NTIS # PB94-121951

SSC-372

MAINTENANCE OF MARINE STRUCTURES; A STATE OF THE ART SUMMARY

SHIP STRUCTURE COMMITTEE

1993

COMMITTEE ON MARINE STRUCTURES

Commission on Engineering and Technical Systems

National Academy of Sciences – National Research Council

The COMMITTEE ON MARINE STRUCTURES has technical cognizance over the interagency Ship Structure Committee's research program.

Peter M. Palermo Chairman, Alexandria, VA
Subrata K. Chakrabarti, Chicago Bridge and Iron, Plainfield, IL
John Landes, University of Tennessee, Knoxville, TN
Bruce G. Collipp, Marine Engineering Consultant, Houston, TX
Robert G. Kline, Marine Engineering Consultant, Winona, MN
Robert G. Loewy, NAE, Rensselaer Polytechnic Institute, Troy, NY
Robert Sielski, National Research Council, Washington, DC
Stephen E. Sharpe, Ship Structure Committee, Washington, DC

LOADS WORK GROUP

Subrata K. Chakrabarti Chairman, Chicago Bridge and Iron Company, Plainfield, IL
Howard M. Bunch, University of Michigan, Ann Arbor, MI
Peter A. Gale, John J. McMullen Associates, Arlington, VA
Hsien Yun Jan, Martech Incorporated, Neshanic Station, NJ
John Niedzwecki, Texas A&M University, College Station, TX
Solomon C. S. Yim, Oregon State University, Corvallis, OR
Maria Celia Ximenes, Chevron Shipping Co., San Francisco, CA

MATERIALS WORK GROUP

John Landes, Chairman, University of Tennessee, Knoxville, TN
William H Hartt, Florida Atlantic University, Boca Raton, FL
Horold S. Reemsnyder, Bethlehem Steel Corp., Bethlehem, PA
Barbara A. Shaw, Pennsylvania State University, University Park, PA
James M. Sawhill, Jr., Newport News Shipbuilding, Newport News, VA
Bruce R. Somers, Lehigh University, Bethlehem, PA
Jerry G. Williams, Conoco, Inc., Ponca City, OK

Cover 3

SHIP STRUCTURE COMMITTEE PUBLICATIONS

SSC-354 Structural Redundancy for Discrete and Continuous Systems by P. K. Das and J. F. Garside 1990

SSC-355 Relation of Inspection Findings to Fatigue Reliability by M. Shinozuka 1989

SSC-356 Fatigue Performance Under Multiaxial Load by Karl A. Stambaugh, Paul R. Van Mater, Jr., and William H. Munse 1990

SSC-357 Carbon Equivalence and Weldability of Microalloyed Steels by C. D. Lundin, T. P. S. Gill, C. Y. P. Qiao, Y. Wang, and K. K. Kang 1990

SSC-358 Structural Behavior After Fatigue by Brian N. Leis 1987

SSC-359 Hydrodynamic Hull Damping (Phase I) by V. Ankudinov 1987

SSC-360 Use of Fiber Reinforced Plastic in Marine Structures by Eric Greene 1990

SSC-361 Hull Strapping of Ships by Nedret S. Basar and Roderick B. Hulla 1990

SSC-362 Shipboard Wave Height Sensor by R. Atwater 1990

SSC-363 Uncertainties in Stress Analysis on Marine Structures by E. Nikolaidis and P. Kaplan 1991

SSC-364 Inelastic Deformation of Plate Panels by Eric Jennings, Kim Grubbs, Charles Zanis, and Louis Raymond 1991

SSC-365 Marine Structural Integrity Programs (MSIP) by Robert G. Bea 1992

SSC-366 Threshold Corrosion Fatigue of Welded Shipbuilding Steels by G. H. Reynolds and J. A. Todd 1992

SSC-367 Fatigue Technology Assessment and Strategies for Fatigue Avoidance in Marine Structures by C. C. Capanoglu 1993

SSC-368 Probability Based Ship Design Procedures: A Demonstration by A. Mansour, M. Lin, L. Hovem, A. Thayamballi 1993

SSC-369 Reduction of S-N Curves for Ship Structural Details by K. Stambaugh, D. Lesson, F. Lawrence, C-Y. Hou, and G. Banas 1993

SSC-370 Underwater Repair Procedures for Ship Hulls (Fatigue and Ductility of Underwater Wet Welds) by K. Grubbs and C. Zanis 1993

SSC-371 Establishment of a Uniform Format for Data Reporting of Structural Material Properties for Reliability Analysis by N. Pussegoda, L. Malik, and A. Dinovitzer 1993

None Ship Structure Committee Publications - A Special Bibliography

Cover 4

SSC-372 Maintenance of Marine Structures; A State of the Art Summary Ship Structure Committee 1993

Member Agencies:

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

Ship Structure Committee

An Interagency Advisory Committee

Address Correspondence to:

Executive Director
Ship Structure Committee
U.S. Coast Guard (G-MI/SSC)
2100 Second Street, S.W.
Washington, D.C. 20593-0001
Ph:(202) 267-0003
Fax:(202) 267-4677

SSC-372
SR-1347

7 April, 1994

MAINTENANCE OF MARINE STRUCTURES;
A STATE OF THE ART SUMMARY

This research provides an overview of the current state of the art of maintaining marine structures as documented by Ship Structure Committee reports over the past decades. This report is intended to feed into the development of future research planning through the development of a baseline. Each chapter directly relates to one of the National Academy of Science's Marine Structure Research Recommendations for FY 1993 topics. In addition to the hard copy report a database was developed to aid researchers in their review of SSC reports in the future. A copy of the database on a 3 1/2" computer disk is available from the Executive Director at the above address for the near term. This project was completed under the Maritime Administration's National Maritime Enhancement Institute program at the University of California, Berkeley.

A. E. Henn

A. E. HENN
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

(A)

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SSC-372	PB94-121951	

4. Title and Subtitle	
Maintenance of Marine Structures; A State of the Art Summary	5. Report Date: May 1993
	6. Performing Organization Code: DTMA
7. Author(s): Bea, R. G., Hutchison, S. C.	8. Performing Organization Report No.: DTMA91-92-CA-200096
9. Performing Organization Name and Address: Department of Naval Architecture and Offshore Eng. University of California at Berkeley 202 Naval Architecture Bldg. Berkeley CA, 94720	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.: SR-1347
12. Sponsoring Agency Name and Address: DOT/Maritime Administration Office of Acquisition, MAR-382 400 Seventh Street, SW., Room 7310 Washington D.C. 20590	13. Type of Report and Period Covered: Final Report May 92-May 93
	14. Sponsoring Agency Code: G-M

15. Supplementary Notes

Sponsored by the Ship Structure Committee and its Member Agencies

16. Abstract

This document is the final research report for Marad sponsored research contract SR-1347. The intent of the research was to provide an overview of the current state of the art of specific areas in the field of ship maintenance through the exclusive review of pertinent Ship Structures Committee (SSC) reports. The topics discussed in the report include; reliability based design, welding, mechanical fastening techniques, fatigue, structural fractures,instrumentation, vibration, corrosion, inspection non-destructive-testing, (NDT), and instrumentation. The topics are in accordance with the National Academy's recommended research topics for 93-94 fiscalyear in the ship structures field. In addition to the research report, a database was developed to aid researchers in finding SSC reports of interest to their specific topics. The database is written in Microsoft Foxpro for Windows, which must be resident on the users' PC in order to use the database. An operator's manual and floppy,(3.5" 1.44MByte), disk is supplied with the report in the end matter.

17. Key Words	18. Distribution Statement
Review Database Maintenance Existing Ships	Distribution unlimited, available from: National Technical Information Service U.S. Department of Commerce Springfield, VA 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	160	

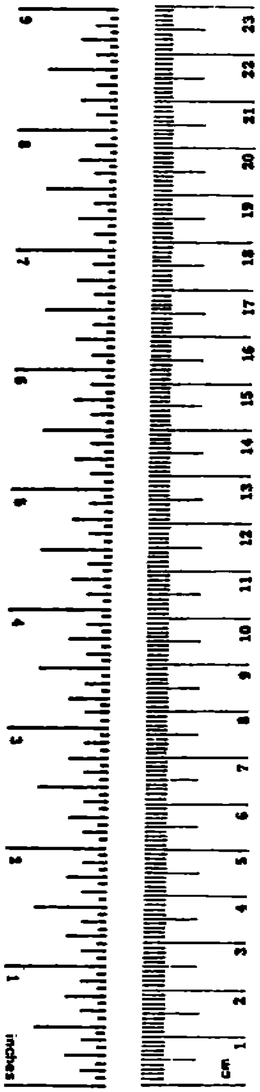
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

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	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	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	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

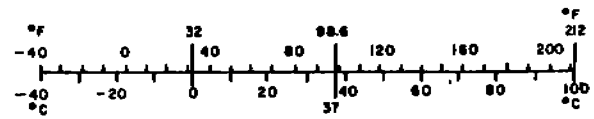


Table of Contents

List of Tables

List of Figures

I.0.0 Introduction

Ships have been relied upon to transport goods in bulk from their source to marketplace for over 2000 years. Routine long distance transport of bulk materials began in the 17th century with the oriental spice trade. The 'east indiamen' undertook voyages taking years and covering thousands of miles between Europe and the Orient. Ships had to be built to withstand the rigors of the long voyages, have enough cargo capacity to make the trips profitable and have space enough to accommodate crews large enough to operate the vessels.

The construction of early vessels was an art, with hull forms and rigs developed through years of experience and personal taste rather than through any standardized guidelines. The relatively small size of the vessels allowed shipwrights to construct a vessel near almost any large body of water, often relying on plans that at times existed only in the mind of the yard master. As a result, the tracking of vessel construction was nearly impossible. Yards often appeared, built only a small number of vessels and disappeared, leaving no record of the details of a vessels construction. However as a result of crude construction methods and small size, these vessels tended to be heavily built with success determined by the speed/cost/deadweight abilities rather than by the more than adequate strength of the vessel. The loss of these sailing merchantmen was nearly always a result of grounding, loss of stability or foundering at sea rather than due to catastrophic structural failure. Since the vessels were heavily built with initial strength far in excess of that required to perform their missions, the condition of older ships could vary widely as a result of varied levels (if any) of maintenance which the vessels had experienced.

The formation of classification societies was in part a response to the accountability problems involved with the multitude of small vessels available to carry freight. To a merchant, the soundness of one [older] vessel was difficult to evaluate. Without an objective expert opinion, that evaluation was often wrong. The loss of goods shipped on ill fated, inferior quality, poorly maintained vessels cost the merchant and underwriters dearly. With the performance of fitness for purpose surveys of vessels by classification societies, risk was minimized through classification of ships with respect to age and apparent seaworthiness. This ranking of vessels helping to determine the risk to financiers and underwriters of speculative ventures involving the sponsoring of vessels on long perilous voyages. The safety of crews also improved due to the new interest of shipowners in getting their vessels favorably classified.

With the application of steam power to ships in the mid 19th Century, ships could be built to serve on any route regardless of season and wind direction. For the first time, a vessel could be driven at high speed into head seas imposing loads on hulls heretofore unexperienced by sailing vessels which were limited to running before or abeam of the wind and prevailing seas. Due to the increases in power available from superheated steam, larger vessels could be built which experienced even greater stresses.

With 'production line' type ship building first seen during world war II, welded steel construction came into wide spread use. It expedited construction and was less prone to plate "springing" under impacts as were riveted hulls. The welded hull was considered to be stronger, lighter and more resilient than it's riveted predecessor. There were problems though, with cracks propagating unchecked through welded structures. Many cases of brittle fracture were reported on Liberty type ships and T-1 tankers. Perhaps the most notorious case of catastrophic brittle fracture was the dockside breakup of the S.S. Schenectady in the winter of 1943. Improvements in steels, welding methods and inspection techniques since then have greatly improved the resistance of ships to such catastrophic failures. However, they still do occur on a disturbingly frequent basis. Since the cost of failure including the loss of freight revenue, shipyard costs, salvage costs and clean-up costs is high, it is important that every effort is made to ensure that the most diligent and technically sophisticated efforts would be utilized in order to assure the structural integrity of the ship.

Since 1946 the Ship Structure Committee has addressed critical problems such as brittle fracture and has sponsored research to improve structural design, construction, maintenance and repair. Three hundred and sixty five separate reports have been published to date. The content of these reports range from the highly technical to practical guidelines for personnel directly involved in shipyard/shipping operations.

The purpose of this report is to provide a state of the art summary and overview of completed research related to ship maintenance. The report is based principally on the work of the SSC and focuses on technological areas of greatest concern to ship operators. While it is intended to be as qualitative as possible, quantitative analysis was necessary in certain areas in order to properly address the concepts.

In addition to this report, a database of SSC report abstracts has been compiled to allow rapid access to all of the reports through a key word search format. Through information availability, this database will further facilitate new technology application within the maritime community.

The topics discussed in this report are based on the key technology and subject areas currently in use by the SSC for research planning. These areas include reliability based design, structural assembly, vibration, fatigue, fracture control, corrosion, inspection, non destructive testing, and structural instrumentation. The report emphasizes the application of technology to the maintenance of ships.

This Page Intentionally Left Blank

II.0.0 Design

Since existing ship maintenance is the focus of this report, design considerations are of limited concern. However, maintenance difficulties and expenses are related to earlier design decisions. Therefore, some design philosophy background is needed to understand maintenance practices and problems.

II.1.0 Durability

Traditionally ships have been designed to meet a minimum allowable scantlings requirement with some additional margin to allow for uncertainties in the somewhat crude analysis tools available to designers. With the advent of more sophisticated design tools and intensified competition in bidding for ship building contracts, the margin between the minimum scantling requirements and the as built scantlings have become quite small.

The method used in shipbuilding to achieve a minimum weight structure is the use of highly stiffened thin plate for weight and cost savings. This design philosophy has led to highly fracture prone, complex, hard to inspect and repair structures [1]. The use of heavier plating with lighter stiffening members would result in a more robust, easier to construct and less corrosion prone structure. Increased steel weight does result in a ship more costly to operate: however the cost of maintenance is drastically reduced by the structure's tolerance for corrosion without approaching any minimum scantling limit. As shown in Figure 1 curve A, a poorly maintained 'lightly' built vessel will incur quite high maintenance costs as it ages. Because of the small margin between the ship's 'as built' and minimum scantlings, it will reach a minimum scantling limit several times throughout it's life. At each occurance, the ship would require extensive and costly repair. Curve B illustrates the same lightly built but better maintained vessel which incurs lower repair costs than A, but will still needs some structural replacement during it's lifetime. Curve C, which represents the heavily built lightly stiffened ship, can corrode throughout it's entire life without reaching a minimum scantling

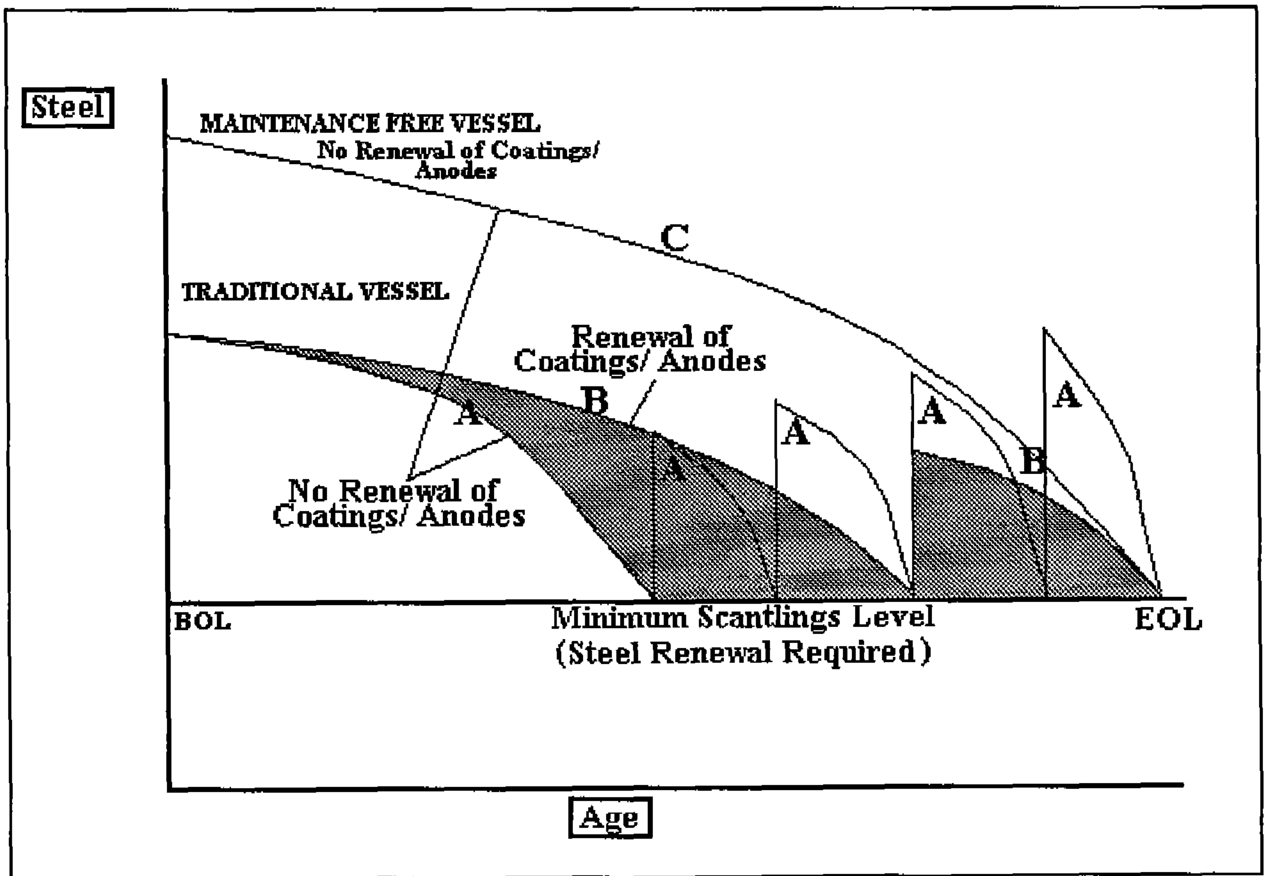


Figure 1 Comparison of Traditional Minimum Scantlings Vessel with "Maintenance-Free" Design.

limit.

Both the initial cost and lifetime maintenance costs and lifetime maintenance costs of the vessel are related to the margin between the ship's as-built and minimum scantlings. This suggests that higher initial steel expenditures may result in a cheaper ship in the long run. In practice the ideal ship would fall somewhere between the three alternatives presented in Figure 1. The decision is dependent upon a number of economic factors that the owner must weigh.

II.2.0 Design for Maintenance and Repair

The primary motivation for the efficient planning and execution of maintenance in a commercial setting is to minimize the net long term cost to the operator. As seen in Figure 1, curve B, poor maintenance practices, (coatings, cathodic protection renewal, and repair quality) could result in the need for repeated and expensive steel renewals. The design of details and sub assemblies can have a significant effect on the minimizing of these costs by ensuring that attempts are made during the initial, (or with respect to the intent of this report, the remedial), design stages to observe the following guidelines;

- Care must be taken in the selection of materials with mechanical properties which are suitable for the types and magnitudes of stresses expected.
- Welding methods for specific locations must be clearly specified, [Chapter II].
- Designers must consider a structure's damage tolerance and long term durability.
- Care must be taken to ensure corrosion resistance, avoid water traps, provide drainage paths, and minimize hidden surfaces, (difficult to coat and inspect), provide for ease of access to, and mounting points for cathodic protection [Chapter VI].
- Design for constructability; inspectability [Chapter IX], (Can NDT equipment reach the critical welds?), and repairs, (If a failure does occur, how will the detail be removed? If it cannot be removed has extra care been taken in it's design?), consider the use of mechanical fastening techniques, [Chapter III] in critical hard to reach areas to minimize welding and in place inspection problems.

