, the following significant attributes are proposed:

1. fracture appearance information, including
   - macroscopic fracture appearance (beachmarks, chevron marks, etc.),
   - crack is branched (true/false),
   - crack speed (stable/unstable), and
   - point of crack initiation (fillet, weld, etc.);
2. material information, including
   - material type (low tensile steel/high tensile steel), and
   - corrosion wastage (none/moderate/severe);
3. loading information, including
   - stress rate (plane strain/plane stress),
   - loading mode (static/cyclic/impact), and
   - dominant stress type (tension/compression/shear); and
4. tank environment information, including
   - tank heating (yes/no),
   - tank type (cargo, dirty, segregated ballast),
   - COW (yes, no),
   - IGS (yes, no), and
   - sacrificial anodes (yes, no).

Note that all attributes requiring laboratory testing are not considered significant since, in reality, they are seldom performed for standard ship structure repair. Alternatively, loading information could be determined by analysis based on the type of detail, the location of the detail within the in ship and the trading route of the ship. In addition, historical information on the performance of specific structural details under specified loading conditions could be maintained in a database to establish the initial probability of a certain failure mode and cause for that detail.

Using the same attributes, the cause of failure may also be investigated. The proposed significant causes for ship structural failure discussed in Chapter 2 are:

1. design problem;
2. insufficient quality control;
3. overloading; and
4. environmental factors.

In order to implement this approach, Table 4.2 should be sent to experts in the field of ship structural failure. An average of the responses could be used for the ship structure failure mode and cause evaluation process. If a large discrepancy in the data exists, a careful evaluation of the responses and the attributes will be required.

Evidential Attributes

Failure Mode	Load			Stress			Temp			Mat	
	Static	Dyn	Impact	Tens	Comp	Shear	Low	Med	High	Brittle	Duct
Brittle Fracture	.28	.20	.52	.82	.11	.07	.60	.32	.08	.84	.15
Buckling	.73	.03	.24	.005	.98	.015	.22	.56	.22	37	.63
Corrosion Fatigue	.005	.99	.005	.87	.03	.10	.12	.68	.20	.23	.77
Creep	.94	.03	.03	.55	.14	.31	.05	.35	.60	.20	.80
Ductile Fracture	.63	.22	.15	.57	.06	.37	.13	.53	.34	.14	.86
Gross Yielding	.77	.07	.16	.50	.18	.32	.13	.53	.34	.02	.98
High Cycle Fatigue	.005	.99	.005	.80	.10	.10	.20	.63	.17	.27	.73
Hydrogen Embrittlement	.80	.10	.10	.92	.03	.05	.10	.78	.12	.05	.95
Low Cycle Fatigue	.005	.99	.005	.77	.10	.13	.10	.50	.40	.12	.88
Stress Corrosion	.80	.10	.10	.92	.03	.05	.10	.72	.18	.07	.93

Table 4.1. FALCON Based Method for Fatigue Mode Evaluation

[Morrill and Wright, 1988]

	Attribute Category	Attribute Sub-Category	Failure Mode						Failure Cause			
			Fatigue	Corrosion fatigue	Brittle fracture	Ductile fracture	Buckle failure	Stress corros	Design prob	Quality control	Overload	Envir factors
Fracture Appearance Attributes	Macroscopic fracture appearance	beachmarks										
		chevron marks										
		flat										
		shear lips										
	Crack is branched	true										
		false										
	Crack speed	stable										
		unstable										
	Point of crack initiation	fillet weld										
		corner										
		other										
Material Attributes	Steel type	low tensile										
		high tensile										
	Corrosion wastage	none										
		moderate										
		severe										
Loading Attributes	Stress rate	plane strain										
		plane stress										
	Loading mode	static										
		cyclic										
		impact										
	Dominant stress type	tension										
		compression										
		shear										
Tank Attributes	Tank heating	yes										
		no										
	Tank type	cargo										
		dirty										
		segregated										
	Tank COW	yes										
		no										
	Tank IGS	yes										
		no										
	Tank anodes	yes										
		no										

Table 4.2. FALCON Based Ship Structural Failure and Cause Attributes

CHAPTER 5. RMS REPAIR ALTERNATIVES SELECTION

5.1. Introduction

A ship structure may be viewed as several levels of structural categories, from global to detail structure. For each level, a different approach to analysis is required. The hierarchy of structure may be viewed as:

- global structure (entire ship) -- made up of many tank structures;
- tank structure (cargo tank, ballast tank) -- made up of several substructures;
- substructure (stiffened panels, etc.) -- made up of many CSDs;
- critical structural details (side shell CSD, deck CSD, etc.) -- made up of several components; and
- CSD component (steel plate, bracket, stiffener, weld, etc.).

To organize and manage this structural information in a database format, a frame-based or object oriented representation is proposed for the Repair Management System (RMS). A frame-based representation takes advantage of inheritance to represent data as discussed in Appendix A. The frame network proposed for the RMS is provided in Figure 5.1.

To demonstrate the process of selecting repair alternatives, concentration will be placed on crude carrier side shell structure and the fatigue mode of failure. In the following sections, the basics of crude carrier side shell structure are explored followed by side shell repair alternative selection.

this structure is of great concern since it may propagate to the side shell and result in cargo leakage. This structure is also subjected to high alternating loads due to the effect of wave pressures.

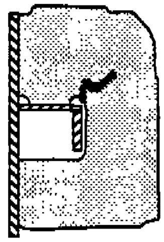
Crude carrier side shell structure consists of six basic components: side shell plate, transverse plate and cutout, longitudinal side shell plate stiffener, flatbar transverse plate stiffener, lugs and brackets. In order to computerize the possible configurations of these components, a method to catalog the available configurations must be developed. Table 5.1 summarizes the possible variations in the components of side shell structure along with a coded representation of each component. Side shell plate is not included since there is only one configuration of this component. As new designs are developed, Table 5.1 must be updated.

To automate the selection of valid redesign alternatives, components should be subdivided further into fixed and interchangeable components. Fixed component are those components that cannot be easily changed during repair because they are an integral part of a higher level structure. Fixed components include the side shell plate, the longitudinal stiffener, and the transverse cutout since they are part of the side shell stiffened panel structure. Interchangeable components are those that can be easily ripped out and replaced with alternate designs. Interchangeable components include the flatbar transverse plate stiffener, lugs and brackets.

5.3. Side Shell Structure Repairs

The repair alternatives can also be categorized in a similar manner. A catalog of possible repair alternatives is listed in Table 5.2. The redesign repair option is the most complex and involves any change in an interchangeable component.

To illustrate how Tables 5.1 and 5.2 are used, consider the following side shell configuration which may be described in terms of Table 5.1 as (L=L, C=1, G=N, F=N, B=N):



If there is a high probability that the crack discovered in a side shell cutout is due to fatigue (based on failure diagnosis), then the repair options from Table 5.2 are VW, IP, or R. Redesign options would consist of changes to interchangeable components. A few of these options are the following:

- Redesign 1: Add lug component (L=L, C=1, G=S, F=N, B=N)
- Redesign 2: Add lug component + hard toe bracket (L=L, C=1, G=S, F=N, B=H)

The combination of 2 redesign options and 2 crack repair options gives a total of six repair options. These options are summarized in Figure 5.3. It is clear that the number of options for all possible redesigns is very high. For the RMS, it is proposed that a shorter list of valid design alternatives be chosen by the user for evaluation.

As shown, repair alternatives that should be considered are a function of the mode of failure and the configuration of the detail. In general, any repair option for a given mode of failure is viable no matter what the cause of failure; however, the analytical evaluation of the alternatives is highly dependent on both the mode and cause of failure. The specific cause of failure will have the following impact on the repair decision process:

- **Design problem** ⇒No impact.
- **Insufficient quality control** ⇒Determine if initial design adequate under proper quality control. Include material and assembly imperfections in analysis. If adequate, refurbish. If not adequate, redesign detail.

- **Overloading** ⇒Determine if load can be reduced or avoided by operational changes. If so, original design adequate. If not, redesign detail.
- **Environmental factors** ⇒Determine if environmental factors can be reduced or eliminated through proper coating, anodes, etc. If so, original design adequate. If not, redesign detail.

The following chapter addresses the analytical aspects of the fatigue mode of failure. The specific impact of the causes of failure and their integration into the RMS are reserved for future work.

Component	Description		Comments/Graphic
Longitudinal (L)	T	T	
	L	Angle	
	B	Bulb	
Cutout (C)	1		
	2		
	3		
	4		
Lug (G)	N	None	
	S	Single	
	D	Double	
Flat Bar (F)	N	None	
	H	Hard Toe	
	S	Soft Toe	
	F, A	Forward, Aft	Location of flat bar
Bracket (B)	N	None	
	H	Hard Toe	
	S	Soft Toe	
	F, A	Forward, Aft	Location of bracket

Table 5.1. Component Designations for Side Shell Structure

Repair	Description	
Cracking Repair (CR)	NR	No repair
	TR	Temporary Repair • VW=v and weld • DP=add double plate • DH=drill hole at crack tip
	PR	Permanent Repair • VW=v and weld • IP=insert new plate • R=redesign detail
General Corrosion Repair (GCR)	NR	No repair
	SP	Spot blast and patch coat
	RR	Reblast and recoat
	IP	Add insert plate and coat
	CP	Modify cathodic protection
Pitting Corrosion Repair (PCR)	NR	No repair
	SE	Spot blast epoxy fill
	SW	Spot blast weld fill
	IP	Add insert plate and coat
	CP	Modify cathodic protection

Table 5.2. Repair Alternatives for Side Shell Structure

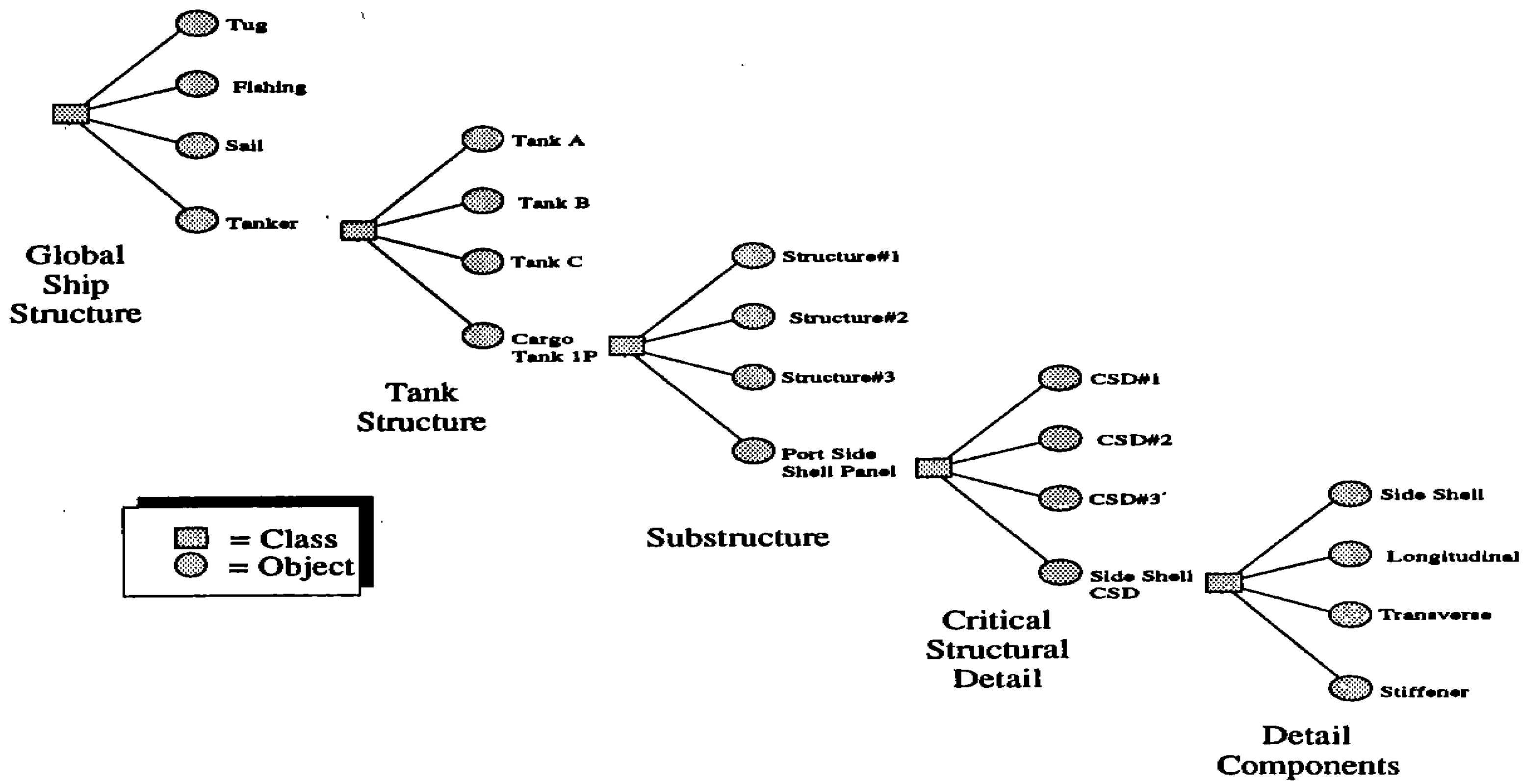
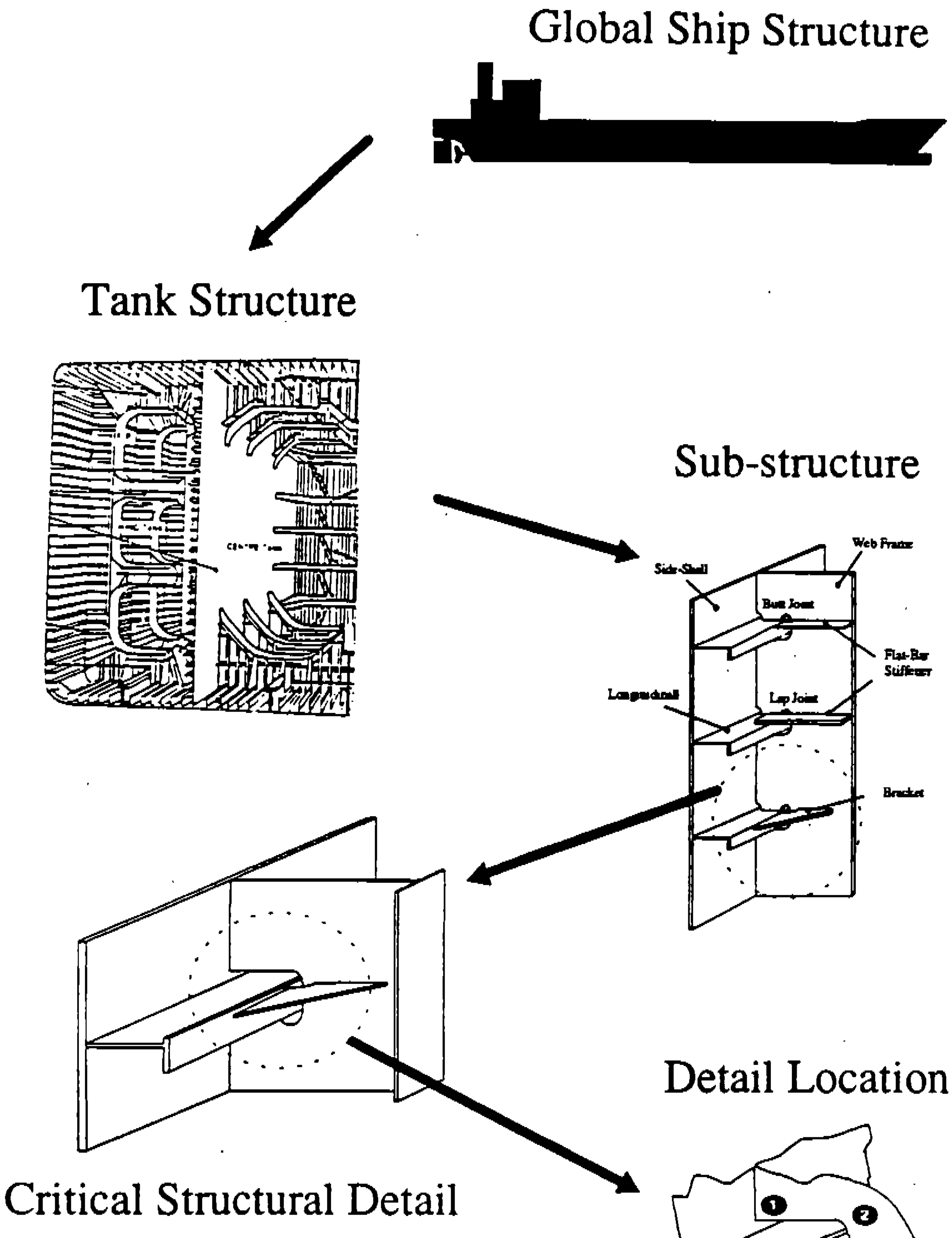
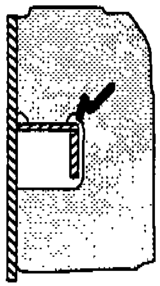
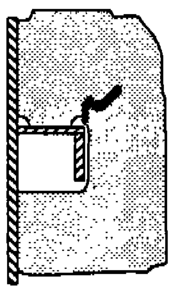


Figure 5.1. RMS Frame Network for Ship Structure


Global Ship Structure
Tank Structure
Sub-structure
Web Frame
Side-Shell
Butt Joint
Flat-Bar Stiffener
Lap Joint
Bracket
Detail Location
Critical Structural Detail

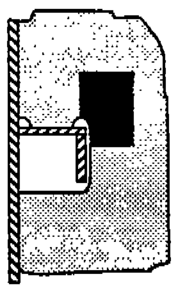


5 inch Crack, discovered at ship life of 10 years



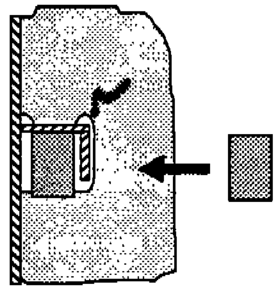
Repair 1:
Grind out crack, weld and paint

? year repair life



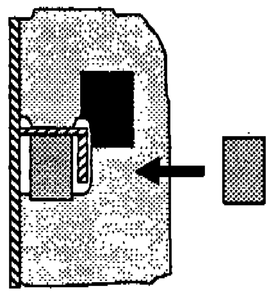
Repair 2:
Cut out section and butt weld

? year repair life



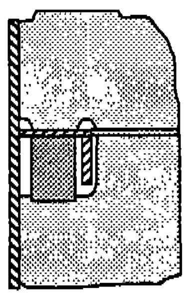
Repair 3:
Add lug plus repair 1

? year repair life



Repair 4:
Add lug plus repair 2

? year repair life



Repair 5:
Add lbracket(s) plus repair 1 or repair 2

? year repair life

CHAPTER 6. RMS REPAIR FATIGUE LIFE ESTIMATION

6.1. Introduction

The key to any repair analysis is the ability to rank repair alternatives according to some index. For the Repair Management System (RMS) the expected life of a repair is used as the index. This index is most useful since time is a critical component in the decision process.

The method of repair life estimations will vary with the mode and cause of failure. For each mode, a different analytical procedure is required. Because ships are plagued primarily by fatigue problems, only the fatigue failure mode is explored in this study.

For quick comparison of repair alternatives as required by the RMS philosophy, it is necessary to adopt an approach that does not rely on lengthy, cumbersome finite-element analysis. The proposed method to be used for the RMS is an approximate method which incorporates existing knowledge of material SN curve characteristics (cyclic stress range versus number of cycles to failure curves) and stress concentration factors for CSDs as discussed below. Other approaches could be adopted for the RMS fatigue evaluation, such as the linear elastic fracture mechanics (LEFM) approach adopted by Roddis for CRACK [Roddis,1992].

6.2. SN Curve Considerations for Fatigue Failure

The following discussion is based collectively on the material from the following references: [DNV,1984], [Bea,1990], [ACEA], [Wirsching,1984,1987].

SN curves for ship structural details have been developed for use in the fatigue evaluation of components. Using the United Kingdom Department of Energy approach, different locations within a detail are assigned a letter designation (B, C, D, E, F, F2, G, W) that represents the fatigue characteristics of that location. SN class designations closer to "A" in the alphabet (i.e., B) represent more durable locations. Class designations for side shell CSDs have be developed by the American Bureau of Shipping [Chen,1992].

Table 6.1 summarizes the design SN curves associated with these designations. These curves, which represent the mean data minus two standard deviations (for design purposes) of log N, may be described by:

$$\log N_f = \log A - 2 \log \sigma_{sd} - m \log S = \log A' - m \log S \tag{6.1}$$

N_f = Predicted number of cycles to failure under stress range S

A = Life intercept

$\log \sigma_{sd}$ = Standard deviation of log N

m = Inverse slope of SN curve

There is a size effect associated with these curves. To account for this, Equation 1 may be modified to the following for all types of welded structure except for butt welds dressed flush and low local bending across the plate thickness:

$$\log N = \log A' - \frac{m}{4} \log\left(\frac{t}{22}\right) - m \log S \tag{6.2}$$

The variable t is the thickness in millimeters through which a crack will grow (e.g., plate thickness).

There are two distinct regions in the figure above Table 6.1. For cycles $N>10^7$ there is a change in slope to model the effect of corrosion. There is some controversy over the actual effect of sea water and cathodic protection on these curves; however, the RMS will allow the SN curve data to be modified to the form desired by the user. For unprotected steel in sea water, a fatigue strength is assumed to be reduced by a factor of 2.0.

Unlike typical SN curves for polished steel in air, there is no endurance limit due to the presence of welds and a corrosive environment. For typical ship operations, a 20 year life would correspond to approximately $0.5x10^8$ cycles, or $2.5x10^6$ cycles per year. This can be checked by approximating the average number of cycles per year by:

$$f_o = 0.70\left(\frac{1 \text{ cycle}}{9 \text{ sec}}\right)\left(\frac{365 \text{ days}}{1 \text{ year}}\right)\left(\frac{24 \text{ hrs}}{1 \text{ day}}\right)\left(\frac{60 \text{ min}}{1 \text{ hr}}\right)\left(\frac{60 \text{ sec}}{1 \text{ min}}\right) \tag{6.3}$$
$$= 2.5x10^6 \text{ cycles / yr}$$

This calculation assumes 70 percent ship operation and an average wave encounter period of 9 seconds (actual values for a particular ship will vary).

6.3 Weibull Loading Model for Marine Environment

To evaluate a component for fatigue, the alternating stress level must be determined. The effect of mean stress can generally be ignored due to its small influence on the fatigue strength of steels [ISSC,1988,1991]. Several models can be used to represent the long term stress range, including wave exceedance diagrams, spectral methods, the Weibull model and the Nolte-Hansford model. A Weibull model to represent the long term distribution of cyclic stress ranges will be used for the RMS due to its relative simplicity. Using the Weibull model, the alternating stress in ship structure is represented by:

$$F(S) = Pr(s > S) = \exp\left(-\left(\frac{S}{\delta}\right)^{\varepsilon}\right) \tag{6.4}$$

F(S)	=	Probability that stress range S is exceeded
ε	=	Weibull shape parameter
δ	=	Weibull scale parameter

The scale parameter δ may be related to the stress range and the return period N_0 by:

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$$\delta = \frac{S_o}{(\ln N_o)^{1/\varepsilon}} \tag{6.5}$$

S_O is the alternating stress that is exceeded on an average of once every N_O cycles (design life or actual life in cycles). So now we have a one parameter distribution represented by:

$$F(S) = \Pr(s > S) = \exp\left(-\left(\frac{S}{S_o}\right)^{\varepsilon} \ln N_o\right) \tag{6.6}$$

Defining N as the number of stress variations of N_O that exceed S this equation may be expressed as:

$$S = S_o\left(1 - \frac{\log N}{\log N_o}\right)^{\frac{1}{\varepsilon}} \tag{6.7}$$

This distribution is plotted in the figure above Table 6.2. The Weibull shape parameter ε will vary with the environment (trading route, sea conditions) and the response of the ship structure to the environment. Specifically, ε will vary with ship length, ship type, location within the ship and the trading route under operation. For crude carriers and cargo ships ε is typically between 0.7 and 1.3 [Munse,1981]. General guidelines may be developed based on experience and analysis, such as provided in Table 6.2 for a typical crude carrier. The Weibull parameter may be obtained more accurately by direct instrumentation or detailed wave and structural analysis.

6.4 Cumulative Fatigue Damage Model

Allowable stress ranges for failure in a number of cycles may be calculated using the Weibull distribution and the Miner-Palmgren rule of cumulative fatigue damage. To evaluate the damage to a detail due the Weibull loading shown above Table 6.2, Miner's rule of cumulative damage is assumed. The number of cycles to failure N_f under a single alternating load S is given by Equation 6.1 and the accumulation of damage D due to the full range of alternating stresses is approximated by:

$$D = \sum_{i=1}^{n} \frac{N(S_i)}{N_f(S_i)} = \frac{T_f B^m \Omega}{A} \tag{6.8}$$

$N(S_i)$ = Number of cycles alternating stress S_i applied

$N_f(S_i)$ = Number of cycles to failure at stress S_i

T_f = Time to failure

B = Uncertainty factor in estimation of fatigue stress

Ω = Stress parameter, mean

A = Life intercept, mean

When the damage is greater than or equal to one failure is usually assumed to occur. Laboratory tests have shown wide variation in the actual cumulative damage at failure. Defining the damage at failure as Δ_f, Equation 6.8 can be rewritten as:

$$T_f = \frac{\Delta_f A}{B^m \Omega} \tag{6.9}$$

For the Weibull stress range model and a single slope SN curve, the stress parameter Ω is given by:

$$\Omega = f_o S_o^m [\ln N_o]^{-(m/\varepsilon)} \Gamma\left(\frac{m}{\varepsilon} + 1\right) \tag{6.10}$$

The average frequency f_0 of the stress cycles was calculated in Equation 6.3. For multiple slope SN curves, a bias factor to Equation 6.8 has been developed for two slopes [Wirsching,1987]. Using these closed-form solutions allowable stress ranges may be tabulated using the parameters of the SN curves, as illustrated in Figure 6.1 for a 20 year fatigue life. Similar curves may be developed for any desired life. A numerical approach that will work for any SN curve could also be adopted. In addition, the mean SN data should be used to remove the bias in the design curves when making comparisons.

To examine how this information can be used to evaluate repairs, consider a crack discovered in 10 years that developed due to high cycle fatigue. Assuming a Weibull parameter and curve designation, the stress range required to produce the failure may be determined. Due to the many assumptions involved, this stress range is only useful when used on a comparative basis. For example, if a crack originating at a cutout corner (C class, m=3.5, log A=14.03, single slope approximation) in the side shell (Weibull parameter 0.9) is discovered in 10 years (T_f=10 years, $f_0=2.5\times10^6$ cycles/year, $No=f_0 T_f=2.5\times10^7$ cycles), then the calculated peak Weibull stress range to cause failure (Δ_f=1) based on the mean SN data and no uncertainty (B=1) is:

$$S_0 = \frac{(\ln (f_o T_f))^{1/\varepsilon}}{B} \left\{ \frac{\Delta_f A}{f_o T_f \Gamma\left(\frac{m}{\varepsilon} + 1\right)} \right\}^{1/m} = 777 \text{ N}/\text{mm}^2 \tag{6.11}$$

If this crack is then ground out and welded up, the SN curve degrades to F class (m=3.0, log A=12.24), the stress range and Weibull parameter remain the same, and the new mean life to failure T_f (Δ_f=1) may be estimated by solving the following by iteration for T_f:

$$T_f = \frac{\Delta_f A [\ln(f_o T_f)]^{(m/\varepsilon)}}{f_o (B S_o)^m \Gamma\left(\frac{m}{\varepsilon} + 1\right)} \Rightarrow T_f = 1.33 \text{ yrs} \tag{6.12}$$

Mean values are computed to remove bias from the comparative analysis and to support decision analysis as discussed in Chapter 4.

6.5. Stress Concentration Factor Considerations for Fatigue Failures

Fatigue is dependent on the local stress in a CSD. The local crack opening stress may be estimated either by detailed finite element analysis or through the intelligent use of stress concentration factors. Stress concentration factors have been developed for various structural details based on both testing and finite-element analysis results. A stress concentration factor is defined mathematically by:

$$K = \frac{\sigma}{\sigma_n} \tag{6.13}$$

σ = Concentrated stress level

σ_n = Nominal stress level

For a ship structural side shell detail, the nominal loadings may be broken up into longitudinal stress due to hull bending (vertical and athwart ship), shear (vertical), and net external pressure. For a complete description of the stress concentration factors from a finite element analysis model, each of these load cases should be applied independently to the part. The results from each of these analyses can then be used to complete a table of stress concentrations that is a function of the detail configuration, the location within the detail, and the applied stress direction. An example of these factors is shown in Table 6.3.

These stress concentrations should be expressed in terms of the tensile stress normal to the expected direction of cracking since typically we deal with Mode I cracking (resulting from tensile stress). A negative stress concentration could be used to represent a reversal between applied nominal stress and the stress at the crack location. Careful consideration of the restraints on the model is also required for all loading cases. When new details are analyzed by finite element methods or by testing, results can be stored in this tabular format for immediate use in the evaluation of repairs. Stress concentration factors for side shell CSDs have been developed by several authorities using various loading conventions [ACEA] [NK,1991].

Depending on the location of the detail within the ship, the effect of these stress concentrations will vary. For example, around the waterline location of the ship, the stress due to vertical bending is minimal (close to the neutral axis) and the stress due to external pressure is very high (wave loading). Therefore, to compare the stress levels at various locations within several repair alternatives, we must develop a table of the relative magnitudes of the loadings as a function of the location within the ship.

To avoid the tedious process of wave spectrum and global structural analysis to identify the local loads, a best estimate based on expert opinions is used to evaluate repairs. Table 6.4 summarizes these expert load ratios for the RMS based on "typical" moment and shear diagrams as illustrated above Table 6.4. The maximum value of one for a given load case represents the ship location of maximum load contribution. A more detailed loading library for future use might account for a finer definition of the location in the ship, the size of the ship, trading route, the beam approximation of the ship and other factors to get a more accurate estimate of the loading variation.

As the actual performances of repairs are evaluated and additional analyses are completed, the stress concentration factors and the expert load ratios could be continually updated, resulting in more accurate repair life estimations.

6.6. RMS Calculation Approach to Changes Due to Repair

When a repair is made, a combination of three things can occur:

1. a change in the SN curve designation of a location due to modifications such as welding;
2. a change in the stress concentration factor (thus alternating stress level) of a location due to change in geometry; and/or

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3. a change in component thickness (thus alternating stress level) due to the addition of a thicker insert plate or doubler.

To compare repair alternatives, these three changes must be accounted for. **First,** N_0 is assumed to be life at inspection. For example, if a crack is discovered at a ship life of 10 years then:

$$N_o = 10\ f_o = 10\ \text{years}\left(\frac{2.5 \times 10^6\ \text{cycles}}{1\ \text{year}}\right) = .25 \times 10^8\ \text{cycles} \tag{6.14}$$

Alternative approaches to determine the mean life of a structural failure are discussed in Chapter 7. **Second,** a best estimate of S_{old} to cause failure based on the SN curve designation, the Weibull shape parameter and the cumulative damage approach is calculated by the following:

$$S_o = \frac{(\ln N_o)^{1/\varepsilon}}{B}\left\{\frac{\Delta_f A}{f_o T_f \Gamma\left(\frac{m}{\varepsilon} + 1\right)}\right\}^{1/m} \tag{6.15}$$

Third, this estimate is modified by the following equation to correct for changes in stress concentration factors and component thicknesses in the repaired detail:

$$S_o' = S_o\left(\frac{K_{repair}}{K_{original}}\right)\left(\frac{t_{original}}{t_{repair}}\right)^n \tag{6.16}$$

K = Stress concentration factor of the repaired and original detail

t = Thickness of the repaired and original detail

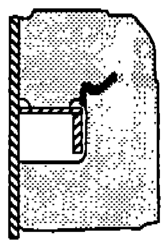
n = Factor which is dependent on the dominant stress direction

Since typically we deal with Mode I cracking (resulting from tensile stress), n will equal 1 in most cases. **Fourth,** a fatigue life that corresponds to the S_0' stress range and the new SN curve parameters is calculated using this new stress level by solving the following for T_f by iteration:

$$T_f = \frac{\Delta_f A [\ln N_o']^{(m/\varepsilon)}}{f_o (B S_o')^m \Gamma\left(\frac{m'}{\varepsilon} + 1\right)} \Rightarrow T_f \qquad (6.17)$$

This life estimation process is represented by Figure 6.2 for a repair situation where the SN curve is degraded from a C to an F curve by repair and additional stress concentrations are added (a poor repair, indeed).

The example situation in Figure 5.3 will be analyzed to illustrate how this evaluation process might proceed. A crack in the cutout radius is assumed to be discovered at a ship life of 10 years (T_f). The "No Repair" option requires more detailed crack growth rate and critical crack length analysis and is not discussed below. As a temporary repair, the stress concentration factor of approximately 9 for the sharp crack can be reduced to approximately 3 simply by drilling a hole at the crack tip [ISSC,1992].



Repair 1

The geometry of this detail has not been modified and the loadings are unaffected. As a result, the stress at the crack location will remain relatively unchanged except for the addition of the weld. The material degradation due to welding is accounted for by the modification of the SN curve from C to F class.

This is not a good repair solution unless the crack originates from a weld or if it is an isolated case. If the crack originates from a welded location, there will be no penalty

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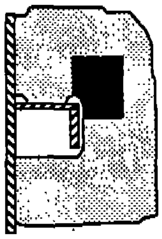
in the SN curve for this repair option. If many similar cracks in the same loading zone exist then a condition of over-stress or under-design probably exists and redesign is the most prudent repair.

The effect of post weld improvements on butt welded plates may be taken into account during analysis using existing statistical data such as in Figure 6.3 [Almar-Naess,1985]. The life extension effect can be significant, but the cost can be prohibitive.



Repair 2

The geometry of this detail has not been modified, but the insert plate thickness may be different from the original plate and the new weld locations should be evaluated based on their impact on the detail. At the original crack location, the life of the repair is assumed to be equal to N_{old} unless the plate thickness t is modified. In this case, the new stress range is estimated by Equation 6.16 using stress concentration factors of 1.0.

At the weld locations, a combination of a stress concentration factor increase due to the change in plate thickness and a change in the SN curve due to the addition of the weld occurs. The stress concentration factor, which is important only for plates that are significantly smaller or larger than the original plate, may be approximated by the stress concentration results for a flat plate with fillets as reported by Peterson or other sources [Peterson,1953]. The new stress range and life at these locations can be estimated by Equations 6.16 and 6.17, respectively.

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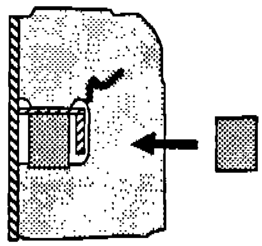


<u>Repair 3</u>

In this case the geometry has been modified so that we have a change in stress level plus a change in SN curve designation at the crack location. The change in stress level is determined by the load ratio in Table 6.4 and the stress concentration factors for the original and modified details at the crack location, Table 6.3. The overall stress concentration factor for both the original and modified detail is determined as:

$$K_{combined} = \sum_{i=1}^{n} K_{ij} R_j \tag{6.20}$$

i = Location number on the detail

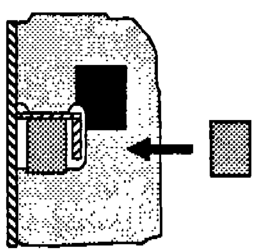
j = Load case number

n = Total number of load cases

K_{ij} = Stress concentration factor for load case i at detail location j

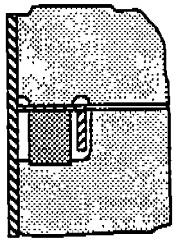
R_j = Load ratio for load case j at the ship location under study.

A linear combination is valid only if stress concentration factors are defined normal to the crack direction and not in terms of combined stresses. The SN curve has been degraded at the lug weld location and at the location of the crack. Each of these locations should be evaluated separately by Equations 6.16 and 6.17.



Repair 4

In this case the geometry has been modified so that we have a change in stress level plus a change in SN curve designation at the weld locations. There is no change in the SN curve at the original crack location, but possibly a change in plate thickness of the inserted plate. Evaluation continues as for Repair 3.

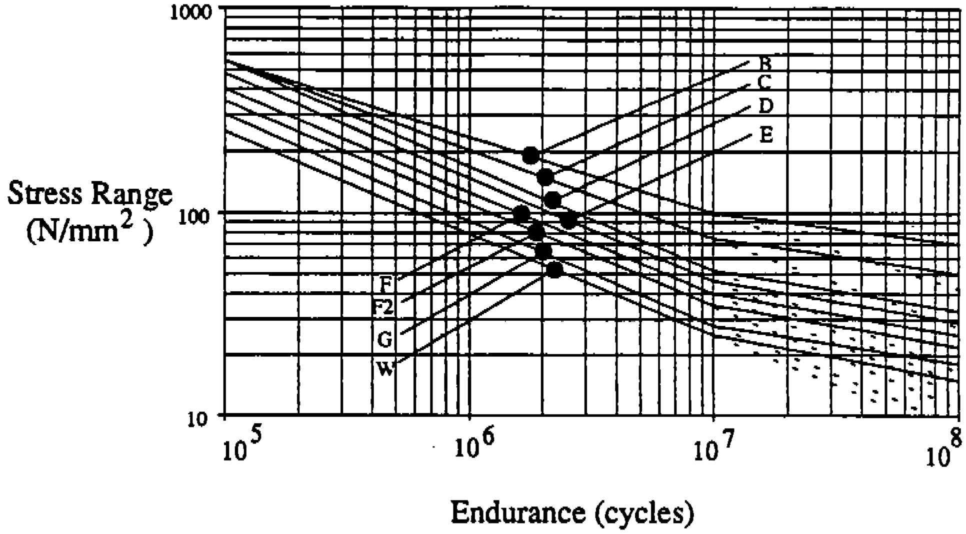


Repair 5

In this case the geometry has been modified beyond repair 4 with the addition of brackets. Evaluation continues as for Repair 4.

6.7 Summary

A simplified approach to the estimation of the fatigue life of repair alternatives has been outlined and demonstrated for a typical crude oil carrier side shell CSD. Depending on the data available, some required information might be missing to estimate the repair life. The RMS should report this missing data and allow for easy addition of any new results to the knowledge-base and database.

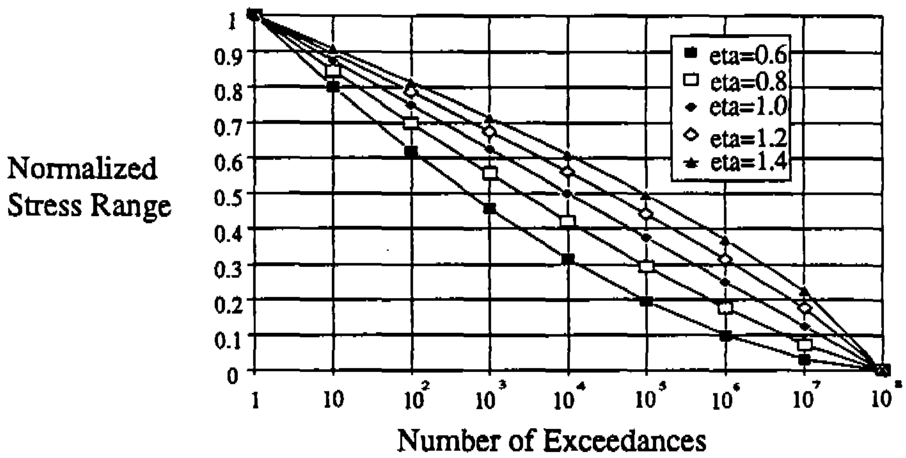


	Parameters $N \leq 10^7$			
Curve Class	A (MPa)	A/A'	m	COV of A*
B	2.34 E15	2.29	4.0	0.44
C	1.08 E14	2.54	3.5	0.50
D	3.99 E12	2.63	3.0	0.51
E	3.29 E12	3.14	3.0	0.63
F	1.73 E12	2.74	3.0	0.54
F2	1.23 E12	2.88	3.0	0.56
G	5.66 E11	2.30	3.0	0.43
W	3.68 E11	2.32	3.0	0.44

Table 6.1. Mean SN Curve Constants in Air or Adequately Protected in Seawater

(SN curve plotted above)

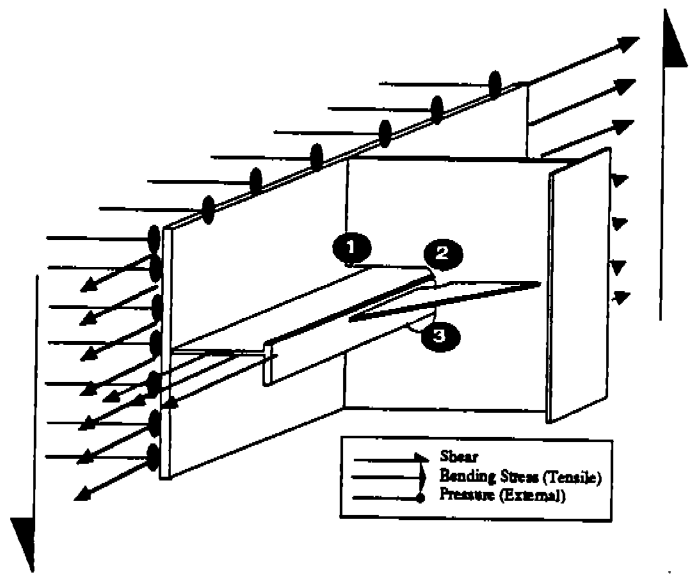
[DNV,1984] ,[Wirsching,1987]*



Structure Location	Weibull Shape Parameter ε
Deck Structure	1.0
Bottom Structure	0.9
Side shell Structure	0.9
Transverse Structure	0.8

Table 6.2. Typical Weibull Shape Parameters for Crude Carrier Structure

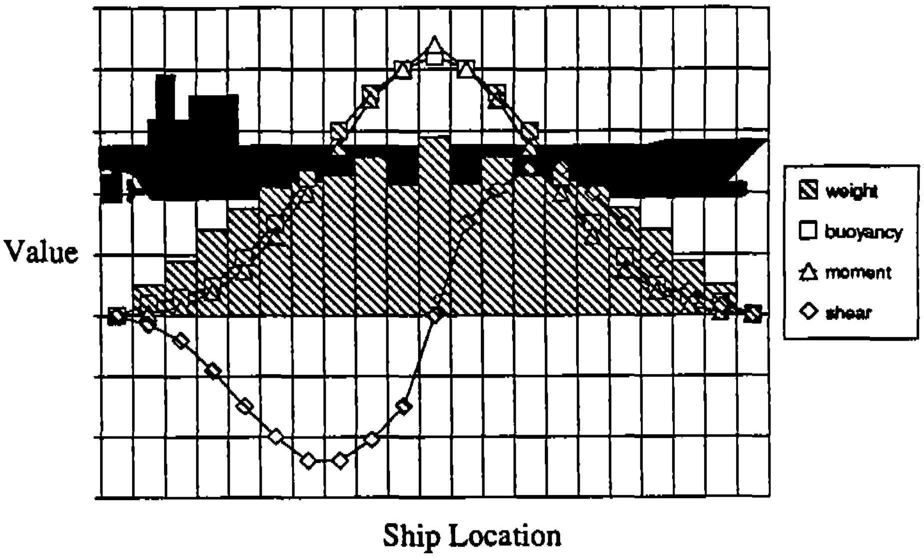
(long term distribution of alternating stress shown above)



	Load	Case		
	1	2	3	4
Location	Vertical Bending	Athwart Bending	Pressure	Shear
1	K_{11}	K_{12}	K_{13}	K_{14}
2	K_{21}	K_{22}	K23	K_{24}
3	K_{31}	K_{32}	K_{33}	K_{34}

Table 6.3. Stress Concentration Factors K, Side Shell Detail A

(loading convention shown above)



		Load		Case	
		1	2	3	4
Fore/Aft Location	**Vertical Location**	Vertical Bending	Athwartship Bending	Pressure	Shear
Forward 1/3	Top 1/3	.5	.5	1	0
	Mid 1/3	0	.5	1	1
	Lower 1/3	.5	.5	1	0
Amidships	Top 1/3	1	1	0	0
	Mid 1/3	0	1	1	.5
	Lower 1/3	1	1	.7	0
Aft 1/3	Top 1/3	.5	.5	0	1
	Mid 1/3	0	.5	1	0
	Lower 1/3	.5	.5	.7	1

Table 6.4. RMS Expert Load Ratios for Side Shell Structure Due to Ship Location

(typical hogging load distribution shown above)

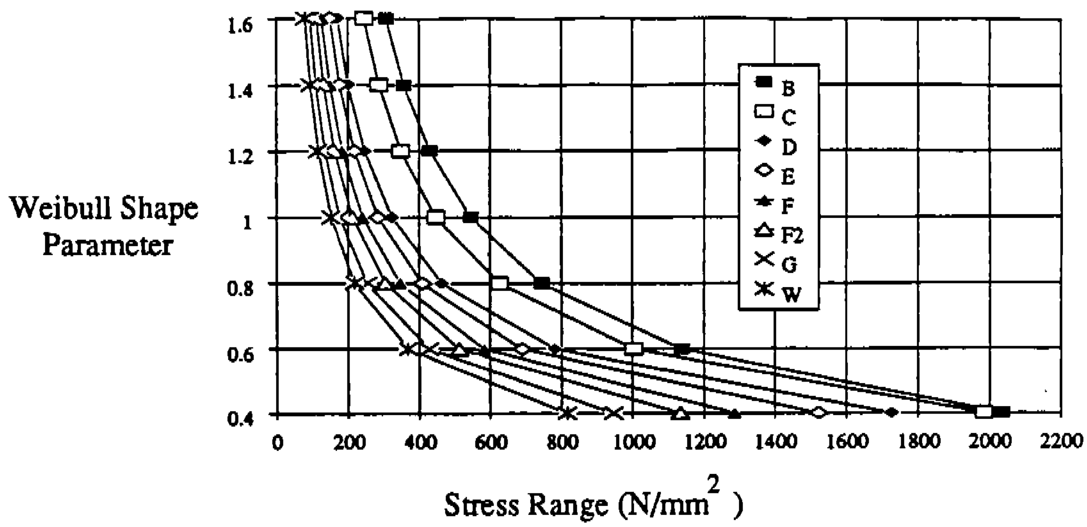


Figure 6.1. Allowable Stress Range for Design, 20 Year Life, U. K. DEn SN Curves

[Chen,1992]

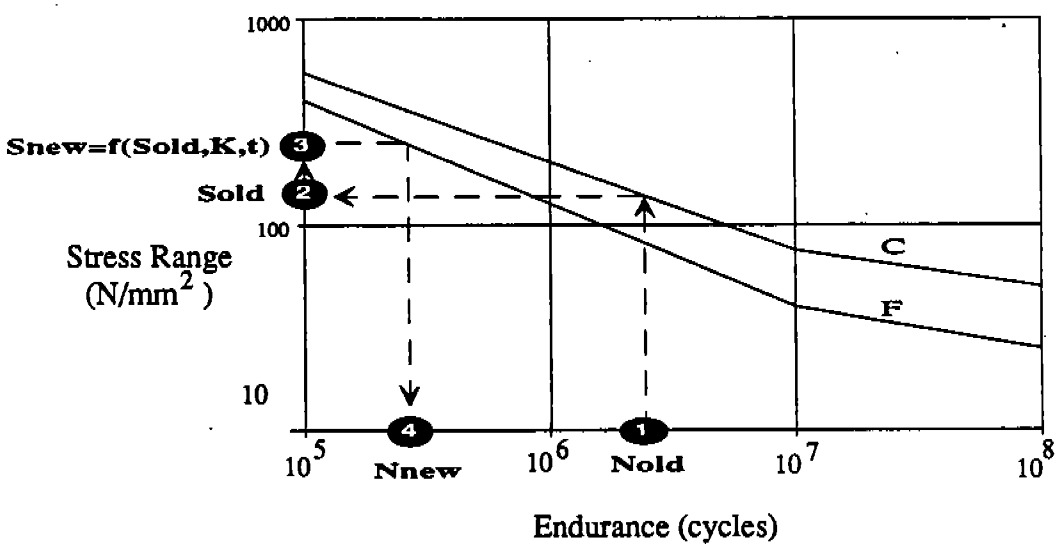


Figure 6.2. Repair Life Evaluation Process

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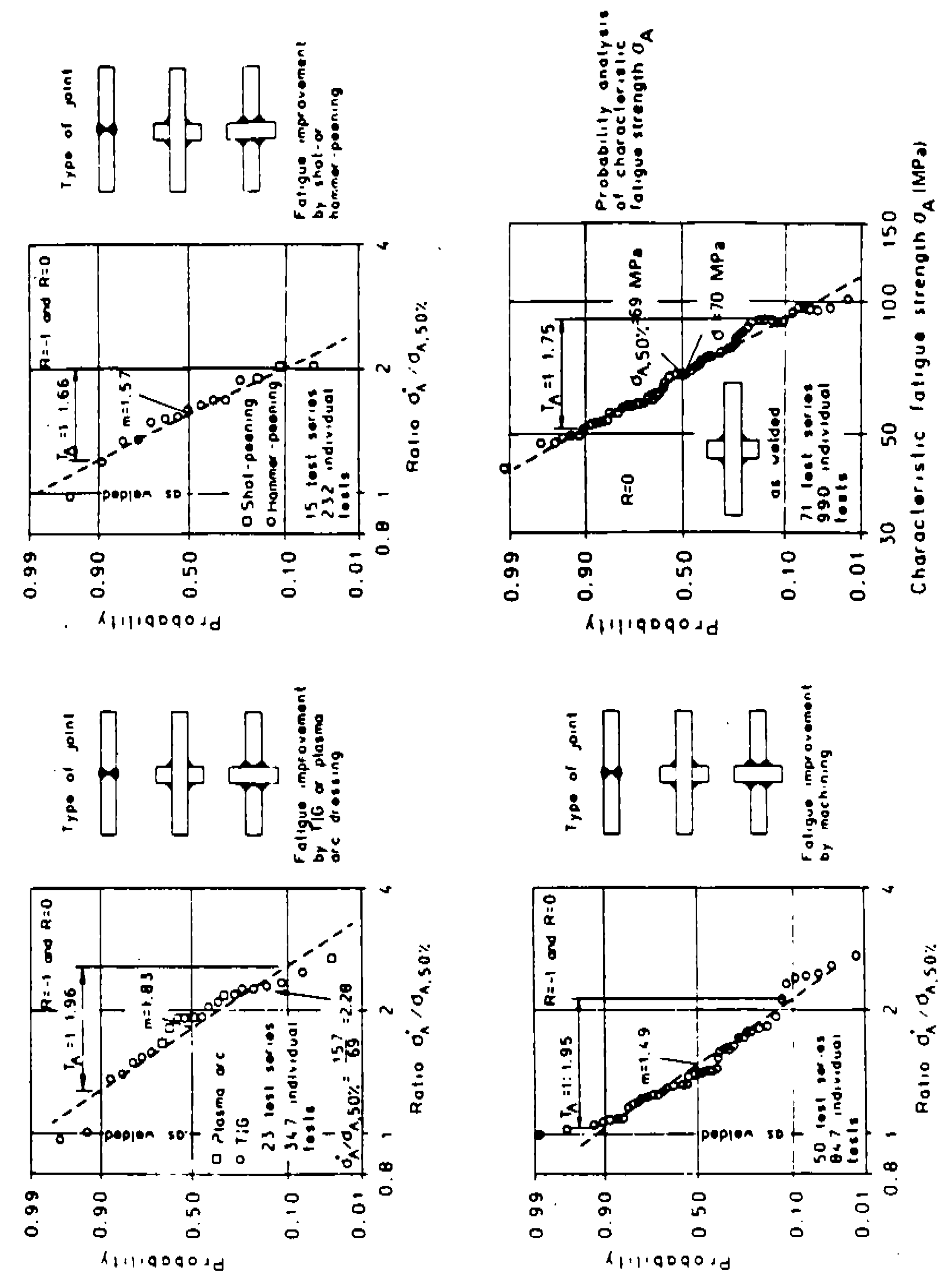

Figure 6.3. Statistics on the Effect of Post Weld Improvement

[Almar-Naess,1985,page 281]

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CHAPTER 7. RMS DECISION ANALYSIS

7.1. Introduction

Up to now, the most critical aspect of the Repair Management System (RMS) repair evaluation has not been discussed--cost. To be effective, a decision analysis that deals with the uncertainties of the problem and the cost criteria of the owner and operator of the ship is required to help evaluate the optimum repair option. In terms of cost, the optimum repair option is defined as the one that results in the minimum total costs (initial plus future) over the life of the ship, Figure 7.1.

Repair decision trees for crack repair and corrosion repair are provided for reference in Figures 7.2 and 7.3, respectively. Decision analysis is a well developed method that has been applied successfully to many engineering problems including marine applications such as platform design [Bea,1984] and shipping financial decisions [Devanney,1971]. Raiffa is a classic reference for background information on decision analysis [Raiffa,1970].

7.2. Uncertainty in Fatigue Evaluation

There are many sources of uncertainty in the fatigue evaluation procedure. In reference to the four step repair life estimation process in Chapter 6, these uncertainties include:

- material parameters, including
    1. SN curve parameters;
- stress analysis process, including
    1. Miner rule assumption,
    2. load ratios, and
    3. Weibull load model;
- detail configuration data (original and repair configuration), including

1. Weibull parameter,

2. stress concentration factors, and

3. SN class designation; and

- mean time to failure of original detail.

Uncertainty in the fatigue analysis involves the first three sections above--material parameters, stress analysis process, and detail configuration data--and is discussed below.

7.3. Uncertainty in Fatigue Analysis

Significant work has been done to address the uncertainties associated with fatigue in the marine environment. The work done by Wirsching is the primary source for the following discussion [Wirsching,1984,1987].

A lognormal variation in the fatigue variables is assumed due to the resulting closed form and exact expression for the probability of failure and the good fit to fatigue data. As a result, the variables conform to the following lognormal probability density function f(y) and cumulative lognormal density function F(y):

$$f(y) = \left[\frac{0.4343}{(2\pi)^{1/2} y\sigma}\right] \exp\left\{\frac{[\ln(y) - \bar{y}]^2}{2\sigma^2}\right\} \tag{7.1}$$

$$F(y) = \Phi\left\{\frac{\ln(y) - \bar{y}}{\sigma}\right\} \tag{7.2}$$

The function $\Phi(z)$ is the standard normal cumulative distribution function. This function is available in tabular form or calculated using the error function by the equation:

$$\Phi(z) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{z}{\sqrt{2}}\right)\right] \tag{7.3}$$

Using mathematics of variations and Equation 6.9 to define the mean time to failure, the probability of fatigue cracking failure (failure is defined by the mean SN data) of a repair at service life T_S for a detail with a mean life T_{f50} is calculated by:

$$P_f = \Pr[T_f \leq T_s] = 1 - \Phi\left(\frac{\ln(T_{f50}/T_s)}{\sigma_{\ln T_f}}\right) = 1 - \Phi(\beta_f) = \Phi(-\beta_f) \qquad (7.4)$$

β_f is the fatigue safety index of the CSD. The standard deviation (the estimate of the variability of the data) of the natural log of the time to failure is given by:

$$\sigma_{\ln T_f} = \sqrt{\ln\left\{(1 + COV_{\Delta_f}^2)(1 + COV_A^2)(1 + COV_B^2)^{m^2}\right\}} \qquad (7.5)$$

The coefficient of variation COV (relative dispersion of the results, ratio of standard deviation to the mean) is calculated by:

$$COV_i = \sqrt{\exp(\sigma_i^2) - 1} \qquad (7.6)$$

The subscript B in Equation 7.5 refers to the variation in the stress analysis process, including variations in component fabrication (M), sea state (S), wave loads (F), member loads (N), and stress concentration factor predictions (H). The variation and the bias due to B are computed by:

$$COV_B = \sqrt{\prod_i (1 + COV_i) - 1} \quad \text{and} \quad B_B = \prod_i B_i \qquad i = M,S,F,N,H \qquad (7.7)$$

Table 7.1 provides typical values for these uncertainties [Wirsching,1987] [Bea,1990]. Using these "typical" uncertainties, the probability of failure of various repair options might be calculated to as shown in Figure 7.4. The lower the probability of failure, the higher the durability. Repair option D in Figure 7.4 (the least durable)

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might represent vee and welding of a crack. The choice of the "best" repair option from this list requires a structured approach to decision making under uncertainty.

7.4. Accurate Assessment of Mean Time to Failure

The repair life estimation process is a multi-step procedure that initially assumes the mean life of a location on a detail to be the life at the discovery of the failure. This information is then used to estimate the required mean extreme stress range to cause failure. This estimate of extreme stress is then used to estimate the lives of various repair options. This simplification is required because the loading history in ship structure is very difficult to evaluate quickly and accurately. Unfortunately, there is a high probability that the failure did not occur at the mean life of the detail.

Role of Instrumentation

There are several ways to get a better estimation of mean life. One approach is to use instrumentation to directly determine the stress history of the ship over the life of the detail. Once the loading history is known, the expected mean life may be calculated directly by Equation 6.9. Several types of instrumentation are currently being explored in the shipping industry. These types include strain gauges, accelerometers, wave height sensors, and weather data. The output from these gauges require significant storage capacity and time intensive post processing to determine the impact of loadings on the fatigue life of the structure.

An alternate gauge that directly measures the fatigue damage the fatigue gauge. Fatigue gauges are small pieces of material (same as material to be tested) with known flaws and fatigue characteristics. Gauges can be welded or epoxied to any surface (parent) and will undergo the same loading history as the parent. The geometry of the gauge can be modified so that fracture occurs at a predetermined percentage of the life of the parent material. The use of several of these gauges in various ship locations could provide a quick, accurate indication of actual accumulated damage in the structural details without any fatigue analysis. This information would provide a solid basis for repair analysis. It would also provide the ship owner with a quick tool to evaluate the overall level of fatigue damage in the structure.

Additional work on the important role of instrumentation in the RMS is reserved for future research.

Role of Historical Data

An alternate and currently more attractive approach to estimate the mean time to failure is a combination of initial design analysis, expert opinion, and statistical analysis of the performance of details from a historical database.

As a starting point, an initial estimation of the mean time to failure T_{f50} can be made by a combination of initial design analysis (as required by the ship classification societies) and expert opinions. For a rough estimation, assume the ship is designed perfectly to the design life T_{design} (usually 20 years) using the design SN curves. Correcting for the two standard deviation safety factor in the design curves, mean life can be estimated by first estimating the safety factor on life:

$$\left.\begin{aligned} N &= AS^m \\ N' &= A'S^m \end{aligned}\right\} \Rightarrow FS_{life} = \frac{N}{N'} = \frac{A}{A'} \cong 2.5 \text{ (see Table 6.1)}$$

$$\therefore\ T_{f50est} = T_{design}(FS_{life}) \cong (20 \text{ years})(2.5) = 50 \text{ years} \tag{7.8}$$

Once the ship is in service, performance data on all critical details can be collected to continually update the mean times to failure. After sufficient data is collected, the first approximation may be replaced.

To illustrate how database information is used, suppose there is a total of 100 of the same side shell CSDs located in ship locations exposed to similar loading patterns. For example, the component configuration (L=L, C=1, G=N, F=N, B=N) located in the same load zone (amidships near the waterline). From the database, a summary of the failure history of a detail can be developed, Table 7.2.

The mean time to failure originally estimated by analysis and expert opinion T_{fest} can now be updated by using the historical probability of failure to recalculate the mean time to failure using Equation 7.4. This updating process is shown graphically in the figure above Table 7.2. This new historically based mean time to failure should only be used after sufficient data is collected. In Table 7.2, sufficient data was assumed after 7 or 8 years when the change in the calculated mean time to failure is small. An alternate approach--curve fitting all the data--is reserved for future research.

Care must be taken when historical performance is used to establish the mean life. For the same location on the same detail at "similar" ship locations (same zone in Table 6.4, exposed to approximately the same alternating stress component Ω), database information on performance may be used directly. To take advantage of additional data for details at "dissimilar" ship locations, a function to determine the expected life under a new loading environment can be developed based on Equation 6.9 and the expert load ratios in Table 6.4. From Equation 6.9 T_f is proportional to $1/\Omega$ so that:

$$\frac{T_{f1}}{T_{f2}} = \frac{\Omega_2}{\Omega_1} = \frac{S_{02}^{m_2}\,[\ln(f_o\,T_{f2})]^{-(m_2/\varepsilon_2)}\,\Gamma\left(\frac{m_2}{\varepsilon_2}+1\right)}{S_{01}^{m1}\,[\ln(f_o\,T_{f1})]^{-(m_1/\varepsilon_1)}\,\Gamma\left(\frac{m_1}{\varepsilon_1}+1\right)} \tag{7.9}$$

Since $m_1=m_2$ for the same location on a detail and assuming $\varepsilon_1 \cong \varepsilon_2$ Equation 7.9 may be simplified to:

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$$\frac{T_{f1}}{T_{f2}} = \left(\frac{S_{02}}{S_{01}}\right)^{m} \left(\frac{\ln(f_o T_{f1})}{\ln(f_o T_{f2})}\right)^{m/e} \quad \text{where} \quad \frac{S_{02}}{S_{01}} = \frac{\sum_{i=1}^{n} K_{ij} R_{j2}}{\sum_{i=1}^{n} K_{ij} R_{j1}} \tag{7.10}$$

Thus, if the time to failure is calculated at location 2, an estimate of the time to failure at location 1 can be made by iteration of Equation 7.10 and added to the estimation of T_{f50}.