The "design for durability" requirement noted above, has definite bearing on the maintenance of existing vessels. When a detail fails, a determination must be made as to whether the failure was a result of bad design or, as is more often the case, poor construction. If the cause was poor construction, the detail is merely removed and replaced, although with a higher level of scrutiny. If the cause was poor design, then a revised design must be developed having a higher level of robustness than that of the previous failed detail. A direct analogy can be drawn to curve B, Figure 1; if a detail is well repaired and re-protected, (coated), it will degrade slowly with the rest of the structure as does the repair in Figure 1, curve B. However, if a repair is poorly planned, the detail will most likely fail again, necessitating the repetition of the repair process. In some cases, repairs are made which not only have the original faulty characteristics, but new ones introduced by an even poorer quality repair process which can lead to even more serious consequences [2]. This process is

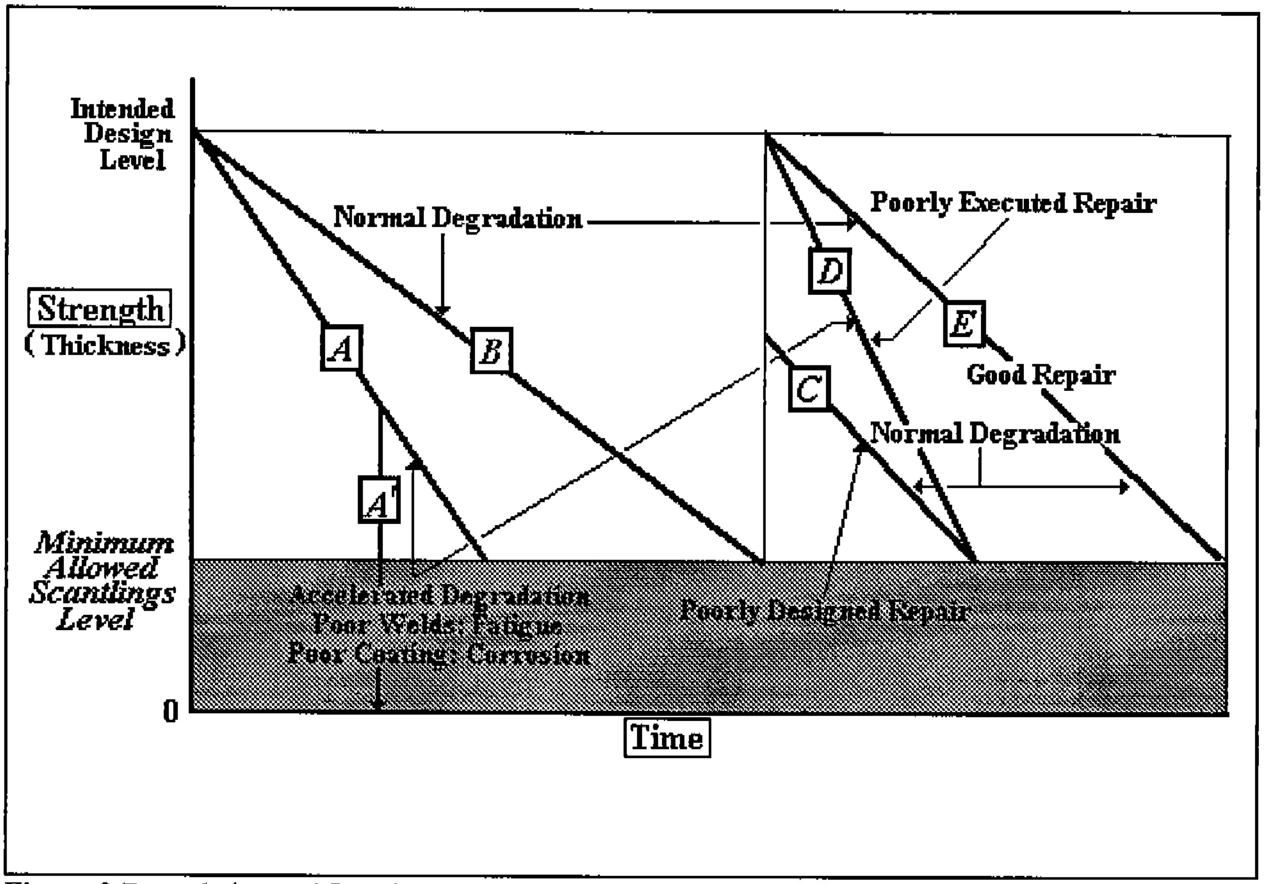


Figure 2 Degradation and Repair Curves

illustrated in Figure 2, where through normal wear and tear, the structure degrades until some repair is necessary, (curve B). If the initial quality of construction is poor, the structure degrades at a higher rate as shown by curve A. This condition necessitates earlier than expected repairs, however if the quality is very poor, or unexpected high loadings are encountered,the detail may fail completely as shown by curve A'. If the complete failure (fracture) occurs, A' shows the strength effectively going to zero, with the load picked up by parallel members, possibly overloading them also . In either case, insufficient design work, faulty construction and lax inspection can all lead to early repair costs. Once repair is needed, a properly designed and executed repair should bring the strength back up to it's intended design level, (curve E), with a subsequent normal rate of degradation. Curve C indicates a poorly designed repair, which will fail early regardless of the quality of the installation. Conversely curve D indicates a well designed, poorly executed repair which will also degrade rapidly as in the case of curve A.

II.3.0 Probability Based Design Methodology

Historically, structures have been designed to withstand the product of a specified set of loading conditions with a factor of safety. Historically, the magnitude of the factor of safety has been subjectively determined. It has been based on the accumulation of experience with similar structures. The goal of a probability based design is the clear definition of the minimum margin required between the structure's maximum expected loading and it's strength, given failure consequences and uncertainties. The procedure involved in the probabilistic approach accepts the fact that there is no absolute assurance of safety for any structure. There is an expected level of structural performance, or likelihood of survival, which is defined by subjecting the structure to a probabilistic set of loads with performance described in terms of probability. The advantage of using probability based design methods is that a large data bank of previous designs is not required, only a combination of distributions for strength and loadings are needed to define a probability of failure. This approach is particularly advantageous when the design of a new type of structure is being contemplated given that no historical data is available from which to extrapolate the new design.

The calculated required margin is ideally a weighted balance between overbuilding to withstand uncertain loads in an uncertain structure, and a cost based consequence of failure factor. The classical methodology used in probability based design is quite elegant in it's elementary form. However the rational quantification of variables needed to complete the process can be quite difficult. As a result, this quantification of variables is one of the areas where a majority of current research is presently being concentrated [3]. The challenges facing the designer are the definition of failure, an acceptable probability of failure, the estimation of uncertainties and the selection of the applicable distribution models to use in the calculations.

II.3.1 Economics Based Approach

This approach enables the designer to optimize the combination of initial capacity, durability, and inspection/maintenance/repair program, in terms of the total life cycle cost utility of the structure. This utility being defined as the minimum possible expected net cost over the lifetime of the structure. The total cost is defined as shown in Eq (1),

$$C_t = C_o + C_I + C_R + C_M \tag{1}$$

where; C_o=Initial Construction Cost
C_F=Failure Cost
C_I=Inspection Cost
C_M=Structural Maintenance costs
C_R=Structural Repair costs

Assuming continuous discounting, each of the C_i's can be expressed as shown in Eq (2);

$$C_X = \sum_{t=0}^{Life} C_x \, e^{-r\,T_x} \tag{2}$$

Where;
C_X=Cost type
C_x=Specific costs at $t=T_x$
r =Assumed average discount rate
T_x=Time at which expense is incurred

II.3.1.a Uncertainties

Of course not being able to see into the future, all of the above quantities are uncertain. Which means that we must assign a best guess probability to each, expressed in terms of a probability

$$E[C] = \sum_{t=0}^{Life} C_X \, P_X \tag{3}$$

P and an expected value **E**, as shown in Eq (3). With the likelihoods, (Probabilities **P**'s), associated with each of the cost variables estimated on the basis of analysis, data or experience.

II.3.1.b Probability of Failure

The probability of failure of the global system, P_F, can be defined as the probability that the "supply" of structural strength is exceeded by a "demand" of a set of loadings. If the ultimate capacity of the hull structure is denoted by R_U, and the ultimate load S_M, the above statement can be expressed as in Eq (4). These two quantities are each assigned a probability distribution, the strength being based on arithmetical combination of the constituent strength distributions, and the loading being based

$$P_F = P(R_U \le S_M) \tag{4}$$

on environmental condition forecasting. A median factor of safety is defined as the quotient of the median ultimate strength and the median ultimate loading, which when divided by the total uncertainty, yields a "Safety index", ß, as shown in Eq (5), (for Normally distributed R and S). Where ß is defined as a *proxy* or normalized measure of the probability of failure. When ß increases, the likelihood of failure decreases. The probability of failure can be approximately related to ß as shown in Eq (6);

$$\beta = \frac{R_{U_{50}} - S_{M_{50}}}{\sqrt{\sigma^2_{R_U} + \sigma^2_{S_M}}} \tag{5}$$

$$P_F \approx 10^{-\beta} \tag{6}$$

A quantitative measure of the "margin", can be expressed as the quotient of the ultimate capacity and the design loading, or the 'Reserve Strength Ratio' or RSR as shown in Eq (7).

$$RSR = \frac{R_U}{S_d} \tag{7}$$

The RSR is used to express the overall robustness of the design, which can be directly translated into the structure's ability to withstand loading without reaching a minimum scantlings limit.

An additional factor which should be considered in the design process is the level of 'residual' or post ductile failure strength that the structure possesses. The consideration of this factor can, in some instances, enable the designer to go with a lighter, (*read*: cheaper), structure that utilizes it's non-linear plastic deformation to survive highly unlikely loading conditions on a single survival incident basis[1].

---

[1] Once again to be evaluated on a probabilistic cost analysis basis.

III.0.0 Steel Structure Assembly: Welding

Almost all modern steel structures are assembled using high temperature electrical arc fusion welding techniques. The success of welding as a technique for the assemblage of steel components has come quite far in the fifty years that it has been used for ship building. The types and methods of welding now used are numerous varying from standard arc welding to sophisticated inert gas methods.

The most obvious advantage of joining two components with a weld is that the continuous joint effectively unifies two components into a single member. However there are many mechanisms which if allowed to occur, can lead to premature failure of the subassembly. The careful training of welders, design for access by welders and perhaps most importantly, the inspection of welds, are all critical in ensuring that a structure, once constructed, will perform to expectation.

Approximately 20 percent of the SSC reports address the subject of welding, indicating the relative importance of this subject with respect to the integrity of ship structures.

In maintaining an existing vessel, there will be subassemblies and details that fail and need repair or replacement. The vast majority of these failures will involve faulty welds [4]. It is thus necessary to investigate welding problems and solutions in a survey of ship maintenance.

III.1.0 Weld Techniques

III.1.1 Fillet Welding

There are fully 60 tons of fillet weld metal in a 50,000 ton ship, all of which is highly fatigue sensitive given it's location at points of stress redirection and between homogeneous plating.

The resistance to fatigue failure of fillet welds can be expressed as in Eq (8) [5].

$$R=R_{ULT}(1-e^{-\mu\Delta})^{\lambda}$$
where; **(8)**
μ *=Empirical regression coefficient*
Δ *=Deformation*

From fatigue testing data, (pulsating tension testing), the regression coefficients shown in Eq(8) were reduced through:

Peening by 75%
Grinding by 50%

Which is to say that the resistance to fatigue is increased by utilizing the above methods to reduce residual stresses and improve the weld profile respectively. Some welds made under ideal conditions may be good welds in every sense but may be somewhat under size. Many inspectors will reject the weld requiring that additional passes be made in order to exceed the minimum size, this is probably a waste of time and resources, however the acceptance of slightly undersize welds places a large burden of responsibility on the inspectors knowledge of which welds are critical in the ship's structure, and since classification society rules can vary in their requirements for minimum weld size by up to 100%, the minimum acceptable weld size has yet to be agreed upon. Since many fatigue failures are initiated from weld toes, this is an area of concern which merits further investigation. A fully plastic yield failure criterion which requires a fully plastic zone along the weld legs as the failure criterion would allow a less restrictive minimum weld size requirement.

The goal in the development of strength criteria for fillet welds is that of developing weld material strength that is as near as possible to that of the attached members. This goal is aimed at minimizing the existence of stress concentrating, high stiffness regions. In order to analyze the strength of fillet welds, ideally the solution of different equations for each of six failure modes should be performed, here two modes will be examined which will show the basic methodology used.

III.1.1.a Longitudinal shear

In order to develop the ideal strength of the attached material through the weld throat, the dimension of the throat should conform with the relation shown in Eq (9), with dimensions as sketched in Figure 3. For loading along planes AA or BB, the proportions should conform to the relations as shown in Eq (9). As long as the conditions

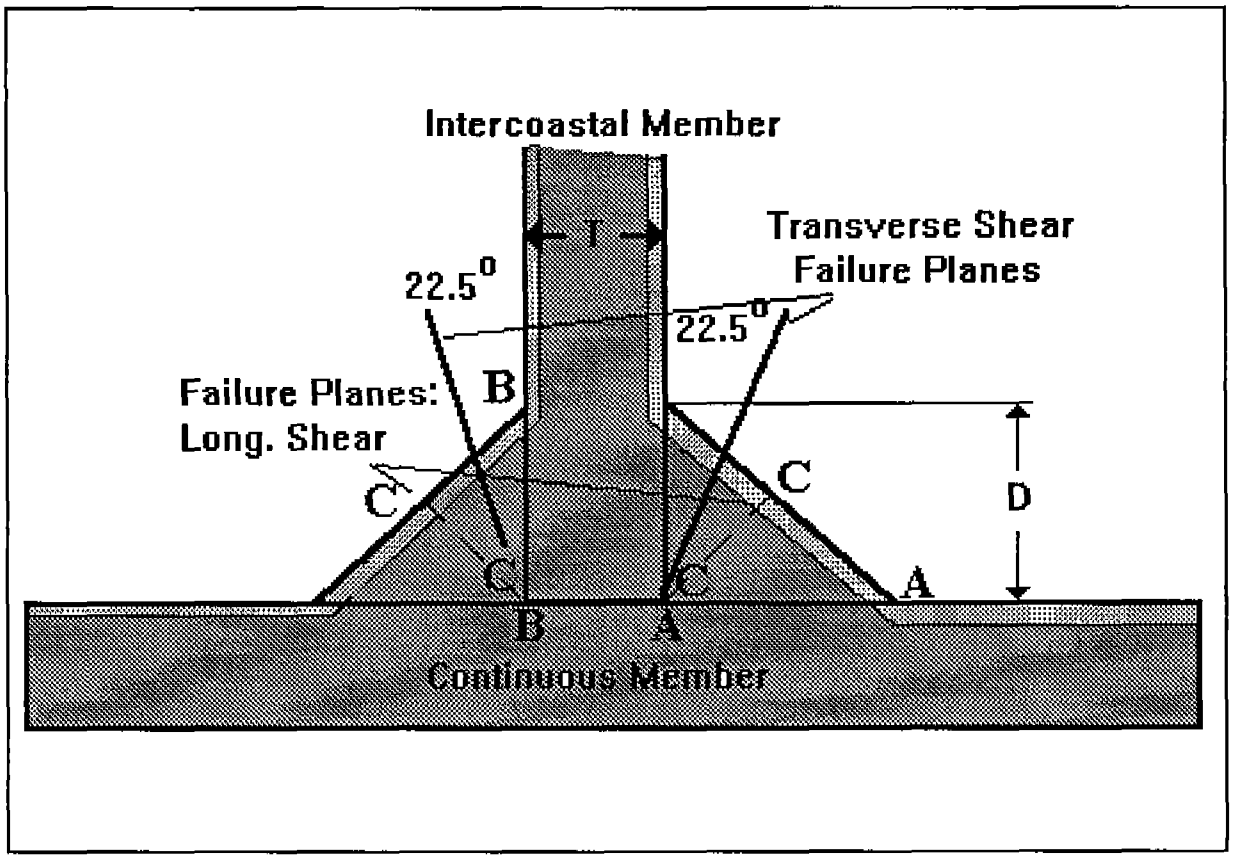


Figure 3 Fillet weld failure planes

$$2 \times D \times Sin45° \times \tau_{wl} = T \times \tau_{ul}$$

$$\therefore D/t = 0.707 \times \frac{\tau_{ul}}{\tau_{wl}} \qquad (9)$$

Where;
τ_{wl}=*Weld material ultimate longitudinal shear stress.*
τ_{ul}=*Ultimate shear stress of intercostal member.*
D=Fillet weld size.
T=Base plate thickness.

indicated in Equations (9) and (10) are satisfied, the fillet weld should develop the full shear strength of the intercostal member.

$$2 \; x \; D \; 1.414 \; x \; \tau_{uc} = T \; x \; \tau_{ui}$$
$$\therefore \; D/T = 0.354 \; \frac{\tau_{ui}}{\tau_{uc}} \tag{10}$$

III.1.1.b. Transverse Shear

Although the failure planes in transverse shear most often occur as shown in Figure 3, (angularly midway between the longitudinal failure planes and the intercostal, or 22.5° from the intercostal), for simplicity sake the failure planes are conservatively taken to be the 45° planes, (conservative since there is less shear area for the 45° planes than for the 22.5° planes, 0.71**D** vs. 0.92**D** respectively). Thus the criterium is identical to those stated for longitudinal shear with the exception of the substitution of σ_{ui}, (the ultimate tensile stress of the intercostal),for τ_{ui}, (the ultimate shear stress of the intercostal). τ_{ult} for most weld deposition metals is 2/3 to 3/4 of the ultimate tensile strength of the base material, thus conservatively the ultimate shear strength can be expressed as shown in Eq (11);

$$\tau_{ui} = 0.75 * \sigma_{ui}$$
$$\tau_{uc} = 0.75 * \sigma_{uc} \tag{11}$$

Due to the greater area of the transverse failure planes it can be shown that the transverse shear strength of the fillet weld is between 1.44 and 1.56 times greater than the longitudinal strength. (This fact is of interest to inspectors in that if loading patterns are known, the most likely points for fillet weld failure can be quite accurately predicted, e.g. longitudinal failures in bottom longitudinal frames is more likely than tripping if girth and primary loads are similar). Thus it is assumed that τ_{wt}=1.44 τ_{wl}, where τ_{wl} is tabulated in welding handbooks as a function of the weld rod electrode series. Comparing this to the criterium set forth by the various classification societies reveals hidden conservatism by introducing bias in the direction of over-welded and consequently expensive structures [5].

Weld size reductions are not achieved by using higher strength weld rod, since doing this merely shifts the failure plane closer to the base metal. Using the afore mentioned relations, a narrow band of minimum weld sizes ranging from .607 to .698 times the intercostal member thickness is found. The more conservative figure of 0.698 is used to determine the acceptable joint efficiency. A final expression for minimum weld size must include a corrosion margin, joint efficiency and intercostal size as expressed in Eq (12).

$$D_{corr}=0.698*\eta_{corr}*(T-2*C)+1.414*C \tag{12}$$

Where;

D_{corr} = *Corroded weld size.*

η_{corr} = *Corroded joint efficiency*

C = *Corrosion allowance*

III.I.2 Joint Efficiency

As indicated in the previous discussion, an expression indicating joint efficiency must be included in any expression specifying minimum joint size. The joint efficiency is a function of joint geometry, loading mechanism and connection method, (weld method and quality), which for a properly connected joint can range from of a low of approximately 50% to unity. In a design setting, efficiencies for standardized joint geometries are determined from tables, which take into account the foregoing set of variables pertinent to the design situation.

III.I.2.a Intermittent Welding

Intermittent welds, when properly executed, can be just as effective as continuous welds with the added benefit of being more economically attractive [6]. In regions of the structure where lightweight material is specified, intermittent welds are used in order to avoid excessively strong joints. Little guidance is given in this area due to the obvious liability problems. Classification societies usually require that specific analysis must be shown for regions where intermittent welding is to be allowed.

III.I.3 Corrosion Allowances for Corrosion Control Systems

In regions of the vessel where approved corrosion control methods are specified, most classification societies allow the reduction of scantlings by a corrosion allowance [see page 90]. For welds which are used in these areas, no reduction is allowed, apart from reductions due to the material thickness of connected members. This dilemma could be eliminated by simply ignoring or reducing the corrosion factor C by an agreed upon factor.

Many shipowners will, in order to build a conservative ship, use a corrosion control system but not use the control system scantling reduction allowance. This is done in the belief that the extra money spent on the material is well spent in avoiding possible future repairs, [See Figure 2], that the material cost is a small fraction of total cost, (with respect to labor cost), and that an over built vessel will be more able to meet schedules in a wider variety of conditions.

The cost of welding for a typical vessel is quite high given the labor intensive nature of the job. Differences in specific welding cost, (cost per linear unit of bead), although quite small can result in large cost differentials for the construction of an entire ship. Therefore any means available to the designer for reducing the amount of welding necessary should be fully taken advantage of, this being especially true given the intense competition in the ship building industry.

III.I.4 Effect of Defects on Structural Integrity

In any complex system deviations in material and assembly will be present, and as a result a construction plan will contain tolerances in order to allow for some errors in assembly and manufacture. The welding process is no different, with tolerances specified in order to allow the welder some room for error in order for him to expeditiously proceed with the assigned work [7].

In order for the design engineer to specify the level of non-conformity, he must understand the effect of the inclusion of defects on the structural integrity of the structure.

III.1.4.a Fatigue Effects

The ultimate strength of a structure is well understood and can be predicted using modern non-linear plastic numerical methods. Temporal failures occurring at significantly lower stress levels are less well understood and are the main reason for specifying maximum levels for defects in weldments. The migration of cracks in structures almost invariably originate from defects introduced at the time of it's construction. The study of fracture mechanics aims to understand the mechanisms involved in the spread of damage, enabling the designer to specify a maximum defect level which can exist with a specified maximum probability of failure at a maximum stress level over a the lifetime of the

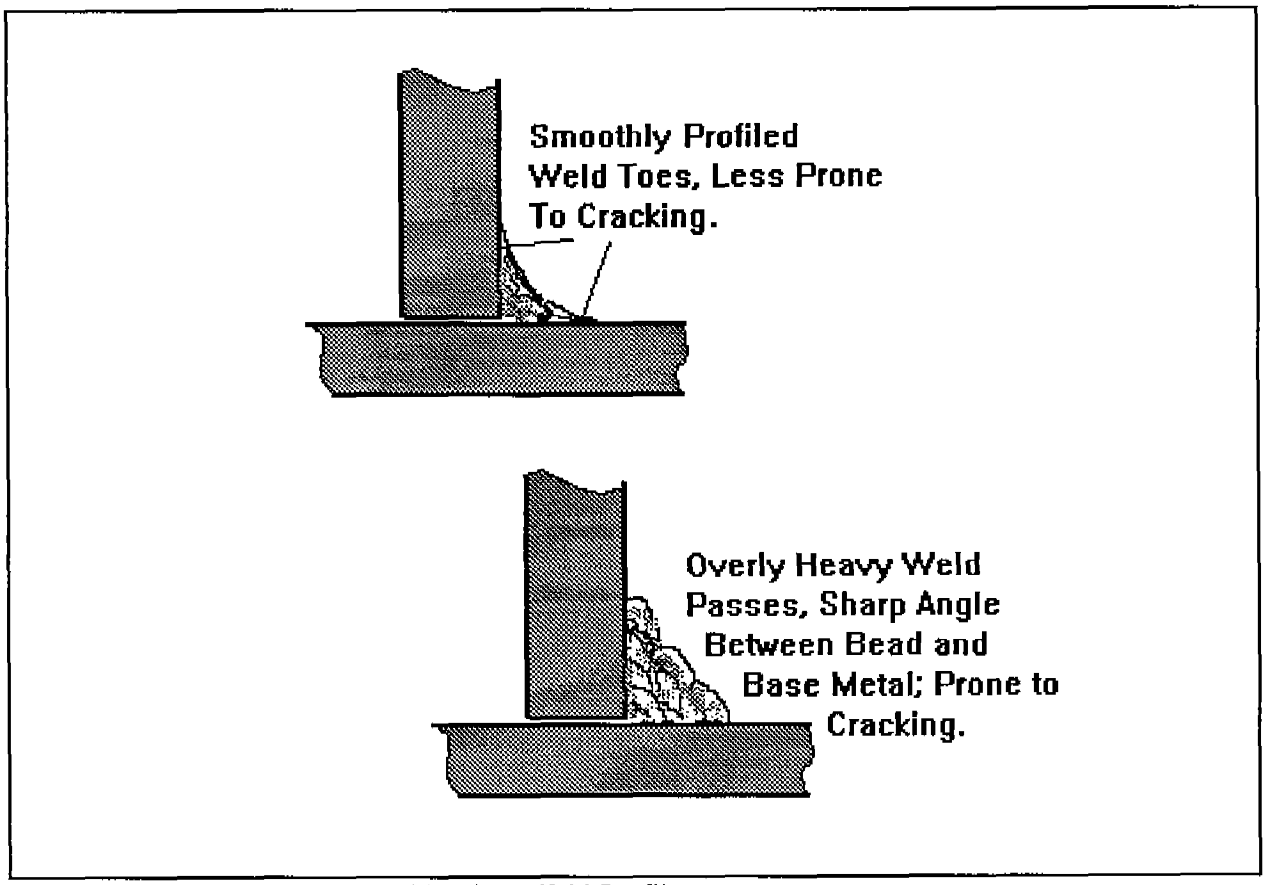


Figure 4 Favorable vs. Unfavorable Fillet Weld Profiles

structure.