7.5. Repair Costs

Repair costs can be broken down into initial and future costs. Once a structural failure is discovered, initial costs include the costs of repair analysis, repair labor and materials, and opportunity costs due to loss of serviceability. Future costs are incurred if the detail fails again (once or multiple times) due to inadequate repair and includes the costs of repair analysis, repair labor and materials, and opportunity costs due to loss of serviceability.

A good estimate of initial costs due to structural repairs can be made using either repair man-hours or repair material weight estimates. As a result, costs for a repair option can be computed by:

$$\begin{aligned} C_i &\equiv (\text{repair hours})\left(\frac{\$}{\text{manhour}}\right) \equiv (\text{repair weight})\left(\frac{\$}{\text{pound}}\right) \\ C_f &\equiv C_i(\text{PVF}) \\ &\Rightarrow \text{present value of costs} \equiv C_i(1+\text{PVF}) \end{aligned} \tag{7.11}$$

PVF is a the present value factor to convert the future costs of failure to present value. The PVF is dependent on the effect of the inflation rate on future repair costs and effect of the rate of return on the present value of the future repair cost. For a repair at time t in the future, the present value of the repair is approximated by:

$$
\begin{aligned}
C_f &= C_i (F/P, i\%, n)(P/F, r\%, n) \\
&\Rightarrow PVF = (F/P, i\%, n)(P/F, r\%, n)
\end{aligned}
\tag{7.12}
$$

Equation 7.12 assumes that the only costs associated with failure are repair costs (repairs made during standard overhaul periods so that no opportunity costs involved). In addition, failure costs associated with environmental pollution and loss of life, Figure 7.5, are not considered due to their low likelihood for the case of local fatigue damage. In an expanded RMS system that deals with global failures, these costs could dominate the decision process and should be included.

7.6. Expected Monetary Value

There are two types of models that may be used to evaluate the expected monetary value (EMV) of a repair alternative. These are discreet and continuous replacement models. The optimum repair option is the one that minimizes the EMV (i.e., minimizes costs).

Discreet Replacement Model

For a single failure of a repair in n years the EMV of a repair option in present dollars is:

$$
\begin{aligned}
EMV &= C_i + C_f(n) = C_i [1 + PVF_d(n)] \\
PVF_d &= \left(\frac{1+i}{1+r}\right)^n
\end{aligned}
\tag{7.13}
$$

Inflation and rate of return are the effective rates per compounding period n. If multiple repairs will be required over the service life T_S, the mean number of repairs MNR and the mean time between repairs MTBR expected for a repair alternative is calculated by:

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$$MNR = integer\left(\frac{T_s}{T_{f50}}\right) \qquad MTBR = T_{f50} \tag{7.14}$$

The total PVF may be estimated by the cash flow represented in Figure 7.6. The PVF of this flow is calculated by:

$$PVF_{dt} \cong \sum_{r=1}^{MNR} PVF_d(n_r) \quad \text{where} \quad n_r = r(MTBR) \tag{7.15}$$

Alternately, the cost at the end of each year may approximated using the probability of failure at the end of one year. Using this model, the total costs up to the service life may be calculated by:

$$PVF_{dt} \cong \sum_{n=1}^{T_s} P_f(n=1) PVF_d(n) \tag{7.16}$$

Continuous Replacement Model

A better estimate of EMV is determined by integrating over the desired service life of the repair using continuous compounding. For continuous compounding, the PVF is defined by:

$$PVF_c = e^{(i-r)n} \tag{7.17}$$

Inflation and rate of return 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:

$$i_{effective} = \left(1 + \frac{i_{nominal}}{k}\right)^k - 1 \tag{7.18}$$

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:

$$PVF_c = \int_{t=0}^{\infty} f(t)e^{(i-r)n}dt \quad (7.19)$$

Since multiple repairs may be likely for a repair option, a better estimate of EMV is obtained by setting a cutoff probability of failure at which replacement is assumed to occur. Using the mean life as a basis (same as for the discreet approach), 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 in Figure 7.7 and the following equation:

$$PVF_c \cong 2\left\{\sum_{r=1}^{MNR}\left[\int_{t_a=(r-1)MTBR}^{r(MTBR)} f(t-t_a)e^{(i-r)t}dt\right] + \int_{t_a=MNR(MTBR)}^{T_L} f(t-t_a)e^{(i-r)t}dt\right\} \quad (7.20)$$

It is important to note that all the above methods will provide some measure of the future costs associated with repairs. All will result in higher future costs for less durable repairs as required, but the magnitudes of these costs will vary. The use of the continuous model is demonstrated in Chapter 8.

7.7. Utility Theory

To account for the decision maker's attitude toward risk and non-monetary outcomes, utility theory is a proven method and could be incorporated into decision analysis in the RMS.

Risk Assessment

Through a series of the decision maker's responses to simpler questions, utility functions can be developed to mathematically represent the decision maker's attitude toward the risks associated with costs, loss of life, environmental impact and any other possible consequence of a decision.

For typical fatigue and other local repairs, the likelihood of environmental impact and loss of life are very low. As a result, a single attribute risk utility function relating repair costs to utility is sufficient for the RMS, Figure 7.8. The maximum utility in this case is 1.0 for zero costs. The goal now is to maximize the utility of a decision. For the risk neutral utility function, the repair option with the minimum EMV will be the same as the one with the maximum utility.

Non-Monetary Outcomes

Another use of utility analysis is the evaluation of non-monetary consequences and the combination of costs associated with these "fuzzy" consequences. For the RMS this would be required when the likelihood of environmental impact or loss of life in Figure 7.5 were significant, such as in the evaluation of the condition of the overall ship structure and the probability of global failure of the hull girder. An example of a multi-attribute utility function that combines the utility of costs with environmental damage was developed for offshore platforms. Defining X_1 as monetary costs and X_2 as barrels of oil released to the environment, the combined utility based on an additive model may be expressed as [Bea,1990]:

$$U(X_1, X_2) = 0.4\left(1 - \frac{X_1}{1.0}\right) + 0.6\left(1 - \frac{X_2}{20}\right) \tag{7.21}$$

This utility function represents a relative scaling of 0.4 and 0.6 for monetary costs and barrels of oil released respectively (decision maker placed more importance on environmental impacts). The additive utility of outcome $(x_1, x_2, \ldots, x_n)$ is calculated by:

$$U(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} k_i \, u(x_i) \tag{7.22}$$

The expected value E of the total utility of an alternative is found by summing over all possible outcomes the probability of each outcome times the utility of the outcome by:

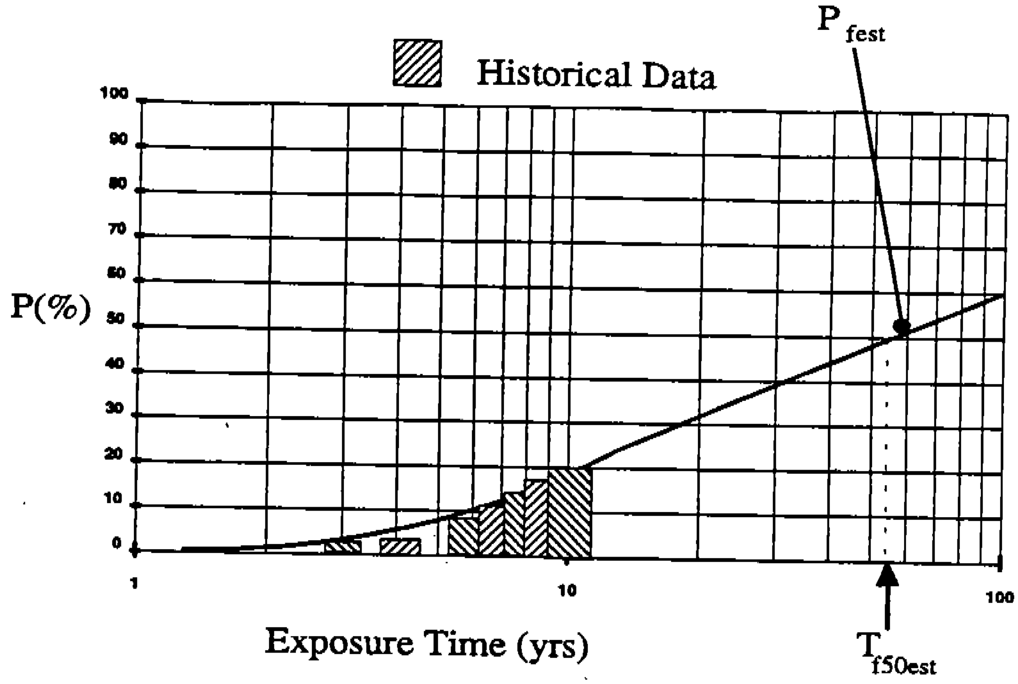
$$E(U) = \sum p(x_1, x_2, \ldots, x_n) \, u(x_1, x_2, \ldots, x_n) \tag{7.23}$$

For a complete discussion of decision analysis with multiple objectives refer to Keeney and Raiffa [Keeney&Raiffa,1976].

Type Uncertainty	Symbol	COV C	σ $\sqrt{\ln(1+C^2)}$	Bias =actual/ estimated
Damage at Failure (estimate Δ_f=1.0)	Δ_f	0.19 - 0.67	0.19 - 0.61	0.69 - 1.15
SN Curve Life Intercept	A	0.43 - 0.67	0.41 - 0.61	---
Fabrication Sea State Wave Loads Member Loads Stress Concentration Factor	M S F N H	0.10 - 0.30 0.40- -0.60 0.10 - 0.30 0.20 - 0.40 0.10 - 0.50	0.10 - 0.29 0.39 - 0.55 0.10 - 0.29 0.20 - 0.39 0.10 - 0.47	0.90 - 1.30 0.60 - 1.20 0.60 - 1.10 0.80 - 1.10 0.80 - 1.20
Stress Range Estimate $C_B = \sqrt{\prod_i (1+C_i) - 1}$ $B_B = \prod_i B_i$	B	0.49 - 1.15	0.89 - 1.32	0.21 - 2.27
Natural Log of Time to Failure $\sigma_{\ln T_f} = \sqrt{\ln\left\{(1+C_{\Delta_f}^2)(1+C_A^2)(1+C_B^2)^{m^2}\right\}}$	$\ln T_f$	---	1.46 - 2.89 (m=3)	---

Table 7.1. Ranges of Coefficients of Variation for Fatigue Life Calculation

[Wirsching,1987]



Sample database analysis of historical failures of csd with the same component configuration in same loading zone:

t Time in Service(yrs)	n_f Number of New Failures in Year	$P_f(t)$ Cumulative Failures for 100 details (%)	T_{f50} Mean Time to Failure (1) (yrs)	T_{f50est} Estimated Mean Time to Failure(2) (yrs)
1	0	0	--	50(3)
2	0	0	--	50(3)
3	2	2	182	50(3)
4	2	4	132	50(3)
6	4	8	99	50(3)
7	3	11	81	81(4)
8	5	16	58	58
9	2	18	56	56
10	2	20	54	54

(1) Based on σ_{lnTf}=2.0, Equation 7.4 and P_f (t)
(2) Average of previous years estimates
(3) Initial estimate based on 20 year design life used due to insufficient data
(4) New estimate used since change in calculated time to failure small

Table 7.2. Sample Historical Database Analysis of Detail Performance

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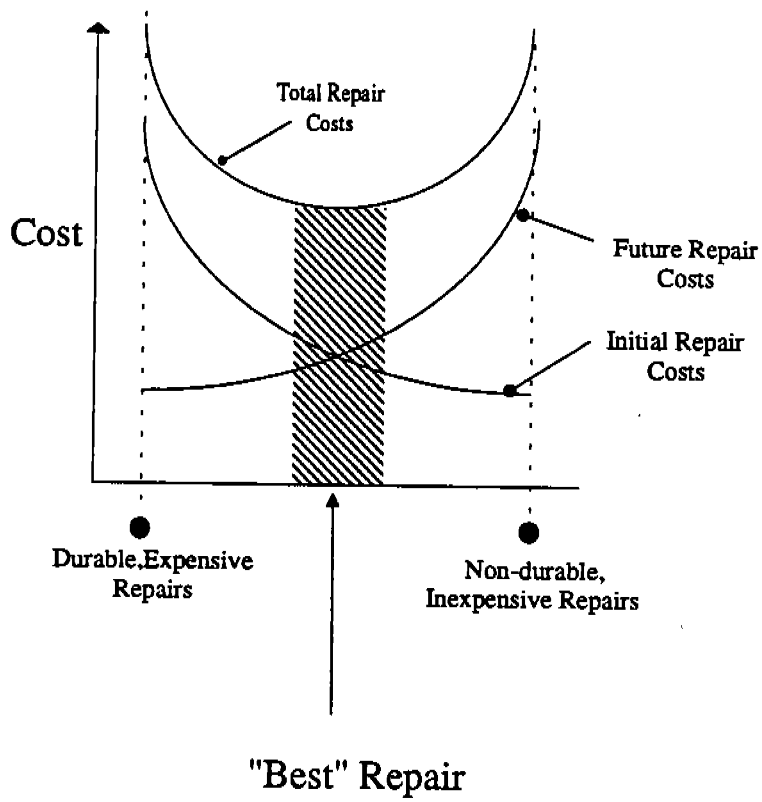
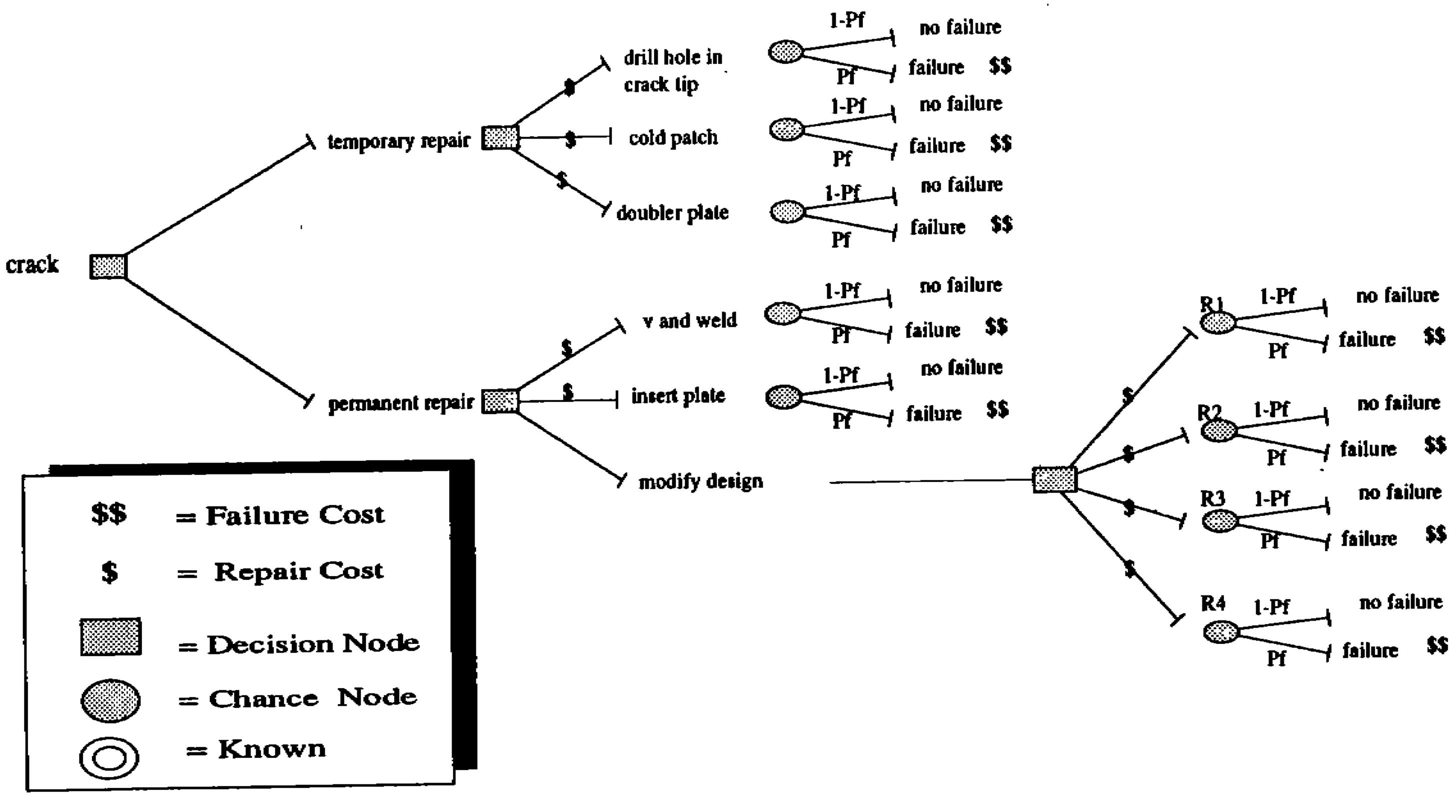


Figure 7.1. Repair Cost Tradeoff



Note: Pf different for each repair option

Figure 7.2. Crack Repair Decision Tree

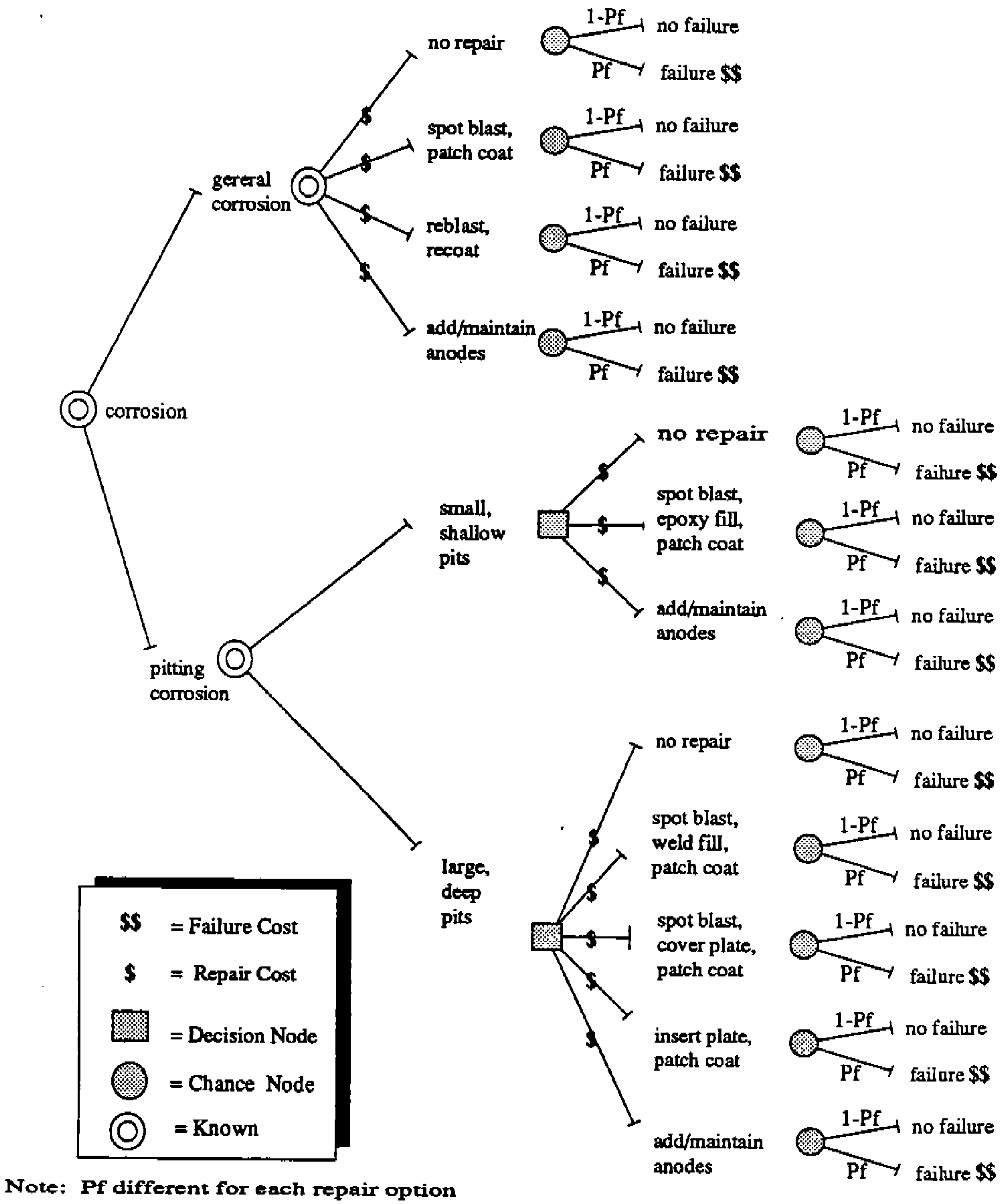


Figure 7.3. Corrosion Repair Decision Tree

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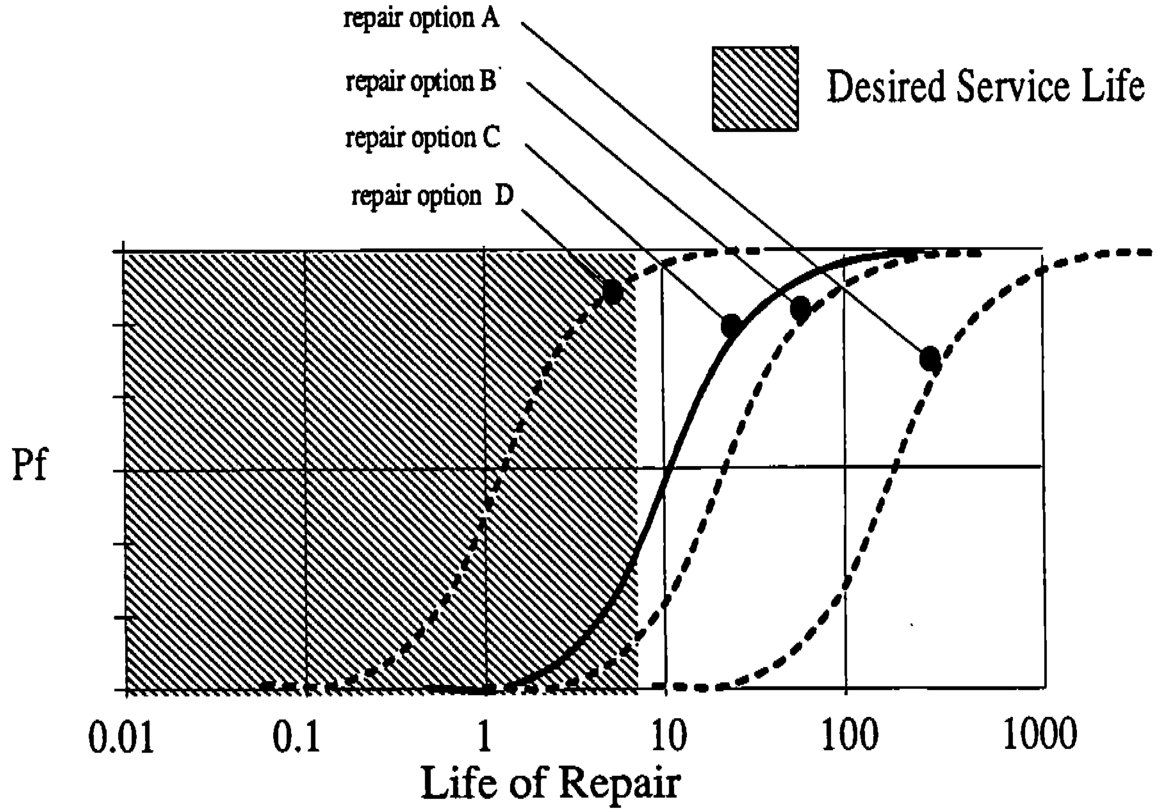

Figure 7.4. Calculated Weibull Stress Distribution and Probability of Failure for Various Repair Options

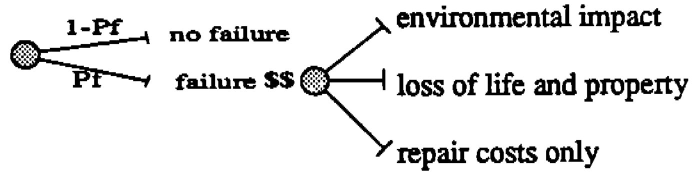

Figure 7.5. Possible Consequences of Failure

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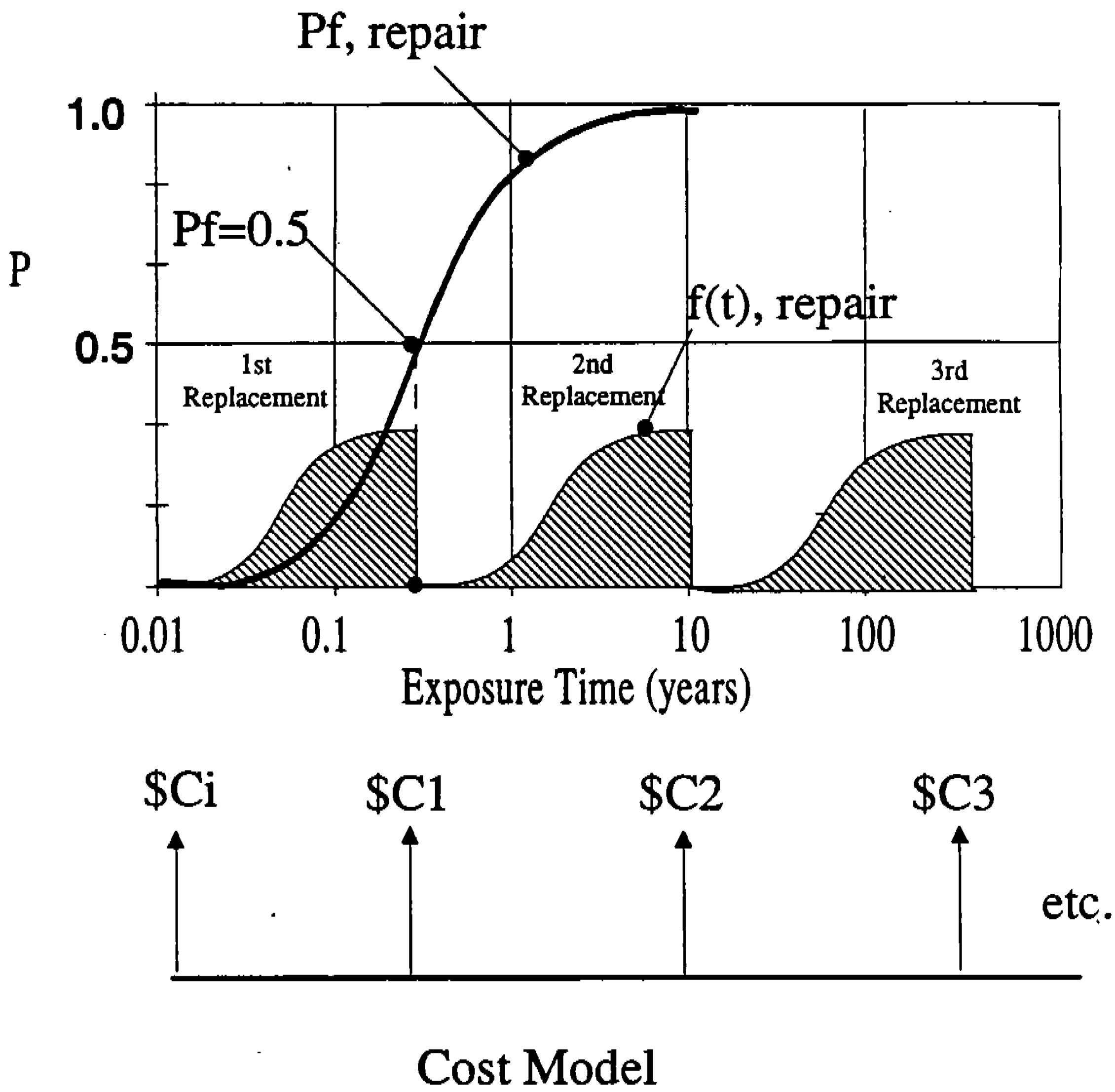

Figure 7.6. Discreet Repair Cost Model

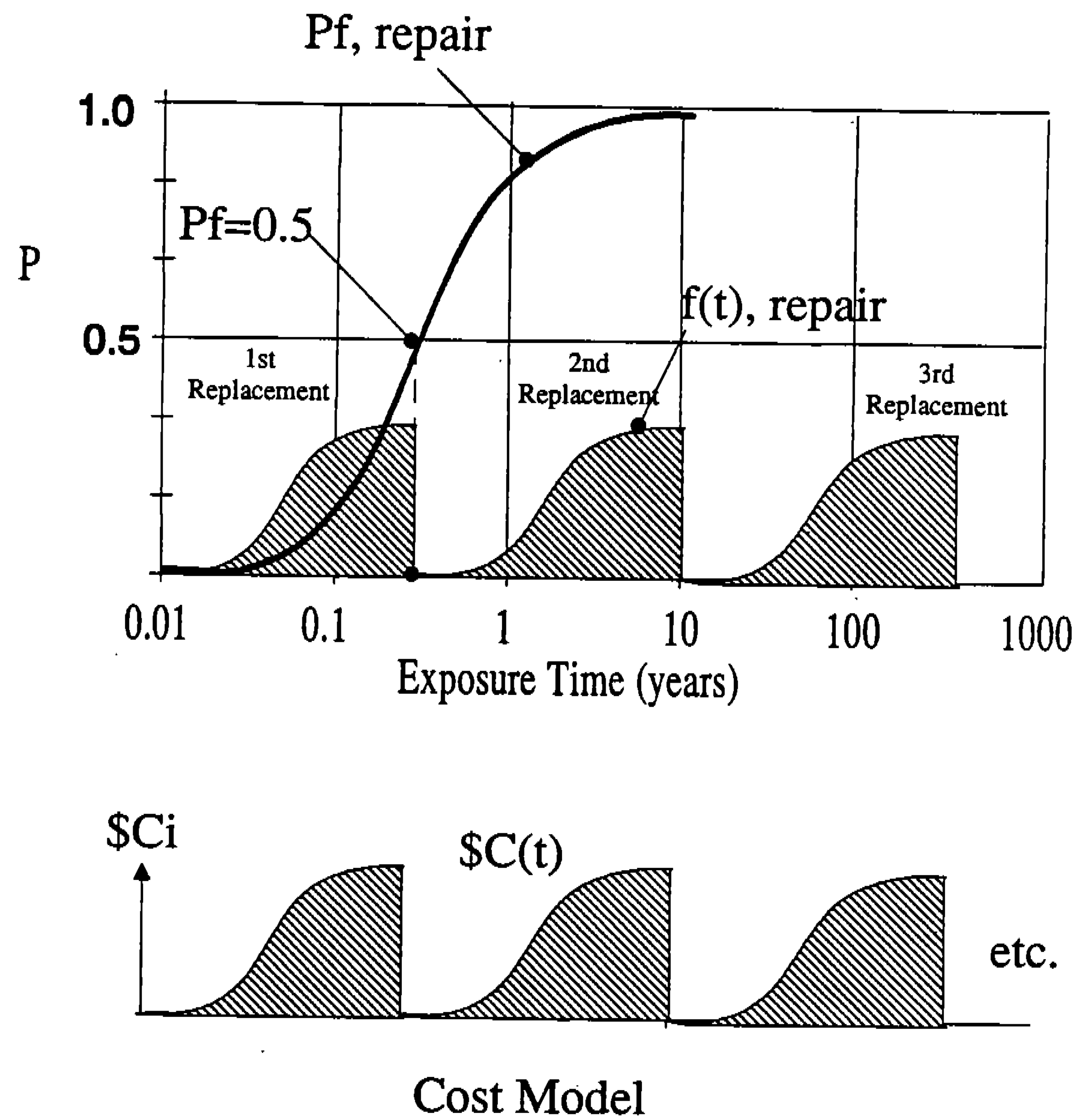

Figure 7.7. Continuous Repair Cost Model

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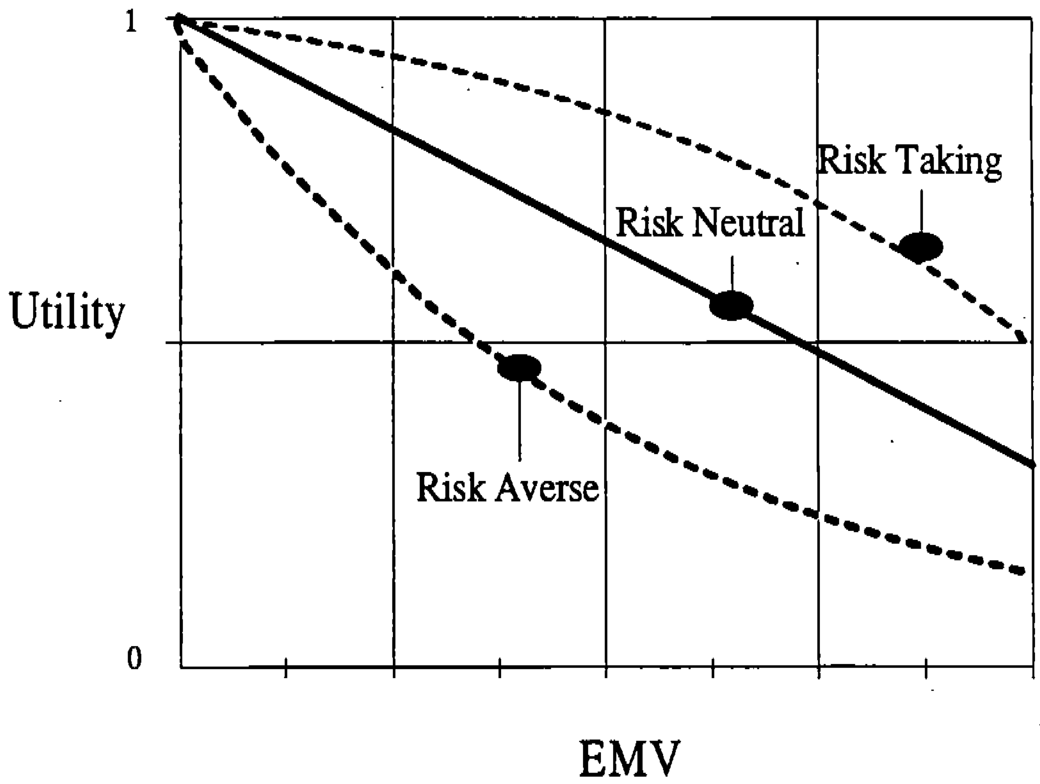


Figure 7.8. Utility Function for Repair EMV

CHAPTER 8. INITIAL RMS COMPUTER CODE

8.1. Introduction

An initial version of the Repair Management System (RMS) has been programmed in FORTRAN to demonstrate the feasibility of the concepts discussed. FORTRAN was selected for demonstration purposes and is not intended to be the programming code for a complete application. A summary of the program and its assumptions is presented followed by a verification of the code.

8.2. Summary of FORTRAN Program

A complete listing of the FORTRAN source code is provided in Appendix B. Included are both the source code and sample input and output files. For reference, a flow chart representing the operation of the program is provided in Figure 8.1.

The program performs portions of the RMS modules discussed in Chapter 3. However, due to the procedural nature of FORTRAN, much of the modular nature desired for the RMS is lost. In addition, databases are replaced by flat input files that are generated by the user to provide information on loadings, CSDs, and SN curves.

The contents of the FORTRAN code are discussed below in terms of each RMS module.

Failure Diagnosis Module

No failure diagnosis is conducted. The program assumes the mode of failure is fatigue and the cause of failure is not due to poor quality control at initial construction or due to corrosive effects.

Repair Alternatives Selection Module

Since the mode of failure is fatigue, only the crack repair options discussed in Chapter 5 are considered. These options include vee and weld, add insert plate, and redesign of the detail.

Detail configurations for any component group (e.g., side shell components) are built based on CSD.DAT. In the input file, the user is allowed to specify each component in a detail type (e.g., longitudinal, transverse cutout, lug, flatbar, bracket), the available component types (e.g., T, L or B longitudinal) and the redesign status of each component (e.g., fixed or interchangeable).

When redesigning the detail, the original crack location may be either welded or replaced. The desired repair option is manually selected by the user. In the case of redesign, the user selects from a list of valid detail configurations which are generated based on the input file CSD.DAT. The user is only allowed to select configurations that have the same fixed components as the original detail as specified in the input file.

Repair Analysis Module

Since the mode of failure is fatigue, only fatigue analysis based on Chapter 6 is conducted. The necessary information to conduct the repair analysis is provided either by the input files or by interactive input by the user.

Ship loading information, including the Weibull parameter, average stress frequency, and expert load zones and ratios are supplied by LOADING.DAT. Stress concentration factors for each loading direction and each configuration location, and SN class designations for each location are supplied by CSD.DAT. SN class parameters, including the assumed degradation in the SN class due to welding, are supplied by SNDATA.DAT. Interactive input includes the ship location, detail configuration and failure location, the mean time to failure of the original detail and the desired repair option. There is no database analysis to estimate the mean time to failure of the detail location as discussed in Chapter 7.

Repair analysis is conducted only at the location of failure. For proper repair analysis in future revisions, the RMS should search for the critical location in each redesign option since redesign redistributes the stresses and induces new weld defects.

Repair Decision Analysis Module

The EMV of each repair option is calculated based on the continuous model in Equation 7.20. The EMV is calculated over a wide time period to allow the user to investigate the costs as a function of the time in service. Initial repair costs are estimated based on relative costs provided in CSD.DAT. These costs include a cost to vee and weld, cost to add an insert plate, and a cost associated with each interchangeable component type. The ability to graph the probability of failure, the probability density function, the EMV and present value function over time is provided. No utility analysis is performed.

8.3. Verification and Case Study Example

To demonstrate and verify the code, the RMS is applied to a small side shell structure case study. In order to apply the RMS to a realistic ship structure problem, information on detail stress concentration factors and SN class designations are required. Since time is not presently available to generate the detail information by finite element analysis, existing literature is used to generate the required information.

The repair of the side shell structural detail shown in Figure 8.2 is explored. Since the stress concentration factors were available for external pressure only, no other loading directions are accounted for in the analysis. This corresponds to a side shell location near the waterline and amidships that is dominated by external wave pressure.

In the analysis, it is assumed that the original detail is a single lug configuration (cutout design and no additional lug) that fails at location 1 as shown in Figure 8.2. Two possible mean times to failure at this ship and detail location are analyzed: (1) a durable initial design with a mean life of 50 years; and (2) a non-durable initial design with a mean life of 20 years. The corresponding eight repair options are:

1. vee and weld crack;
2. add insert plate;
3. add flatbar stiffener plus vee and weld;
4. add lug plus vee and weld;
5. add lug and flatbar plus vee and weld;
6. add flatbar stiffener plus insert plate;
7. add lug plus insert plate; and
8. add lug and flatbar plus insert plate.

Relative repair costs, which are based on very rough approximations, are as follows:

- \$1000 to vee and weld;
- \$3000 to add insert plate;
- \$3000 to add lug; and
- \$3000 to add flatbar.

Any combination of changes due to redesign is estimated by the program as the sum of the associated costs.

The input files for the two analyses and a sample of the output files are provided in Appendix B. A summary of these results at a repair service life of 10 years and zero inflation and interest rates is provided in Table 8.1. These results have been verified by an equation solving program. Graphical representations of these results are generated automatically by the program (probability of failure and EMV versus exposure time).

Based on this analysis, the "best" repair option depends on the durability assumed for the initial design. For the durable initial design, repair option 1 (vee and weld) is best and for the non-durable initial design, repair option 2 (add insert plate) is best.

To visualize these results, the probability of failure, PVF, initial costs, and EMV are plotted as a function of the durability of the repair option for both analyses. Repair durability is defined as the ratio of the mean time to failure of the repair to the desired service life of the repair.

As expected, the durability of the repair is directly related to the probability of failure and the present value function, Figure 8.3. The higher the durability, the lower the probability of failure and the lower the PVF.

If a repair decision is based solely on the initial costs, the decision is clear: vee and weld. If a repair decision is based on the EMV, initial costs become less important for the low durability repair options due to the high value of the PVF, Figure 8.4. This is an expected result: non-durable initial designs require more durable repairs.

To draw any conclusions from this case study, additional work is required. This work includes the development of stress concentration factors for the neglected loading directions and code modifications to search for the critical fatigue locations on redesign repair options. In addition, a review of the relative costs, expected interest rates, and the expert load ratios is necessary. All these will have a significant impact on the decision. With this information and a large database of available CSD configurations, even this simple version of the RMS could be a valuable tool for the assessment of repair options.

		(1) Durable Initial Design, T_{f50}=50 yrs					(2) Non-Durable Initial Design, T_{f50}=20 yrs				
Repair Option	C_i ($)	MTBR (yrs)	P_f	PVF	EMV ($)	Rank	MTBR (yrs)	P_f	PVF	EMV ($)	Rank
1. Vee and weld crack	1000	5.2	.61	1.22	2,216	1	1.3	.81	7.72	8,721	2
2. Add insert plate	3000	50.0	.27	.54	4,632	2	10.0	.50	1.00	5,979	1
3. Add flatbar stiffener plus vee and weld	4000	6.3	.57	1.15	8,609	3	1.6	.79	6.38	29,535	4
4. Add lug plus vee and weld	4000	1.1	.83	6.32	29,278	6	0.27	.94	33.76	139,048	7
5. Add lug and flatbar plus vee and weld	7000	1.4	.79	6.91	55,395	8	0.36	.93	27.86	202,023	8
6. Add flatbar stiffener plus insert plate	4000	62.7	.24	.49	8,939	4	12.6	.47	.93	11,551	3
7. Add lug plus insert plate	4000	8.1	.53	0.95	11,703	5	1.5	.76	6.66	45,968	5
8. Add lug and flatbar plus insert plate	7000	11.1	.48	0.96	17,662	7	2.1	.71	4.77	51,897	6

Table 8.1. Summary of RMS Verification Case Results, Zero Interest, 10 Year Exposure, Location 1 Only

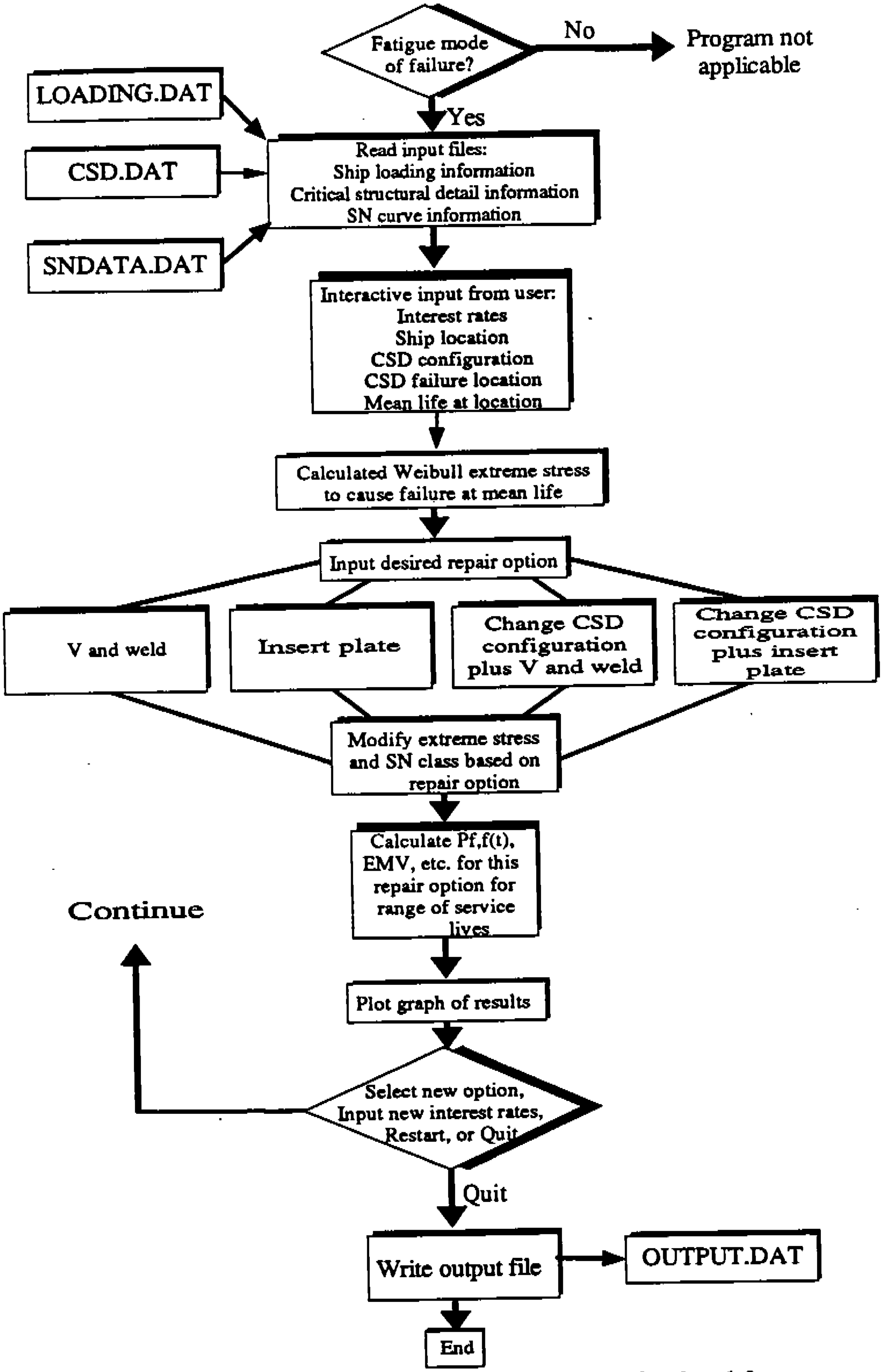
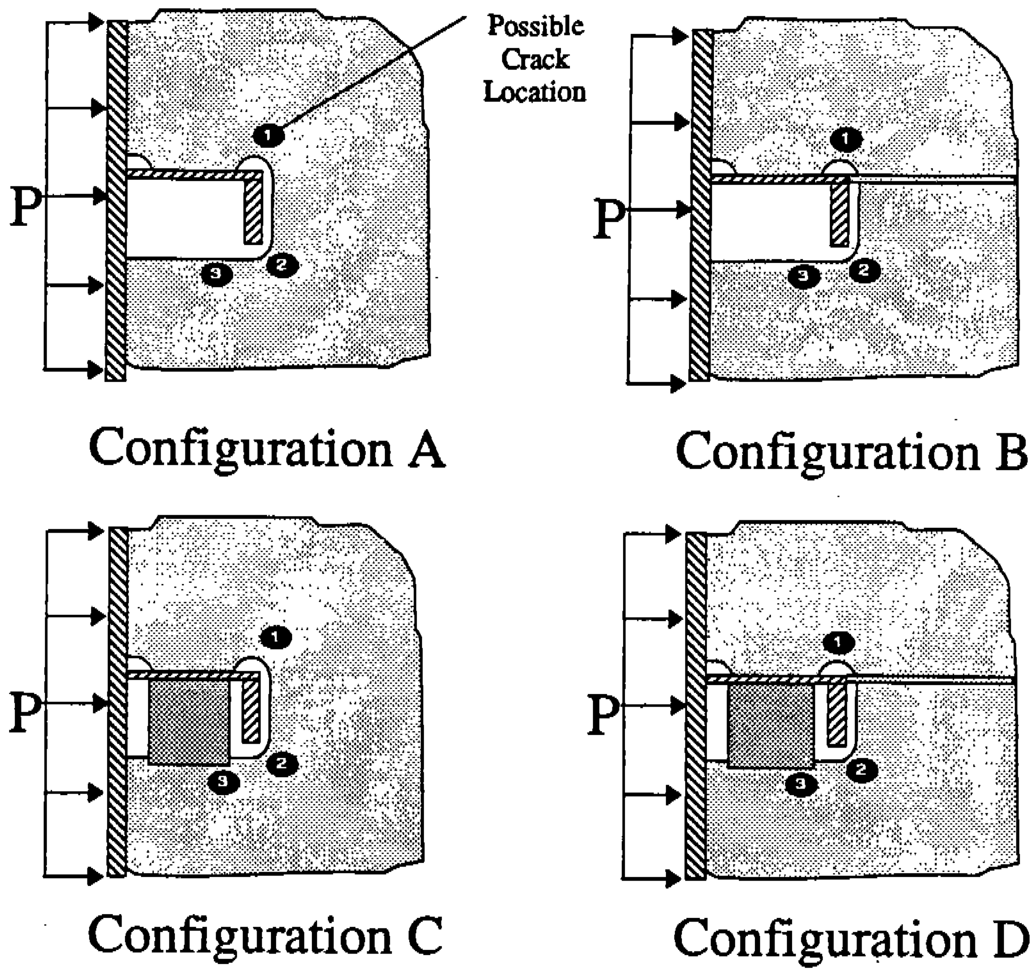


Figure 8.1. Flow Chart for RMS Version 1.0



	Stress Concentration(1)			SN Class Designation			SN Class After V&Weld		
Configuration	1	2	3	1	2	3	1	2	3
A. Single sided lug	2.0	2.1	1.0	C	C	B	F	F	F
B. Single-sided lug w/ flatbar	1.9	2.0	1.0	C	C	B	F	F	F
C. Double- sided lug	3.0	2.6	2.4	C	C	F	F	F	F2
D. Double-sided lug w/ flatbar	2.8	2.5	2.3	C	C	F	F	F	F2

(1) Due to expenal pressure loading only

Figure 8.2. Side Shell CSD Case Study Example

[approximated based on best available information]

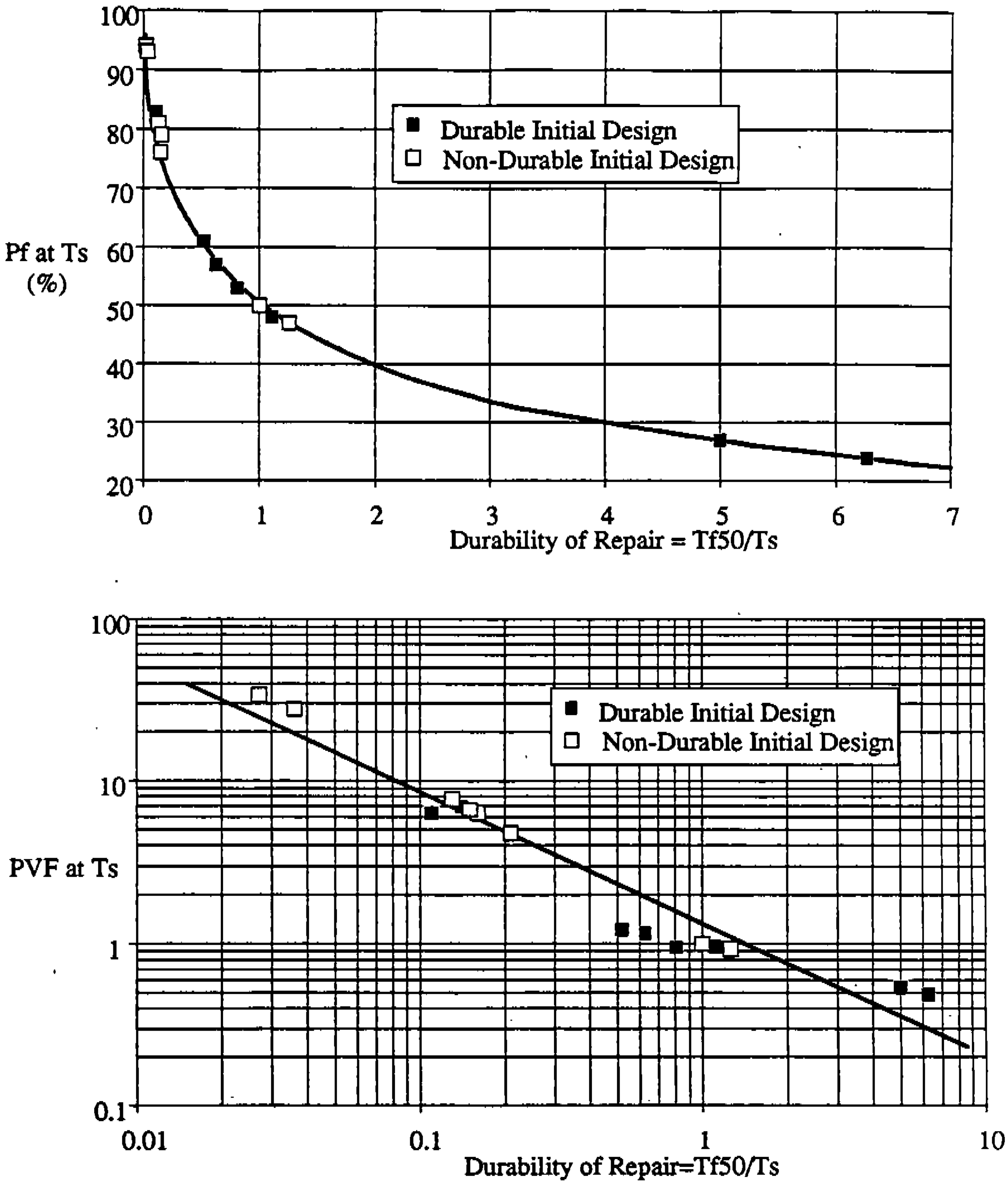


Figure 8.3. Probability of Failure and PVF Case Study Results, Zero Interest, 10 Year Exposure, Location 1 Only

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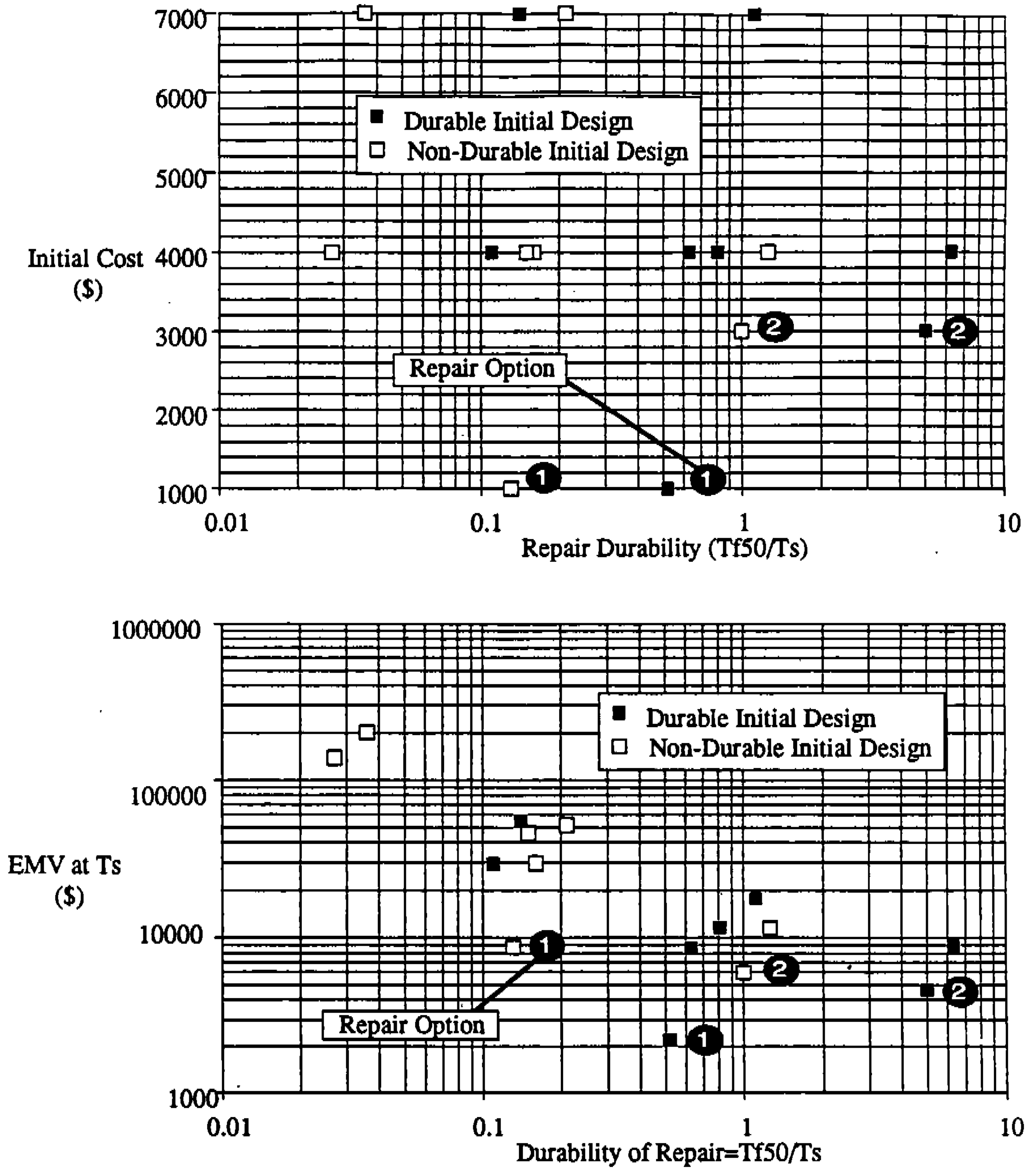

Figure 8.4. Initial Repair Costs and EMV, CSD Case Study Results, Zero Interest, 10 Year Exposure, Location 1 Only

CHAPTER 9. CONCLUSIONS AND FUTURE DIRECTIONS

9.1 Conclusions

A framework for the development of a Repair Management System (RMS) to aid in ship structural failure diagnosis and repair evaluation has been developed. The RMS is the first known attempt to handle the complexities of ship structural repair analysis in a framework that provides both elements critical to good repair--quick decisions and thorough evaluations.

The RMS follows the natural steps of repair evaluation and includes failure diagnosis, repair alternatives selection, repair alternative analysis, and decision analysis. Research concentration has been placed on the most troublesome problem in crude oil carriers today: the fatigue damage of side shell critical structural details. To avoid difficult and time consuming finite element analyses, a simplified repair analysis procedure has been developed to fit into the RMS framework. An initial version of the RMS specifically designed for the repair of fatigue damage has been developed using a simple programming environment (FORTRAN).

This research illustrates that, despite the complexities of the repair decision process, the RMS can assist in making quick, intelligent repair decisions for the repair of crude oil carriers. The initial version of the RMS outlined in Chapter 8 can be developed into a powerful tool to aid repair engineers in fatigue repair analysis. This development effort must include:

- development of a user friendly, graphical interface;
- development of a simple database system to easily manage the input data;
- development and maintenance of a complete library of details that represent both old and current designs;

- structuring the finite element analysis results in the RMS stress concentration factor format for quick repair analysis;
- tuning of the load ratios or the development of a new system to determine relative loads (including the possible use of instrumentation); and
- continued verification of the RMS system.

The case study performed on the repair of a transverse cutout failure on side shell structure using the initial version of the RMS clearly illustrates the usefulness of this simple RMS version. The RMS can quickly perform a comparative analysis of repairs, and with proper information on the loadings, critical structural details, and costs, consistent repair decisions can be made quickly. In addition, the case study stressed the significance of understanding the durability of the existing structure in order to make intelligent repair decisions. If the durability of the existing structure is not known to some level of confidence, no repair analysis will be successful.

To implement the complete RMS concept envisioned in Chapter 3, significant effort and a long term commitment are required. This effort would involve all phases of repair analysis and require a more sophisticated programming environment, such as C or an expert system shell. High priority in this effort should be placed on proper knowledge representation. Knowledge representation is critical to a successful application, and a thorough evaluation of rule syntax, organization, use of metarules, and conflict resolution are required.

9.2. Future Directions

The repair of crude oil carriers was used as a basis to discuss the possible application of computer technology to handle a difficult engineering problem. The scope of the current work was highly constrained and limited due to the time available. As a result, many enhancements to the current research are possible.

One suggested enhancement is the expansion and improvement of the programming methods and available database information. In the current RMS, FORTRAN is used to demonstrate feasibility, but it is not intended that FORTRAN be used for a larger application. Alternate environments, including C and expert system shells such as Nexpert Object should be explored thoroughly. The role of the database in the current RMS is to (1) determine the mean life to failure of specific details within the ship based on the historical database, (2) store information on structural components (stress concentration factors) and loadings (stress ratios, Weibull shape factors) and (3) store default repair options for specific damage situations. By integrating existing ship condition databases and developing new and more accurate "expert" stress concentration factors, stress ratios and shape parameters, the power of the RMS could be increased quickly. Once the complete RMS system is implemented, expansion to ship components other than side shell structure could proceed, including deck structure, bottom structure, transverse structure, special structure (knuckle joints, etc.), and any other structure of interest.

A second suggested enhancement is the expansion of the available analysis types. Fatigue is not the only mode of failure in ships, but the most common. Other important analyses include buckling, corrosion, global strength, and ship condition assessment. Of these, the ship condition assessment is probably the most important, and more appropriate to the RMS style of analysis. Ship condition assessment is directly related to the ship condition database and could prove invaluable to classification societies in their efforts to keep up with fleets of aging ships.

Third, failure mode and cause analysis is an obvious area for future work. A majority of ship failures, especially in crude oil carriers, are clearly due to fatigue. As a result, detailed mode and cause analysis is not currently as important as evaluating fatigue failures. However, as ship designs change new modes and causes of failure occur, and a tool to help evaluate these new modes and causes could prove to be important.

Fourth, since inspection is such a monumental task on crude oil carriers, the RMS could be expanded to guide inspectors to ship locations with the highest probability of failure. This ability would be closely tied to a reliability analysis of the entire ship structure and a tracking of the failure probabilities for all components. Continuous updating of the failure probabilities using historical data or instrumentation is possible. Updated failure probabilities could be used directly for repair analyses.

Fifth, a clear explanation facility to teach the users of the RMS about repair analysis could be a valuable for training tool for repair personnel. Such facilities are easily added within the framework of expert systems.