As shown in Figure 4, the most critical failure initiation site for a weld is the weld toe, this point represents an abrupt change in the geometry of the structure and is a prime stress concentration point. For this reason, smaller weld beads can actually reduce stress concentrations reducing the probability of the initiation of a fatigue crack. Porosity defects in weldments tend to have a lesser criticality in terms of initiating fatigue cracking, as they tend to be approximately spherical which means no sharp discontinuities exist for crack initiation. The comparison of the stress concentration factors, K_t's, also reinforces this statement[2].

Residual stresses in welds significantly decrease their endurance. The stresses tend to be tensile on the surface and compressive at around mid thickness in the weld, this is the reason that peening [*See page 14*] and post weld heat treatment of the weld surface can increase the expected fatigue life of the weld[3].

The interaction of loads in welds tend to retard crack growth, which is usually not accounted for in linear elastic fracture mechanics which have been shown to yield overly conservative fatigue endurance limits. These superimposed loads are most prevalent in structures exposed to random loading such as those experienced by marine structures. Thus the actual crack growth rate is lower than that predicted by the linear summation of individual loading regimes at differing frequencies. The modeling of fatigue behavior is discussed in chapter V.

---

[2] The stress concentration for a pore in an infinite body subjected to axial tension is 2.05. The stress concentration factor for a toe of a butt weld is 3.06 for a 1/2 inch plate with a weld toe radius of .02 inch, a height of 0.17 inch and a reinforcement width of 0.29 inch.

[3] Peening the weld surface counteracts the tensile stress at the surface relieving residual stresses. The increase of compressive residual stresses is acceptable since it can be shown that compressive residual stress in welds tends to increase the expected endurance of the weld.

III.2.0 Delayed Cracking

Delayed cracking of joints in welded structures is a significant problem with regard to structural integrity. These cracks occur in the Heat Affected Zones, (HAZ's), of the welds in low alloy and carbon steels[4], and occasionally in the weld material itself. As the name implies, this type of cracking develops over a period of time, (several hours to several days [8]), after the weld has been completed. Often the crack will not open to the surface meaning that they are hard to detect.

Delayed cracking is hard to detect and can occur in initially good looking passable welds. Although delayed cracking is relatively easy to prevent, compliance with the requirements necessary in it's prevention can be difficult to assure because of the delayed nature of crack formation[5] [8]

III.2.1 Description of Delayed Cracking

Delayed cracks form on a microscale near a weld joint when the necessary conditions are present. After a sequence of certain events take place, the crack grows until it is large enough to be seen either visually or by other means of Non Destructive Testing, (NDT). If detected, the delayed cracked weld must be removed and re-welded in order to prevent possible catastrophic failure in service.

Delayed cracks appear in several locations around weld joints as shown in Figure 5, and summarized in Table I. The root and toe cracks are considered the most serious delayed crack types since they occur nearer to the surface where bending stresses imposed on a joint are the most severe. Toe and root cracks are also frequently associated with other types of defects such as undercutting or

---

[4] Low strength steels such as ABS-A, ABS-B and ABS-C are not susceptible to delayed cracking, thus delayed cracking precautions do not apply. However the majority of a ships structure is constructed of high strength steels which are quite susceptible.

[5] Welders may not understand the consequences of delayed cracking, which combined with the initially acceptable appearance of the weld, may result in their ignoring the requirements necessary to minimize the chances of delayed crack initiation.

incomplete penetration. These surface defects increase the stress concentration at the vicinity of the crack even further increasing the chance of joint failure.

Another consequence of delayed cracking is the effect it has on production scheduling and fabrication costs. The usual procedure for inspecting the welds for delayed cracking, is to delay inspection in order to allow time for the cracks to grow. USCG regulations [8] call for a delay of *seven* days prior to inspecting welds, meaning that if delayed cracking is found, between removal of the weld, re welding, waiting for seven more days and then reinspecting, total production time and costs are considerably affected.

Table I Summary of Delayed Crack Locations and Detection

- Transverse weld metal cracks:
  Less frequently encountered, weld metals usually contain less carbon and are thus less apt to form a microstructure susceptible to cracking upon cooling.

- Underbead cracks:
  Longitudinally positioned, occurring parallel to the fusion line, entirely in HAZ, does not propagate to the surface, must be detected by Ultrasonic methods.

- Root Cracks:
  Initiate at weld root and propagate into the HAZ or weld metal, if occurring in fillet welds, cannot be detected by any practical means, in butt welds detectable by Ultrasonic testing.

- Toe cracks:
  Occur in the edge of the weld and are open to the surface, magnetic particle or dye penetrant detectable, very 'tight' cracks not detectable by visual inspection.

III.2.2 Conditions for Occurrence of Delayed Cracking

Three conditions must be present for delayed cracking to occur in a welded joint:

- Atomic hydrogen, (H_1 not H_2, molecular hydrogen), must be present.
- The heat affected zone and/or weld metal must have a hardened microstructure.
- The weld joint must have significant internal stresses.

All of these conditions must be present for delayed cracking to occur. The formation or absence of

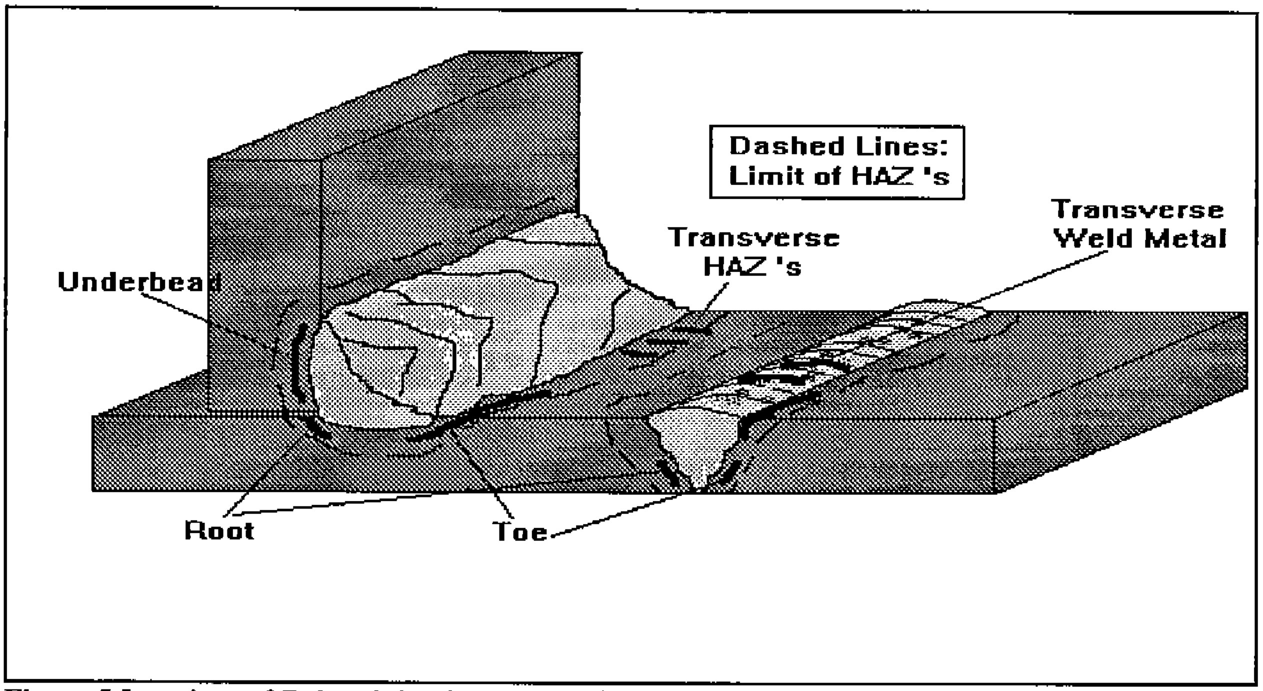


Figure 5 Locations of Delayed Cracks Around Fillet and Butt Welds

the hardened microstructure, (mainly a function of the material properties, and to a lesser extent the cooldown rate), will determine whether or not delayed cracking *will* occur. The *rate* at which delayed cracks develop is a function of the steel's susceptibility to delayed cracking, (micro-structure), the amount of hydrogen present and the level of stress in the joint.

The delayed cracking susceptibility in steels is a direct function of the steel's chemical composition, which determines the hardening characteristics when the material cools after welding. The main alloying element that determines the steels's susceptibility is it's carbon content. In high carbon steels, the susceptibility to delayed cracking can be minimized through the control of welding heat input, cooling rate and other procedural factors.

Atomic hydrogen is formed in the highly ionizing gas envelope that surrounds the welding arc. The arc breaks down any hydrogen bearing compounds present releasing atomic hydrogen ${}_1H^1$ that migrates into the weld metal. Typical sources of hydrogen include:

○Damp electrode coverings

- Moisture on joint surfaces
- Damp electrodes
- Organic covered electrodes
- Organic material present on the base metal

The elimination of moisture, the use of inert gas shielded welding techniques or submerged arc welding, can significantly reduce the risk of delayed cracking.

Stress conditions are due to unequal shrinkage in the weld and HAZ as it cools after welding. The magnitude of stress is a function of the joint design, plate thickness, and welding procedure. These stresses can be controlled to a point through control of welding procedures that reduce or more evenly distribute the amount of shrinkage.

III.2.3 Mechanism of Delayed Cracking

Although the exact mechanism of delayed cracking is not known, several theories have been proposed to explain what is actually happening. Over time, various theories explaining the delayed cracking phenomenon have been accepted and subsequently rejected. The currently accepted theory is the triaxial stress theory. The triaxial stress theory basically states that hydrogen will diffuse through steel to regions of high triaxial stresses [8]. Such regions are always present on a microscale in a martensitic[6] microstructure [9]. If a critical stress level exists and a critical amount of hydrogen is present in this area, a microcrack will initiate. As the crack appears, the region ahead of the crack is subjected to increased triaxial stresses and further diffusion of hydrogen into this region occurs. The concentration of hydrogen again builds up until it reaches a critical level for the crack to propagates a little bit further. This process continues until the crack reaches a macro scale and it is then called a delayed crack. The arrest of the crack, (as with any fracture), occurs when it reaches regions of

[6] When steel is cooled from a molten state, it passes through a eutectoid state, meaning that the alloying elements solidify nearly together. If a steel is cooled too rapidly, this will not occur, rather a structure called *martensite* will form rather than steel. This substance is very hard structure with little ductility, (a necessary property in steels).

differing material properties or lower stresses, (beyond the HAZ into the base metal in this case).

From the standpoint of prevention, the theory that is in fashion has no bearing on the procedural steps to be taken in the prevention of delayed cracking. (All of the theories agreeing on the same initiation conditions necessary for delayed cracking to occur). Thus to prevent this phenomenon, at least one of the three [page 22] conditions necessary must be removed from the weld area.

III.2.3 Prevention

III.2.3.a Microstructure

In Figure 6 below, the three designated zones indicate the type of structural changes that occur in steel as it is heated or cooled. In addition, three cooling curves labeled I, II and III are shown which indicate various *rates* of cooling and the micro-structural changes which occur. The fastest cooling rate is shown by curve I. As the steel cools at this rate, no structural changes occur until a temperature of about 500°F is reached, whereupon the austenite changes completely into hard martensite, (the worst case with respect to delayed cracking). This cooling rate is representative of a sudden water quench of the weld joint. The slowest cooling rate curve, III, passes through the austenite to ferrite region so that all the austenite is transformed into ferrite. This curve corresponds to the cooling rate of a pre-heated HAZ, (which is why pre-heating of the weld joint is so favorable). Curve II corresponds to the approximate cooldown of a non pre-heated HAZ, where in cooling the austenite is converted to bainite, ferrite and some martensite. This diagram illustrates how the use of pre-heating a weld joint can prevent the formation of martensite, the structure necessary for the formation of delayed cracking.

The use of higher carbon steels, (which is quite common in shipbuilding applications), will tend to shift the upper transition curves to the right, meaning that even more pre-heating and slower cooldowns are necessary to avoid the formation of martensite.

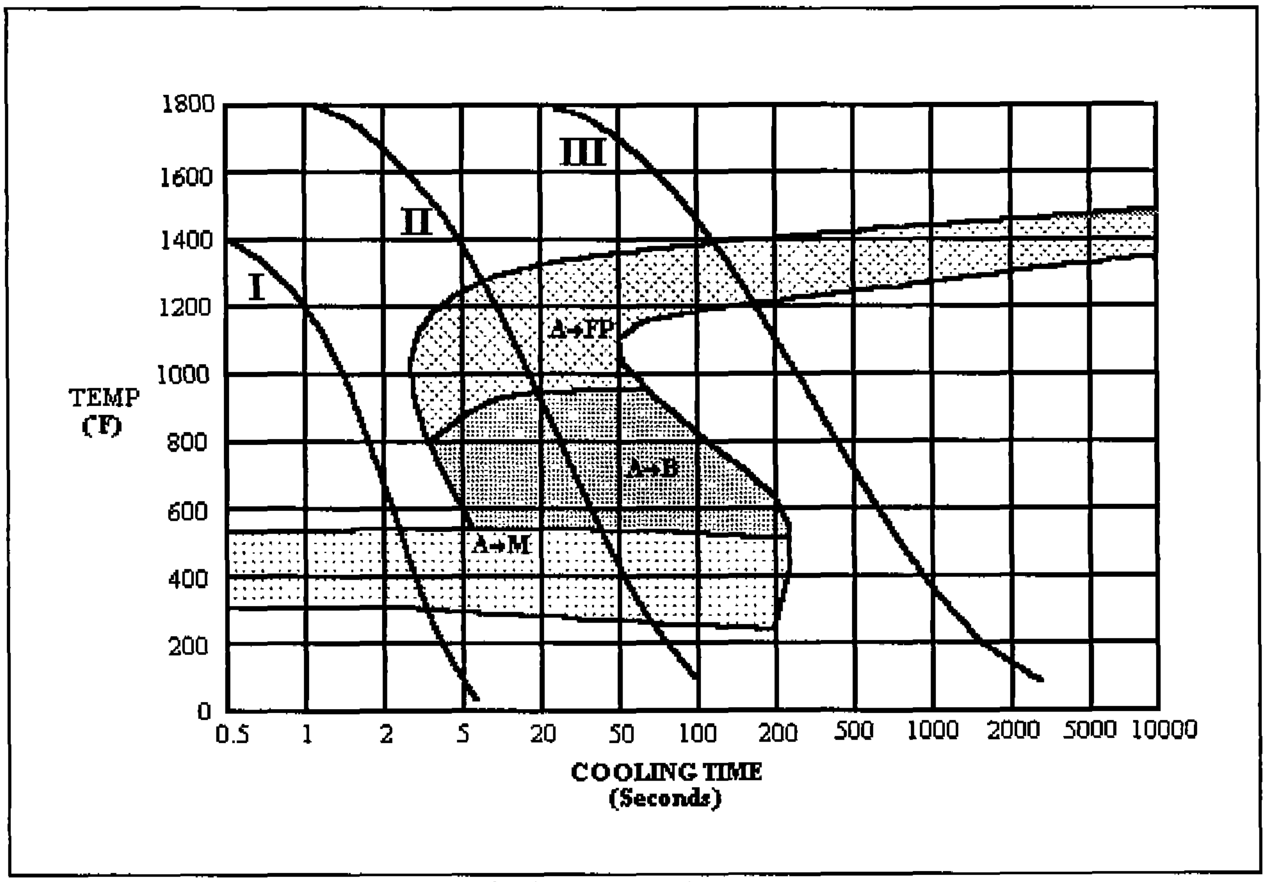


Figure 6 Steel Crystalline Transformation/ Cooldown Curves

III.2.3.b Hydrogen

The minimization of the possibility of atomic hydrogen introduction of into the weld region is perhaps the best understood, yet difficult to ensure step in the prevention of delayed cracking. The preheating of the weld, in addition to the metallurgical benefits described in the previous paragraph, will tend to dry the joint and burn off any foreign organic material in the vicinity. The use of electrodes with low hydrogen contents is the next step in minimizing the chance of hydrogen introduction. Electrodes which have the numbers 15, 16, 18, or 28 in their designation, (e.g. E80<u>16</u> or E110<u>18</u>), are low hydrogen electrodes. However, steps must be taken to prevent their contamination due to their tendency to absorb moisture from the air:

○New electrodes must be baked to drive off any moisture, (per Mfg. directions).

○Baked electrodes must be stored in an oven in order to prevent subsequent moisture pick-up, (250°-300°F).
○Electrodes must be handled with care to avoid moisture or organic material contamination.
○A supply of heated electrodes should be kept as near to the site as possible.
○If a heated supply of electrodes is not available, electrodes should be used within the following times:

E-70XX	4 hours
E-80XX	2 hours
E-90XX	1 hour
E-110XX	½ hour

○Any electrodes exposed longer than the above should be rebaked as new electrodes.
○The above rebake should only be done ONCE, thus rebaked electrodes should be used first.
○Any electrodes that become visibly contaminated should be discarded.

III.2.3.c Stresses

The stresses present in a welded joint consist of 'local' stresses and 'external' stresses. The local stresses are caused by the welding operation itself. The base plate expands and contracts as the heating is applied and removed. The weld metal shrinks as it cools after solidifying. Multiple passes cause repeated heating and cooling cycles. Welding variations, (non-uniformities), mean that this thermal cycling will not be uniform along the joint. All of these act together to create internal stresses in the joint after the weld is completed. External sources are not related to the welding process but will add to the internal local stresses. External sources arise due to forcing parts into alignment, the self weight of the part(s) being welded, shrinkage from other welds, lifting and moving the welded part, etc.

This Page Intentionally Left Blank

IV.0.0 Structural Assembly: Fastenings

The connection of many sub-assemblies, (especially those prone to damage, corrosion or rapid wear), in marine structures is accomplished using mechanical fastening techniques. As shown in Table II, the use of mechanical fasteners in certain situations has several important advantages over the blanket use of welding. Which is to say that the use of mechanically fastened details should be considered prior to assuming that all subassemblies should be affixed by welding. This being especially true in a repair environment, where in certain situations, the welds themselves may be at the root of the problem [30]. The redesign of problem details for assembly using mechanical fastenings may solve problems that cause these details to fail in the first place, many of which are cited in Table II below. For nonstructural joints, not all of the points cited in Table III are of concern.

Table II Mechanical Fastening Advantages

- Ease of installation, most types requiring only simple hand tools and basic skill levels.
- Lack of material problems in the immediate vicinity of Heat Affected Zones, (HAZ's).
- Crack arresting properties inherent to discontinuous joints.
- Ease of inspection and repair.
- Possible isolation of sub-structures from loads, e.g. deckhouses isolated from hull loads using intermediate flexible jointing methods.
- Ease of removal for access, inspection, repair or replacement.
- Increased accuracy of detailed analysis due to problems with the modeling of stresses in welds, (See Page 58).
- Ease of emergency re-enforcement of partially failed details.

However for structural hull plating to stiffener or bulkhead to framing joints, all the considerations listed in Table III must be addressed when a mechanical fastening system has been chosen or suggested, (most of the concerns listed in Table III are of concern for any joint with the exception of tooling and hole tolerances) . These points have been included in various aircraft design manuals [10], included herein since as ship structure strength to weight ratios continue to increase, the seemingly diverse technologies are actually beginning to converge in many ways. The main structural

Table III Fastener Selection Considerations

A) Joint Type
  1) Single lap
  2) Double lap
  3) Butt
  4) Fluid Tight
  5) High Load Transfer
B) Loading
  1) Direction
  2) Magnitude
  3) Frequency
C) Environment
  1) Thermal
  2) Corrosion
  3) Material Compatibility
  4) Material Properties
D) Structural Life Requirements
  1) Stress Limitations
  2) Fatigue Limits
  3) SCF's
E) Maintainability/ Repairs
  1) Tooling for Installation
  2) " " for Maintenance
  3) Accessibility after Assembly
F) Required Reliability Level
G) Hole Tolerances
  1) Fastener Fit
  2) Fastener Installation
  3) Fastener Repair/ Replacement

concern in a highly cyclic loading environment is of course that of fatigue. The fatigue of airframes is one of the main areas of research in the aircraft structural design field, which is years ahead of those involved in the study of ship structures[7]. With the increasing use of high yield low ductility steels in shipbuilding, designers can draw on established technologies to solve problems inherent in newer ships. The seemingly retrogressive shift to mechanical fastenings is one of the more elegant solutions

[7] The ship structure has only quite recently began to utilize high yield materials to create highly stressed relatively light-weight structures. From it's inception, out of necessity, airframe designers were forced to create light-weight highly stressed structures. Due to the convergence of the technologies, some utilization of methods should be possible.

to the fatigue problem, with extensive research data available through studies carried out by the aircraft industry. For the purposes of the ensuing discussion the advances made in the field of airframe mechanical fastening technology will be used in the discussion of mechanical fastening of ships. Although the scale of ship and aircraft structures differ by an order of magnitude, the engineering principles involved are the same.

With regard to existing ships, it is proposed that many previously welded sub-assemblies could be fastened using mechanical methods, allowing:

- Superior Fatigue Resistance
- Pre-Fabrication
- Ease of Structural Modification
- Ease of Installation (hand tools and lifting/alignment apparatus)
- Reduction of Concerns about the Strength of Welds
- Reduction in NDT cost

IV.1.0 Mechanical Fastening Considerations

Prior to WWII nearly every ship built had been mechanically fastened in one manner or another. The advent of welding made for rapid construction but had problems with cracking and durability. When the aircraft industry began to fabricate aircraft from metal it also for a time utilized welding of skins to stiffeners, however with ever increasing standards of reliability it was determined that use of rivets or screws resulted in a structure of superior durability and fracture resistance.