Finally, the important role of instrumentation should be thoroughly evaluated. Much of the discussion in the evaluation of fatigue repair alternatives in the RMS was focused on the estimation of stresses and fatigue damage, and resulted in calculations with high levels of uncertainty. The role of instrumentation would be to reduce the level of uncertainty in order to improve repair and other decisions. Once a good estimate of ship loading patterns is attained through the intelligent use of instruments such as fatigue gauges, strain gauging, accelerometers and others, many exciting avenues of analysis are open. Failure mode and cause evaluation, repair of failures, condition assessment, maintenance predictions, inspection guidance, ballasting and ship operation guidance could all benefit.

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APPENDIX A: EXPERT SYSTEM BASICS

1.0 Introduction

The field of expert systems is the practical branch of the broader field of artificial intelligence (AI). An expert system "is a computer program that performs a task normally done by an expert or consultant and which, in so doing, uses captured, heuristic knowledge" [Dym,1991]. As a result, any computer program which succeeds in helping the user reach a decision, whether written in procedural code like FORTRAN or special purpose AI programming language, is an expert system. The less knowledgeable the user of the code needs to be, the more "expert" the expert system.

Expert systems have been developed for many problems that are unsuited for simple procedural programming methods. Design and diagnosis problems, which are typically performed by experts with in-depth knowledge of the problem to be solved, are good examples. The following is a brief summary of the basic theory behind expert systems based on Agogino's notes [Agogino,1991] unless otherwise noted.

For additional information on expert systems, see Dym for basic theory [Dym,1991] and Maher or Pham for specific engineering applications [Maher,1987] [Pham,1988].

2.0 Components of an Expert System

Expert systems can be broken into four basic components--a knowledge-base, database, inference engine, and user interface.

Knowledge-Base

In an expert system, knowledge from experts in the form of a set of rules and facts is accumulated into a "knowledge-base" much like data in a database system. This knowledge-base may be modified and updated as additional information is acquired (knowledge-maintenance).

Rules can be expressed in three basic forms: (1) production rules, (2) subjective probability, and (3) fuzzy inference. A typical production rule is expressed using prefix predicate calculus as an IF-THEN rule such as:

$$\left.\begin{array}{c}\textbf{IF A THEN B}\\ \text{or}\\ \textbf{(IF A B)}\end{array}\right\} \Rightarrow \text{If A is true then B is true}$$

Logical operators in addition to IF and THEN may be used to express knowledge in the rule form, including AND, OR, and NOT. The effect of these operators is defined using the following truth table (t=true, f=false):

A	B	(IF A B)	(NOT A)	(AND A B)	(OR A B)
t	t	t	f	t	t
t	f	f	t	f	t
f	t	t	--	f	t
f	f	t	--	f	f

Subjective probability and fuzzy logic were developed to handle knowledge that is not deterministic. An example of subjective probability is:

$$\textbf{IF A THEN B} = \begin{cases} 10. \text{ with a probability of } 0.2 \\ 12. \text{ with a probability of } 0.5 \\ 19. \text{ with a probabiltity of } 0.3 \end{cases}$$

In fuzzy logic, there is also an uncertainty associated with A.

For many engineering problems, both symbolic (rules) and numeric processing are required. These are referred to as "coupled" expert systems.

Database

Any general information that is required by the expert system is placed in a general database. This information includes relevant information such as engineering data, historical information, list of components, etc.

User Interface

In order to operate the expert system in a user-friendly manner, a user interface is required. This interface can be used to maintain the knowledge and databases, ask the user for any required input, allow control of the session and display pertinent information and advise.

Inference Engine

Symbolic processing is used by the expert system's "inference engine" to reach a hypotheses based on information supplied by the user, the knowledge-base and the general database. For production rules, logical deduction is used to attempt to reach a new conclusion based on the existing information. The logical rules include:

- Modus Ponens (MP)
- Modus Tollens (MT)
- And Elimination (AE)
- AND Introduction (AI)
- Universal Instantiation (UI)
- Existential Instantiation (EI)

Using these rules with backward and/or forward reasoning new states of knowledge can be reached. Backward reasoning starts with a goal state and attempts to verify the goal by working backwards. Forward reasoning uses the existing knowledge to prove a hypothesis.

In many cases, the knowledge required to reach a hypothesis is uncertain or unknown, i.e. the knowledge is non-monotonic. Many approaches have been developed to help reason under these conditions of uncertainty. These approaches include default reasoning, non-monotonic logic, three valued logic, certainty factors and belief functions, probabilistic reasoning, fuzzy logic and commonsense reasoning, possibility theory and the Dempster-Shafer theory.

3.0 Programming Environments

Because programming the rules and inference procedures can be cumbersome using procedural programming languages such as FORTRAN, specialized AI programming languages have been developed to handle the symbolic processing required to efficiently handle non-numerical data (knowledge). These languages include LISP and PROLOG. Other languages such as C and object-oriented languages are the most appropriate for expert system applications.

To promote quick prototyping, expert system "shells" are sometimes used. These systems provide a user-friendly front end to the expert system programming environment (usually C, LISP, or PROLOG). To support future expansions of an application, a shell which is powerful and flexible should be chosen to avoid problems in the future. Additional desirable features of a shell for design problems are the following [Mills,1991]:

- capability to query the user during the inference process,
- explanation mechanism that allows the user to determine the reason for each step in the system,
- graphic display of knowledge-base,
- capability to prioritize or weight rules,
- capability to indicate conflicting or incomplete data when encountered,
- user defined multiple inheritance,
- ability to choose direction of search within the knowledge-base, and
- frame-based knowledge representation.

It is also desirable to be able to port the application to various platforms. Several shells meet this criteria, such as Nexpert Object from Neuron Data.

4.0 References

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Mills, Stephen, Muirat M. Tanik, "Selection of Expert System Tools for Engineering Design Applications", in Workshop on Expert Systems and Applications, edited by Murat M. Tanik and A. Ertas, American Society of Mechanical Engineers, 1991, pg. 41.

Pham, D.T., Expert Systems in Engineering, IFS Publications, New York, 1988.

APPENDIX B: RMS SOURCE CODE

The FORTRAN source code for Version 1.0 of RMS is provided on the following pages. The following are provided in order:

- FORTRAN code,
- sample input files, and
- sample output file.

An IBM format diskette containing these files and the executable version of the code is provided at the end of the report.

The code was written using Microsoft FORTRAN Version 3.5 with the Microsoft graphics library calls for plotting. The code contains adequate comments, including definitions of all important variables. The code is arranged into a main program, graphics routines, file reading routines, miscellaneous routines, and mathematical routines. Routines are arranged in alphabetical order in each section.

Sample input files are also provided. A total of three input files are required:

- LOADING.DAT (ship loading information),
- CSD.DAT (critical structural detail information), and
- SNDATA.DAT (SN curve information)

The specific contents of these files are discussed in the sample file comment lines. Input files contain three basic types of input lines which are designated by the first character in the line. A comment line uses a "*" in the first column. These comment lines are ignored by the reading routines and may be placed almost anywhere in the input file. An action line is indicated by a "=" followed by a specific action keyword which directs the program to read specific input information on the following line(s). These lines cannot be interrupted by a comment line. A line with no "*" or "=" in the first column is input data. The end of an input file is indicated by "=end". All input is case sensitive, and lower case should be used as shown.

A sample output file OUTPUT.DAT is also provided. This output is based on a session using the provided input files.

FORTRAN SOURCE CODE: RMS.FOR

```
c=======1=========2=========3==========4==========5=========6=========7==
c     REPAIR MANAGEMENT SYSTEM, Version 1.0
c     Programmed by Keith Gallion
c     Last Updated 5/10/92
c=======1=========2=========3==========4==========5=========6=========7==
c     Program to illustrate a simplified sytem of repair analysis for
c     fatigue mode of ship structural failures.
c=======1=========2=========3==========4==========5=========6=========7==

      INCLUDE  'FGRAPH.FI'
      INCLUDE  'FGRAPH.FD'

c     Graphics variables
      INTEGER*2 dummy
      LOGICAL  fourcolors
      EXTERNAL fourcolors

c     Main program variables
c        a,m            SN Class life intercept and inverse slope
c        bias       Bias in mean life calculation (set to 1.0)
c        costmin    Minimum cost for normalized EMV plotting
c        costmax    Maximum cost for normalized EMV plotting
c        covi       Coefficient of variation in, respectively, damage at
c                 failure, SN life intercept & Stress calculation
c        dfail      Cumulative fatigue damage at failure
c        emvpdf(i,j)    Expected monetary value for continuous model
c               for service life i, repair number j
c        emvnorm(i,j)  Normalized emv for plotting
c        location   Location in ship of detail (zone #)
c        origcsd    Configuration # of detail to be repaired
c        origloc    Location # on detail of failure
c        origsn     SN class at origloc for origcsd
c        origtf     Mean time to fatigue failure of origcsd at origloc
c        ratio      Ratio of tensile stress normal to crack between
c                 original and modified configuration of repair
c        repcsd     Configuration # of repair redesign
c        repcost(i)  Cost of repair option i
c        repso(i)   Calculated Weibull extreme stress of repcsd at
c                 origloc for repair option i
c        repsn(i)   SN class at origloc of repcsd for repair option i
c        repnum     Current repair #
c        reptf(i)   Calculated time to failure for repair i
c        reptitle(i)    Title of repair option i
c        so       Calculated Weibull extreme stress to cause failure
c                 in the original detail at origtf
c        time(i,j) Time in service for plotting time i for repair
c                 option j
c        ts       Total desired time in service of a repair
c        pf(i,j)    Probability of failure of repair j at time i
c        pdf(i,j)   Probability denity of failure of repair j at
c                 time i
c        pvf(i,j)   Present value function of repair j at time i

      CHARACTER*1 ans
      CHARACTER*2 origsn,repsn(10)
      CHARACTER*40 reptitle(10)
      INTEGER i,location,origcsd,repcsd,origloc,repnum
      REAL origtf,reptf(10),a,m,so,repso(10),bias,dfail,ts,ratio,
     &         emvpdf(50,10),emvnorm(50,10),
     &         pf(50,10),pdf(50,10),pvf(50,10),
     &         time(50,10),
     &         repcost(10),costmin,costmax,covd,cova,covb

      REAL pvfpf,pvfpdf,pvftotal
      EXTERNAL pvfpf,pvfpdf,pvftotal
```

```
c     Variables to complete FUNCTION for emv
c        reptf1    Current repair mean time to failure
c        sdlnt     Standard deviation in the ln of time to failure
c        ror           Rate of return on money
c        infl      Inflation rate
c        ta      Beginning of repair period for multiple repair
c                cost model

      REAL reptf1,sdlnt,ror,infl,ta
      COMMON /emvvars/ reptf1,sdlnt,ror,infl,ta

c     Variables for reading of loading file
c        eta           Weibull shape parameter of loading
c        fo      Average loading frequency, cycles per year
c        grpname   Group name of loading file
c        numload   Total number of loading directions
c        numloc    Total number of ship loading zones
c        r(i,j)    Expert load ratios for location i in direction j
c        shiploc(i)  Name of ship loading zone i
c        shipname  Name of ship

      CHARACTER*33 shipname,grpname,shiploc(20)
      INTEGER numloc,numload
      REAL fo,eta,r(20,20)
      COMMON /loading/ shipname,grpname,shiploc,numloc,numload,
     &          fo,eta,r

c     Variables for reading of csd file
c        csdnum    Total number of critical structural details in file
c        compname(i)    Name of component i
c        compnum   Total number of components in csd file
c        costcomp(i,j)  Relative cost of compont i for component type j
c        costvw    Relative cost to add insert plate
c        costip    Relative cost to v and weld
c        csd(i,j)  Critical structural component makeup
c        fixity(i) Fixity of component i (1=fixed,0=interchangeable)
c        numcomp   Total number of components
c        numcloc   Total number of locations for evaluation on detail
c        numcload  Total number of loading directions for stress
concentration
c        scf(i,j,k)  Stress concentration factor for csdnum i, locaton j,
direction k
c        snclass(i,j)  SN class of csdnum i at location j
c        typename(i,j)  Component makeup of component i
c        typenum(i)  Total number of types of component i

      CHARACTER*1 typename(20,20),csd(20,20)
      CHARACTER*2 snclass(20,20)
      CHARACTER*33 compname(20)
      INTEGER numcomp,numcloc,numcload,compnum,typenum(20),
     &          fixity(20),csdnum
      REAL scf(20,20,20),costcomp(20,20),costvw,costip
      COMMON /detail/ typename,csd,snclass,compname,numcomp,numcloc,
     &          numcload,compnum,typenum,fixity,csdnum,scf,costcomp,
     &          costvw,costip

c     Variables for reading SN curve data
c        classname(i)  Name of SN class i
c        classvw(i) Name of SN class that classname i degrades
c                to with welding
c        numclass  Total number of SN classes
c        snm(i),sna(i) SN class slope and life intercept for class i
c        snname    Name of SN curve types (e.g., U.K.)

      CHARACTER*2 classname(20),classvw(20)
      CHARACTER*33 snname
      INTEGER numclass
      REAL snm(20),sna(20)
      COMMON /sndata/ classname,classvw,snname,numclass,snm,sna

c     Open output file
```

```
      OPEN (unit=7,file='output.dat')
    1 REWIND(7)

c     Set up graphics information.  Standard MS Fortran graphics
c     library calls.

      IF(fourcolors()) THEN
         dummy = setbkcolor($BLUE)
         dummy = settextcolor(1)
         CALL clearscreen($GCLEARSCREEN)
         dummy = setcolor($WHITE)
         dummy = registerfonts('c:\fortran\lib\*.fon')
         IF (dummy.LT.0) THEN
            WRITE(6,*) 'registerfonts(c:\fortran\lib\*.fon) = ',
     &                  dummy
            PAUSE 'registerfonts>  font file not available'
         ELSE
            dummy=setfont("t'tms rmn' h20 w12 p b")
         ENDIF
      ELSE
         WRITE (6,*) 'This program requires a CGA, EGA, or',
     &              ' VGA graphics card.'
         GOTO 9999
      ENDIF

c     Write introductory information to screen

      WRITE(6,1000)
      WRITE(7,1000)
 1000 FORMAT(
     &' ********************************************************',/
     &'              RMS--REPAIR MANAGEMENT SYSTEM',/
     &'                    Version 1.0',/
     &'               Last Updated 4/29/92',/,/
     &'          A System for Simplified Repair Analysis',/
     &'          for Fatigue Mode of Ship Structural Failure',/
     &' ********************************************************',/,/
     &'            UNIVERSITY OF CALIFORNIA, BERKELEY',/
     &'        NAVAL ARCHITECTURE AND OFFSHORE ENGINEERING',/,/
     &' Based on input files providing information on loading,',/
     &' critical structural detail, and material properties,',/
     &' this program estimates mean fatigue life, probability of',/
     &' failure distribution, and expected monetary value for the',/
     &' repair alternatives selected.')

c     Read loading, csd, and sn data files

      WRITE(6,1001)
      WRITE(7,1001)
 1001 FORMAT(/
     &' The following input data files are required:',/
     &'      LOADING.DAT      Ship Loading Data',/
     &'      CSD.DAT          Critical Structural Detail Data',/
     &'      SNCURVE.DAT      Fatigue Curve Data')
      CALL readload
      CALL readcsd
      CALL readsn

      WRITE(6,1010) shipname,grpname
 1010 FORMAT(/
     &' Based on the input files selected, the following',/
     &' ship and CSD group are to be analysed:',/
     &'      Ship =',2x,a33,/
     &'      CSD  =',2x,a33,/)
      PAUSE 'Press <cr> to continue.'
      CALL clearscreen( $GCLEARSCREEN )

c     Request interactively input from user concerning:
c      1.  desired time in service for repair
c      2.  inflation rate and rate of return
```

```
c       3.  CSD location in ship
c       4.  CSD configuration
c       5.  location on CSD of fatigue failure
c       6.  mean time to failure at failure location--this information
c             must be based on a combination of historical data and
c             structural analysis and is critical to the analysis.
      WRITE(6,1011)
 1011 FORMAT(/
     &' RMS Version 1.0 supports only the fatigue mode of failure',/
     &' Is the mode of failure fatigue? <cr>=yes')
      READ(5,1065) ans
      IF (ans.NE.'y'.AND.ans.ne.'Y'.AND.ans.NE.' ') THEN
         PAUSE 'Program aborted.  Press <cr> to exit!!!'
         GOTO 999
      ENDIF
      WRITE(6,*) 'Enter expected time in service of repair (yrs)'
      READ(5,*) ts
      WRITE(6,1012) '      time ',ts
 1012 FORMAT(' ECHO: 'a10,'=',f8.2,/)
 1013 FORMAT(' ECHO: 'a10,'=',i4,/)

      WRITE(6,*) 'Enter expected effective inflation rate per year'
      READ(5,*) infl
      WRITE(6,1012) 'inflation ',infl

      WRITE(6,*) 'Enter expected effective rate of return per year'
      READ(5,*) ror
      WRITE(6,1012) '    return ',ror

      WRITE(6,*) 'Select ship location of detail to repair:'
      WRITE(6,1020) (i,shiploc(i),i=1,numloc)
 1020 FORMAT(1x,5x,i2,'.',2x,a33)
      READ(5,*) location
      WRITE(6,1013) ' location ',location

      CALL options
      WRITE(6,*) 'Select configuration # of the failed detail:'
      READ(5,*) origcsd
      WRITE(6,1013) '     config',origcsd

      WRITE(6,1021)
 1021 FORMAT(' Input the location on the detail of failure based',/
     &' on the numbering convention in CSD data file')
      READ(5,*) origloc
      WRITE(6,1013) ' location ',origloc

      WRITE(6,*) 'Input mean time to failure at this location (yrs)'
      READ(5,*) origtf
      WRITE(6,1012) '      time ',origtf

c     Determine Weibull extreme stress to produce failure
c     at mean life SO

      origsn=snclass(origcsd,origloc)
      CALL snparam(origsn,m,a)
      dfail=1.
      bias=1.
      CALL exstress(so,a,m,fo,eta,origtf,dfail,bias)

      WRITE(6,1050) so,origtf,fo,eta,origsn,m,a
 1050 FORMAT(/
     &' The estimated Weibull extreme stress to cause',
     &' failure',/
     &' is ',f8.2,' N/mm^2 for the original detal with',/
     &'      Mean time to failure = ',f8.2,' years',/
     &'      Average frequency    = ',e8.2,' cycles/yr',/
     &'      Weibull shape param  = ',f8.2,/
     &'      SN parameters',/
     &'          class  = ',5x,a2,/
     &'          m      = ',f8.2,/
     &'          A      = ',e8.3,/)
```

```
      PAUSE 'Press <cr> to continue.'

c     Interactively select desired repair alternative.

      repnum=0
   15 CONTINUE
      CALL clearscreen( $GCLEARSCREEN )
      WRITE(6,1060)
 1060 FORMAT(/
     &' Select repair alternative to investigate:',/
     &'       1.  V and weld crack',/
     &'       2.  Add insert plate',/
     &'       3.  Redesign + V and weld crack',/
     &'       4.  Redesign + insert plate',/
     &'       x.  Quit and output to file')
      READ(5,1065) ans
 1065 FORMAT(a1)

c     Depending on the alternative, determine the appropriate
c     sn curve REPSN, modified Weibull stress range REPSO, and repair
c     cost estimate REPCOST

      IF (ans.NE.'x'.AND.ans.NE.'X'.AND.ans.NE.' ') THEN
         repnum=repnum+1
         repcost(repnum)=0.
      ENDIF
      IF (ans.EQ.'1') THEN
         reptitle(repnum)=' V and Weld Only'
         CALL snclassvw(repsn(repnum),origsn)
         CALL stressvw(repso(repnum),so)
         repcost(repnum)=costvw
      ELSE IF (ans.EQ.'2') THEN
         reptitle(repnum)=' Add Insert Plate Only'
         repsn(repnum)=origsn
         CALL stressip(repso(repnum),so)
         repcost(repnum)=costip
      ELSE IF (ans.EQ.'3') THEN
         reptitle(repnum)=' Redesign plus V and Weld Crack'
         CALL options
         CALL select(repcsd,origcsd)
         repsn(repnum)=snclass(repcsd,origloc)
         CALL snclassvw(repsn(repnum),repsn(repnum))
         CALL stressratio(ratio,repcsd,origcsd,origloc,location)
         CALL stressvw(repso(repnum),so)
         repso(repnum)=ratio*repso(repnum)
         CALL cost(repcost(repnum),repcsd,origcsd)
         repcost(repnum)=costvw+repcost(repnum)
       ELSE IF (ans.EQ.'4') THEN
         reptitle(repnum)=' Redesign plus Add Insert Plate'
         CALL options
         CALL select(repcsd,origcsd)
         repsn(repnum)=snclass(repcsd,origloc)
         CALL stressratio(ratio,repcsd,origcsd,origloc,location)
         CALL stressip(repso(repnum),so)
         repso(repnum)=ratio*repso(repnum)
         CALL cost(repcost(repnum),repcsd,origcsd)
         repcost(repnum)=costip+repcost(repnum)
      ELSE IF (ans.EQ.'x'.or.ans.EQ.'X') THEN
         GOTO 999
      ELSE
         WRITE(6,*) 'Invalid option! Try again.'
         GOTO 15
      ENDIF

c     Iterate to determine the expected mean time to failure for the
c     repair alternative chosen REPTF()

      CALL snparam(repsn(repnum),m,a)
      dfail=1.
      bias=1.
      CALL tfaili(reptf1,a,m,fo,eta,repso(repnum),dfail,bias)
```


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```
      reptf(repnum)=reptf1

      WRITE(6,1080) repnum,reptitle(repnum),reptf1,
     &         so,repso(repnum),fo,eta,repsn(repnum),m,a
 1080 FORMAT(/
     &' REPAIR NUMBER ',i2,': ',a40,/
     &' ============================================== ',/
     &' The estimated mean life of this repair is',f8.2,' years',
     &' based on:',/
     &'      Original extreme stress = ',f8.2,' N/mm^2',/
     &'      Repair extreme stress   = ',f8.2,' N/mm^2',/
     &'      Average frequency       = ',e8.2,' cycles/yr',/
     &'      Weibull shape param     = ',f8.2,/
     &'      Repair SN parameters',/
     &'          class   = ',5x,a2,/
     &'          m       = ',f8.2,/
     &'          A       = ',e8.3,/)

c     Calculate all relevant information for this alternative,
c     including probability of failure PF and expected monetary
c     value EMV for a range of two time the service life

c     Pf calculations and plotting

   20 CONTINUE
      covd=0.
      cova=0.
      covb=.89
      sdlnt=sqrt(log((1.+covd**2)*(1+cova**2)*(1+covb**2)**(m**2)))
      time(1,repnum)=0.
      pf(1,repnum)=0.
      pdf(1,repnum)=0.
      DO 21 i=1,INT(2*ts)
         time(i+1,repnum)=REAL(i)
         pf(i+1,repnum)=probfail(reptf1,REAL(i),sdlnt)
         pdf(i+1,repnum)=pdflognorm(reptf1,REAL(i),sdlnt)
   21 CONTINUE

c     Plot Pf and PDF

      WRITE(6,*) 'Plot Pf curves? <cr>=yes'
      READ(5,1065) ans
      IF (ans.EQ.'y'.OR.ans.EQ.'Y'.OR.ans.EQ.' ') THEN
         CALL graph(time,pf,INT(2*ts+1),repnum,
     &           0.,2.*ts,0.,1.,
     &           'PROBABILITY FAILURE OF REPAIR ',
     &           'Exposure Time (yrs)           ',
     &           'Pf                            ',
     &           'Option #                      ')
      ENDIF

      WRITE(6,*) 'Plot PDF curves? <cr>=yes'
      READ(5,1065) ans
      IF (ans.EQ.'y'.OR.ans.EQ.'Y'.OR.ans.EQ.' ') THEN
         CALL graph(time,pdf,INT(2*ts+1),repnum,
     &           0.,2.*ts,0.,.2,
     &           'PROBABILITY DENSITY OF REPAIR ',
     &           'Exposure Time (yrs)           ',
     &           'Pr                            ',
     &           'Option #                      ')
      ENDIF

c     EMV calculation and plotting

      WRITE(6,*) 'Calculating EMV values. Please be patient!'
      pvf(1,repnum)=0.
      emvpdf(1,repnum)=repcost(repnum)
      DO 31 i=1,INT(2*ts)
         emvpdf(i+1,repnum)=repcost(repnum)*
     &              (1.+pvftotal(pvfpdf,real(i)))
         pvf(i+1,repnum)=pvftotal(pvfpdf,real(i))
```


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```
   31 CONTINUE
      WRITE(6,1100) repnum,reptitle(repnum),ts,
     &         100.*pf(INT(ts+1),repnum),
     &         sdlnt,reptf1,
     &         emvpdf(INT(ts+1),repnum),ts/reptf1,
     &         pvf(INT(ts+1),repnum),
     &         100.*infl,100.*ror,repcost(repnum)
 1100 FORMAT(/
     &' REPAIR NUMBER ',i2,': ',a40,/
     &' ============================================= ',/,/
     &' At the service life of ',f8.2,' years the probability',/
     &' of failure for this repair is ',f8.2,'% based on:',/
     &'      sd of ln(Tf)               =  ',f8.2,/
     &'      Tf  mean time to failure   =  ',f8.2,' years',/
     &' The expected monetary value of this repair decision',/
     &' is $',f12.2,' based on the following data:',/,/
     &'      EMV = Ci(1+PVF)',/
     &'      MNR mean number of repairs =  ',f8.2,/
     &'      PVF present value function =  ',f8.2,/
     &'      i   rate of inflation      =  ',f8.2,' %',/
     &'      r   rate of return         =  ',f8.2,' %',/
     &'      Ci  initial repair costs   = $',f8.2,/)

c     Plot EMV

   30 WRITE(6,*) 'Plot emv curve? <cr>=yes'
      READ(5,1065) ans

      IF (ans.EQ.'y'.OR.ans.EQ.'Y'.OR.ans.EQ.' ') THEN

c     Find maximum cost to normalize all costs to $1
c     Normalize costs and save to emvnorm

         CALL testdata(emvpdf,INT(2*ts+1),repnum,costmin,costmax)
         DO 33 j=1,repnum
            DO 33 i=1,INT(2*ts+1)
            emvnorm(i,j)=emvpdf(i,j)/costmax
   33    CONTINUE
         CALL graph(time,emvnorm,INT(2*ts+1),repnum,
     &           0.,2.*ts,0.,1.,
     &           'NORMALIZED EMV OF REPAIR      ',
     &           'Exposure Time (yrs)           ',
     &           'EMV ($)                       ',
     &           'Option#                       ')

         CALL graph(time,pvf,INT(2*ts+1),repnum,
     &           0.,2.*ts,0.,10.,
     &           'PRESENT VALUE FUNCTION        ',
     &           'Exposure Time (yrs)           ',
     &           'EMV ($)                       ',
     &           'Option#                       ')
      ENDIF

c     CONTINUE selecting alternatives, restart or quit.

   99 CONTINUE
      WRITE(6,1110)
 1110 FORMAT(/
     &' Select option:',/
     &'      1.  Enter new repair alternative <cr>',/
     &'      2.  Enter new interest rates to plot',/
     &'          3.  Review plots again',/
     &'      r.  Restart repair evaluation',/
     &'      x.  Quit and output to file')
      READ(5,1065) ans
      IF (ans.EQ.'1'.OR.ans.EQ.' ') GOTO 15
      IF (ans.EQ.'2') THEN
       WRITE(6,*) 'Enter expected effective inflation rate per year'
       READ(5,*) infl
       WRITE(6,1012) 'inflation ',infl
       WRITE(6,*) 'Enter expected effective rate of return per year'
```


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```
      READ(5,*) ror
      WRITE(6,1012) '    return ',ror
      WRITE(6,*) 'Recalculating EMV values. Please be patient!'
      DO 40 j=1,repnum
          WRITE(6,*) '... Repair Option ',j
          DO 40 i=1,INT(2*ts)
            reptf1=reptf(j)
            emvpdf(i+1,j)=repcost(j)*
     &                (1.+pvftotal(pvfpdf,real(i)))
            pvf(i+1,j)=pvftotal(pvfpdf,real(i))
   40 CONTINUE
      GOTO 30
     ENDIF
     IF (ans.EQ.'3') GOTO 20
     IF (ans.EQ.'r'.OR.ans.EQ.'R') GOTO 1
     IF (ans.EQ.'x'.OR.ans.EQ.'X') GOTO 999
     WRITE(6,*) 'Invalid option'
     GOTO 99

c    Send output summary of final options to output file and close

 999 CONTINUE

c    Write summary of option selected

     WRITE(7,2100) location,origcsd,origloc,origtf
     WRITE(7,2200) so,origtf,fo,eta,origsn,m,a
 2100 FORMAT(/,
    &' Original failed detail:',/
    &'      ship zone #          = ',i2,/
    &'      csd #                = ',i2,/
    &'      location on detail   = ',i2,/
    &'      mean time to failure = ',f8.2)
 2200 FORMAT(/
    &' The estimated Weibull extreme stress to cause',
    &' failure',/
    &' is ',f8.2,' N/mm^2 for the original detal with',/
    &'      Mean time to failure = ',f8.2,' years',/
    &'      Average frequency    = ',e8.2,' cycles/yr',/
    &'      Weibull shape param  = ',f8.2,/
    &'      SN parameters',/
    &'          class  = ',5x,a2,/
    &'          m      = ',f8.2,/
    &'          A      = ',e8.3)

c    Write summary of repair options

     DO 220 i=1,repnum
        CALL snparam(repsn(i),m,a)
        WRITE(7,2300) i,reptitle(i),reptf(i),
    &             so,repso(i),fo,eta,repsn(i),m,a
        WRITE(7,2310) ts,
    &             100.*pf(INT(ts+1),i),
    &             sdlnt,reptf(i),
    &             emvpdf(INT(ts+1),i),ts/reptf(i),
    &             pvf(INT(ts+1),i),
    &             100.*infl,100.*ror,repcost(i)
     WRITE(7,2320)
     DO 220 j=1,INT(2*ts+1)
       WRITE(7,2330) time(j,i),pf(j,i),pdf(j,i),pvf(j,i),emvpdf(j,i)
  220 CONTINUE
 2300 FORMAT(/
    &' REPAIR NUMBER ',i2,': ',a40,/
    &' ============================================= ',/
    &' The estimated mean life of this repair is',f8.2,' years',
    &' based on:',/
    &'      Original extreme stress = ',f8.2,' N/mm^2',/
    &'      Repair extreme stress   = ',f8.2,' N/mm^2',/
    &'      Average frequency       = ',e8.2,' cycles/yr',/
    &'      Weibull shape param     = ',f8.2,/
    &'      Repair SN parameters',/
```

```
     &'            class    = ',5x,a2,/
     &'            m        = ',f8.2,/
     &'            A        = ',e8.3)
 2310 FORMAT(/
     &' At the service life of ',f8.2,' years the probability',/
     &' of failure for this repair is ',f8.2,'% based on:',/
     &'       sd of ln(Tf)                =  ',f8.2,/
     &'       Tf  mean time to failure    =  ',f8.2,' years',/,/
     &' The expected monetary value of this repair decision',/
     &' is $',f12.2,' based on the following data:',/,/
     &'       EMV = Ci(1+PVF)',/
     &'       MNR mean number of repairs =  ',f8.2,/
     &'       PVF present value function =  ',f8.2,/
     &'       i   rate of inflation      =  ',f8.2,' %',/
     &'       r   rate of return         =  ',f8.2,' %',/
     &'       Ci  initial repair costs   = $',f8.2,/)
 2320 FORMAT(/
     &' Summary of data for various exposure times:',/,/
     &'          Time       Pf      PDF=f(t)    PVF     EMV ',/
     &'          (yrs)                                  ($)',/
     &'       ----------------------------------------')
 2330 FORMAT(2x,5(2x,f8.2))

c     END the program smoothly

 9999 CLOSE(7)
      PAUSE 'Output written to OUTPUT.DAT.  Press <cr> to continue!'
      dummy = setvideomode( $DEFAULTMODE )
      CALL unregisterfonts()
      STOP
      END

c======1========2=========3==========4==========5=========6=========7==
c     GRAPHICS ROUTINES
c======1========2=========3==========4==========5=========6=========7==
      LOGICAL FUNCTION fourcolors()

c     Function to enter graphics mode.

      INCLUDE  'FGRAPH.FD'

      INTEGER*2 dummy
      RECORD /videoconfig/ screen
      COMMON screen

C     Set to maximum number of available colors.

      CALL getvideoconfig( screen )
      SELECT CASE( screen.adapter )
         CASE( $CGA, $OCGA )
            dummy = setvideomode( $MRES4COLOR )
         CASE( $EGA, $OEGA )
            dummy = setvideomode( $ERESCOLOR )
         CASE( $VGA, $OVGA )
            dummy = setvideomode( $VRES16COLOR )
         CASE DEFAULT
            dummy = 0
      END SELECT

      CALL getvideoconfig( screen )
      fourcolors = .TRUE.
      IF( dummy .EQ. 0 ) fourcolors = .FALSE.
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE graph(x,y,n,m,xmin,xmax,ymin,ymax,
     &          title,xtitle,ytitle,ltitle)

c     Graph n datapoints for m datasets   for x(n,m) and y(n,m)

      INCLUDE  'FGRAPH.FD'
```

```
      INTEGER n,m
      CHARACTER*1 ans
      CHARACTER*30 title,xtitle,ytitle,ltitle
      REAL x(50,10),y(50,10),xmin,xmax,ymin,ymax

      INTEGER*2 dummy
      INTEGER*2 xwidth, yheight, cols, rows
      COMMON screen
      RECORD /videoconfig/ screen
      RECORD /wxycoord/ wxy

      CALL getvideoconfig(screen)
      dummy = setbkcolor($BLUE)
      dummy = setcolor($WHITE)
      xwidth  = screen.numxpixels
      yheight = screen.numypixels
      cols    = screen.numtextcols
      rows    = screen.numtextrows

C     Setup window to data

    1 CALL clearscreen($GCLEARSCREEN)
      CALL setviewport( 0, yheight, xwidth, 0)
      dummy = rectangle($GBORDER,2,yheight-2,xwidth-3,2)
      CALL setviewport( 100, yheight-100, xwidth-100, 100)
      dummy = setwindow(.TRUE.,dble(xmin),dble(ymax),
     &          dble(xmax),dble(ymin))

c     Draw grid

      CALL drawdata(x,y,n,m)
      CALL drawgrid(xmin,xmax,ymin,ymax)

C     Label grid

      CALL setviewport( 50, yheight-75, xwidth-75, 75)
      dummy = setwindow(.TRUE.,0.,1.,1.,0.)
      CALL labelgrid(xmin,xmax,ymin,ymax)

C     Add legend

      CALL setviewport( xwidth-75, yheight-75, xwidth, 0)
      dummy = setwindow(.TRUE.,0.,1.,1.,0.)
      dummy = setcolor($WHITE)
      CALL moveto_w(.05,.85,wxy)
      CALL outgtext(ltitle)
      CALL legend(m)

C     Add text to plot

      dummy = setcolor($WHITE)
      CALL setviewport( 0, yheight, xwidth, 0)
      dummy = setwindow(.TRUE.,0.,1.,1.,0.)
      dummy=setfont("t'tms rmn' h26 w16 p b")
      CALL moveto_w(.05,.95,wxy)
      CALL outgtext(title)
      dummy=setfont("t'tms rmn' h20 w12 p b")
      CALL moveto_w(.3,.1,wxy)
      CALL outgtext(xtitle)
      CALL moveto_w(.01,.5,wxy)
      CALL outgtext(ytitle)

      READ(*,*)       ! Wait for ENTER key to be pressed
      CALL clearscreen( $GCLEARSCREEN )
      WRITE(6,*) ' Rescale plot? <cr>=no'
      READ(5,1000) ans
 1000 FORMAT(a1)
      IF (ans.EQ.'y'.OR.ans.Eq.'Y') THEN
         WRITE(6,*) ' Enter xmin,xmax,ymin,ymax'
         READ(5,*) xmin,xmax,ymin,ymax
```

```
         GOTO 1
      ENDIF
      dummy = setcolor($WHITE)
      dummy = setbkcolor($BLUE)
      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE drawdata(x,y,n,m)

c     Routine to plot the data with varying line color.

      INCLUDE  'FGRAPH.FD'

      INTEGER i,j,n,m
      INTEGER*2       dummy
      REAL x(50,10),y(50,10)
      RECORD /videoconfig/ screen
      RECORD /wxycoord/    wxy
      COMMON               screen

c     Plot the points.

      DO 10 j=1,m
         dummy = setcolor(INT2(j+2))
         CALL moveto_w(dble(x(1,j)),dble(y(1,j)),wxy)
         DO 10 i=2,n
            dummy = lineto_w(dble(x(i,j)),dble(y(i,j)))
   10 CONTINUE
      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE drawgrid(xmin,xmax,ymin,ymax)

c     Routine to draw a grid to the data.

      INCLUDE  'FGRAPH.FD'

      INTEGER i
      INTEGER*2 dummy
      REAL xmin,xmax,ymin,ymax,x,y,step
      RECORD /videoconfig/ screen
      RECORD /wxycoord/ wxy
      COMMON screen

c     Draw vertical grid

      dummy = setcolor($WHITE)
      step=(xmax-xmin)/10.
      x=xmin
      DO 10 i=1,11
        CALL moveto_w(dble(x),dble(ymin),wxy)
        dummy = lineto_w(dble(x),dble(ymax))
        x=x+step
   10 CONTINUE

c     Draw horizontal grid

      step=(ymax-ymin)/10.
      y=ymin
      DO 11 i=1,11
        CALL moveto_w(dble(xmin),dble(y),wxy)
        dummy = lineto_w(dble(xmax),dble(y))
        y=y+step
   11 CONTINUE
      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE labelgrid(xmin,xmax,ymin,ymax)
```

```
c     Routine to lable scale on axes.

      INCLUDE  'FGRAPH.FD'

      INTEGER i
      INTEGER*2 dummy
      CHARACTER*5 label
      REAL x,y,xr,yr,step,stepr,xmin,xmax,ymin,ymax
      RECORD /videoconfig/ screen
      RECORD /wxycoord/ wxy
      COMMON screen

c     Label x axis

      dummy = setcolor($WHITE)
      dummy=setfont("t'tms rmn' h16 w9 p b")
      step=1./6.
      stepr=(xmax-xmin)/5.
      x=0.05
      xr=xmin
      DO 10 i=0,10,2
        CALL moveto_w(dble(x),dble(0.05),wxy)
        CALL textreal(label,xr)
        CALL outgtext(label)
        x=x+step
        xr=xr+stepr
   10 CONTINUE

c     Label y axis

      y=0.
      yr=ymin
      step=1./6.
      stepr=(ymax-ymin)/5.
      DO 11 i=0,10,2
        CALL moveto_w(dble(0.),dble(y+.1),wxy)
        CALL textreal(label,yr)
        CALL outgtext(label)
      y=y+step
      yr=yr+stepr
   11 CONTINUE
      RETURN
      END

c======1=======2========3=========4=========5========6========7==
      SUBROUTINE legend(m)

c     Routine to add m legend entrees with varying colors.

      INCLUDE  'FGRAPH.FD'

      INTEGER i,m
      INTEGER*2 dummy
      CHARACTER*5 label
      REAL y,step
      RECORD /videoconfig/ screen
      RECORD /wxycoord/ wxy
      COMMON screen

      dummy=setfont("t'tms rmn' h16 w9 p b")
      step=1./10.
      y=.8
      DO 10 i=1,m
        dummy = setcolor(INT2(i+2))
        dummy=rectangle_w($GFILLINTERIOR,.1,dble(y),.5,dble(y-.05))
        CALL moveto_w(dble(.51),dble(y),wxy)
        dummy = setcolor($WHITE)
        CALL textint(label,i)
        CALL outgtext(label)
        y=y-step
```

```
   10 CONTINUE
      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE textreal(text,num)

c     Routine to convert REAL number to text for plotting

      CHARACTER*30 dummy
      CHARACTER*5 text
      REAL num

      WRITE(dummy,1000) num
 1000 format(f5.2)
      READ(dummy,1001) text
 1001 format(a5)
      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE textint(text,num)

c     Routine to convert INTEGER to text for plotting

      CHARACTER*30 dummy
      CHARACTER*5 text
      INTEGER num

      WRITE(dummy,1000) num
 1000 format(i5)
      READ(dummy,1001) text
 1001 format(a5)
      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
c     FILE READING ROUTINES
c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE readcsd

c     Routine to read csd file

      CHARACTER*1 char1,typename(20,20),csd(20,20)
      CHARACTER*2 snclass(20,20)
      CHARACTER*4 keyword
      CHARACTER*33 compname(20)
      INTEGER k,numcomp,numcloc,numcload,compnum,typenum(20),
     &         fixity(20),csdnum
      REAL scf(20,20,20),costcomp(20,20),costvw,costip
      COMMON /detail/ typename,csd,snclass,compname,numcomp,numcloc,
     &         numcload,compnum,typenum,fixity,csdnum,scf,costcomp,
     &         costvw,costip

      compnum=0
      csdnum=0

      OPEN (unit=3,file='csd.dat',status='old')
      REWIND (3)
   10 CONTINUE
      READ (3,1000) char1,keyword

      IF (char1.EQ.'*') GOTO 10
      IF (char1.EQ.'=') THEN
        IF (keyword.EQ.'grou') THEN
            READ (3,*) numcomp,numcloc,numcload
        ELSE IF (keyword.EQ.'cost') THEN
            READ (3,*) costvw,costip
        ELSE IF (keyword.EQ.'fixe') THEN
            compnum=compnum+1
            READ (3,1001) compname(compnum)
```

```
            READ (3,*) typenum(compnum)
            READ (3,1002) (typename(compnum,i),i=1,20)
            fixity(compnum)=1
        ELSE IF (keyword.EQ.'inte') THEN
            compnum=compnum+1
            READ (3,1001) compname(compnum)
            READ (3,*) typenum(compnum)
            READ (3,1002) (typename(compnum,i),i=1,20)
            READ (3,*) (costcomp(compnum,i),i=1,typenum(compnum))
            fixity(compnum)=0
        ELSE IF (keyword.EQ.'data') THEN
            csdnum=csdnum+1
            READ (3,1002) (csd(csdnum,i),i=1,20)
            DO 20 k=1,numcloc
              READ (3,1003) snclass(csdnum,k)
              READ (3,*) (scf(csdnum,k,i),i=1,numcload)
   20       CONTINUE
        ELSE IF (keyword.EQ.'end ') THEN
            CLOSE(3)
            GOTO 99
        ENDIF
      ENDIF
      GOTO 10
 1000 FORMAT(a1,a4)
 1001 FORMAT(a33)
 1002 FORMAT(20(a1))
 1003 FORMAT(a2)

c     Write summary of csd input file

   99 CONTINUE
      WRITE(7,2000) numcomp,numcloc,numcload,costvw,costip
 2000 FORMAT(/
     &' CSD.DAT:',/
     &'*********',/
     &'      number of components          = ',i2,/
     &'      number of locations on detail = ',i2,/
     &'      number of loading directions  = ',i2,/
     &'      relative cost to vee and weld = $',f8.2,/
     &'      relative cost to insert plate = $',f8.2)
      DO 203 i=1,numcomp
          IF (fixity(i).eq.1) THEN
             WRITE(7,2004) ' Fixed component:                '
          ELSE
             WRITE(7,2004) ' Interchangable component:       '
          ENDIF
 2004 FORMAT(/,A30)
          WRITE(7,2005) compname(i)
          DO 203 j=1,typenum(i)
             IF (fixity(i).eq.0) THEN
                 WRITE(7,2007) typename(i,j),costcomp(i,j)
             ELSE
                 WRITE(7,2007) typename(i,j),0.00
             ENDIF
  203     CONTINUE
 2005 FORMAT(/
     &' Component name = ',a33,/
     &'          typename       relative cost ($)')
 2007 FORMAT(10x,a1,10x,f8.2)
      WRITE(7,2100) (i,i=1,10)
      DO 210 i=1,numcomp
          WRITE(7,2110) compname(i),(csd(j,i),j=1,10)
  210 CONTINUE
 2100 FORMAT(/
     &' Summary of csd configurations:',/,/
     &'                                         Configuration #',/
     &'   Component            ',10(2x,i1),/
     &' -------------------------------------------------------')
 2110 FORMAT(1x,a20,10(2x,a1))
      DO 220 i=1,csdnum
          WRITE(7,2200) i
```

```
          DO 220 k=1,numcloc
             WRITE(7,2210) k,snclass(i,k),(scf(i,k,j),j=1,4)
  220 CONTINUE
 2200 FORMAT(/
     &' Critical structural detail = ',i2,/
     &'       location    SN class    stress concentration factors',/
     &'       ---------------------------------------------------')
 2210 FORMAT(8x,i2,11x,a2,8x,4(f5.2))
      RETURN
      END

c=======1========2========3=========4=========5=========6=========7==
       SUBROUTINE readload

c     Routine to read loadings file

      CHARACTER*1 char1
      CHARACTER*4 keyword
      CHARACTER*33 shipname,grpname,shiploc(20)
      INTEGER numloc,numload
      REAL fo,eta,r(20,20)
      COMMON /loading/ shipname,grpname,shiploc,numloc,numload,
     &         fo,eta,r

      OPEN (unit=3,file='loading.dat',status='old')
      REWIND (3)
   10 CONTINUE
      READ (3,1000) char1,keyword

      IF (char1.EQ.'*') GOTO 10
      IF (char1.EQ.'=') THEN
        IF (keyword.EQ.'ship') THEN
            READ (3,1001) shipname
        ELSE IF (keyword.EQ.'grou') THEN
            READ (3,1001) grpname
        ELSE IF (keyword.EQ.'oper') THEN
            READ (3,*) fo
        ELSE IF (keyword.EQ.'weib') THEN
            READ (3,*) eta
        ELSE IF (keyword.EQ.'rati') THEN
            READ (3,*) numloc,numload
            DO 20 i=1,numloc
               READ(3,1001) shiploc(i)
               READ(3,*) (r(i,j),j=1,numload)
   20       CONTINUE
        ELSE IF (keyword.EQ.'end ') THEN
            CLOSE(3)
            GOTO 99
        ENDIF
      ENDIF
      GOTO 10
 1000 FORMAT(a1,a4)
 1001 FORMAT(a33)

c     Write summary of loading input file

   99 WRITE(7,2010) shipname,grpname,fo,eta
      WRITE(7,2020)
      DO 200 i=1,numloc
         WRITE(7,2030) i,shiploc(i),(r(i,j),j=1,4)
  200 CONTINUE
 2010 FORMAT(/,/
     &' LOADING.DAT:',/
     &' ************',/
     &'       ship name                = ',a33,/
     &'       load group               = ',a33,/
     &'       average load frequency   = ',e8.2,' cycles/yr',/
     &'       Weibull shape parameter  = ',f8.2)
 2020 FORMAT(/
     &' loading zones                          load ratios',/
     &' ------------------------------------------------------------')
```

```
 2030 FORMAT(1x,i2,'.',2x,a33,4(1x,f4.2))

      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE readsn

c     Routine to read sn data file

      CHARACTER*1 char1
      CHARACTER*4 keyword
      CHARACTER*2 classname(20),classvw(20)
      CHARACTER*33 snname
      INTEGER numclass
      REAL snm(20),sna(20)
      COMMON /sndata/ classname,classvw,snname,numclass,snm,sna

      OPEN (unit=3,file='sndata.dat',status='old')
      REWIND (3)

      numclass=0
   10 CONTINUE
      READ (3,1000) char1,keyword

      IF (char1.EQ.'*') GOTO 10
      IF (char1.EQ.'=') THEN
        IF (keyword.EQ.'grou') THEN
            READ (3,1001) snname
        ELSE IF (keyword.EQ.'para') THEN
            numclass=numclass+1
            READ (3,1002) classname(numclass)
            READ (3,*) snm(numclass),sna(numclass)
            READ (3,1002) classvw(numclass)
        ELSE IF (keyword.EQ.'end ') THEN
            CLOSE(3)
            GOTO 99
        ENDIF
      ENDIF
      GOTO 10

 1000 FORMAT(a1,a4)
 1001 FORMAT(a33)
 1002 FORMAT(a2)
   99 RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
c     MISCELLANEOUS ROUTINES
c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE cost(repcost,repcsd,origcsd)

c     Routine to estimate the cost of changing a design during
c     repair.  Cost based on the number of interchangable components
c     modIFied in repair

      INTEGER repcsd,origcsd,i,j
      REAL repcost,costr,costo

c     Variables for reading of csd file
      CHARACTER*1 typename(20,20),csd(20,20)
      CHARACTER*2 snclass(20,20)
      CHARACTER*33 compname(20)
      INTEGER numcomp,numcloc,numcload,compnum,typenum(20),
     &          fixity(20),csdnum
      REAL scf(20,20,20),costcomp(20,20),costvw,costip
      COMMON /detail/ typename,csd,snclass,compname,numcomp,numcloc,
     &          numcload,compnum,typenum,fixity,csdnum,scf,costcomp,
     &          costvw,costip

      DO 10 i=1,numcomp
```

```
      IF (fixity(i).EQ.1) GOTO 10
      IF (csd(repcsd,i).EQ.csd(origcsd,i)) GOTO 10
      costo=0.
      costr=0.
      DO 20 j=1,typenum(i)
        IF (csd(origcsd,i).EQ.typename(i,j))
    &          costo=costcomp(i,j)
        IF (csd(repcsd,i).EQ.typename(i,j))
    &          costr=costcomp(i,j)
   20 CONTINUE
c     repcost=repcost+(costr-costo)
      repcost=repcost+costr
   10 CONTINUE
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE exstress(so,a,m,fo,eta,tfail,dfail,bias)

c     Function to detmine the Weibull extreme stress range based on
c     the SN parameters a and m, the average frequency fo, the
c     Weibull parameters eta and so, the mean time to failure tfail,
c     the damage at failure dfail, and the bias in the stress
c     calculation.

      REAL a,m,fo,eta,tfail,dfail,bias,so

      so=((dfail*a)/(fo*tfail*gamma(m/eta+1.)))**(1./m)
     &       *((log(fo*tfail))**(1./eta)/bias)

      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE options

      INTEGER i

c     Variables for reading of csd file
      CHARACTER*1 typename(20,20),csd(20,20)
      CHARACTER*2 snclass(20,20)
      CHARACTER*33 compname(20)
      INTEGER numcomp,numcloc,numcload,compnum,typenum(20),
     &        fixity(20),csdnum
      REAL scf(20,20,20),costcomp(20,20),costvw,costip
      COMMON /detail/ typename,csd,snclass,compname,numcomp,numcloc,
     &        numcload,compnum,typenum,fixity,csdnum,scf,costcomp,
     &        costvw,costip

      WRITE(6,1035) (i,i=1,10)
      DO 50 i=1,numcomp
         WRITE(6,1040) compname(i),(csd(j,i),j=1,10)
   50 CONTINUE
      WRITE(6,*)

 1035 format(/
     &'                              Configuration #',/
     &'  Component           ',10(2x,i1),/
     &' ------------------------------------------------------')
 1040 format(1x,a20,10(2x,a1))
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      REAL FUNCTION pvfpdf(t)

c     Function to RETURN the present value function (continuous
c     model) at time t for repair period ta to tb

      REAL t,nominfl,nomror
```

```
c     Variables to complete function for emv
      REAL reptf1,sdlnt,ror,infl,ta
      COMMON /emvvars/ reptf1,sdlnt,ror,infl,ta

c     Convert effective interest rates to nominal rates. INFL and ROR
c     originally input on per year basis.  For t close to zero use
c     rate of zero to avoid overflow error

      IF (t.LE.0.01) THEN
         nominfl=0.
         nomror=0.
      ELSE IF (t.NE.0.0) THEN
         nominfl=t*((infl+1.)**(1./t)-1.)
         nomror=t*((ror+1.)**(1./t)-1.)
      ENDIF

c     Calculate pvf
      pvfpdf=2.*pdflognorm(reptf1,t-ta,sdlnt)*exp((nominfl-nomror)*t)
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      REAL FUNCTION pvftotal(func,ts)

c     Routine to calclate the future cost of repairs based on
c     replacement at a probability of failure of 0.5 (at mean life)

      REAL func
      EXTERNAL func

      INTEGER i,mnr
      REAL ts,a,b,pvft,pvf,small
      PARAMETER (small=.0001)

c     Variables to complete function for emv
      REAL reptf1,sdlnt,ror,infl,ta
      COMMON /emvvars/ reptf1,sdlnt,ror,infl,ta

      mnr=INT(AINT(ts/reptf1)+small)
      pvft=0.
      IF (mnr.LE.1) THEN
         a=0.
         ta=a-small
         b=ts
      ELSE
         DO 10 i=1,mnr
            a=real((i-1)*reptf1)
            ta=a-small
            b=real(i*reptf1)
            CALL qtrap(func,a,b,pvf)
            pvft=pvft+pvf
   10    CONTINUE
         a=b
         ta=a-small
         b=ts
      ENDIF
      CALL qtrap(func,a,b,pvf)
      pvftotal=pvft+pvf
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE select(repcsd,origcsd)

c     Routine to check if the redesign repair selected is
c     allowed.    If a fixed component defined in the csd input
c     file changes, this is not allowed.

      INTEGER repcsd,origcsd

c     Variables for reading of csd file
```

```
      CHARACTER*1 typename(20,20),csd(20,20)
      CHARACTER*2 snclass(20,20)
      CHARACTER*33 compname(20)
      INTEGER numcomp,numcloc,numcload,compnum,typenum(20),
     &        fixity(20),csdnum
      REAL scf(20,20,20),costcomp(20,20),costvw,costip
      COMMON /detail/ typename,csd,snclass,compname,numcomp,numcloc,
     &         numcload,compnum,typenum,fixity,csdnum,scf,costcomp,
     &         costvw,costip

    5 WRITE(6,*) 'Select repair configuration #:'
      READ(5,*) repcsd
      WRITE(6,1012) '    config',repcsd
 1012 FORMAT(' ECHO: ',a10,'=',i4,/)
      IF (repcsd.EQ.origcsd) THEN
         WRITE(6,*) 'Invalid detail: same as original detal'
         GOTO 5
      ENDIF
      DO 10 i=1,numcomp
         IF (fixity(i).EQ.1) THEN
            IF (csd(repcsd,i).NE.csd(origcsd,i)) THEN
              WRITE(6,*) 'Invalid detail: fixed component change'
              GOTO 5
            ENDIF
         ENDIF
   10 CONTINUE
      RETURN
      END

c=======1=========2=========3==========4==========5=========6=========7==
      SUBROUTINE snclassvw(vwclass,snclass)

c     Routine to return degraded SN curve class due to repair

      CHARACTER*2 snclass,vwclass
      INTEGER i

c     Variables for reading SN curve data
      CHARACTER*2 classname(20),classvw(20)
      CHARACTER*33 snname
      INTEGER numclass
      REAL snm(20),sna(20)
      COMMON /sndata/ classname,classvw,snname,numclass,snm,sna

      DO 10 i=1,numclass
         IF (classname(i).EQ.snclass) THEN
            vwclass=classvw(i)
            RETURN
         ENDIF
   10 CONTINUE
      PAUSE 'snclassvw>  class not found'
      RETURN
      END

c=======1=========2=========3==========4==========5=========6=========7==
      SUBROUTINE snparam(snclass,m,a)

c     Routine to return SN parameters

      CHARACTER*2 snclass
      INTEGER i
      REAL a,m

c     Variables for reading SN curve data
      CHARACTER*2 classname(20),classvw(20)
      CHARACTER*33 snname
      INTEGER numclass
      REAL snm(20),sna(20)
      COMMON /sndata/ classname,classvw,snname,numclass,snm,sna

      DO 10 i=1,numclass
```

```
         IF (classname(i).EQ.snclass) THEN
            m=snm(i)
            a=sna(i)
            RETURN
         ENDIF
   10 CONTINUE
      PAUSE 'snparam>  class not found'
      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE stressratio(ratio,repcsd,origcsd,origloc,location)

      INTEGER repcsd,origcsd,origloc,location,i
      REAL ratio,sumo,sumr

c     Variables for reading of loading file
      CHARACTER*33 shipname,grpname,shiploc(20)
      INTEGER numloc,numload
      REAL fo,eta,r(20,20)
      COMMON /loading/ shipname,grpname,shiploc,numloc,numload,
     &         fo,eta,r

c     Variables for reading of csd file
      CHARACTER*1 typename(20,20),csd(20,20)
      CHARACTER*2 snclass(20,20)
      CHARACTER*33 compname(20)
      INTEGER numcomp,numcloc,numcload,compnum,typenum(20),
     &         fixity(20),csdnum
      REAL scf(20,20,20),costcomp(20,20),costvw,costip
      COMMON /detail/ typename,csd,snclass,compname,numcomp,numcloc,
     &         numcload,compnum,typenum,fixity,csdnum,scf,costcomp,
     &         costvw,costip

      sumr=0.
      sumo=0.
      DO 10 i=1,numcload
        sumr=scf(repcsd,origloc,i)*r(location,i)+sumr
        sumo=scf(origcsd,origloc,i)*r(location,i)+sumo
   10 CONTINUE
      ratio=sumr/sumo
      RETURN
      END

c======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE stressip(repso,so)

c     Routine to calculate the stress change at the failure location
c     after insert plate added.  Change due to change in plate
c     thickness only.  Complete evaluation should analyse the
c     butt weld location for stress concentration and SN degragation
c     effects

      CHARACTER*1 ans
      REAL repso,so

      WRITE(6,*) 'Is insert thickness = original thickness? <cr>=yes'
      READ(5,1000) ans
 1000 format(a1)
      IF (ans.EQ.'n'.OR.ans.EQ.'N') THEN
         WRITE(6,*) 'Input orginal, replacement thickness'
         READ(5,*) to,tr
         WRITE(6,1001) to/tr
 1001    FORMAT(' Stress multiplied by ',F4.2,' to account for'
     &           ' change in thickness',/
     &           ' WARNING: weld locations at perimeter of insert plate',
     &           ' should be evaluated!',/)
         PAUSE 'Press <cr> to continue'
         repso=so*to/tr
      ELSE
         repso=so
```

```
      ENDIF
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE stressvw(repso,so)

c     Recalculate stress in v and weld option to give credit for
c     post weld improvement.  Current model reduces stress level
c     by 1/3 to account for improvements

      REAL repso,so,factor
      PARAMETER (factor=0.667)

      WRITE(6,*) 'Appy post-weld improvements? <cr>=no'
      READ(5,1000) ans
 1000 format(a1)
      IF (ans.EQ.'y'.OR.ans.EQ.'Y') THEN
         WRITE(6,1001) factor
 1001    FORMAT(' Stress multiplied by ',F4.2,
     &          ' to account for improvements')
         PAUSE 'Press <cr> to continue'
         repso=so*factor
      ELSE
         repso=so
      ENDIF
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE testdata(x,n,m,xmin,xmax)

c     Routine to scale data to screen coordinates

      INTEGER i,j,n,m
      REAL x(50,10),xmin,xmax

      xmax=-9.e9
      xmin=9.e9

      DO 10 j=1,m
         DO 10 i=1,n
            IF(x(i,j).GT.xmax) xmax=x(i,j)
            IF(x(i,j).LT.xmin) xmin=x(i,j)
   10 CONTINUE
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE tfaili(tf,a,m,fo,eta,so,dfail,bias)

c     Function to iterate to determine the time to failure based
c     on the SN parameters a and m, the average frequency fo, the
c     Weibull parameters eta and so, the damage at failure dfail,
c     and the bias in the stress calculation bias.

      INTEGER count,maxcount
      REAL a,m,fo,eta,so,dfail,bias,t1,t2,g,tf,small
      PARAMETER (maxcount=10000,small=0.001)

      count=0
      t1=huge(t1)
      g=gamma(m/eta+1.)
   10 CONTINUE
      t2=dfail*a*(log(fo*t1))**(m/eta)/(fo*g*(bias*so)**m)
      IF (ABS(t2-t1).GT.small) THEN
         t1=(t1+t2)/2.
         count=count+1
         IF (count.EQ.maxcount) THEN
            WRITE(6,*) 'tfaili> maxcount iterations reached'
            WRITE(6,*) 't1 = ',t1
```

```
          WRITE(6,*) 't2 = ',t2
          PAUSE 'Press <cntl>+C now to abort program!!'
          GOTO 99
        ENDIF
        GOTO 10
      ENDIF
      tf=(t1+t2)/2.
   99 RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
c     MATHEMATICS ROUTINES
c=======1========2=========3==========4==========5=========6=========7==
      REAL FUNCTION cdflognorm(m,x,sd)

c     Function to returen the cumulative lognormal distribution
c     function

      REAL m,x,sd,si
      si=log(m/x)/sd
      cdflognorm=(1.+erf(si/(SQRT(2.))))/2.
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      REAL FUNCTION erf(x)

c     Return the error function of x

      REAL x
      IF (x.LT.0.) THEN
        erf=-gammp(0.5,x**2)
      ELSE
        erf=gammp(0.5,x**2)
      ENDIF
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      FUNCTION gamma(xx)

c     Function to return the gamma function of xx based on gammln(xx)

      REAL xx
      gamma=exp(gammln(xx))
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      REAL FUNCTION gammln(xx)

c     Returns value gamma(xx) for xx > 0.  Full accuracy for xx > 1.
c     Source:  Numerical Recipes, Art of ScientIFic Computing, 1986

      INTEGER j
      REAL cof(6),stp,half,one,fpf,x,xx,tmp,ser

      data cof/76.18009173d0,-86.50532033d0,24.01409822d0,
     &         -1.231739516d0,0.120858003d-2,-0.536382d-5/
      data stp/2.50662827465d0/
      data half,one,fpf/0.5d0,1.0d0,5.5d0/

      x=xx-one
      tmp=x+fpf
      tmp=(x+half)*log(tmp)-tmp
      ser=one
      DO 11 j=1,6
        x=x+one
        ser=ser+cof(j)/x
   11 CONTINUE
      gammln=tmp+log(stp*ser)
```

```
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      REAL FUNCTION gammp(a,x)

c     Returns incomplete gamma function P(a,x)
c     Source:  Numerical Recipes, Art of ScientIFic Computing, 1986

      REAL a,x,gamser,gln,gammcf
      IF (x.LT.0..OR.a.le.0.) PAUSE
      IF (x.LT.a+1.) THEN
         call gser(gamser,a,x,gln)
         gammp=gamser
      ELSE
         call gcf(gammcf,a,x,gln)
         gammp=1.-gammcf
      ENDIF
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE gcf(gammcf,a,x,gln)

c     Returns the incomplete gamma function Q(a,x) evaluated by its
c     CONTINUEd fraction representation as GAMMCF.