One of the problems inherent in the use of mechanical fasteners is the proliferation of the types of fasteners available. This problem has been overcome in many industries by specifying that only select sizes, thread types, material grades, and fastener configurations be used in design work. This eliminates the problem of vast selections of fastener types that contractors must purchase and/or have on had for assembly, repairs or replacement. This also increases the likelihood that field repairs can be accomplished using a smaller inventory of spares carried on board a vessel. The choice also must be made regarding the standard to be used in fastener selection, i.e. MilSpec, SAE, DIN, English, Metric, NASA... standards. The standard chosen is invariably a function of the vessel's trade route e.g. the standard most commonly used in candidate repair/overhaul yards along the route.

IV.2.0 Fastener Types and Applications

Fatigue rated mechanical fasteners are available in a seemingly infinite number of configurations for installation by unskilled to highly skilled personnel using hand tools or highly sophisticated machinery.

Installation conditions include:

- Interference Fits
- Net Fits
- Clearance Fits
- Taper Hole/Shank Fits

With holes being formed by:

- Precision Drilling
- Broaching

Often holes located in highly cycled environments are cold worked, [10], to increase fatigue resistance.

Fasteners are installed by;

- Squeeze Operations
- Pull or Push Operation
- Slip Fitted

The fasteners are retained using;

- Torqued Nuts
- Swaged Collars
- Fastener Deformationn

The following list includes some of the more common fastener types available for or amenable to marine applications, together with possible applications in a ship structure.

IV.2.1 BUS Fasteners

The BUS Hi-Lok fasteners are two piece, high strength, torque controlled, threaded structural fasteners designed for use in naval and commercial marine applications. The system consists of a high strength bolt; a high torque clamping nut with a wrenching hex torque-off feature for torque control; and a matching light weight installation tool. The system is designed to provide hole seal-off capabilities, making it suitable for fluid boundary applications.

IV.2.2 Six Wing Fasteners

Six-Wing fasteners are available for high tensile applications. These fasteners have a protruding torque head and are available for high tensile, shear and temperature applications. The Six-Wing series is available in several alloys with tensile strengths of 160-240 KSI, [10], (which has obvious strength advantages over welded connections which are lucky to develop the strength of the *base metal*). The fastener is designed for joints requiring high clamping forces, tensile strength and fatigue resistance.

This fastener is suitable for attachment of machinery to deck mountings, and its' high torque capability allows ease of removal should machinery or fastener replacement become necessary.

IV.2.3 Blind Fasteners

These are available in flush and protruding head designs in various alloys. A use of this type of fastener in a flush head corrosion resistant alloy would be that of panel close out.

IV.2.4 Lock Bolts

Lockbolts come in a variety of configurations with flush and protruding heads, a variety of alloys, and protective finishes and are used for structural joints in tension and shear. These have been utilized in marine structures for attachment of the deckhouse to the deck via lap joints formed by the deck house and a steel deck combing.

IV.3.0 Riveting

Rivets are available in a wide variety of alloys, heat treats, coatings and head configurations. Rivets are available in fatigue and fluid tight ratings for structural applications, and can be installed in

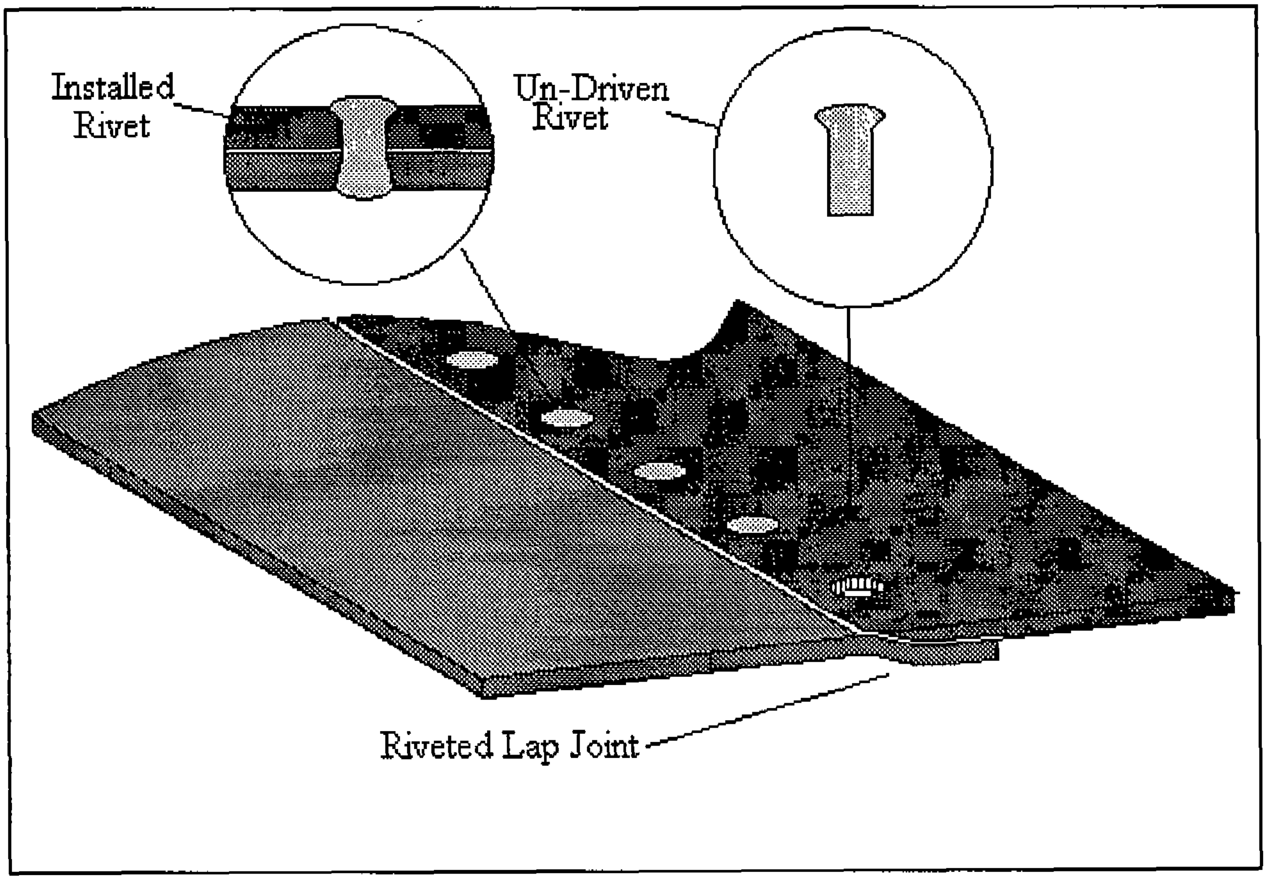


Figure 7 Riveted Lap Joint

materials varying from thin sheets to thick lap joints, (Figure 7). They do not require tight hole tolerances, are easily installed by hand driving, machine riveting, electromagnetic riveting, or by using portable squeeze type hand riveting tools. Marine applications can be easily seen in photos of pre-war merchant ships which were fastened almost exclusively by rivets. Some possible applications of riveting in modern steel vessels include;

- Splice-Butt joints in the primary structure, similar to those used in aircraft wings
- "Jumboized" modular structures could be joined using fatigue rated fasteners in pre assembled units
- Modular internal structure could be attached using portable "squeeze" type units, eliminating the need for continuous welding which tends to deform the shape of a structure.

The following articles discuss various material developments, tooling, and riveting techniques which have been proven or show promise for shipboard applications.

IV.3.1 Nitinol

Nitinol is an alloy composed of nickel, titanium, iron and cobalt. It was developed for the U.S. Navy as a riveting material with the ability to be formed into a configuration, chilled, reformed and installed, regaining it's original configuration upon warming. The use of nitinol is advantageous in that it forms a very tight fit, it loads the hole in compression resisting fatigue, and has high strength.

IV.3.2 Drilling

Preparation for rivet installation over large areas is conventionally performed using automated drilling techniques. The installation of rivets is semi-automatic in that rivet loading into the riveter can be automatic using pneumatic, hydraulic or electromagnetic power sources.

IV.3.3 Electromagnetic Riveting (EMR)

This method of riveting, developed by the aerospace industry, uses electromagnetic energy to form the rivets, [Figure 7]. The equipment is portable, relatively inexpensive, and easy to use, allowing highly repeatable quality production. EMR when used in conjunction with production type track drilling equipment, affords cost effective production capability for structural fastener installation but is capable of functioning independently. The advantages of EMR include;

- Proven performance in wing spar[8] production
- High installation rate capability
- Built in repeatability and quality control
- Interference profiles in thick materials not achievable with conventional riveting processes
- Rivet head uniformity
- Low noise operation
- Minimizes operator fatigue
- Low skill requirements
- Conventional quick change dies
- Low cost

---

[8] The wing spar being the central structural section (beam) in an aircraft wing which carries the loads produced by aerodynamic, propulsive, control surface and landing gear loads.

- Balanced forming forces

IV.4.0 Cold expansion sleeve system

Under applied load, each rivet or fastener hole has a region of stress concentration of 200-300%, [11], of that in the surrounding structure. Cold working or introducing residual compressive stresses in the region of the holes reduces the chance of tensile fatigue cracks from initiating at the holes through compressive pre-loading. The cold expansion sleeve system uses a cylindrical sleeve which is placed into the hole and expanded using a mandrel which is forced through it causing compressive plastic flow of the surrounding metal. The sleeve is removed and the fastener inserted. The system has the following advantages;

- It allows greater expansion of fastener holes than previous methods
- The process produces a controlled amount of cold working
- The use of a pre-lubricated sleeve reduces problems of galling and tool breakage
- All work can be accomplished by one man from one side of the structure

IV.5.0 Explosive Bonding

This process was first developed for the chemical industry, which developed the method in response to the need for a method of joining two dissimilar metals in a continuous manner. The method has application in the joining of aluminum deckhouses to steel hulls, specifically the fabrication of a transition joint to serve as an interface between dissimilar metals.

The process consists of placing the "clad" metal above and parallel to the base metal, placing an explosive charge over the entire surface of the base metal and detonating it from one end. The detonation causes a fluid flow phenomenon in the impinging metal which forms an extremely strong bond between the two metals, stronger than the weakest metal.

IV.6.0 Adhesive Bonding

The state of the art in adhesive technology has advanced considerably in the past several decades, principally due to efforts by the aerospace industry. Advances in polymer chemistry have made possible adhesives with high strength, good environmental resistances, excellent manufacturing characteristics and moderate costs. The bond integrity of an adhesive joint is highly dependent on the surface preparation meaning that consistent high strength bonds in metal applications will usually require some type of chemical-immersion pre-bond treatment. Due to it's wide variety of applications in aircraft structures, the state of the art for bonding aluminum alloys is far more advanced than that of other metals. The most successful bonding preparation in use for iron alloys has been the precoating of the surfaces with a chromate primer prior to bonding.

The use of adhesive bonded subassemblies although not yet widely accepted by the maritime community for metal applications, does show promise for future developments. The fact that direct contact is not achieved between metals implies usefulness for the bonding of dissimilar metals. As an alternative to welding or mechanical assembly of non-critical structural assemblies, adhesive bonding could be used to provide the advantages of the continuous weldment with the stable non heat effected nature of mechanical assembly. An additional side benefit of bonding is it's resistance to sonic fatigue, or high frequency fatigue noticeable in lightweight structures in high noise areas.

This Page Intentionally Left Blank

V.0.0 Vibration Control and Attenuation

Mechanical vibration, when transmitted throughout a structure is a cause not only of discomfort to those working or living within the structure, but a potential cause of fatigue and failure of mechanical fasteners, welds, and other fatigue prone subassemblies[12]. Since, as noted previously, a majority of the failures noted in modern merchant ships are of a dynamic nature, it is very important to understand these dynamic forces which can cause dynamic type failures, (fatigue). Since wave and impact loads are a function of hull design and operational demands, the discussion of vibratory loads will be focused mainly on those which are mechanically generated.

The configuration of most modern vessels with bridge and accommodations well aft, in combination with the high power propulsion plants, has served to increase crew awareness of machinery vibrations. However this arrangement has also had the effect of placing operators far from bow sections which experience the highest level of hydrodynamic and impact loads. The net result being a reduced awareness of structural and hull vibration [13]. For this reason the careful inspection of vessel characteristics in normally unmanned spaces during sea trials is of even greater importance[9] with regard to early detection and correction of potentially damaging levels of structural vibration. The ability to detect excessive vibrations in a marine structure is very dependent on the conditions during testing; they must be performed while the structure is in it's element, e.g. main engines run up to service speed, normal seaway loadings, and routine heavy equipment operation. Operation of the system in it's element is imperative in order to obtain data which may reveal a problem.

Since the complexity of a marine system dictates the involvement of many different designers,

---

[9] The increasing reliability and economy of structural instrumentation systems, which when combined with the structural damage cost and consequence of failure, makes the installation of such systems increasingly attractive.

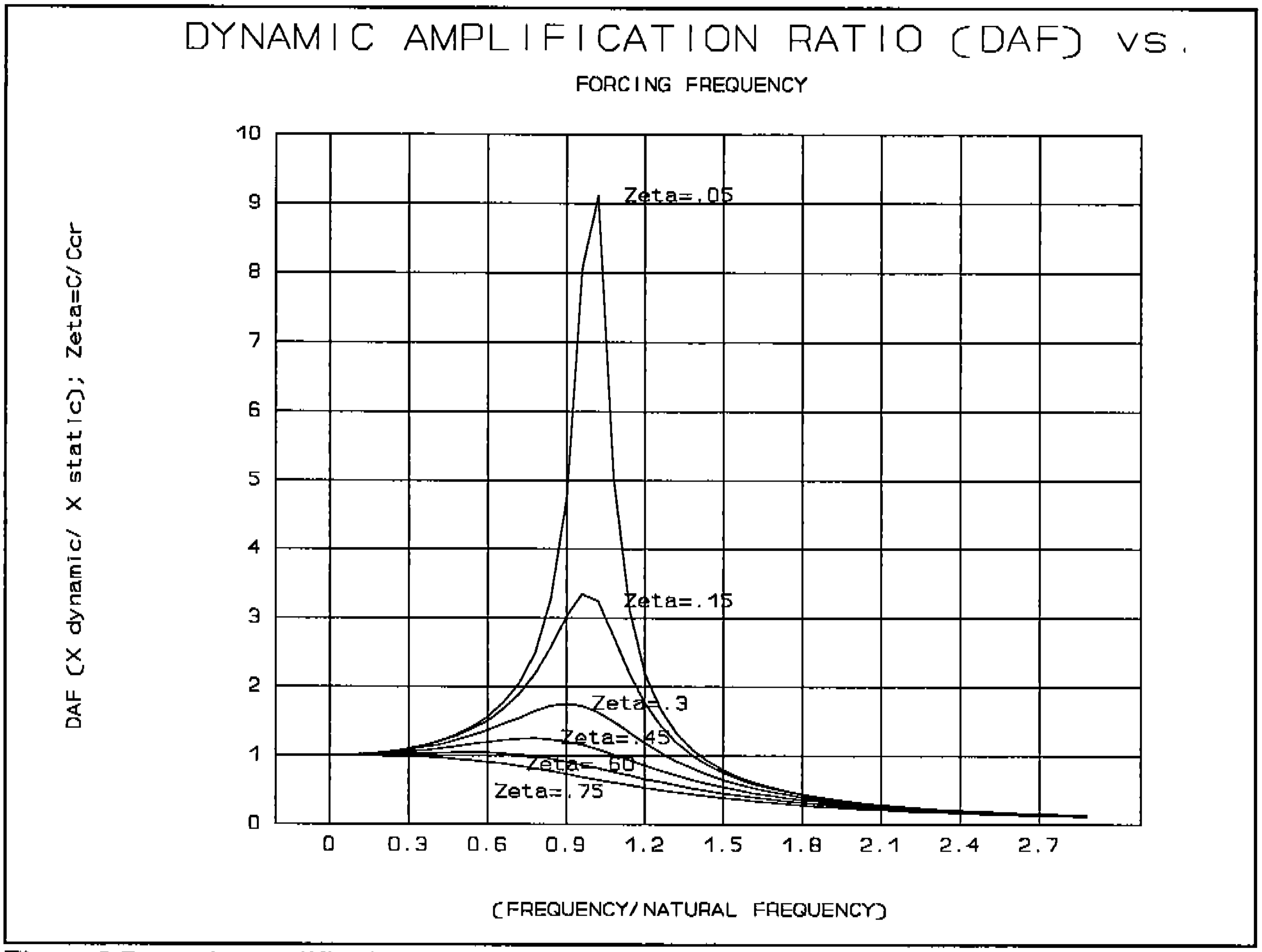


Figure 8 Dynamic Amplification vs. Frequency as a Function of Damping Ratio

each with a slightly different design objective depending on the subsystem he is working on, means that unrelated subsystems may, (and often do), have undesirable effects when run simultaneously: e.g. unpleasant and potentially damaging generation of beat[10] harmonics if run at slightly different load or speeds[14, 16]. Some typical vibration related problems are given in Table IV, [14], showing the wide variety of problems that undesired levels of vibration can cause.

In the interest of discussing only the factors that might be easily remedied, (machinery,

[10] "Beat" frequencies can be generated by running two or more monochromatic sources at slightly differing speeds producing low frequency periodic interference vibrations. This phenomenon is seen when two engines are run at nearly the same speed producing a low "thrumming". Since most of the equipment on a vessel is run at or near a 50 or 60 Hertz frequency, if machinery isolation or damping is insufficient, potentially damaging mechanical vibrations can result.

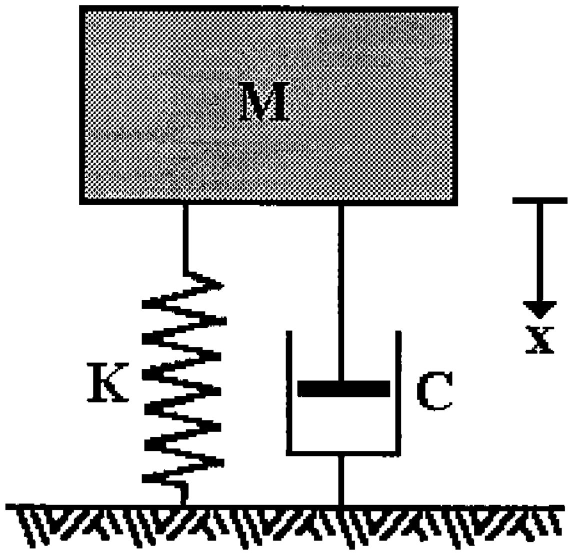


Figure 9 Spring-Mass-Damper Model

appendage or mechanically induced structural vibration), the correction of vibrations induced by hydrodynamic effects [11] will be discussed only briefly due to the complex nature of the turbulent flow and separation effects which commonly induce these vibrations.

V.1.0 Background

Although theoretically all the machinery present on board a ship will contribute to the total vibratory signature of the vessel, to analyze the total system response is extremely difficult and for the most part unnecessary. Most of the vibration problems which are cited as problematic can be considered as local in nature and can therefore be analyzed as such [14, 16]. One of the most

[11] These vibrations including slamming and whipping of the ship are most commonly a function of hull design and require extensive redesign to remedy.

Table IV Detrimental Effects of Vibration

- Damage or non-utility of various navigation aids at certain speeds.
- Cracked welds near deckhouses.
- Fractures in piping, (possible deadly consequences).
- Premature wear of shock mountings.
- Chemical exchange element breakdowns.
- Premature bearing failures.
- Excessive rudder vibration leading to loss.
- Reduction gear damage.
- Damage to PDE main bearings.
- Ship speed reductions so as to allow tolerable levels of habitability.

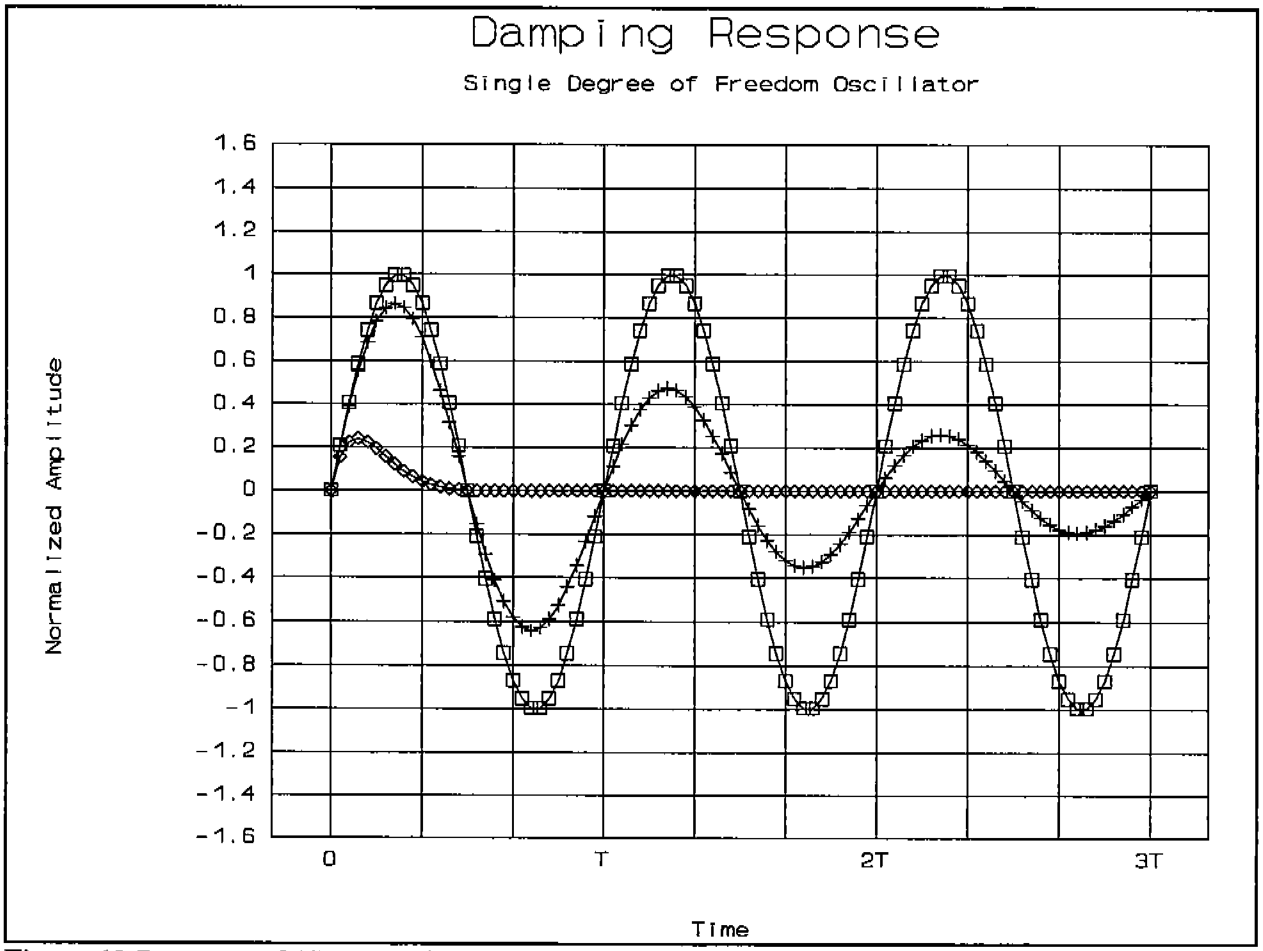


Figure 10 Response of SDOF Oscillator With Various Degrees of Damping

common examples found in ships is the vibrations present in a propeller drive system induced by screw-hull interaction, shafting imbalance/misalignment, or improper bearing or main engine mounts.