      INTEGER n,itmax
      REAL gammcf,a,x,gln,eps,gold,a0,a1,b0,b1,fac,an,ana,g
      parameter(itmax=100,eps=3.e-7)
      gln=gammln(a)
      gold=0.
      a0=1.
      a1=x
      b0=0.
      b1=1.
      fac=1.
      DO 11 n=1,itmax
         an=float(n)
         ana=an-a
         a0=(a1+a0*ana)*fac
         b0=(b1+b0*ana)*fac
         anf=an*fac
         a1=x*a0+anf*a1
         b1=x*b0+anf*b1
         IF (a1.NE.0.) THEN
            fac=1./a1
            g=b1*fac
            IF (ABS((g-gold)/g).LT.eps) GOTO 1
            gold=g
         ENDIF
   11 CONTINUE
      PAUSE 'GCF>  A too large, ITMAX too small'
    1 gammcf=exp(-x+a*log(x)-gln)*g
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE gser(gamser,a,x,gln)

c     Returns the inlomplete gamma function P(a,x) evaluated by its
c     series representaiton as gamser. Also RETURNs gamma(a) as gln.

      INTEGER n,itmax
      REAL gamser,a,x,gln,ap,sum,del,eps
      parameter(itmax=100,eps=3.e-7)
      gln=gammln(a)
      IF (x.le.0.) THEN
         IF(x.LT.0.) PAUSE
         gamser=0.
         RETURN
```

```
      ENDIF
      ap=a
      sum=1./a
      del=sum
      DO 11 n=1,itmax
         ap=ap+1
         del=del*x/ap
         sum=sum+del
         IF (ABS(del).LT.ABS(sum)*eps) GOTO 1
   11 CONTINUE
      PAUSE 'gser>  A too large, ITMAX too small'
    1 gamser=sum*exp(-x+a*log(x)-gln)
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      REAL FUNCTION pdflognorm(m,x,sd)

c     Function to returen the lognormal probability desity function

      REAL m,x,sd,a,b,si
      si=log(m/x)/sd
      a=exp(-(si**2)/2.)
      b=1./(sd*x*SQRT(2.*3.141592654))
      pdflognorm=a*b
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      REAL FUNCTION probfail(tf,ts,sd)

c     Function to returen the probability of failure based on the
c     lognormal probability desity function

      REAL tf,ts,sd
      probfail=1-cdflognorm(tf,ts,sd)
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE qtrap(func,a,b,s)

c     Returns as s the integral of the function func from a to b.
c     The parameters eps can be set to the desired fractional
c     accuracy and jmax so that 2^(jmax-1) is the maximum
c     allowed number of steps.
c     Source:  Numerical Recipes, Art of Scientific Computing, 1986

      REAL func
      EXTERNAL func

      INTEGER j,jmax
      REAL a,b,s,eps,olds
      parameter (eps=1.e-2,jmax=20)

      olds=-1.e30
      DO 11 j=1,jmax
         call trapzd(func,a,b,s,j)
         IF (ABS(s-olds).LT.eps*ABS(olds)) RETURN
         olds=s
   11 CONTINUE
      WRITE(6,*) 'lower limit=',a
      WRITE(6,*) 'upper limit=',b
      PAUSE 'qtrap>  too many steps in integration'
      RETURN
      END

c=======1========2=========3==========4==========5=========6=========7==
      SUBROUTINE trapzd(func,a,b,s,n)
c
c     Routine computes the N'th stage of refinement of an extended
```

```
c     trapezoidal rule.  func is input as the name of the function
c     to be integrated between limits a and b.  s should not be
c     modIFied between sequential calls.  Accuracy improved with
c     increasing n.
c     Source:  Numerical Recipes, Art of ScientIFic Computing, 1986

      REAL func
      EXTERNAL func

      INTEGER n,it
      REAL a,b,s,tnm,x,del,sum

      IF (n.EQ.1) THEN
        s=0.5*(b-a)*(func(a)+func(b))
        it=1
      ELSE
        tnm=REAL(it)
        del=(b-a)/tnm
        x=a+0.5*del
        sum=0.
        DO 12 j=1,it
           sum=sum+func(x)
           x=x+del
12      CONTINUE
        s=0.5*(s+(b-a)*sum/tnm)
        it=2*it
      ENDIF
      RETURN
      END
```

SAMPLE INPUT DATA FILE: LOADING.DAT

```
*LOADING.DAT
*Loading information for ship
*5/10/92
*
*Ship name
*
=ship
test tanker
*
*Component group
*
=group
sideshell
*
*Average cycles per year fo
*
=operation
2500000.
*
*Weibull shape parameter for component group
*
=weibull
0.9
*
*Load ratios for component group
*#divisions,#loads
*title division 1/ratio 1,ratio 2 ... ratio n     etc
*
=ratios (vertical bending,athwartship bending,pressure,shear)
9,4
Forward 1/3,Top 1/3
.5,.5,1,0
Forward 1/3,Middle 1/3
0,.5,1,1
Forward 1/3,Lower 1/3
.5,.5,1,0
Middle 1/3,Top 1/3
1,1,0,0
Middle 1/3,Middle 1/3
0,1,1,.5
Middle 1/3,Lower 1/3
1,1,.7,0
Aft 1/3,Top 1/3
.5,.5,0,1
Aft 1/3,Middle 1/3
0,.5,1,0
Aft 1/3,Lower 1/3
.5,.5,.7,1
=end
```

SAMPLE INPUT DATA FILE: CSD.DAT

```
*CSD.DAT
*Sideshell critical structural detail data
*Last updated 5/10/92
*General csd information (total #components,#locations/detail,#loads)
*
=group
5,3,4
*
*Relative costs (v&w cost,insert plate cost)
*
=costs
1000,3000
*
*Components that cannot be changed easily
*Fixed components (name,#types,types)
*
=fixed
longitudinal
3
TLB
=fixed
cutout
4
1234
*
*Component that can be changed easily
*Interchangeable componponents (name,#types,types,costs each type)
*
*lugs (none,single,or double)
=interchangeable
lug
3
NSD
0,3000,6000
*
*flatbar (none,single,or double)
=interchangeable
flatbar
3
NSD
0,3000,6000
*
*brackets (none,single,or double)
=interchangeable
bracket
3
NSD
0,3000,6000
*
*Data for CSDs using ABS data for cutout type 1
*Stress concentration factors available for external pressure only
*
*component makeup in order (longitudinal,cutout,lug,flatbar,bracket types)
*location 1 sn class
*location 1 scfs (vertical bending,athwartship bending,pressure,shear)
*etc.
*
*1.  L type longitudinal, Single sided lug (cutout without additional lug)
=data
L1NNN
C
0.0,0.0,2.0,0.0
C
0.0,0.0,2.1,0.0
B
0.0,0.0,1.0,0.0
```


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(1) include an estimate of the probable cost of any indemnification programs which may be recommended;

(2) include an examination of all viable means of financing the cost of any recommended indemnification; and

(3) be completed and submitted to Congress within two years from the effective date of enactment of this chapter.

The General Accounting Office shall review the adequacy of the study submitted to Congress pursuant to paragraph (3) and shall report the results of its review to the Congress within six months of the date such study is submitted to Congress.

(b) Classification, storage, and retrieval study

The Council on Environmental Quality, in consultation with the Administrator, the Secretary of Health and Human Services, the Secretary of Commerce, and the heads of other appropriate Federal departments or agencies, shall coordinate a study of the feasibility of establishing (1) a standard classification system for chemical substances and related substances, and (2) a standard means for storing and for obtaining rapid access to information respecting such substances. A report on such study shall be completed and submitted to Congress not later than 18 months after the effective date of enactment of this chapter.

(Oct. 11, 1976, Pub.L. 94–469, Title I, § 25, 90 Stat. 2046; Oct. 17, 1979, Pub.L. 96–88, Title V, § 509(b), 93 Stat. 695; redesignated Title I, Oct. 22, 1986, Pub.L. 99–519, § 3(c)(1), 100 Stat. 2989.)

§ 2625. Administration [TSCA § 26]

(a) Cooperation of Federal agencies

Upon request by the Administrator, each Federal department and agency is authorized—

(1) to make its services, personnel, and facilities available (with or without reimbursement) to the Administrator to assist the Administrator in the administration of this chapter; and

(2) to furnish to the Administrator such information, data, estimates, and statistics, and to allow the Administrator access to all information in its possession as the Administrator may reasonably determine to be necessary for the administration of this chapter.

(b) Fees

(1) The Administrator may, by rule, require the payment of a reasonable fee from any person required to submit data under section 2603 or 2604 of this title to defray the cost of administering this chapter. Such rules shall not provide for any fee in excess of $2,500 or, in the case of a small business concern, any fee in excess of $100. In setting a fee under this paragraph, the Administrator shall take into account the ability to pay of the person required to submit the data and the cost to the Administrator of reviewing such data. Such rules may provide for sharing such a fee in any case in which the expenses of testing are shared under section 2603 or 2604 of this title.

(2) The Administrator, after consultation with the Administrator of the Small Business Administration, shall by rule prescribe standards for determining the persons which qualify as small business concerns for purposes of paragraph (1).

(c) Action with respect to categories

(1) Any action authorized or required to be taken by the Administrator under any provision of this chapter with respect to a chemical substance or mixture may be taken by the Administrator in accordance with that provision with respect to a category of chemical substances or mixtures. Whenever the Administrator takes action under a provision of this chapter with respect to a category of chemical substances or mixtures, any reference in this chapter to a chemical substance or mixture (insofar as it relates to such action) shall be deemed to be a reference to each chemical substance or mixture in such category.

(2) For purposes of paragraph (1):

(A) The term "category of chemical substances" means a group of chemical substances the members of which are similar in molecular structure, in physical, chemical, or biological properties, in use, or in mode of entrance into the human body or into the environment, or the members of which are in some other way suitable for classification as such for purposes of this chapter, except that such term does not mean a group of chemical substances which are grouped together solely on the basis of their being new chemical substances.

(B) The term "category of mixtures" means a group of mixtures the members of which are similar in molecular structure, in physical, chemical, or biological properties, in use, or in the mode of entrance into the human body or into the environment, or the members of which are in some other way suitable for classification as such for purposes of this chapter.

(d) Assistance office

The Administrator shall establish in the Environmental Protection Agency an identifiable office to provide technical and other nonfinancial assistance to manufacturers and processors of chemical substances and mixtures respecting the requirements of this chapter applicable to such manufacturers and processors, the policy of the Agency respecting the application of such requirements to such manufacturers and processors, and the means and methods by which such manufacturers and processors may comply with such requirements.

(e) Financial disclosures

(1) Except as provided under paragraph (3), each officer or employee of the Environmental Protection Agency and the Department of Health and Human Services who—

(A) performs any function or duty under this chapter, and

(B) has any known financial interest (i) in any person subject to this chapter or any rule or order in effect under this chapter, or (ii) in any person who applies for or receives any grant or contract under this chapter,

shall, on February 1, 1978, and on February 1 of each year thereafter, file with the Administrator or the Secretary of Health and Human Services (hereinafter in this subsection referred to as the "Secretary"), as appropriate, a written statement concerning all such interests held by such officer or employee during the preceding calendar year. Such statement shall be made available to the public.

(2) The Administrator and the Secretary shall—

(A) act within 90 days of January 1, 1977—

(i) to define the term "known financial interests" for purposes of paragraph (1), and

(ii) to establish the methods by which the requirement to file written statements specified in paragraph (1) will be monitored and enforced, including appropriate provisions for review by the Administrator and the Secretary of such statements; and

(B) report to the Congress on June 1, 1978, and on June 1 of each year thereafter with respect to such statements and the actions taken in regard thereto during the preceding calendar year.

(3) The Administrator may by rule identify specific positions with the Environmental Protection Agency, and the Secretary may by rule identify specific positions with the Department of Health and Human Services, which are of a nonregulatory or nonpolicymaking nature, and the Administrator and the Secretary may by rule provide that officers or employees occupying such positions shall be exempt from the requirements of paragraph (1).

(4) This subsection does not supersede any requirement of chapter 11 of Title 18.

(5) Any officer or employee who is subject to, and knowingly violates, this subsection or any rule issued thereunder, shall be fined not more than $2,500 or imprisoned not more than one year, or both.

(f) Statement of basis and purpose

Any final order issued under this chapter shall be accompanied by a statement of its basis and purpose. The contents and adequacy of any such statement shall not be subject to judicial review in any respect.

(g) Assistant Administrator

(1) The President, by and with the advice and consent of the Senate, shall appoint an Assistant Administrator for Toxic Substances of the Environmental Protection Agency. Such Assistant Administrator shall be qualified individual who is, by reason of background and experience, especially qualified to direct a program concerning the effects of chemicals on human health and the environment. Such Assistant Administrator shall be responsible for (A) the collection of data, (B) the preparation of studies, (C) the making of recommendations to the Administrator for regulatory and other actions to carry out the purposes and to facilitate the administration of this chapter, and (D) such other functions as the Administrator may assign or delegate.

(2) The Assistant Administrator to be appointed under paragraph (1) shall be in addition to the Assistant Administrators of the Environmental Protection Agency authorized by section 1(d) of Reorganization Plan No. 3 of 1970.

(Oct. 11, 1976, Pub.L. 94–469, Title I, § 26, 90 Stat. 2046; Oct. 17, 1979, Pub.L. 96–88, Title V, § 509(b), 93 Stat. 695; Sept. 13, 1982, Pub.L. 97–258, § 4(b), 96 Stat. 1067; redesignated Title I, Oct. 22, 1986, Pub.L. 99–519, § 3(c)(1), 100 Stat. 2989.)

CODE OF FEDERAL REGULATIONS

Requirements for reporting financial interests, see 40 CFR 3.300 to 3.305.

LIBRARY REFERENCES

Health and Environment ⇐25.5(9).
C.J.S. Health and Environment § 65 et seq.

§ 2626. Development and evaluation of test methods [TSCA § 27]

(a) In general

The Secretary of Health and Human Services, in consultation with the Administrator and acting

```
*
*2.  L type longitudinal, Single sided lug with flatbar
=data
L1NSN
C
0.0,0.0,1.9,0.0
C
0.0,0.0,2.0,0.0
B
0.0,0.0,1.0,0.0
*
*3.  L type longitudinal, Double sided lug (cutout 1 with additional lug)
=data
L1SNN
C
0.0,0.0,3.0,0.0
C
0.0,0.0,2.6,0.0
F
0.0,0.0,2.4,0.0
*
*4.  L type longitudinal, Double sided lug with flatbar
=data
L1SSN
C
0.0,0.0,2.8,0.0
C
0.0,0.0,2.5,0.0
F
0.0,0.0,2.3,0.0
*
*5.  T type longitudinal, Single sided lug (cutout without additional lug)
=data
T1NNN
C
0.0,0.0,1.8,0.0
C
0.0,0.0,1.9,0.0
B
0.0,0.0,1.0,0.0
*
*6.  T type longitudinal, Single sided lug with flatbar
=data
T1NSN
C
0.0,0.0,1.7,0.0
C
0.0,0.0,1.8,0.0
B
0.0,0.0,1.0,0.0
*
*7.  T type longitudinal, Double sided lug (cutout 1 with additional lug)
=data
T1SNN
C
0.0,0.0,2.7,0.0
C
0.0,0.0,2.4,0.0
F
0.0,0.0,2.2,0.0
*
*8.  T type longitudinal, Double sided lug with flatbar
=data
T1SSN
C
0.0,0.0,2.5,0.0
C
0.0,0.0,2.3,0.0
F
0.0,0.0,2.1,0.0
=end
```

SAMPLE INPUT DATA FILE: SNDATA.DAT

```
*SNDATA.DAT
*SN data parameters
*4/29/92
*
*Name of SN curves
=group
UK DeN SN curves
*
*Parameters
*SN class/inverse slope m,life intercept A/v&weld SN class
*
=parameters
B
4.0,2.34e15
F
=parameters
C
3.5,1.08e14
F
=parameters
D
3.0,3.99e12
F
=parameters
E
3.0,3.29e12
F
=parameters
F
3.0,1.73e12
F2
=parameters
F2
3.0,1.23e12
F2
=parameters
G
3.0,5.66e11
G
=parameters
W
3.0,3.68e11
W
=end
```

SAMPLE OUTPUT DATA FILE: OUTPUT.DAT

```
ABS Verification Case,Location 1,L Type longitudinal,0% interest

********************************************************
           RMS--REPAIR MANAGEMENT SYSTEM
                  Version 1.0
             Last Updated 4/29/92

       A System for Simplified Repair Analysis
       for Fatigue Mode of Ship Structural Failure
********************************************************

        UNIVERSITY OF CALIFORNIA, BERKELEY
    NAVAL ARCHITECTURE AND OFFSHORE ENGINEERING

Based on input files providing information on loading,
critical structural detail, and material properties,
this program estimates mean fatigue life, probability of
failure distribution, and expected monetary value for the
repair alternatives selected.

The following input data files are required:
     LOADING.DAT      Ship Loading Data
     CSD.DAT          Critical Structural Detail Data
     SNCURVE.DAT      Fatigue Curve Data


LOADING.DAT:
************
     ship name                = test tanker
     load group               = sideshell
     average load frequency   =  .25E+07 cycles/yr
     Weibull shape parameter  =      .90

loading zones                            load ratios
-------------------------------------------------------------
 1.  Forward 1/3,Top 1/3                    .50  .50 1.00  .00
 2.  Forward 1/3,Middle 1/3                 .00  .50 1.00 1.00
 3.  Forward 1/3,Lower 1/3                  .50  .50 1.00  .00
 4.  Middle 1/3,Top 1/3                    1.00 1.00  .00  .00
 5.  Middle 1/3,Middle 1/3                  .00 1.00 1.00  .50
 6.  Middle 1/3,Lower 1/3                  1.00 1.00  .70  .00
 7.  Aft 1/3,Top 1/3                        .50  .50  .00 1.00
 8.  Aft 1/3,Middle 1/3                     .00  .50 1.00  .00
 9.  Aft 1/3,Lower 1/3                      .50  .50  .70 1.00

CSD.DAT:
*********
     number of components         =  5
     number of locations on detail =  3
     number of loading directions  =  4
     relative cost to vee and weld = $ 1000.00
     relative cost to insert plate = $ 3000.00

Fixed component:

Component name = longitudinal
     typename       relative cost ($)
         T                .00
         L                .00
         B                .00

Fixed component:

Component name = cutout
     typename       relative cost ($)
```

```
         1               .00
         2               .00
         3               .00
         4               .00

Interchangable component:

Component name = lug
     typename      relative cost ($)
         N               .00
         S             3000.00
         D             6000.00

Interchangable component:

Component name = flatbar
     typename      relative cost ($)
         N               .00
         S             3000.00
         D             6000.00

Interchangable component:

Component name = bracket
     typename      relative cost ($)
         N               .00
         S             3000.00
         D             6000.00

Summary of csd configurations:

                              Configuration #
  Component           1  2  3  4  5  6  7  8  9  *
------------------------------------------------------
longitudinal          L  L  L  L  T  T  T  T
cutout                1  1  1  1  1  1  1  1
lug                   N  N  S  S  N  N  S  S
flatbar               N  S  N  S  N  S  N  S
bracket               N  N  N  N  N  N  N  N

Critical structural detail =  1
     location    SN class    stress concentration factors
     ----------------------------------------------------
        1         C              .00  .00 2.00  .00
        2         C              .00  .00 2.10  .00
        3         B              .00  .00 1.00  .00

Critical structural detail =  2
     location    SN class    stress concentration factors
     ----------------------------------------------------
        1         C              .00  .00 1.90  .00
        2         C              .00  .00 2.00  .00
        3         B              .00  .00 1.00  .00

Critical structural detail =  3
     location    SN class    stress concentration factors
     ----------------------------------------------------
        1         C              .00  .00 3.00  .00
        2         C              .00  .00 2.60  .00
        3         F              .00  .00 2.40  .00

Critical structural detail =  4
     location    SN class    stress concentration factors
     ----------------------------------------------------
        1         C              .00  .00 2.80  .00
        2         C              .00  .00 2.50  .00
        3         F              .00  .00 2.30  .00

Critical structural detail =  5
     location    SN class    stress concentration factors
     ----------------------------------------------------
```

```
        1          C           .00  .00 1.80  .00
        2          C           .00  .00 1.90  .00
        3          B           .00  .00 1.00  .00

Critical structural detail =  6
     location    SN class    stress concentration factors
     ---------------------------------------------------
        1          C           .00  .00 1.70  .00
        2          C           .00  .00 1.80  .00
        3          B           .00  .00 1.00  .00

Critical structural detail =  7
     location    SN class    stress concentration factors
     ---------------------------------------------------
        1          C           .00  .00 2.70  .00
        2          C           .00  .00 2.40  .00
        3          F           .00  .00 2.20  .00

Critical structural detail =  8
     location    SN class    stress concentration factors
     ---------------------------------------------------
        1          C           .00  .00 2.50  .00
        2          C           .00  .00 2.30  .00
        3          F           .00  .00 2.10  .00

Original failed detail:
     ship zone #          =  5
     csd #                =  1
     location on detail   =  1
     mean time to failure =    50.00

The estimated Weibull extreme stress to cause failure
is   542.13 N/mm^2 for the original detal with
     Mean time to failure =    50.00 years
     Average frequency    =  .25E+07 cycles/yr
     Weibull shape param  =      .90
     SN parameters
         class  =       C
         m      =     3.50
         A      = .108E+15

REPAIR NUMBER  1:  V and Weld Only
================================================
The estimated mean life of this repair is    5.24 years based on:
     Original extreme stress =    542.13 N/mm^2
     Repair extreme stress   =    542.13 N/mm^2
     Average frequency       =  .25E+07 cycles/yr
     Weibull shape param     =       .90
     Repair SN parameters
         class   =       F
         m       =     3.00
         A       = .173E+13

At the service life of    10.00 years the probability
of failure for this repair is    61.09% based on:
     sd of ln(Tf)              =       2.67
     Tf  mean time to failure  =       5.24 years

The expected monetary value of this repair decision
is $     2216.27 based on the following data:

     EMV = Ci(1+PVF)
     MNR mean number of repairs =      1.91
     PVF present value function =      1.22
     i   rate of inflation      =       .00 %
     r   rate of return         =       .00 %
     Ci  initial repair costs   = $ 1000.00


Summary of data for various exposure times:
```

Time (yrs)	Pf	PDF=f(t)	PVF	EMV ($)
.00	.00	.00	.00	1000.00
1.00	.23	.13	.47	1468.14
2.00	.34	.08	.67	1669.93
3.00	.40	.06	.80	1804.76
4.00	.45	.04	.90	1901.86
5.00	.49	.03	.98	1977.85
6.00	.52	.03	1.04	2039.74
7.00	.55	.02	1.10	2096.94
8.00	.57	.02	1.14	2142.17
9.00	.59	.02	1.18	2181.55
10.00	.61	.02	1.22	2216.27
11.00	.63	.02	2.30	3296.19
12.00	.64	.01	2.57	3572.57
13.00	.65	.01	2.73	3734.05
14.00	.67	.01	2.85	3845.83
15.00	.68	.01	2.93	3930.98
16.00	.69	.01	3.18	4175.13
17.00	.70	.01	3.52	4515.37
18.00	.70	.01	3.69	4694.80
19.00	.71	.01	3.82	4815.57
20.00	.72	.01	3.91	4906.09

```
REPAIR NUMBER  2:  Add Insert Plate Only
==============================================
The estimated mean life of this repair is   50.00 years based on:
     Original extreme stress =   542.13 N/mm^2
     Repair extreme stress   =   542.13 N/mm^2
     Average frequency       =  .25E+07 cycles/yr
     Weibull shape param     =      .90
     Repair SN parameters
         class    =      C
         m        =      3.50
         A        = .108E+15

At the service life of    10.00 years the probability
of failure for this repair is    27.36% based on:
     sd of ln(Tf)               =      2.67
     Tf  mean time to failure   =     50.00 years

The expected monetary value of this repair decision
is $      4632.54 based on the following data:

     EMV = Ci(1+PVF)
     MNR mean number of repairs =        .20
     PVF present value function =        .54
     i   rate of inflation      =        .00 %
     r   rate of return         =        .00 %
     Ci  initial repair costs   = $ 3000.00
```

Summary of data for various exposure times:

Time (yrs)	Pf	PDF=f(t)	PVF	EMV ($)
.00	.00	.00	.00	3000.00
1.00	.07	.05	.14	3427.47
2.00	.11	.04	.23	3683.03
3.00	.15	.03	.29	3873.24
4.00	.17	.02	.34	4027.58
5.00	.19	.02	.39	4163.57
6.00	.21	.02	.43	4278.51
7.00	.23	.02	.46	4380.53
8.00	.25	.01	.49	4472.35
9.00	.26	.01	.52	4555.89
10.00	.27	.01	.54	4632.54
11.00	.29	.01	.57	4703.36
12.00	.30	.01	.59	4769.20

13.00	.31	.01	.61	4830.70
14.00	.32	.01	.63	4888.39
15.00	.33	.01	.65	4942.73
16.00	.33	.01	.66	4994.06
17.00	.34	.01	.68	5042.70
18.00	.35	.01	.70	5099.21
19.00	.36	.01	.71	5143.83
20.00	.37	.01	.73	5186.44

```
REPAIR NUMBER  3:  Redesign plus V and Weld Crack
================================================
The estimated mean life of this repair is    6.36 years based on:
     Original extreme stress =   542.13 N/mm^2
     Repair extreme stress   =   515.02 N/mm^2
     Average frequency       =  .25E+07 cycles/yr
     Weibull shape param     =       .90
     Repair SN parameters
         class    =       F
         m        =      3.00
         A        = .173E+13

At the service life of    10.00 years the probability
of failure for this repair is    57.83% based on:
     sd of ln(Tf)                =       2.67
     Tf  mean time to failure    =       6.36 years

The expected monetary value of this repair decision
is $      8609.15 based on the following data:

     EMV = Ci(1+PVF)
     MNR mean number of repairs =       1.57
     PVF present value function =       1.15
     i   rate of inflation      =        .00 %
     r   rate of return         =        .00 %
     Ci  initial repair costs   = $ 4000.00
```

Summary of data for various exposure times:

Time (yrs)	Pf	PDF=f(t)	PVF	EMV ($)
.00	.00	.00	.00	4000.00
1.00	.21	.13	.42	5673.57
2.00	.31	.08	.61	6442.21
3.00	.37	.05	.74	6963.80
4.00	.42	.04	.84	7346.08
5.00	.46	.03	.91	7648.41
6.00	.49	.03	.97	7896.77
7.00	.52	.02	1.03	8106.23
8.00	.54	.02	1.08	8306.59
9.00	.56	.02	1.12	8467.02
10.00	.58	.02	1.15	8609.15
11.00	.59	.02	1.18	8736.31
12.00	.61	.01	1.21	8851.00
13.00	.62	.01	2.16	12641.45
14.00	.63	.01	2.47	13882.14
15.00	.65	.01	2.64	14554.50
16.00	.66	.01	2.76	15033.17
17.00	.67	.01	2.85	15389.47
18.00	.68	.01	2.92	15674.71
19.00	.68	.01	2.98	15910.98
20.00	.69	.01	3.38	17519.10

```
REPAIR NUMBER  4:  Redesign plus V and Weld Crack
================================================
The estimated mean life of this repair is    1.12 years based on:
     Original extreme stress =   542.13 N/mm^2
     Repair extreme stress   =   813.19 N/mm^2
     Average frequency       =  .25E+07 cycles/yr
     Weibull shape param     =       .90
```

```
     Repair SN parameters
         class    =      F
         m        =     3.00
         A        = .173E+13

At the service life of    10.00 years the probability
of failure for this repair is    83.06% based on:
     sd of ln(Tf)                =       2.67
     Tf  mean time to failure    =       1.12 years

The expected monetary value of this repair decision
is $    29277.55 based on the following data:

     EMV = Ci(1+PVF)
     MNR mean number of repairs =        8.95
     PVF present value function =        6.32
     i   rate of inflation      =         .00 %
     r   rate of return         =         .00 %
     Ci  initial repair costs   = $ 4000.00
```

Summary of data for various exposure times:

Time (yrs)	Pf	PDF=f(t)	PVF	EMV ($)
.00	.00	.00	.00	4000.00
1.00	.48	.17	.96	7829.81
2.00	.60	.08	.88	7522.49
3.00	.67	.05	2.20	12808.07
4.00	.71	.04	2.81	15254.41
5.00	.74	.03	3.41	17649.24
6.00	.77	.02	4.00	20004.51
7.00	.79	.02	4.57	22275.28
8.00	.80	.02	5.10	24398.88
9.00	.82	.01	5.55	26207.85
10.00	.83	.01	6.32	29277.55
11.00	.84	.01	6.95	31790.04
12.00	.85	.01	7.57	34274.55
13.00	.86	.01	8.19	36740.21
14.00	.87	.01	8.79	39171.66
15.00	.87	.01	9.38	41539.45
16.00	.88	.01	9.97	43860.88
17.00	.88	.01	10.52	46076.95
18.00	.89	.00	11.03	48100.86
19.00	.89	.00	11.39	49563.94
20.00	.90	.00	12.31	53240.57

```
REPAIR NUMBER  5:  Redesign plus V and Weld Crack
================================================
The estimated mean life of this repair is    1.46 years based on:
     Original extreme stress =   542.13 N/mm^2
     Repair extreme stress   =   758.98 N/mm^2
     Average frequency       =  .25E+07 cycles/yr
     Weibull shape param     =      .90
     Repair SN parameters
         class    =      F
         m        =     3.00
         A        = .173E+13

At the service life of    10.00 years the probability
of failure for this repair is    79.97% based on:
     sd of ln(Tf)                =       2.67
     Tf  mean time to failure    =       1.46 years

The expected monetary value of this repair decision
is $    55395.36 based on the following data:

     EMV = Ci(1+PVF)
     MNR mean number of repairs =        6.86
     PVF present value function =        6.91
```


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```
i   rate of inflation     =       .00 %
r   rate of return        =       .00 %
Ci  initial repair costs  = $ 7000.00
```

Summary of data for various exposure times:

Time (yrs)	Pf	PDF=f(t)	PVF	EMV ($)
.00	.00	.00	.00	7000.00
1.00	.43	.17	.87	13065.44
2.00	.55	.09	1.11	14748.28
3.00	.62	.06	2.20	22427.84
4.00	.67	.04	2.88	27188.82
5.00	.70	.03	3.69	32856.30
6.00	.73	.02	4.33	37282.73
7.00	.75	.02	4.90	41298.23
8.00	.77	.02	5.73	47093.88
9.00	.79	.01	6.41	51904.55
10.00	.80	.01	6.91	55395.36
11.00	.81	.01	7.75	61284.39
12.00	.82	.01	8.48	66379.03
13.00	.83	.01	8.93	69481.55
14.00	.84	.01	9.78	75451.11
15.00	.85	.01	10.54	80761.84
16.00	.85	.01	10.94	83558.21
17.00	.86	.01	11.80	89598.05
18.00	.86	.01	12.58	95078.52
19.00	.87	.00	13.08	98541.88
20.00	.87	.00	13.82	********

REPAIR NUMBER 6: Redesign plus Add Insert Plate

```
=============================================
The estimated mean life of this repair is    62.71 years based on:
     Original extreme stress =    542.13 N/mm^2
     Repair extreme stress   =    515.02 N/mm^2
     Average frequency       =   .25E+07 cycles/yr
     Weibull shape param     =       .90
     Repair SN parameters
         class     =       C
         m         =     3.50
         A         = .108E+15

At the service life of    10.00 years the probability
of failure for this repair is    24.61% based on:
     sd of ln(Tf)              =      2.67
     Tf  mean time to failure  =     62.71 years

The expected monetary value of this repair decision
is $      8939.78 based on the following data:

     EMV = Ci(1+PVF)
     MNR mean number of repairs =       .16
     PVF present value function =       .49
     i   rate of inflation      =       .00 %
     r   rate of return         =       .00 %
     Ci  initial repair costs   = $ 6000.00
```

Summary of data for various exposure times:

Time (yrs)	Pf	PDF=f(t)	PVF	EMV ($)
.00	.00	.00	.00	6000.00
1.00	.06	.05	.12	6725.70
2.00	.10	.03	.20	7180.87
3.00	.13	.03	.25	7525.98
4.00	.15	.02	.30	7809.23
5.00	.17	.02	.34	8051.14

6.00	.19	.02	.38	8263.01
7.00	.21	.02	.41	8464.13
8.00	.22	.01	.44	8636.78
9.00	.23	.01	.47	8794.50
10.00	.25	.01	.49	8939.78
11.00	.26	.01	.51	9074.48
12.00	.27	.01	.53	9200.07
13.00	.28	.01	.55	9317.73
14.00	.29	.01	.57	9428.41
15.00	.30	.01	.59	9532.90
16.00	.30	.01	.61	9631.85
17.00	.31	.01	.62	9725.82
18.00	.32	.01	.64	9815.27
19.00	.33	.01	.65	9900.63
20.00	.33	.01	.66	9982.23

```
REPAIR NUMBER  7:  Redesign plus Add Insert Plate
================================================
The estimated mean life of this repair is    8.12 years based on:
     Original extreme stress =   542.13 N/mm^2
     Repair extreme stress   =   813.19 N/mm^2
     Average frequency       =  .25E+07 cycles/yr
     Weibull shape param     =       .90
     Repair SN parameters
         class    =       C
         m        =      3.50
         A        = .108E+15

At the service life of    10.00 years the probability
of failure for this repair is    53.11% based on:
     sd of ln(Tf)               =       2.67
     Tf  mean time to failure   =       8.12 years

The expected monetary value of this repair decision
is $    11703.41 based on the following data:

     EMV = Ci(1+PVF)
     MNR mean number of repairs =       1.23
     PVF present value function =        .95
     i   rate of inflation      =        .00 %
     r   rate of return         =        .00 %
     Ci  initial repair costs   = $ 6000.00
```

Summary of data for various exposure times:

Time (yrs)	Pf	PDF=f(t)	PVF	EMV ($)
.00	.00	.00	.00	6000.00
1.00	.22	.11	.43	8583.86
2.00	.30	.07	.60	9584.73
3.00	.35	.05	.70	10229.96
4.00	.40	.04	.78	10708.29
5.00	.43	.03	.74	10465.72
6.00	.46	.02	.91	11432.03
7.00	.48	.02	.95	11701.49
8.00	.50	.02	.99	11934.90
9.00	.52	.02	.92	11533.82
10.00	.53	.01	.95	11703.41
11.00	.55	.01	.98	11859.46
12.00	.56	.01	1.11	12636.43
13.00	.57	.01	1.13	12772.49
14.00	.58	.01	1.16	12935.90
15.00	.59	.01	1.18	13053.79
16.00	.60	.01	1.19	13163.24
17.00	.61	.01	2.36	20172.65
18.00	.62	.01	2.55	21316.17
19.00	.62	.01	2.67	22018.27
20.00	.63	.01	2.75	22527.51

REPAIR NUMBER 8: Redesign plus Add Insert Plate
==

The estimated mean life of this repair is 11.10 years based on:
- Original extreme stress = 542.13 N/mm^2
- Repair extreme stress = 758.98 N/mm^2
- Average frequency = .25E+07 cycles/yr
- Weibull shape param = .90
- Repair SN parameters
  - class = C
  - m = 3.50
  - A = .108E+15

At the service life of 10.00 years the probability of failure for this repair is 48.44% based on:
- sd of ln(Tf) = 2.67
- Tf mean time to failure = 11.10 years

The expected monetary value of this repair decision is $ 17662.32 based on the following data:

- EMV = Ci(1+PVF)
- MNR mean number of repairs = .90
- PVF present value function = .96
- i rate of inflation = .00 %
- r rate of return = .00 %
- Ci initial repair costs = $ 9000.00

Summary of data for various exposure times:

Time (yrs)	Pf	PDF=f(t)	PVF	EMV ($)
.00	.00	.00	.00	9000.00
1.00	.18	.10	.37	12292.70
2.00	.26	.06	.52	13674.47
3.00	.31	.04	.62	14589.67
4.00	.35	.03	.70	15279.25
5.00	.38	.03	.62	14549.94
6.00	.41	.02	.81	16330.59
7.00	.43	.02	.86	16729.86
8.00	.45	.02	.90	17078.13
9.00	.47	.02	.79	16136.10
10.00	.48	.01	.96	17662.32
11.00	.50	.01	.99	17911.72
12.00	.51	.01	1.02	18138.87
13.00	.52	.01	1.04	18347.14
14.00	.53	.01	1.06	18539.17
15.00	.54	.01	1.08	18717.11
16.00	.55	.01	.97	17721.08
17.00	.56	.01	.98	17860.35
18.00	.57	.01	1.00	17992.85
19.00	.58	.01	1.01	18119.37
20.00	.59	.01	1.03	18240.60

APPENDIX C: PREVIOUS REPAIR STUDY WORK

The purpose of this appendix is to provide information on previous work completed in Study 4. The repairs study has undergone four distinct phases represented by three different Graduate Student Researchers (GSRs). These phases are:

Phase	GSR	Start Date	End Date
1	Robert Baker	June 1990	Dec 1990
2	Martin Cepauskas	Jan 1991	Jan 1991
3	None	Jan 1991	June 1991
4	Keith Gallion	June 1991	May 1992

The following is a summary of the work completed during the first two phases and the causes of redirection. The results of the current research represent Phase 4 of the repairs study which was approved by the SMP Project Technical Committee on January 17, 1992.

Martin Cepauskas entered the study to wrap up the work of Robert Baker and to recommend a future direction for the study. Starting on the next page is part of his report of the status and recommendations for the successful completion of the Repair Study.

STUDY #4 REPAIRS STATUS AS OF JANUARY 18, 1991

On January 7 - 8, 1991 the Structural Maintenance of New and Existing Ships Project Technical Committee held a meeting at U. C. Berkeley. During this meeting the status and re-direction of Study 4 on Repairs and New Build Guidelines was discussed. Currently, Study 4 is encountering problems in acquiring sufficient data on repairs and maintenance in order to carry out this study properly. In addition to this problem there is a lack of presently available "qualified and motivated" research assistants.

Three alternatives for the successful completion of this study were presented to the PTC for discussion. Based on the current problems, the PTC's decision was to suspend the Repair Study as of 1/18/91 until 9/91 when a "qualified and motivated" research assistant will be available to properly continue this project. Between 1/18/91 and 9/91, the PTC members also agreed to make a concerted effort to obtain more "sufficient definitive data on cracking, coating, and cathodic protection repairs and maintenance." This information should be forwarded directly to Professor Bob Bea.

Current Overall Study 4 Status

In generalizing the project's status to date, the study has progressed as well as possible with the limited amount of data available. The course that the study has been following has focused on the owner's point of view. Most of the current information being used for the ship summaries, verifications and repair/corrosion case studies has been obtained from the ship owners. In order for the project to continue using the current format and information available, all of the PTC members will have to provide more pertinent information on the details of the repair of the corrosion and fatigue failures (e.g. steel weights used, time of repair, effectiveness of the repair, more details on the location and repair method used). It seems that the problem with obtaining this information is that the pertinent data needed for this study is not readily accessible. This information must be located by the PTC members and forwarded in a timely manner.

All of the information, reports, surveys, etc. obtained up to 1/18/91 can be located in Bob Baker's files. These files have been organized into separate folders which are respectively identified.

Redirection and Reorganization of Study 4

The January PTC meeting decided to suspend this repair study until 9/91 when a "qualified and motivated" research assistant will be available. This delay will alter the Study 4 schedule as follows:

- The repair study will begin again in 9/91 and be completed by 9/92 with a new research assistant.
- The New-Build guidelines study will be initiated in 9/91 and be completed by 9/92. This study will be performed by a separate research assistant.

The Study 4 delay between 1/18/91 and 9/91 will allow time for the PTC members to gather pertinent information for this study. This new information will enable the new research assistants to successfully develop and complete this study to meet the project goals and expectations. Study 4 will proceed as planned and outlined granted that the new information received is sufficient. To date, limited information has been made available to successfully complete this study as planned.

All information should be forwarded directly to Professor Bob Bea.

List of Findings to Date

This list of findings was furnished by Bob Baker. This information is based on his experience with working on this study for the first six months of this Structural Maintenance for New and Existing Ships project.

1. Database makes problem areas readily apparent by giving percent of types of repairs/cracks for any vessel. Comparisons can be made with other vessels of the class to give further insight into problem areas.
2. Not all repairs are sound from a Naval Architectural standpoint, even with the better operators. Some repairs are made by the "seat of the pants" approach and cracks begin to reappear during the next inspection. There are times when poor repairs are made due to time and budget limitations at the shipyard. These sometimes resulted in recracking.
3. Not all cracks are repaired. Cracks in the side shell and in the major structural members of the ship are repaired.
4. Ship life is determined by the following factors:
   - Future plans of the company.
   - "Second hand values" as determined by the supply and demand for tonnage for a vessel of that particular size as dictated by the oil markets.
   - Development of legislation.
5. Corrosion protection philosophies vary between organizations.
   - Installation of anodes in ballast or cargo tanks.
   - Extent of coating in ballast and cargo tanks.
6. Surface preparation of coating area seemed to be the key ingredient in getting the maximum life for tank coatings.
7. The combination of anodes and coatings gave the best protection.
8. Repair decisions are not always based on the most sound engineering approach from a Naval Architectural standpoint.
9. Lack of organization in files to retrieve information quickly on steel repairs and coatings. Much information is missing due to this poor record keeping.
10. Large variance in sophistication of tracking crack repairs and coatings.

11. Lack of computerization by most operators for handling and keeping track of repair budgets and engineering documentation.
12. Differences in the type of repairs proposed by the office technical department and what is actually done at the shipyard. This may be due to budget constraints or differences of opinions.
13. Two other companies besides Chevron were at the time of the initiation of this project developing their own crack data bases for tracking cracks.
14. Three companies were simultaneously coming up with three phases of repairs to side shell longitudinals at web frames.
15. Lack of respect for U.S. Coast Guard expertise in approval of repairs at shipyards.

Previous problems with the repair portion of the study:

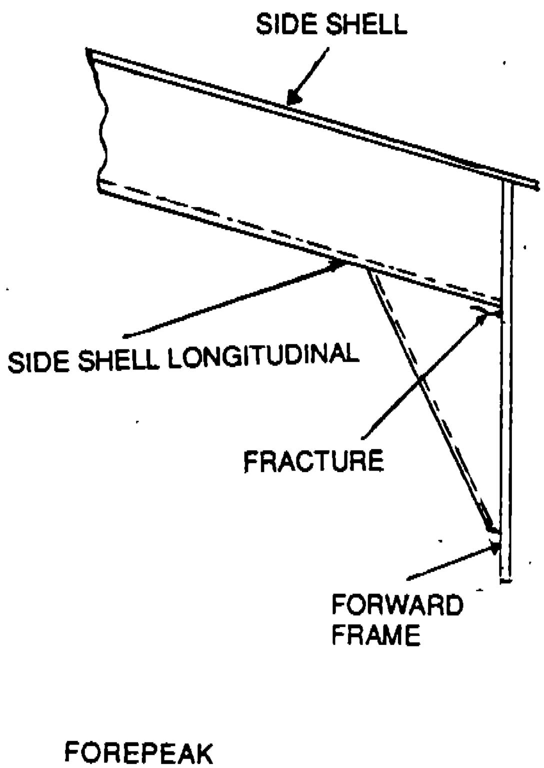
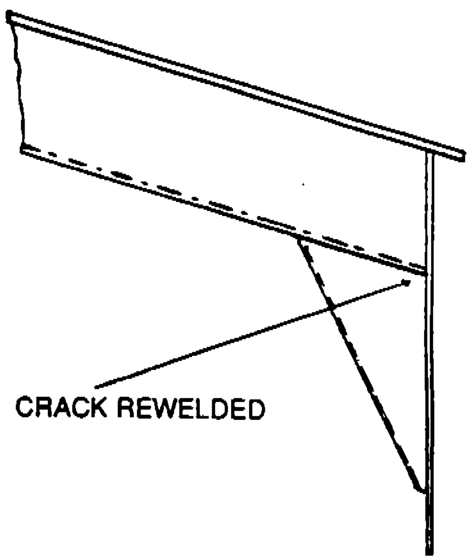
1. Acquisition of data on timely basis.
2. More information is needed to complete fields of the data base. Survey reports that have been received do not contain complete information:
    - Coating information missing.
    - Details on repairs not incorporated into reports.
    - Interface required between research assistant and company contact is usually required to identify the causes of cracks and repairs.
    - Information on survey reports is sometimes unclear where the crack is actually located.
3. Conflicting reports on reasons, times and location of cracks.
4. Poor documentation and file organization of repairs and surveys for the histories of the vessels in general.
5. Incomplete information presented to the study for the repair history of the vessel. On some vessels, summary reports were based on only one survey

report. Multiple surveys provide insight to repair decisions; repair histories as to the repair failures; and problem areas become more apparent due to repetitive cracking.

6. Working with vessels of the same class provides insight to problem areas, especially in selecting verification cases.

LOCATION: Connection of longitudinals to transverse frame

EXAMPLE No. 1: Fractured bracket at side shell longitudinal at forward traverse bulkhead

TYPICAL DAMAGE	PROPOSED REPAIR
	

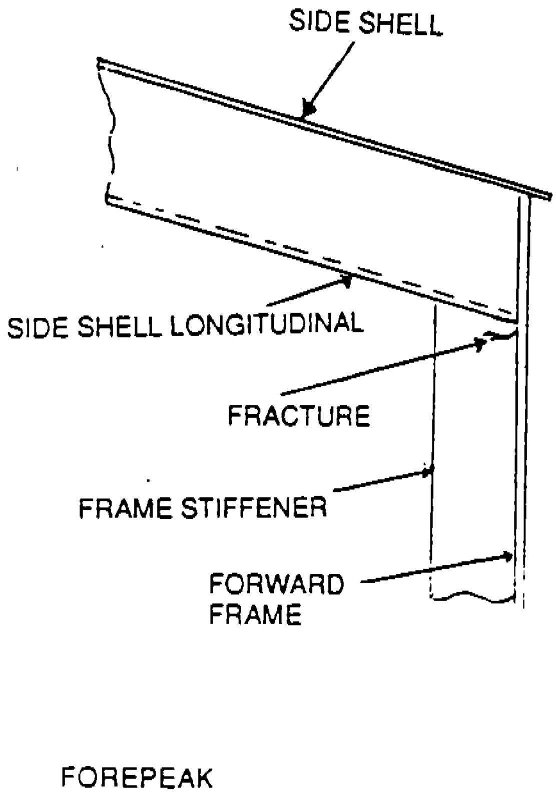
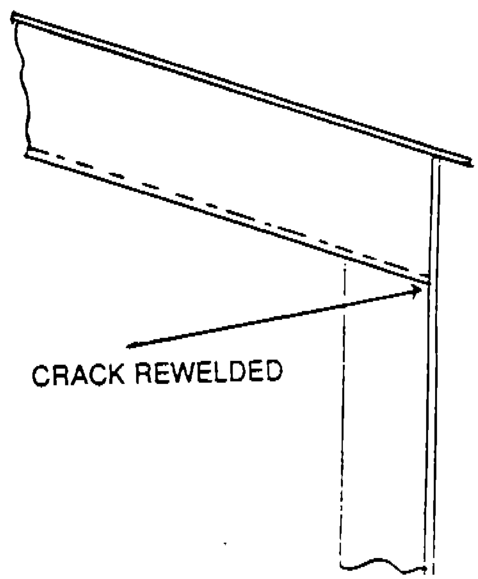
FACTORS CONTRIBUTING TO DAMAGE

1. Under designed end bracket.
2. Higher tensile steel side shell longitudinal resulting in greater stress.
3. Deflection of the adjacent side shell transverse under load.
4. Dynamic sea way loads / ship motions of forward end of ship.

STRUCTURAL MAINTENANCE FOR NEW AND EXISTING SHIPS
REPAIR CASE STUDY 1

LOCATION: Connection of longitudinals to transverse frame

EXAMPLE No. 2: Fractured stiffener at side shell longitudinal at forward traverse bulkhead

TYPICAL DAMAGE	PROPOSED REPAIR
	

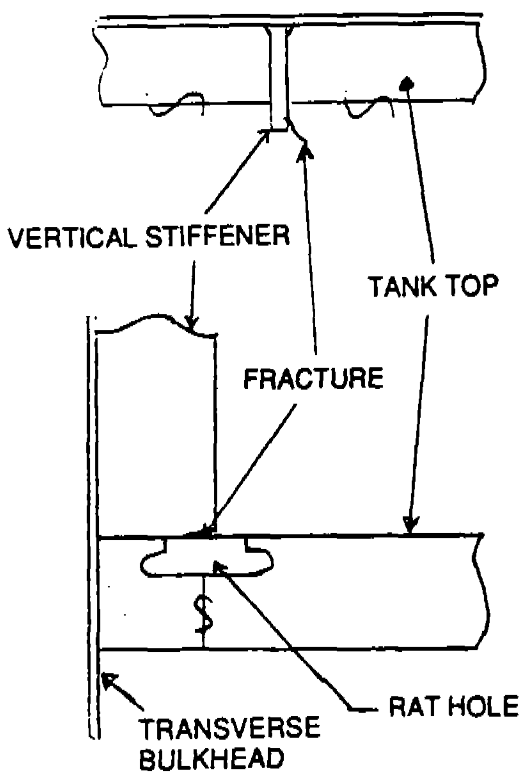
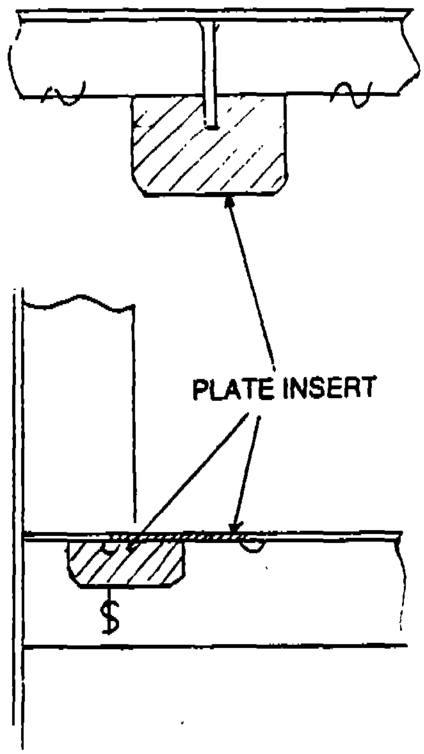
FACTORS CONTRIBUTING TO DAMAGE

1. Higher tensile steel side shell longitudinal resulting in greater stress.
2. Deflection of the adjacent side shell transverse under load.
3. Dynamic sea way loads / ship motions of forward end of ship.

STRUCTURAL MAINTENANCE FOR NEW AND EXISTING SHIPS
REPAIR CASE STUDY 2

LOCATION: Transverse bulkhead vertical stiffener intersection at tank top of double bottom

EXAMPLE No. 1: Cracks at vertical stiffener weld and tank top plate

TYPICAL DAMAGE	REPAIR
	

FACTORS CONTRIBUTING TO DAMAGE

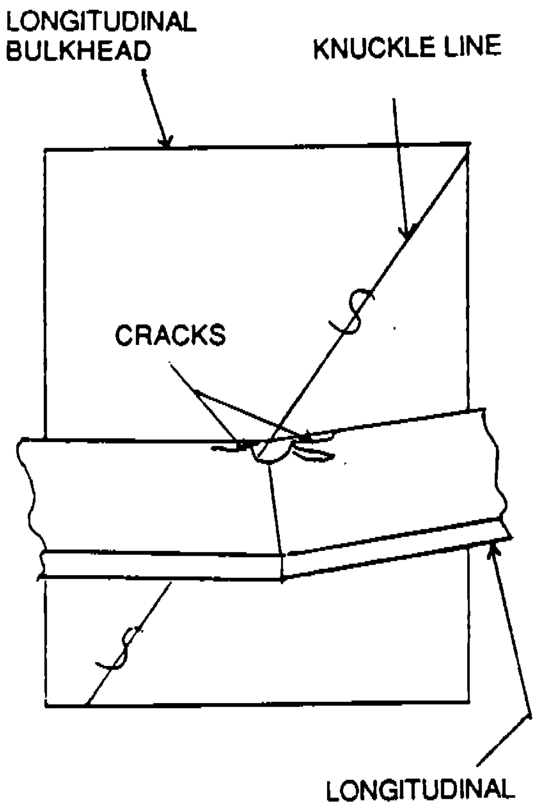
1. Poor detail design due to lack of tripping brackets.
2. Weld undercuts and excessive root openings.
3. Rat hole under tank top is too large creating stress area.
4. Mis-alignment of vertical bulkhead stiffeners and longitudinals under the tank top.

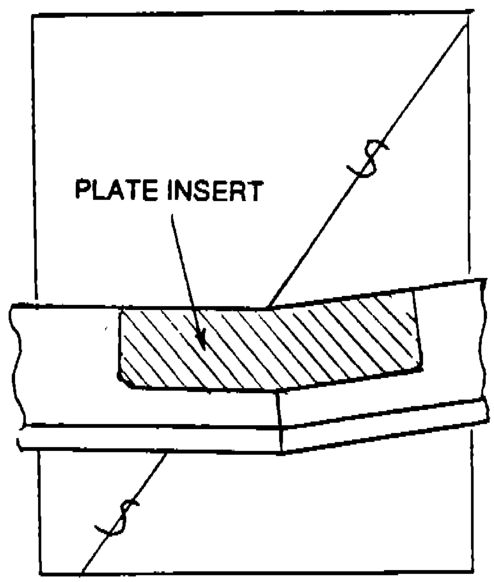
STRUCTURAL MAINTENANCE FOR NEW AND EXISTING SHIPS
REPAIR CASE STUDY 3

LOCATION: Longitudinal bulkhead stiffener at knuckle line of the longitudinal bulkhead

EXAMPLE No. 3: Cracks and wastage at longitudinal stiffener

TYPICAL DAMAGE	REPAIR





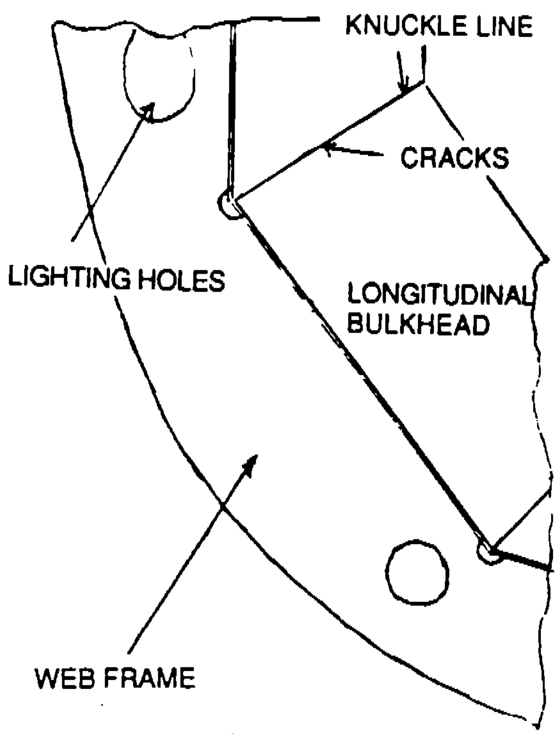
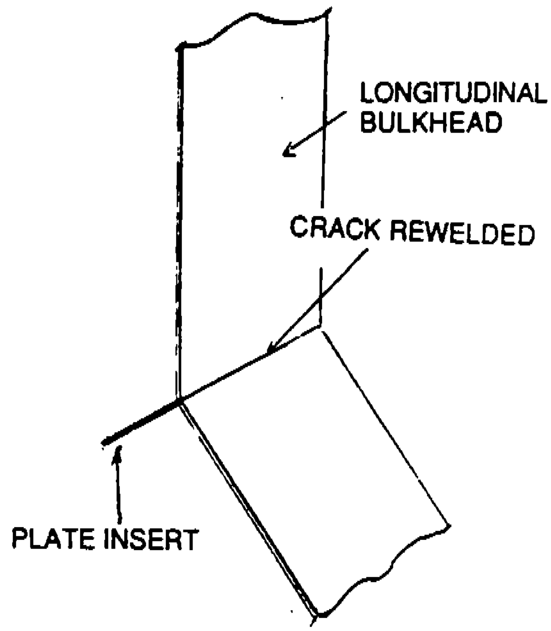
FACTORS CONTRIBUTING TO DAMAGE

1. Grooving corrosion wastage and fatigue.
2. Dynamic seaway loads / ship motion of forward end of ship.
3. High stress area at intersection of knuckle line caused accelerated coating breakdown and corroision along with fatigue.

STRUCTURAL MAINTENANCE FOR NEW AND EXISTING SHIPS
REPAIR CASE STUDY 4

LOCATION: Inclined longitudinal bulkhead weld connections in aftermost cargo tank

EXAMPLE No. 2: Cracks along longitudinal bulkhead knuckle weld connections

TYPICAL DAMAGE	REPAIR
 AFTER CARGO TANK	

FACTORS CONTRIBUTING TO DAMAGE

1. Corrosion wastage.
2. High stress area at intersection of knuckle line caused accelerated coating breakdown and corroision.

STRUCTURAL MAINTENANCE FOR NEW AND EXISTING SHIPS
REPAIR CASE STUDY 5

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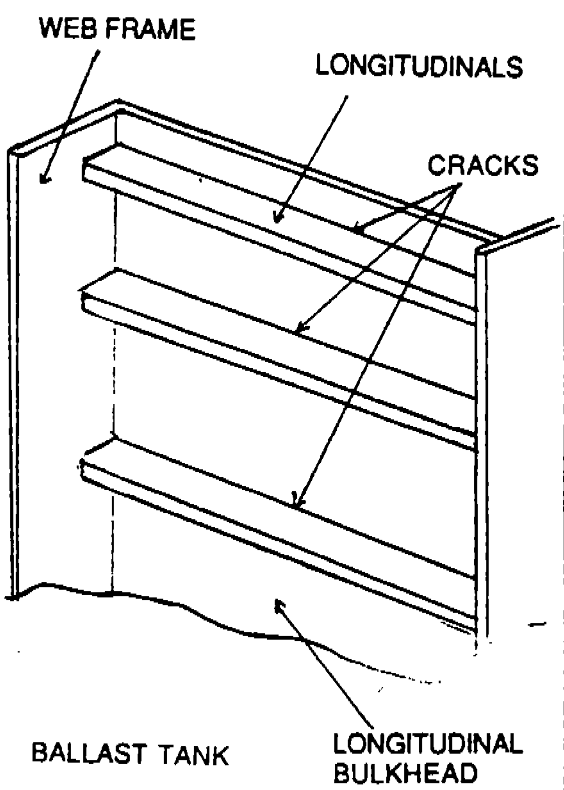
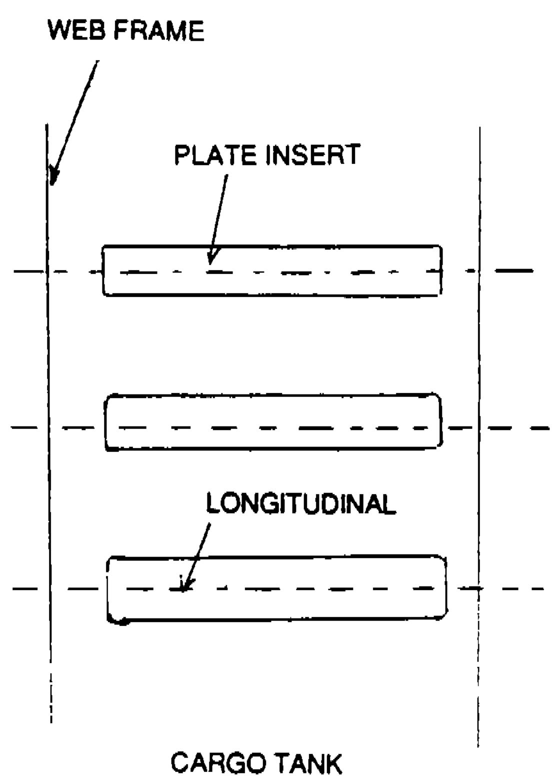
LOCATION: Along longitudinals of longitudinal bulkhead separating cargo and ballast tanks

EXAMPLE No. 4: Cracks in longitudinal bulkhead along topside of longitudinals

TYPICAL DAMAGE	REPAIR
	

FACTORS CONTRIBUTING TO DAMAGE

1. Grooving corrosion and fatigue.
2. Deflection of longitudinal bulkhead underload accelerating coating break down and fatigue.

STRUCTURAL MAINTENANCE FOR NEW AND EXISTING SHIPS
REPAIR CASE STUDY 6

191, 192X A11