This system is modeled with the screw as the cyclic forcing function, (with frequency taken as the product of the rotational speed and the number of blades), the shaft torsional and/or bending stiffness as the restoring force, and the material damping properties as the mechanical damper. The boundary conditions imposed by the cutlass, line shaft, and thrust bearings are taken as fixed or corresponding to local hull stiffness and damping properties. In most cases the system is analyzed using a simplified model which has as few variable boundary conditions as possible, expediting and exaggerating the effects of changes in system parameters. For example, the effect of slightly varying the degree of damping in the simplest possible model, (a single degree of freedom damped oscillator), can be seen in Figure 8 to be very significant, (especially in the neighborhood of the resonant frequency where dynamic amplification [DAF[12]] effects become pronounced). The curves presented in Figure 8 are plots of Eq (14), which models the behavior of a simple single degree of freedom oscillator [Figure 9] under the influence of a periodic forcing function. Zeta is representative of the damping *ratio*, or the fraction of critical damping, (the damping level where a single excitation pulse will produce a displacement with no oscillations [Figure 10]), present in the system. This non-dimensional quantity is based on the solution of the equation of motion for a free, (no periodical forcing function), single degree of freedom damped oscillator [see Figure 9] as shown in Eq (13). The advantage of this approach is that the quantification of damping is not necessary, only an idea of the damping relative to the critical damping, solved for as shown in Eq (14). These equations are very powerful in that quick estimates of the effect of various changes in the system, (mass, restoring force and damping), can be readily understood.

[12] The Dynamic Amplification Factor (DAF) is the ratio of the amplitude of motion at a specific frequency to the static deflection amplitude, which as seen in Figure 8 can be quite high near resonant frequencies with small damping ratios.

$$\sum F = M\ddot{x} + C\dot{x} + Kx = 0$$

Thus;

$$x = -\frac{C}{2M} \pm \sqrt{\frac{C^2}{4M^2} - \frac{K}{M}} \tag{13}$$

Where for critical damping, x=0

$$\therefore\ C_{CR} = 2\sqrt{KM},\ where\ \zeta = \frac{C}{C_{CR}}$$

$$Dynamic\ Amplification\ Factor = \frac{1}{\sqrt{(1-(\frac{\omega}{\omega_n})^2)^2 + (2\zeta\frac{\omega}{\omega_n})^2}} \tag{14}$$

Where;

ω = *Forcing frequency*

ω_n = *Resonant frequency*

$$\zeta = Damping\ ratio = \frac{C}{C_{CR}} = \frac{C}{2\sqrt{KM}}$$

V.2.0 Subsystem Considerations

V.2.1 Hull Girder

The hull girder is comprised of the vessel's internal framing, bottom, side and deck plating which collectively provides the strength necessary for satisfactory performance of the design in all expected sea conditions. Globally, the hull responds as a "free-free" beam with vibration mode shapes independent of any fixed nodes, which means that there are many fundamental mode shapes possible due to the lack of mechanical restraint in any of the six domains of dynamic motion. The hull girder is thus subject to numerous vibration related problems, e.g. premature fatigue failures, jamming of mechanisms, etc.

The most common cause of vibration in the hull girder is interaction of the propeller and hull, where the characteristics of the vibration are primarily established by the propeller and stern configurations. The correction of excessive vibrations due to this interaction are most easily accomplished through modification or replacement of the existing screw(s) with screw(s) of different pitch/ diameter or, most commonly, a different number of blades[13]. Temporary relief from this type of vibration is achieved by simply operating at power levels above or below the resonant peak of the system, (although operation above the peak requires two potentially damaging transitions through the resonant frequency, one on the up bell and one on the down).

V.2.2 Shaft Frequency Forces

First order mechanical forces associated with shaft rotational speed may result from any of the following [15];

- Shaft imbalance
- Propeller imbalance
- Propeller pitch errors
- Engine imbalance
- Bent shafting
- Journal eccentricity
- Coupling misalignment

Shaft frequency forces normally occur within a low frequency range, (directly proportional to shaft speed which is normally on the order of 100 RPM). They are of considerable concern due to the large amplitude forces possible, (directly proportional to the vessel SHP and shaft rotational speed), exciting significant hull modes at or near full power [15]. This is of special concern on modern high power low speed direct drive diesel applications with very high coupled driveline mass[14], which means that the only real way of alleviating a vibration problem is to detune the system, since varying mass or damping would require impractically large changes in the system.

V.2.3 Propeller Forces

The periodic forces induced by the blade tips passing through regions of time and space

[13] The excitation frequency of the propeller-hull interface is determined by the frequency of the blade tips passing near the hull, (usually in the case of single screw ships, the 12:00 position), e.g. a six blade propeller turning 100RPM will generate a frequency of 600 pulses per minute or 10 Hz.

[14] In a direct drive system, the rotating mass includes the pistons, connecting rods, counterweights, crank-shaft, flywheel, couplings, shafting, and the screw.

varying pressure fields, (as a result of the turbulent flow in proximity to the hull), cause both longitudinal and transverse excitation forces on the shafting. This interaction transmits vibrations principally at the shaft and higher order harmonic frequencies. Of primary importance in the consideration of *hull excitation* is the first mode. Random vibrations tend to be a result of propeller cavitation effects. Cavitation occurs when the pressure on the forward trailing edge of the screw falls below the vapor pressure of the water, resulting in the formation of water vapor pockets. When these vapor regions are carried away from the screw, in either a tangential or radial direction, they are collapsed violently. The collapse of the vapor in the region of the hull plating creates distinctive "booming" impacts, causing even further imbalance of forces on the screw, (additionally leading to rapid deterioration or "burning" of the propeller blades due to material erosion).

Modern hull design has evolved in response to attempts to minimize the shaft frequency excitation of the structure. The after sections of modern ships appear quite different than their predecessors due primarily to the desire to minimize propeller induced vibratory forces by [16];

- maximizing the distance between the propeller, hull, and rudder, (see Figure 11).
- high aspect low cavitation propeller blades,
- flow improvement schemes intended to minimize the confusion of the water flowing into the screw.

The spade rudder has become almost universal, eliminating the traditional gudgeon shoe design which placed a stationary hydrodynamic interference directly below the screw on older designs, (Figure 11), introducing a secondary member into which radial blade wash collided doubling excitation frequency on screws an odd number of blades, and increasing excitation on screws with an even number of blades. The loss of lateral rigidity of the lower rudder has led to some vibratory problems [14, 16] due to the lack of lateral restraint at the lower end of the rudder[15], however the benefits of

[15] The cantilevered spade rudder requires a much heavier rudder stock than the traditional gudgeon shoe design. Lateral vibration problems occur as a result of insufficient lateral structure supporting this heavy strut. In some cases the entire after sections of a vessel must be modified when the stock is place well aft in a narrow stern with soft angular stiffness.

the design far outweigh this disadvantage.

The use of highly skewed, high aspect ratio propellers with seven or more blades has also moved the fundamental frequency of the propeller-hull system further away, (higher), from the low fundamental hull frequencies, (the skewness[16] of these propellers reduce the severity of passage through pressure gradients since the entire blade takes longer to pass, generating longer, gentler pressure waves thus decreasing excitation).

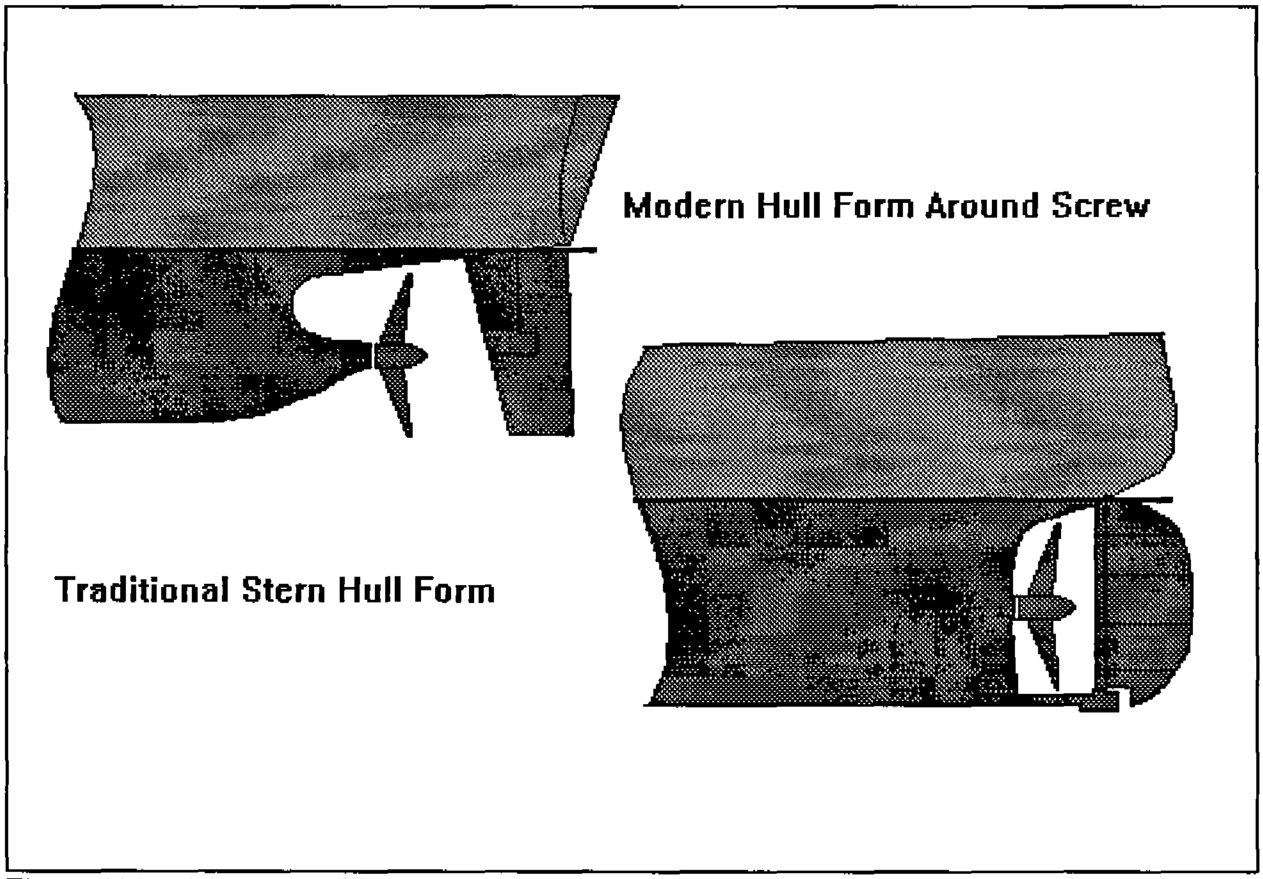


Figure 11 Modern vs. Traditional Merchant Ship Stern Configurations

V.3.0 Substructure Vibration

For the purpose of this discussion, substructures are defined as any structure of sufficient mass

[16] Skewness refers to the "sweep" of the propeller blades, or the amount by which the chord centers lag behind that at the root as one moves from the root to the tip.

or capable of developing sufficient force to have dynamic characteristics of their own, which because of direct coupling with the hull girder, can significantly influence the global vibratory characteristics of the hull. Excessive vibration of a major substructure can be the result of transmission of forces from the hull girder or forces generated by mounted equipment within the substructure.

Typical substructures on a vessel would include;

- Superstructures, deckhouses
- Main deck structures, cargo handling equipment etc.
- Propulsion and auxiliary machinery
- Heavy cargo

The dynamic response of deckhouses and superstructures are primarily a function of the stiffness of the hull-deck stiffness at the joint. This type of problem usually requires an extensive testing program to isolate problems which tend to be very expensive to repair.

V.3.1 Local structural Vibration

Local structural vibrations are usually the result of cyclic motion transmitted from the parent structure into a local detail. These local details are normally designed based on experience with similar details, thus receiving very little dynamic analysis during the design stage. In most cases these local vibrations are detected during trials and easily remedied if the underlying principles are understood. Undetected structural vibration induces dynamic stresses in the detail which in addition to the normal operational stress can cause premature fatigue failure of the detail. For this reason it is imperative that a thorough inspection of the structure is performed when it is placed in service to correct excessive vibrations in details, ensuring that their integrity is not jeopardized by early vibration induced fatigue.

V.4.0 Criteria for Acceptable Levels of Vibration

Several codes exist which specify "acceptable" levels of vibration, SNAME T&R code C-1, "Code for Shipboard Vibration Measurement," and ISO 4876, "Code for the Measurement and

Reporting of Shipboard Vibration Data," both have similar requirements. In the absence of any other criteria these codes can be used as a standard for the measurement and evaluation of vibration levels aboard ship.

Vibration is considered excessive if it results in ;

- o Damage of shipboard equipment
- o Structural damage
- o Adverse effects on passengers or crew

Normally vibration will result in personnel complaints before it reaches a level whereby structural damage is likely to occur. This may not be the case with remote subassemblies which can experience periodic high amplitude vibrations, not noticed by the operators, which can lead to premature failure.

Various methods using a wide variety of equipment can be used to measure and evaluate the vibration of structures, although an experienced operators' "feel" for the structure may still be the most revealing method of uncovering the source(s) of trouble.

V.5.0 Vibration Evaluation and Corrective Action

Once it has been established that an unsatisfactory vibration situation exists, the source of the problem must be isolated, data on the characteristics of the vibration gathered, a model of the system designed and tested, and finally alternatives for repair evaluated in order to determine the most effective method for solving the problem.

In the design of the model for use in evaluating the data and solutions, the first step is to determine the components which comprise the model's mass(es), spring(s), damper(s) and force(s) in the vibrating system. The number of degrees of freedom of the system must be determined in order to evaluate the nature of the vibration, since identical structures vibrating in different directions may be excited by completely independent phenomenon. If it is determined that the system has multiple degrees of freedom, it may be necessary to gather extensive data in order to define the motion adequately; (generally complicated vibration modes should be referred to consulting vibration engineers due to the involved specialized methods involved in the analysis).

As mentioned, the seriousness of vibrations can most often be evaluated by an experienced operator with a "feel" for the normal vibration of the ship. The vibration of loose gear, lightweight panels or rails might be extremely annoying, but of little concern structurally. Bearing squeal or rotating machinery rumbling on the other hand may be indicative of serious problems, thus in the initial evaluation of vibrations throughout the structure, a somewhat subjective decision must be made regarding the severity and level of criticality of detected vibrations.

V.5.1 Hull Vibration

Hull vibrations will normally be detected immediately during sea trials, excessive levels will probably show up in the form of excessive stern vibration levels at specific speeds and headings. The cause is invariably due to either loose or damaged structural members or screw-hull interaction. Solution is usually accomplished by reenforcement or less preferably screw replacement.

V.5.2 Excitation

The excitation of hull vibration can be the result of poor flow into the propeller(s), creating multiple vibration modes in the shafting and stern area. The remedies include;

- Increasing the skewness of the propeller
- Installation of fins to direct flow into the screw
- Increased radial and axial clearances

Propeller cavitation may be the result of poor screw design or poor flow into the propeller, these forces can damage the screw and result in high cyclic forces on the hull. The remedies include;

- Reducing speed or maneuvering rates[17]
- Redesign screw

---

[17] Maneuvering rate being defined as the rapidity with which changes in power level are accomplished; e.g. the rate [RPM/time] that the screw is accelerated when responding to power level orders. If the rates are reduced, the vessel will have time to respond, (speed up), as the RPM's are increased, resulting in reduced cavitation due to lack of flow to a racing propeller with low speed of advance.

Propeller imbalance will result in lateral vibrations of the shafting and rapid wear of the bearings, this can be caused by a damaged or faulty screw. This condition is remedied by replacing or balancing the screw.

The forces imposed on the hull girder by a sea way may excite the hull through several mechanisms. Bow slamming is the most familiar and is mainly a problem of operator sensitivity to conditions. Initial design of the lower bow sections can minimize the severity of this phenomenon, but for existing ships, unless extensive modifications are made, slamming is a fact of life. Hull springing can occur on vessels with low fundamental frequencies, (vessels with low section modulli such as great lakes bulk carriers, which consists of dynamic alternations of sag and hog profiles. The solution to this problem again is mainly operational, that is if large amplitude springing occurs, the operators should change heading and speed to alter the excitation, (wave encounter), frequency. In addition, the subsequent distribution of cargo be altered in order change the vessels shear and bending curves in order to minimize the tendency for rapid transition between hogging to sagging modes.

V.6.0 General Approach

In order to alleviate, (minimize periodic displacements), vibration problems, there are several different options. The problem structure can be braced against vibrations, effectively tying it to a larger structure with a higher mass and degree of stiffness. Rotating machinery can be balanced, effectively reducing its unbalanced mass and thus the imbalance force at critical frequencies. Structures excited by fluid forces can be detuned or redesigned so that flow separation is not as severe or vortex shedding is spoiled. Of great interest to those seeking further guidance in this area is [14, 16] which contains several excellent case studies of shipboard vibration problems and their solutions.

This Page Intentionally Left Blank

VI.0.0 Fatigue

Fatigue is easily the most prevalent structural failure mechanism in offshore structures. The fatigue environment being uniquely severe due to the cyclic loads imposed by the waves continuously encountered by a ship or any other structure at sea [17]. Although a ship may be designed to withstand the ultimate stresses imposed by immense storm waves, (very low frequency high intensity events), failure can and does occur due to seemingly low stresses generated by the continuous encounter of smaller although significant ocean swells, (high frequency nominal intensity events), as well as the routine impact loads resulting from the routine loading[18] and maneuvering of a ship. Given that a ship has a life of 20 years and is at sea 75% of the time, assuming that the median wave encounter period is on the order of 5 seconds, (approximate wave periodicity), the ship will have experienced nearly 100 million loading cycles. Thus one can see that no matter how robust the structure, with this many potential cycles imposed some work hardening and embrittlement is bound to occur.

Fatigue has become an even greater concern when the increasing stress levels imposed on modern ship details is considered. This condition arises as a result of the trend toward the use of steels with higher yield strengths, (and consequently less ductility)[19]. The use of these steels has the advantage of increased deadweight with constant gross weight which translates into a more profitable ship due to it's lighter structural weight, however the construction and maintenance of this lighter weight more highly stressed structure requires an increased level of attentiveness than previous lower stressed structures. Although yield and ultimate strength of higher strength steels are higher, the

[18] A vessel undergoes routine cyclic stress due to the variance of still water bending moments during the transfer of cargo, stores, ballast and fuel.

[19] There are high strength steels with high levels of ductility, however they are quite expensive due to the extensive heat treatment required. The decision must be made on a case by case basis using economic optimization methods.

fatigue strength does not increase in proportion to either [18].

VI.1.0 Discussion

Fatigue failure is most evident in the complicated geometry of the internal structural framing of the ship. The connection of various 3 dimensional internal components and the subsequent redirection of force vectors gives rise to stress concentrations, which can contain stresses many times that experienced by the originating members. When the connections and details are well designed and fabricated, these stress concentrations can be minimized, however if poorly designed and constructed details are used cracks can develop, and if proper maintenance and repair is not carried out cracks can grow leading to the possible failure of details and even the loss of the ship.

With regard to the maintenance of existing ships, the subject of fatigue is limited to the detection and modification of existing, (detected), failing or failed details to minimize the chance of future failures. Due to the complexity of a ship structure, some details are bound to experience overload and failure. This being especially true in a new class of ship (prototype) where design calculations are bound to be in error in some areas. Proper inspection, maintenance and repair procedures [see Chapter I] and operation of the ship per design specifications are the first line of defense against these potential failures. Once a trouble spot is identified, analysis of the detail in order to identify the cause(s) of failure followed by careful repair and documentation of the solution and action taken is necessary[20]. The documentation should include a ship's machinery history log, entry into a generic detail database and a bulletin directed to the classification society.

VI.2.0 Fracture Controls

Cracking was not a critical structural failure mode prior to the 1940's when welding became the preferred method of connection of individual components used to construct ship structures. The

---

[20] This is not to say that attempts should be made to analyze the problem away, but attempts should be made to verify loading in order to design a reasonable re-enforcement scheme for the local structure.

discontinuous nature of riveted joints served to effectively arrest any crack propagation, (which is why modern aircraft are riveted together vs. fusion bonding {welding} of sections),[10]. The solution in the past to failures has been the incorporation of large factors of safety order to reduce working stresses to a level where it was assumed that cracking would not occur. However as mentioned, the trend towards higher yield steels and low factors of safety due to improved analysis techniques, has resulted in relatively brittle, unforgiving structures.

Fracture control can be broken down into five basic categories [19]:

- Control of stress levels/ Redundancy
- Minimizing Stress Concentration Factors (SCFs)
- Control of welding procedures
- Inspection
- Material selection

Improvements in structural analysis methods have allowed the designer to estimate the stresses and strains on structures given a set of loading conditions with a great deal of accuracy. The increasing ease with which the creation and analysis of numerical structural models has given the designer the ability to perform fully non-linear structural analysis enabling him to utilize all of the material's reserve strength (post yield) to determine the true ultimate strength of a structure. As a result, factors of safety have been reduced, which has subsequently resulted in higher loading levels in the structure, creating a more fracture prone environment. One of the greatest advantages of improved analysis techniques, (e.g. FEM), is the ability to identify regions of high stress concentration for a multitude of loadings and prospective geometries. In order to minimize the probability of fracture occurrence, efforts must be made to minimize the severity of these stress concentrations by either attempting to more evenly distribute loads throughout the structure or increasing scantlings proportionally. When this is accomplished, any existing flaws are less likely to experience overload leading to fracture.

The introduction of flaws is unavoidable during either construction or less prevalently during the life of the structure, and although essentially impossible to eliminate, quite possible to minimize. Introduction of cracks during construction can occur due to overloading of subassemblies during fit-up due to stresses imposed during crane operations[21], equipment placement, launching and innumerable other operations which can impose uneven loading on subassemblies not designed to carry loads out of certain orientations. There are many sources of flaws, welding imperfections (mainly), material impurities, misalignment of joints, residual stresses from forming (welding, casting/forging), heat treating etc. The minimizing of fracture initiation points can be accomplished during the construction or repair phases through high quality welding and inspection, both of which tend to be influenced to a great extent by workforce competence and workmanship. Which is to say that the welders must consistently produce high quality welds versus welds which will probably pass if inspected[22]. If surveys of structural failure in ship structures are examined, it is easy to see that poor welding is perhaps the leading cause of fracture initiation [20].

The availability of uniformly high quality steel is quite good, the task of the designer is to select the material whose properties are well suited for the loading and environment expected [21]. Standardized material testing techniques include the charpy V-notch test which indicates the material's fracture toughness, Brinell and Rockwell hardness tests which indicate the material's hardness and of course fatigue testing which although used more specifically to examine specific joint geometries, can be used to determine the material's resistance to fatigue and work hardening.

---

[21] This problem is most evident in the assembly of platform jackets during crane operations. The jacket is usually constructed in flat faces lying on the ground and then lifted into a vertical position by a team of cranes. If the cranes are just slightly unbalanced, immense loads can be imposed on the tubular joints of the truss work as it is erected resulting in fractures.

[22] Workers must be made to feel that errors are expected and should be reported, in this way all personnel can be trained in their avoidance and all will learn from them, as opposed to the traditional, (read: American), punitive system which encourages workers to hide errors. *Dr. Edwards Deming, on Quality Control.*

VI.3.0 Allowable Stresses in Fatigue Design

The logarithmic *stress vs. number of cycles* curves, *(SN)* curves, used for the determination of the suitability of a detail's fatigue life, are determined using the fracture mechanics approach in the laboratory for various detail configurations and loading environments.

The American Petroleum Institutes' *Guidelines for the Design of Offshore Structures*[23], (API-RP 2A), defines 2 curves for any given detail, one more conservative and another which requires the welds to be properly profiled to minimize the generation of stress risers at the weld toes. "Peening" or literally beating on the welds with a purpose made hammer also serves to reduce residual stresses in the welds since the residual stresses on the weld surfaces tend to be tensile in nature, (the introduction of compression tends to neutralize the tensile residual stresses-***which can reach yield stress in the weld***). The allowance for greater fatigue life in design using the profiled SN curve encourages the designer to specify profiled welds. The SN curve selected defines an allowable stress level for a proposed design life load history or visa versa. However the allowable fatigue loading does tend to under estimate true fatigue life due to the placement of the allowable limit 2 standard deviations of the data below the median SN curve, thus ensuring that 97.7% of the test points lie above the allowable stress line. If in addition to using the conservative -2σ curve, a significant safety factor is included, the design will tend to be quite unnecessarily robust and costly. In addition when the structure is exposed to random variable amplitude loading, crack growth retardation occurs which is not accounted for in the super-position of linear elastic discreet frequency loading regimes, which introduces further conservatism into the analysis. Thus when considering the addition of conservatism into the design, these facts should be kept in mind [22].

The definition of failure should also be examined, depending on the detail's criticality, failure

---

[23] This reference is useful in that the criticality of welds for permanent offshore structures is very high, and has resulted in some very serious research work with regard to fatigue.

might be defined as the complete fracture of the detail, excessive displacement of some part of the detail, or any of innumerable other criteria. The detection probability must also be taken into account, e.g. the resistance to damage should be proportional to the difficulty of inspection [of the particular detail [23].

Conservatism is warranted with respect to the actual stresses experienced within the welded joint itself due to the difficulty of measuring the stresses in a welded joint. SCF's within the joint can vary by orders of magnitude due to geometrical stress concentrations, residual stress in the heat affected zone and other factors such as shear lag. The FEM has difficulty in modeling thicker regions where multiple weld passes are necessary to achieve the desired weld profile, and also where material thickness is increased[24]. Therefore although very good estimates of stresses in the members up to the joint itself can be made, the stresses in the actual fused joint are still difficult to model accurately.

VI.4.0 Fatigue Life

The fatigue life of a structure can be considered to be the finite number of cycles required to achieve failure as defined by the assumptions for the specific empirical SN curve. The cycles are broken up into discreet ranges (blocks) e.g. discreet wave height ranges which impose proportional loadings in the detail. For each range, a specific number of cycles to failure is defined with a range damage ratio equal to the quotient of the cycles experienced and the number of cycles to failure. The overall damage ratio is as defined in Eq (15), where N=number of cycles to failure and n_i=number of cycles that the detail has experienced up to any point in time. One of the questionable assumptions in

$$D=\sum_{i=1}^{N}\frac{n_i}{N} \tag{15}$$

[24] It can be shown experimentally that the allowable stress decreases by the change in thickness raised to the -0.25 i.e. if $t_2=2*t_1$ $\sigma_{allow(2)}=(\frac{1}{2})^{(0.25)}*\sigma_{allow(1)}$ or 84%

the design procedure is that the rate of damage accumulation at the Beginning Of the structure Life, (BOL), (for a specific stress level) is identical to that at the End Of structure Life ,(EOL), even though crack propagation is in a different phase. Justification is given by the fact that it can be shown that after a crack initiates, it will propagate at a relatively constant rate, (assuming that the conditions necessary for brittle fracture to occur are not satisfied; namely that material temperature does not fall below the Nil Ductility Temperature *NDT*[25], assuming the other conditions are satisfied, namely a flaw and tensile stress). Thus the accumulation of damage is considered to be a linear process from crack initiation to fracture. The fatigue life is defined as the inverse of the damage accumulation level.

VI.4.1 Fatigue Life Prediction

The prediction of the exact number of cycles that a specific ship detail will endure, even if assuming a constant stress amplitude, is quite difficult given the variabilities in geometry and the complexity of loadings imposed on the detail. There have been hundreds of test programs carried out with the aim of the determination of the fatigue characteristics of various classes of details in order to develop design guidelines and verify fatigue design hypotheses, and as a result there is a plethora of fatigue data available which attempts to represent SN curves for the various test specimens [17].

VI.4.1.a Miner's Rule

This approach is based upon the assumption that the structural loading and the strength of the structure in terms of stress levels and number of cycles to failure can be quantified. The method is derived from S-N test data and the assumption that damage accumulation is linear. Therefore the fatigue life is assumed to be the weighted sum of the individual lives at various stress levels, S, as given by applicable S-N curves with each being weighted by the assumed fraction of time that

---

[25] *NDT* (Italics) will be used as the abbreviation for Nil Ductility Temperature vs NDT for Non Destructive Testing.

exposure to the specific loading level occurs. The loading can be expressed as a histogram where the ordinates are number of cycles and the abscissa is divided into stress ranges. A resulting non-dimensional damage ratio can be expressed as shown in Eq (16) where $\cap_L$ depends on the number of cycles at each stress level [19, 23].

In linear-Elastic fracture mechanics the stress field at the tip of the crack is described in terms of stress intensity as in Eq (17) where F is a geometrical correction factor and a is crack length. In all methods for crack growth predictions, the stress intensity factor is the main independent variable determining the rate at which the cracking progresses. That is to say that

$$\begin{array}{l} \eta_l \geq \sum_{i=1}^{\beta} \frac{\eta_i}{N_i} \\ \textit{where;} \\ \eta_L = \textit{Limit damage ratio} \\ \beta = \textit{Number of stress blocks} \\ \eta_i = \textit{Number of stress blocks} \in \textit{block } i \\ N_i = \textit{Number of cycles} \rightarrow \textit{failure} \end{array} \tag{16}$$

da/dn≈F(K_{max}-K_{min}) or the crack growth rate is some function of the range of stress applied to a flaw. When fatigue data is plotted against stress intensity on Log-Log paper, an S shaped curve results, (Figure 12), which is commonly divided into three distinct regions: Region I is the early non-linear region referred to as the "threshold" region, in this region small changes in stress range produce large changes in growth rate. Region II is the "steady state" region which is nearly linear in that changes in stress range produce nearly linear changes in growth rate. Finally region III or the "unstable" region, like region I is non-linear and is the region in which failure occurs. The entire curve can be modeled

$$K = F \cdot \sigma\sqrt{a} \quad [KSI\sqrt{inch}] \tag{17}$$

by Eq (18) where C and M are material dependant constants determined empirically.

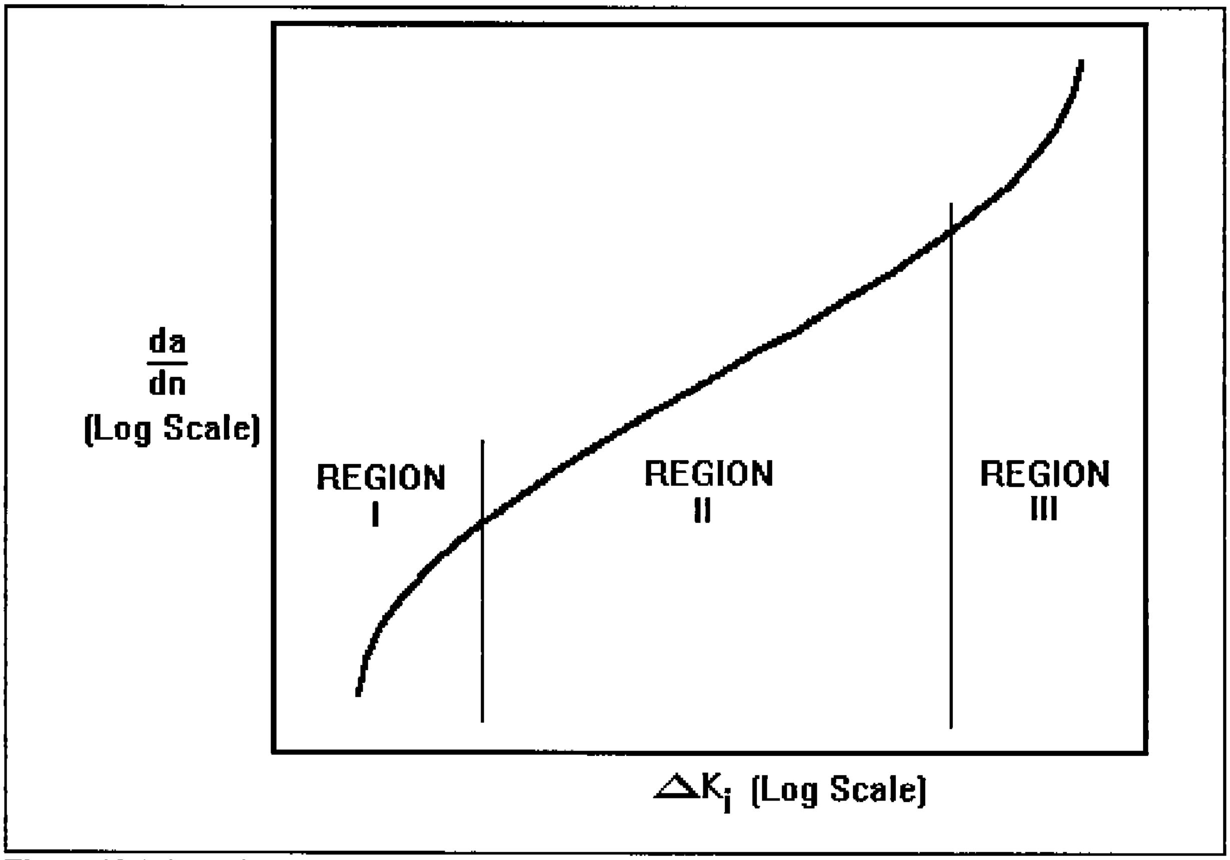


Figure 12 Schematic Representation of Crack Growth in Steels

$$\frac{da}{dn}=C(\Delta K)^{m} \tag{18}$$

VI.5.0 Munse Fatigue Design Procedure (MFDP)

When variable amplitude stress histories are used to predict the fatigue life of a detail, different SN curves result [24]. The MFDP takes this into account by introducing a correction factor **Z**, which when multiplied by the allowable constant amplitude strength for a given life, will predict the fatigue strength for a variable loading history. Additionally the natural scatter in fatigue data is accounted for by uncertainties in fabrication and stress analysis using the concept of total uncertainty given by Eq (19);

$$\Omega_{total}=\sqrt{\Omega^{2}_{f}+\Omega^{2}_{c}+(\Omega^{2}_{s}*C^{2})} \tag{19}$$

Where;

Ω_n= Uncertainty in TOTAL fatigue life

Ω_f= Uncertainty in fatigue data life: RMS of COV of fatigue data life about the SN regression line and the error in the fatigue model: effects of imperfections in the linear damage accumulation assumption.

Ω_c= Uncertainty in mean intercept of the SN regression line: in particular effects of fabrication

Ω_s= Uncertainty in the mean stress range: effects of impact and errors in stress analysis and determination.

The largest uncertainty is of course the stress range that the structure will encounter. Having estimated the uncertainty, a reliability factor R_f is estimated after assuming appropriate distribution models and desired level of reliability. The MFDP estimates the maximum allowable stress range DELTA S_D from the particular detail's closest matching type of weldment SN curve, the average fatigue strength at the desired life, and finally multiplying by the random load correction and the reliability factor.

For Welds subjected to a constant amplitude stress range, the mean fatigue life N is given by Eq (20), [24].

$$N=\frac{C}{(\Delta S_N)^m} \tag{20}$$

Where C and m are empirical constants obtained from least squares analysis of SN data. Munse's procedure uses the extended straight SN line at the stress ratio R=0 as its basis and neglects effects of mean stress, material properties and residual stress. After cycle counting, the variable load history is plotted in a stress range histogram. Mean stress level and sequence effects are regarded as secondary effects. Since random loadings for weld details cannot be determined exactly, the Munse procedure uses probability distribution functions to represent the weld fatigue loading. Six distributions are employed to represent different common variable loading histories:

- Beta
- Log-normal
- Weibull
- Exponential
- Rayleigh
- Shifted Exponential

It is necessary to determine which distribution or distributions provide the best fit to the loading history. The random load factor is a function of the desired life and are tabulated in various design guidelines. The reliability factor is given by Eq (21).

$$R_f=\left(\frac{[P_f(N)]\Omega_n^{1.08}}{\Gamma(1+\Omega_n^{1.08})}\right)^{1/m} \tag{21}$$

Where;

$P_f(N)$= probability of failure
Ω_N=Total uncertainty
Γ =Gamma Function
50% Reliability Rf=1.00
90% Reliability Rf=0.70
95% Reliability Rf=0.60
99% Reliability Rf=0.45

This procedure provides an accurate prediction of fatigue life and is straight forward to carry out [24]. The difficulty lies in the determination of the proper distribution and the quantification of the uncertainties. The utilization of successful values used in similar applications is recommended with the addition or subtraction of some additional modeling uncertainty depending on the subjective confidence of the designer. This may be due to more or less confidence in the quality of fabrication of the detail at hand, the materials/ assembly method, or the ease of access to the workpiece.

VI.6.0 Alternate Approach

An alternate approach as proposed by Munse [17] is based on the calculation of a "design allowable" stress range, S_{rd}, for fatigue. This stress range is the maximum peak to peak stress range expected at the point in question once under the most severe sea state and during the entire life of the structure. Comparing that stress range to the allowable stress for other failure modes indicates the controlling mode of failure. In all cases the S_{rd} must be less than the one time maximum allowable stress. The approach defines S_{rd} as the product of the mean value of constant amplitude stress range at the design life N_d, a reliability factor, R_f and a random load factor ε, Eq (22). The mean value of

S_n is found using the applicable SN curve for the expected life of the structure, (number of cycles).

$$S_{rd}=S_n \bullet R_f \bullet \varepsilon \tag{22}$$

The reliability factor is meant to account for uncertainties in the fatigue data, workmanship, fabrication, use of the equivalent stress concept, errors in load history and errors in the stress analysis. The reliability factor is modeled assuming that R_f is a random variable with a Weibul pdf and the use of a relationship for the P(survival) through N loading cycles. The effect of this factor is to reduce a mean stress range to an equivalent stress range which corresponds to a designated probability of survival greater than the 50% level of the mean stress range. The random load factor, ε, is introduced in order to make possible the use of existing constant cycle fatigue data in designing for variable loading service conditions.

VI.7.0 Initiation Life Model

It is generally agreed that cracks will initiate at points of stress concentration, namely notches, pores or other defects which interrupt the continuity of material [25]. This initiation mechanism results due to the plastic deformation in the region of the initiator, due to the high stress concentration and thus stress level well above the yield stress. This can occur with the majority of the assembly well below yield again due to the magnification of stress at the initiation site. Cyclic loading applied in the region of the initiating flaw will thus result in a propagating crack whose progress is directly proportional to the lading and loading rate. The endurance of a particular detail is divided into two distinct phases: that of crack initiation and that of propagation. The modeling of fatigue life must therefore consist of two models, an initiation model and a propagation model.

VI.7.1 Initiation: Notch Analysis

After the occurrence of plastic deformation as described above, the stresses and strains can be determined using the following notch analysis technique [19, 23]. An elastic stress concentration

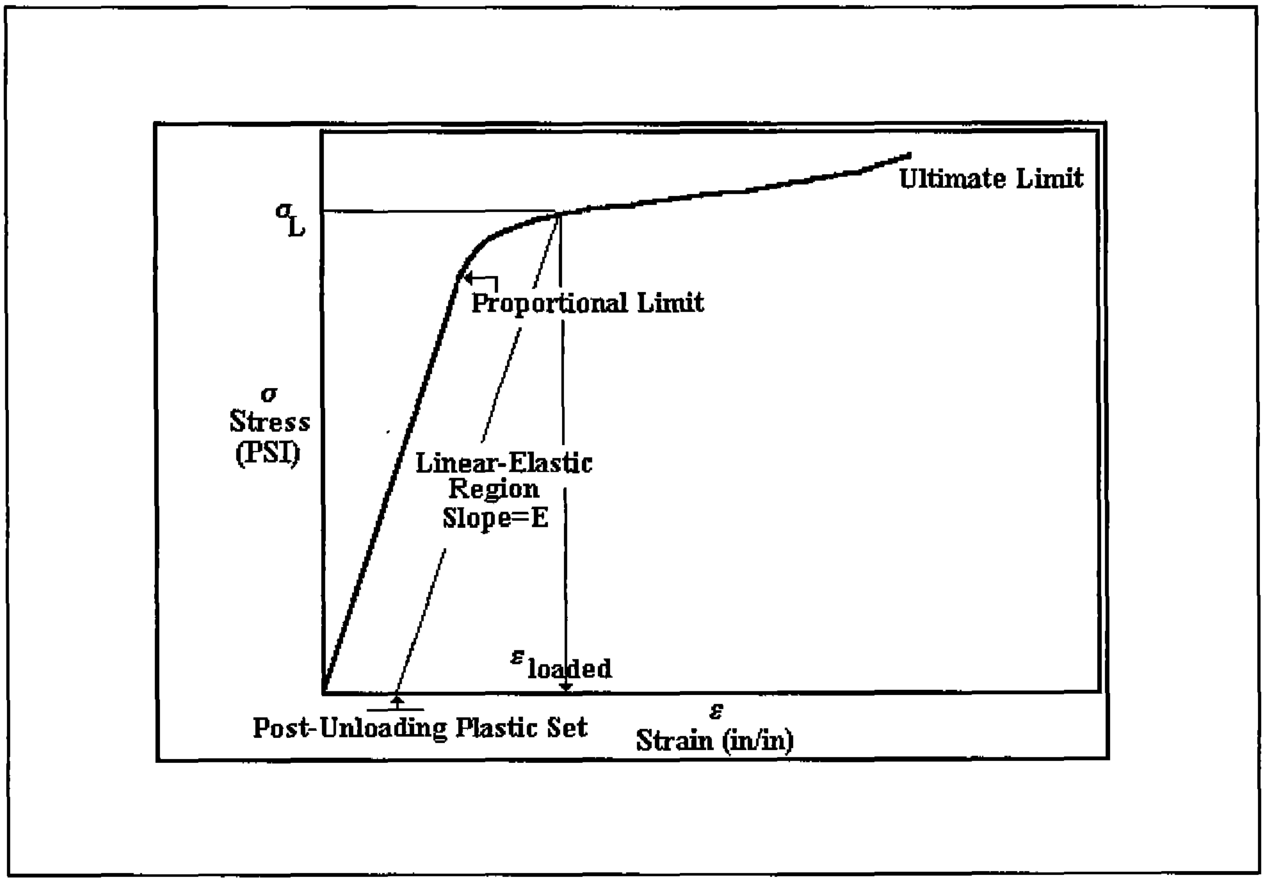


Figure 13 Stress-Strain Curve for Metal

factor,K_t, which is defined as the quotient of local stress and remote stress, is determined by using either FEM or elasticity theory. After the notch region has plastically deformed K_t can no longer be used to directly predict the local stress as the plastic stress will rise at a lesser rate and the plastic strain at a greater rate. Instantaneous stress and strain conversion factors must be used beyond the elastic limit due to the non-linear nature of the problem, (see Figure 13); this relation is expressed in Eq (23). Since delta e is the quotient of the nominal stress range and the modulus of elasticity, the

$$K_t=\left(\frac{\Delta\sigma\,\Delta e}{\Delta S\,\Delta e}\right)^{\frac{1}{2}} \tag{23}$$

Where;
ΔS=Nominal stress range
Δe=Nominal strain range

expression can be given as in Eq (24). This is Neuber's rule expressing the local stress/strain behavior at the notch root to the nominal stress and elastic stress concentration factors. Using the power law hardening relationship; the relation in Eq (24) can be expressed as in Eq (25);

$$\Delta e=\frac{\Delta\sigma}{E}+\left(\Delta\frac{\sigma}{K}\right)^{\frac{1}{n}} \tag{24}$$

where K is the strength coefficient and n is the strain hardening exponent, finally the expression is expressed with only the stress range as the unknown in Eq (26).

$$\Delta\frac{S^2}{E}K_t^2=\Delta\sigma\left(\frac{\Delta\sigma}{E}+\left(\frac{\Delta\sigma}{K}\right)^{\frac{1}{n}}\right) \tag{25}$$

which is solved through successive iterations for the elastic stress concentration.

Since in practice the predicted life for a notched specimen tends to be overly conservative, a fatigue notch factor, K_f, is introduced which is used in place of K_t, which is defined as shown in Eq (27)[19, 23];

$$K_f=\frac{\sigma_{un\text{-}notched\ @\ EOL}}{\sigma_{notched}} \tag{26}$$

K_f can be expressed in terms of K_t, notch tip radius, r, and a material dependant strength parameter, a as shown in Eq (28); This important relation points out the fact that small notches are less sensitive to fatigue and that ductile materials are less fatigue prone than strong materials, which is intuitively correct.

$$K_f = 1 + \left(\frac{K_t - 1}{1 + a/r}\right)$$
where; (27)
$$a = \left(\frac{300}{\sigma_u}\right)^1 .8 x 10^{-3} \textit{inches}$$
r *= Crack tip radius*

The actual prediction of the number of cycles to crack initiation can be expressed in terms of the above expressions when the specimen is cycled between strain limits in the Coffin-Mason Equation given in Eq (29). By relating the strain calculated at the notch root to the strain life data,

$$\Delta\frac{\epsilon}{2} = \epsilon'_f (2N_f)^c + \left(\frac{\sigma'_f - \sigma_m}{E}\right)(2N_f)^b$$

Where;

(1) $\Delta\frac{\epsilon}{2}$ *= Strain amplitude*
(2) ϵ'_f *= Fatigue ductility coefficient* (28)
(3) σ'_f *= fatigue strength coefficient*
(4) σ_m *= Mean stress*
(5) $2N_f$ *= Number of reversals→failure*
(6) C *= Fatigue ductility exponent*
(7) b *= Fatigue strength exponent*

the number of cycles to initiate a fatigue crack at the notch can be estimated. Quantities 2,3,7 and 8 in Eq (29) above are obtained by either low cycle fatigue testing or through estimation.

VI.7.2 Propagation: Crack Growth

The second phase in the fatigue crack mechanism is that of crack growth. The growth rates have been shown to be a function of the stress intensity at the crack tip, the ratio of the minimum stress to the maximum stress and specific material properties as mentioned in the previous section. The growth rate can thus be expressed as shown in Eq (30);

The stress intensity factor is determined as a function of the geometry, the stress range and the instantaneous crack length and shape. An expression for the stress intensity factor can be expressed as shown in Eq (31);

$$\frac{da}{dn}=\frac{A\ \Delta K^{m}}{1-R}$$

Where;

$$R=\frac{S_{\min}}{S_{\max}} \qquad (29)$$

ΔK=Stress intensity factor

A,m are material constants

$$\Delta K=\left(\frac{M_s M_t M_k}{\Phi_o}\right)\Delta S\sqrt{(\pi a)}$$

Where;

M_s=Crack surface area (30)

M_t=Plate thickness

M_k=Stress gradient

Φ_o=Crack shape

ΔS=Stress range

The geometrical descriptors, (M's), shown in Eq (31) must be included in order to differentiate the infinite number of possible crack shapes, orientations and sizes. The M_s factor which accounts for the front free surface can be described as in Eq (32);

$$M_s=1.0-0.12\left(1-\frac{a}{2C}\right)^2 \qquad (31)$$

where a/c is the ratio of the minor to major ellipsoidal axes. If the crack is embedded in the material, M_s=1.0. The M_t factor, accounts for plate thickness and is tabulated in mechanics of materials handbooks in tables of stress intensity factors. The factor M_k is used to account for the stress differential near flaw vs remote regions of the material, as above it is tabulated in handbooks. The crack shape factor Φ_o is calculated as given in Eq (33);

$$\Phi_o=\int_0^{\pi/2}[1-(1-(\frac{a}{c})^2 Sin^2\phi]^{\frac{1}{2}}\ d\phi \qquad (32)$$

VII.0.0 Structural Fractures

The prevention of fracture of rigid steel ship structures is the overwhelmingly prevalent concern amongst those involved in the design, construction and maintenance of these structures [26]. In order to minimize the occurrence of fractures due to design, construction or accidental loading, steel structures are constructed according to codes or optimum performance specifications. Ships are constructed mainly in accordance with codes although some unusual designs are built to performance standards due to lack of pertinent codes. In addition to minimum strength requirements, the use of redundancy, "fail-safe" structural design and the use of "safe metals" are specified [27]. Redundant structures are designed such that multiple load paths exist at loading levels low enough such that the additional loadings which are imposed on adjacent members due to the loss of a specified maximum number of the original load paths, (reliability level; see Chapter I), can be tolerated by the remaining elements. A "fail-safe" philosophy consists of designing the structure so that failures in the structure are physically limited to isolated sub assemblies, e.g. crack arresters and certain schemes of sub assembly isolation. The "safe metal" approach is somewhat implicit in material specification for modern structures, with the brittle fracture and fatigue problems being prime examples of the type of failure mechanisms that this approach is meant to avert, (i.e. the specification of minimum ductility, toughness, transition temperature... in addition to material strength properties).

The degree of fracture resistance of a structure is a direct result of not only the thoroughness of the engineering analysis directed at minimizing the problem, but most importantly the level of fabrication quality that exists once the structure is built. Implicit in this statement is quality of qualification, inspection and material monitoring which exists during construction. The minimizing of fracture consequence and severity when fractures do occur is one of the main functions of thorough and routine structural inspection program. Catastrophic failures of structures due to known existing flaws are not rare, emphasizing the importance of prompt action upon the discovery of fractures.

Although structural redundancy may allow the continuing operation of a vessel with substantial fractures, unexpected or unusual loads may cause unforseen damage which can combine with existing damage causing massive failures. In damage reports, an isolated lone crack is seen less often than multiple seemingly random cracks emphasizing the somewhat random forms that fractures take.

VII.1.0 Fracture Initiation

The initiation of fractures observed in surveys such as that carried out in the SSC detail survey report series, indicate that the overwhelming majority of fractures initiate in the region of assembly flaws [28,29,30] . These flaws, if located near sub assemblies where large changes in stiffness occur, near regions of high stress, or regions with a high degree of alternating stress invariably fail through the slow or fast migration of fractures. In addition, if high levels of residual stress due to poor fit-up and/or poor welding method are present, the failures will occur at even lower loading levels.

VII.2.0 Fracture Prevention

In some cases, known "hot spots" in the structure, detected during design or modification analysis, will fail in fatigue due to scantlings designed to withstand ultimate rather than the working loads critical in fatigue failure. A high degree of diligence must be exercised in detail design to;

- Design details which are straight forward to assemble, minimizing the chance of the introduction of high levels of residual stresses due to difficulty of proper fit-up.

- Wherever possible eliminate sharp notches or other initiation points for cracks, (as in the above, design such that these initiators are not introduced due to the difficulty of fabrication of specified details). If drainage channels or other types of slotting of material is necessary, (e.g. in horizontal plate elements, such as tank tops or longitudinal flanges) they should be aligned such that the axes are parallel with the orientation of expected principle stresses, (minimize the possibility of fatigue cracking).

- Wherever failures are at all expected, (and especially in critical structures), crack arresters or interruptions in load paths should be used to limit fractures to local assemblies, (thus limiting the nature of damage to that of local vs. global).

- *ENSURE* whenever possible the specification and *USE* of materials with sufficient resistance to expected loadings in details, (in many cases failure occurs due to the use of materials other than those specified in plans, rendering the engineering work involved in the drawing up of those plans all but void).

- Establish tolerances which are easily met by the expected competence level of the force to perform the work.

- If at all possible search for data, i.e. SSC294 A Survey of in Service Structural Details [30], on performance of various designs in order to utilize past experience with existing detail types utilizing only configurations which have been successful.

VII.3.0 Crack Arresters

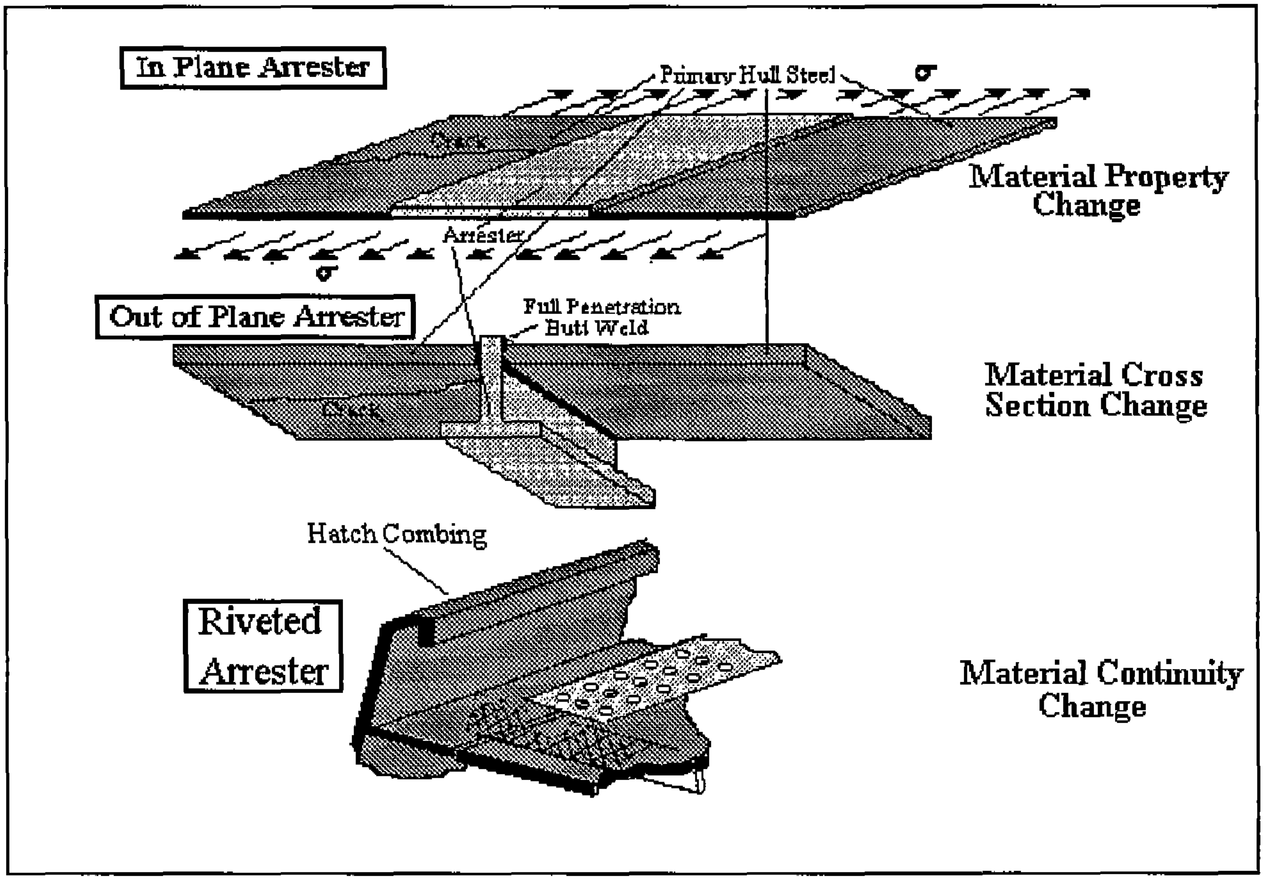


Figure 14 Crack Arrest Schemes

Crack Arresters are the "fail safe" component in a complete fracture prevention system. In the event that cracking does occur, the intent is that crack arresters will have been placed near enough to one and other that the crack cannot propagate to the extent that it becomes structurally threatening.

The requirements for an effective crack arrester system are [31];

- Proper Material, toughness, strength and compatibility with surrounding material.
- Effective Geometry
- Strategic Location

The material must be able to stop a propagating crack, thus it must be much tougher than the base metal. It has been found that an arrester toughness of approximately 4x that of the base metal is sufficiently effective in arresting cracks.

The most common geometrical arrangement of crack arresters fall into one of the three categories as sketched in Figure 14 including;

- Riveted seams
- Welded strakes, (in plane arresters)
- Welded stiffeners, (out of plane arresters)

Riveted strips are less common in newer ships due to the expense and time consuming nature of riveting. This scheme's crack arrest ability is accomplished when the crack propagates into a discontinuity or into a rivet hole, which is commonly agreed upon as the most effective crack arrest mechanism[26][32]. Many fittings and auxiliary equipment are through bolted to the primary structure such as water tight doors, flanges, and hatch combings, which provide these discontinuities and holes for crack termination.

Welded in plane strakes serve to arrest cracking in two ways, they are usually of a slightly heavier section than the adjacent primary structure, and they are of a material grade with far superior toughness and fracture resistance to that of the primary structure. It is suggested that for most large commercial vessels where this material is used in sheer, side shell, and deck strakes, that the strake be at least 6 feet in width [31, 33]. For primary hull bending stresses, the most effective locations for this material is in the two regions of highest stress, namely the main deck edge and the turn of the

---

[26] Emergency crack repair procedures all dictate the boring of a stopping hole at the end of cracks to preclude further growth, prior to welding. Since the hole is smooth all the way around its girth, there is nowhere for the crack to re-initiate.

bilge, and to resist primary shear loads, on the side shell at the approximate level of the neutral axis, as sketched in Figure 15.

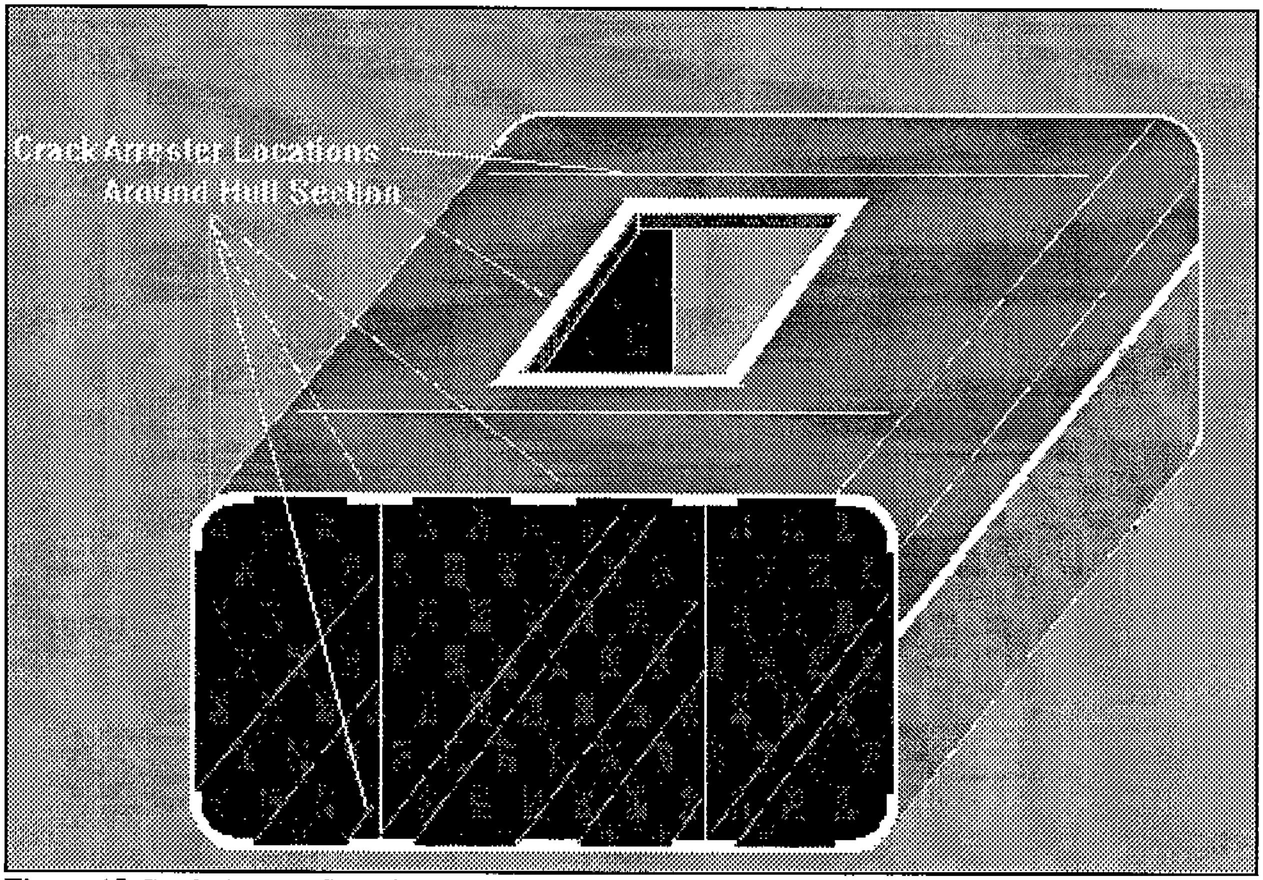


Figure 15 Crack Arrester Locations Around Hull Section

In ships with large deck openings, such as the deck hatch openings in container ships, regions of high stress concentration of torsional and primary stresses exist in the region of the container hold openings at the main deck level. The use of material surrounding these openings is actually a combination of the transverse, longitudinal and riveted type reinforcements acting to minimize cracking around the openings and combings as shown in Figure 15.

VII.4.0 Flaws

From surveys, the most often cited fracture initiation flaws are [33];

- Slag Inclusions

- Material cracks, (delaminations, corrosion cracking...)
- Material/Weld Porosity
- Undercutting
- Lack of Weld penetration

An all too common scenario for fractures is the initiation of a fatigue crack which grows slowly, and, (if undetected), steadily until it reaches critical size for brittle fracture which occurs and fails the detail when conditions are opportune for brittle fracture, ($T \leq NDT$, tensile stress condition, and critical flaw size) [20]. The occurrence of brittle fracture, although minimized through extensive materials testing and improvement, does still occur in vessels operating in cold conditions, (many fractures from surveys occur in northern latitudes in winter), seemingly emphasizing the criticality of thorough inspections during the fall and continuously in the winter to prevent these occurrences.

VII.4.1 Indications

The most useful tools available in the study of fracture in offshore structures, are cracked sections removed from a failed structure (Figure 16). The failure analysis of failed specimens carried out constitutes the data which is most directly used in the definition of construction codes and standards used by the industry. Several key checks can be quickly performed on a broken specimen to determine [20];

- The direction of crack propagation, and thus the general area of initiation.
- The type of fracture, i.e. Fatigue, Overload, Brittle...
- The mode of fracture, i.e. Plastic, Elastic Plastic or Plane.

The indications clearly visible on a <u>fatigue fracture</u> sample include the following [31, 33];

- A "Clamshell" pattern visible on the crack surface, indicative of the slow sequential nature of fatigue propagation.
- Due to the slow nature of the crack propagation, corrosion may be visible on the "older" parts of the crack surface, (lower damage accumulation level).
- Extensive evidence of plastic deformation adjacent to the crack, indicative of the high stress field around the crack root, (ridges somewhat proportional to clamshell pattern).
- Crack oriented normal to a principle stress field.

The indications clearly visible on a <u>brittle fracture</u> sample include [31, 33];

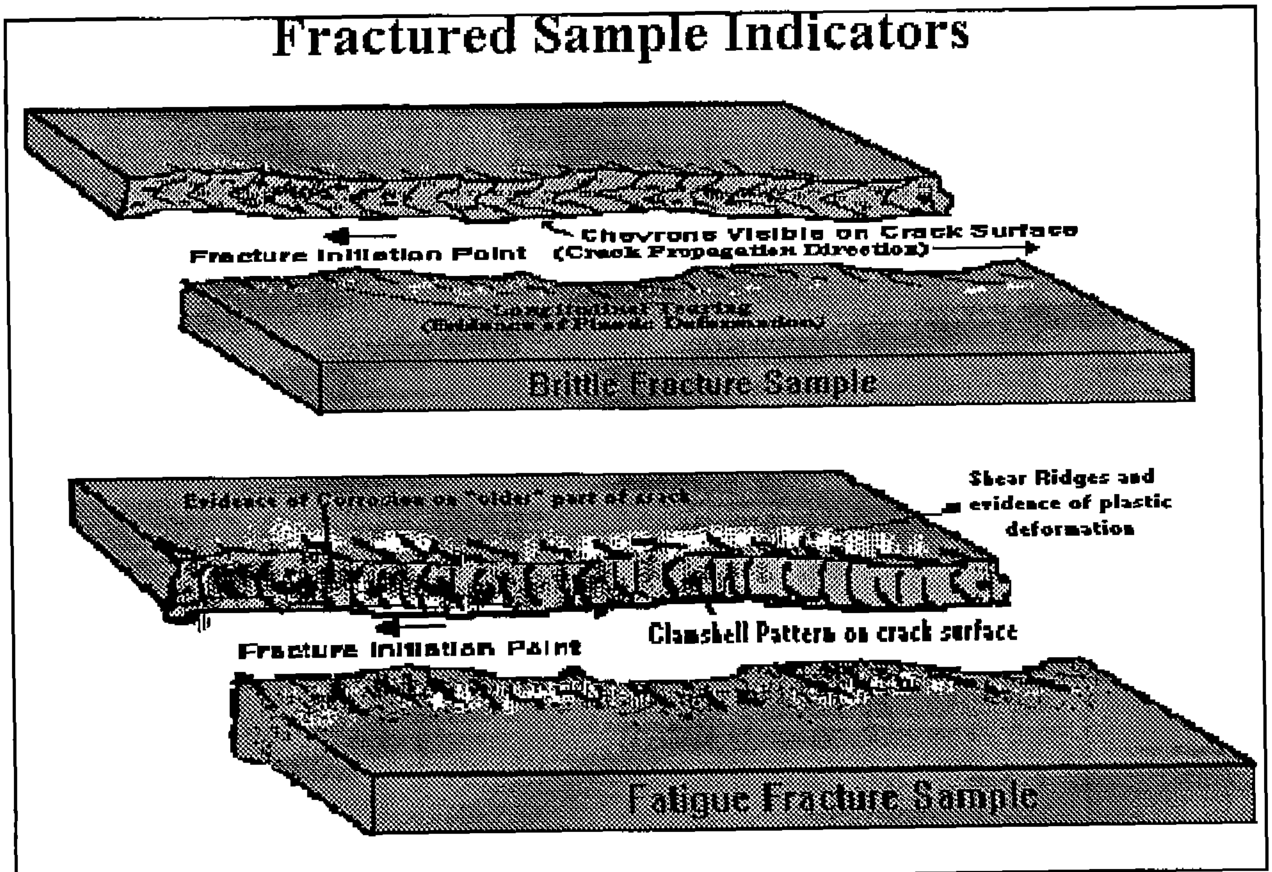


Figure 16 Fracture Mode Identification Sketch

- o Distinctive "Chevron" markings on the crack surface, these chevrons "pointing" in the opposite direction as crack propagation, (towards the initiation point).
- o Clean new crack, indicative of rapid propagation through the material.
- o Little evidence of plastic deformation.
- o Fracture occurrence during a period of low ambient temperature, near or below NDT.

Thus from simple visual observations, important information about the cause of fractures can immediately[27] be deduced. Subsequent laboratory testing provides material composition and exact initiation mode, however the above visual observations can provide the majority of macroscopic fault analysis information.

---

[27] It is very important to inspect the fracture as soon as possible after it's discovery, with efforts made to record all possible pertinent information, since important indications can be masked with time due to corrosion and temporary repairs.

VII.5.0 Brittle Fracture

The brittle fracture failure mechanism became a significant global failure mechanism with the advent of the all welded ship during world war II. Of the 5000 liberty and T-2 vessels constructed during the war, by 1946 200 had experienced serious fractures and 9 had broken completely in two. In 1947 the American Bureau of Shipping, (ABS), established chemical composition guidelines for

Table V Brittle Fracture Prevention Checkpoints

- Service Temp, 0° C is considered to be a safe minimum temp for design purposes, however many, (most) of the failures occur at lower temperatures.
- Residual stresses, increasing the intensity of stresses imposed by normal loading allowing the detail to reach critical stress levels during non critical global loading conditions.
- Design, the inclusion of sharp intersections or detail designs which are prone to welding errors should be avoided.
- Welding, completeness of prep, completeness of fusion, removal of slag, proper weld rods, lack of porosity, and lack of cracking in welds.
- Material toughness, suitable for intended operating conditions.
- Fatigue environment, location in the structure e.g. cyclic stress environment.

ship steels requiring that they be classified not only in terms of strength but in terms of toughness and fracture resistance. Although significant progress has been made in the field of brittle fracture prevention, brittle fracture still occurs in modern ships. Therefore when involved in the maintenance and repair of even quite modern ships, diligence must be exercised in order to guard against this destructive phenomenon. The surest method is to ensure that mechanisms are present to arrest fractures should they occur. The factors which must be considered with respect to brittle fracture are given in Table V [34]. The three most critical initiation factors for brittle fracture are toughness, initiation flaw size and stress level when T ≤ NDT[28], the above additional considerations in Table V affecting the severity of the fracture when these critical criterium are met [26].

The study of fracture mechanics has shown that all the above factors can be interrelated to predict (or design against) the susceptibility of a welded structure to brittle fracture. Fracture mechanics is based on stress analysis and thus does not depend on empirical correlations to translate laboratory results into practical design information. Fracture mechanics is based on the fact that the stress distribution ahead of a flaw can be characterized in terms of a single parameter K_I, the stress intensity factor [KSI/√in]. K_I is a function of the nominal stress, (σ), and the flaw size, (a), which if known at failure can provide the designer with critical flaw sizes to be guarded against in the specification of design tolerances and geometry.

VII.5.1 Toughness Requirements

Material toughness is determined using impact tests which express the materials toughness in terms of the energy that the material can absorb without fractures propagating from various flaw sites. The fracture energy is plotted vs. temperature, which is varied in order to determine the transition or Nil Ductility Temperature, NDT, as sketched in Figure 18 the general appearance of the resulting curves are shown. The energy ordinates are divided into three regions;Plane Strain behavior refers to fracture under elastic stresses with little or no shear-lip formation, essentially classical brittle fracture. Plastic behavior refers to ductile failure under yielding conditions with large shear lip formation. In between these is a transitional region or the Elastic-Plastic region, in this area traits of either or both modes are observed.

For structures subjected to only static loadings, the static curve shown in Figure 18 should be

---

[28] NDT; Nil Ductility Temperature, the temperature below which the material exhibits primarily brittle behavior. Determined by conducting such tests as the Charpy V-Notch, (CVN), which test the impact resistance of notched specimens at various temperatures in order to determine their toughness and transition temperature.

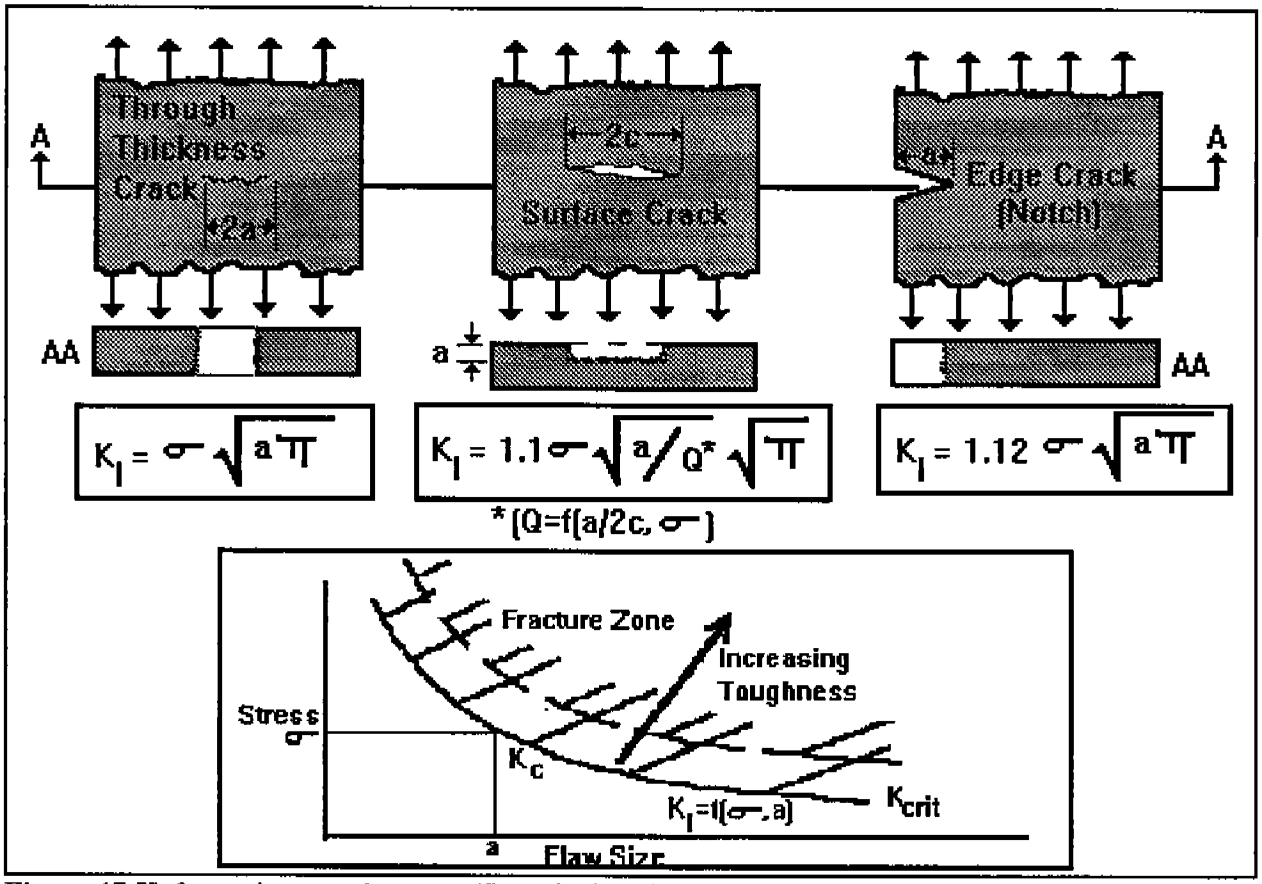


Figure 17 K_I for various cracks, stress/flaw size/toughness curves.

used whereas for dynamically loaded structures the more restrictive impact curve should be used[29]. As shown in Figure 18, the steel used to construct a structure should have a margin between its expected minimum operating temperature and the transition temperature of the steel. Using a reliability based design method to obtain the desired margin, a steel with a curve similar to steel 2 would be selected given the indicated desired performance level.

If at 0°F K_{ID}, (the critical dynamic toughness), is about 60% of the σ_{YD}, (the dynamic yield strength), then at 32°F the ratio can be taken to be about 90%. Using the concepts of fracture mechanics, as well as engineering experience, observations regarding the level of performance at 32°F

[29] Since for a dynamic loading, such as a dropped object the applied force can be twice the object's weight.

for steels and weldments that satisfy the primary toughness requirement of NDT ≤ 0°F and the auxiliary toughness requirement that $K_{IC}/\sigma_{YD} \geq 0.9$ at 32°F:

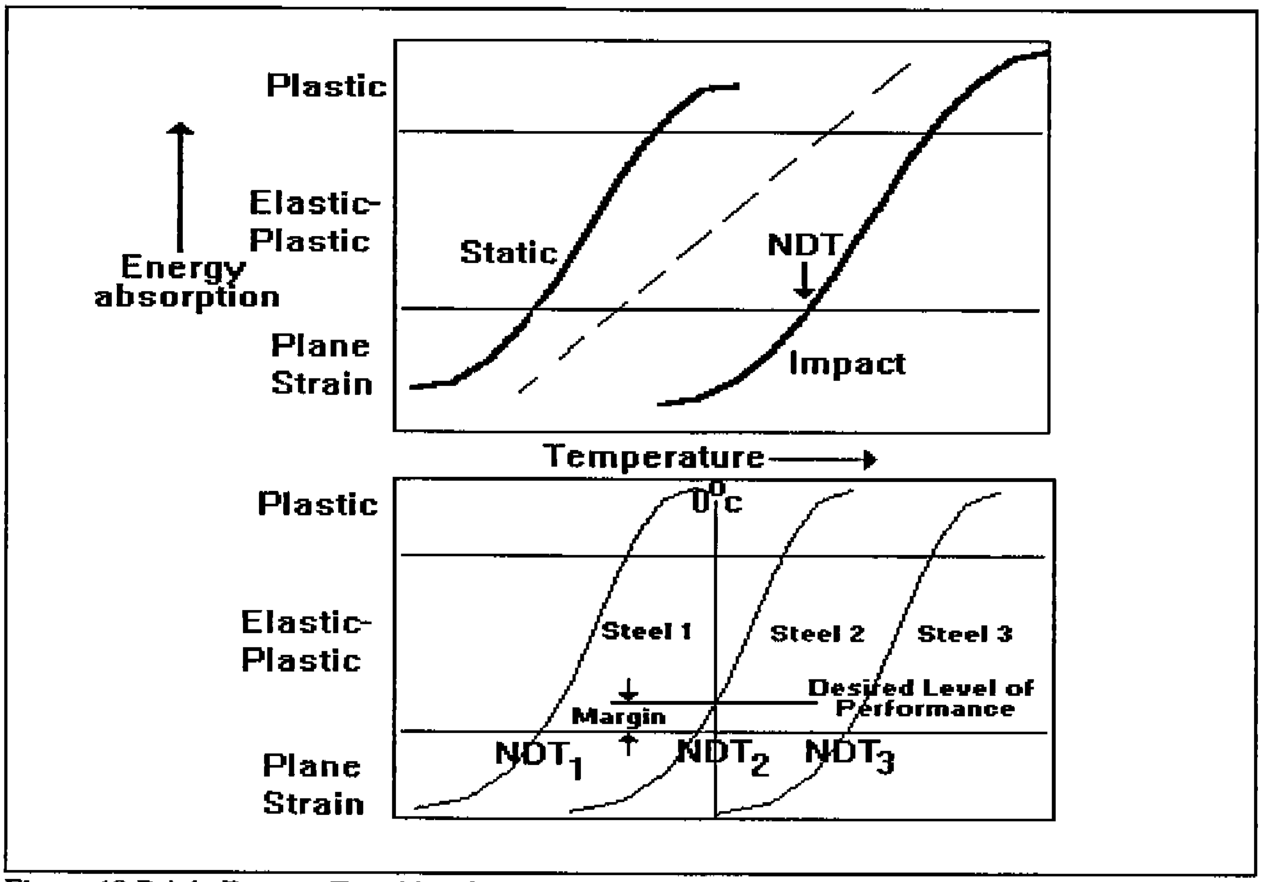


Figure 18 Brittle Fracture Transition Curves

- The start of the transition from brittle to ductile behavior will begin below the minimum service temperature of 32°F. Thus at the minimum service temperature the materials will exhibit non plane-strain behavior in the presence of a crack under impact.

- The material will experience some fibrous fracture appearance at 32°F, an indicator of resistance to brittle fracture.

- Although precise stress-flaw size behavior cannot be made for material exhibiting elastic-plastic behavior, critical crack size for 40KSI steel can be made as follows:

- For $K_{ID} \approx 0.9\ \sigma_{YD}$ and a nominal stress range of 14 KSI the critical crack size at 32°F is estimated to be 8-10 inches.

- For about 24 KSI, (one of the largest primary stress levels ever actually recorded in a vessel), the critical crack size is estimated to be about 3 inches.

- For the worst case dynamic loading of yield point magnitude, the dynamic critical crack size is estimated to be about ½ inch.

For plate thicknesses commonly used in commercial ships, (less than 2 inches thick), the thickness of the plate has a second order effect on the transition temperature of the material, as compared with the first order effects of loading rate and notch acuity. For this reason the testing of less than full thickness samples is acceptable since changes in toughness are very small.

VIII.0.0 Corrosion Considerations

The highly corrosive sea water environment that steel maritime structures are expected to operate for their entire lifetimes is easily the most chemically punishing of any environment in which large steel structures are expected to operate. The highly oxygenated salt water is highly reactive with the iron contained in all mild steels. From the day the structural steel arrives at the shipyard to be used in a new vessel, to the vessel's decommissioning, a continuous battle with corrosion is waged.

There are several methods of corrosion inhibition available for use in the marine environment to retard wastage and subsequent loss of structural integrity. Since the degree of corrosion which occurs on the outer shell, deck and super structure of a vessel is readily apparent due to it's external nature, diligent topsides maintenance can ensure a relatively corrosion free structure in these areas. The internal structure, on the other hand, is often inaccessible to routine inspection due to cargo or remoteness from normal operating areas of the ship. In addition, many of the cargoes carried, (especially in tankships / OBO carriers), can be corrosive, reactive or otherwise harmful to the integrity of the corrosion control system. The ease with which the internal vs. external structural components are blasted, recoated, or replaced constitute tasks with very different levels of difficulty, (and thus cost). Thus the corrosion control systems for the internal structure of the vessel must be of a higher level of robustness than topsides or wetted surface systems.

VIII.1.0 Corrosion Control Factors

VIII.1.1 Tank Washing

Tank washing is carried out whenever a tank is to carry a "cleaner" cargo than was previously carried [35]. In the past tank washing was accomplished using high pressure jets of seawater to clean sludge and debris from the tank surfaces. This practice resulted in the need to discharge contaminated seawater overboard and had very unfavorable corrosion implications. These included;

- Hydraulic erosion near washdown nozzles tended to erode the coating, (High pressures-up to 200 PSI- are needed in order to reach remote areas of the tank).

- The introduction of sea water into the tank means that there will invariably be a small layer of seawater at the bottom of the tank contributing to localized pitting. Beneath this layer of seawater there is usually a layer of salty sludge whose salinity is further increased with each seawater introduction.

- When it is necessary to use hot water to cut the sludge, an even more corrosive environment is created. The washing is beneficial in that it removes any foreign build up from installed zincs enabling them to be effective when the tank is refilled, (especially if it is to be in ballast).

VIII.1.2 Crude Oil Washing (COW)

In order to alleviate some of the problems associated with the use of seawater to clean tanks on tankships, the substitution of a petroleum solvent for seawater has been used to successfully clean ballast tanks of sludge and waxy deposits. The elimination of water and salt from the environment reduces the hostility of the environment during washing and eliminates the continuous introduction of residual non strippable seawater puddles from tank bottoms. The disposal of the washing medium is simple due to the fact that it is merely a fuel oil sprayed at elevated pressures[30].

VIII.2.0 Cathodic Protection

Cathodic protection provides corrosion protection through the attachment of dissimilar metals of lesser nobility, (higher oxidation potential than the structure's metal). The resulting electrochemical cell tends to shed the atoms of the anode, "sacrificing" itself and rather than the base metal, thus protecting the base structure from reduction due to the shedding of it's own atoms.

The longer an anode, the higher the current it will generate, reducing the number of anodes needed. The cross sectional area will determine the anode's useful life. Thus the sizing of anodes must be a compromise between mechanical considerations (keeping the anodes attached, relatively out

---

[30] Due to the spraying of oil into the tank atmosphere, an increased level diligence must be exercised with respect to fire hazards. The use of gas inerting methods in tanks undergoing COW is highly recommended.

of the way, and small enough so that they do not generate high drag forces if mounted externally), and the protection required. The anode sizing for protection is a function of many variables, including salinity, temperature and the condition of any coatings present. The current density requirements are usually expressed in milli-Amperes per square foot or meter, the magnitude required being based on historical data of protection levels vs. corrosion rates. Cathodic protection requirements vary greatly from one structural region to another, with the greatest requirements in areas with large horizontal surfaces. The simple placement of large anodes very near to one another, forming large overlapping active regions, is to be avoided since over protection can cause coating damage.

The anodes can be attached by welding or bolting to attached pads. Although welding is cheaper initially, the use of bolts allows much quicker and simpler replacement.

Cathodic protection provides two basic types of protection, primary and secondary. Primary protection is that afforded by the anodes when installed on bare steel as the only corrosion inhibition system. Using only primary control, corrosion should be limited to approximately 20% of non protected, (bare steel), rate. Secondary control is that afforded by using cathodic protection in consort with a coating system. In this way corrosion in areas of defects which occur in the coating system are protected by the anodes.

The location of the anodes on the vessel requires some consideration as well, on the submerged outer shell anodes are located in a pattern which affords minimum overlapping protection along the entire wetted surface. The anodes are usually aligned as parallel as possible to the streamlines along the ship's hull, minimizing drag force and thus the tendency for them to be sheared off by either hydrodynamic forces or impacts with foreign objects. The placement of anodes within the hull must be done with the levels, types and frequency of fluid types in mind. Since most tanks are never filled completely, cathodic protection will not protect tank tops, which must be protected through the use of coatings. The tank sides and bottoms are areas where cathodic protection is most effective, especially in wing tanks where ballast is often carried [35]. The tank bottoms are nearly always covered with between a few inches to a foot of sea water no matter the cargo[31], thus it is quite common to see anodes mounted on tank bottoms or diagonally on bottom longitudinal webs.

In order for the anode to afford full protection, it must be fully immersed in an electrolyte, (electrically conductive fluid), and it must be clean i.e. no paint or other coatings should be allowed to cover the anodes. This problem is particularly important in cargo/ballast tanks where sediment and waxy build up can form due to the presence of crude on the anodes, (this is another reason tank washing is important before changing cargo types).

There are several metals used for cathodic protection including Aluminum (Al), Zinc (Zn) and Magnesium (Mg). The use of Mg anodes was halted due to both their tendency to spark (due to high driving voltage), and also a nasty tendency of producing hydrogen gas, (which have lead to catastrophic explosive hydrogen ignitions in cargo tanks). Mg also tended to overprotect adjacent areas causing heavy salt deposits around the anodes. Mg anodes were banned for use in cargo tanks in 1964 by the USCG.

Although Al anodes were initially banned for use along with Mg due to theirtendency to arc and spark when attachments failed and the anodes fell to the tank bottom, the aluminum anode has been re allowed under the restriction that an anodes TOTAL potential energy not exceed 200 ft-lbf above the tank bottom[32]. Al is again used due to several advantageous features;

- Self Cleaning: If submerged in waxy crude, not cleaned, and then submerged in seawater, the aluminum anode quickly reestablishes effectiveness.

---

[31] This seawater tends to evaporate between tank fill/pump-down cycles, meaning that the Chloride content of the water concentrates, (the constituent of salt water that is responsible for most corrosion processes;

$$[Na_{+} + Cl^{-} + H_2O + Fe^{++} \rightarrow FeO,(\text{rust}) + HCl + Na_2O],$$

When anodes are present the anode metal ions take the place of the iron ions, due to their higher oxidation potential.

[32] e.g. a 25lb anode can be no more than 8 ft. above the tank bottom.

- High current density: Fewer aluminum anodes will provide the same protection as zinc anodes.

The use of Zinc anodes is by far the most popular and has no restrictions placed on their installation.

VIII.3.0 Adhesive Coatings: General

Protective adhesive coatings are by far the most familiar method of corrosion control, however there are a wide variety of corrosion inhibiting coatings available for use. The selection of the proper system is of paramount importance with regard to long term costs. The selection of a proper system is a function of several considerations including [36];

- Constituency of material in contact with the coating
- pH of fluids in contact with the surface
- Temperature " "
- Reactivity " "
- Type of metal to be coated
- Cost benefit analysis of yard time: i.e. projected high PVC[33]
- Desired hardness of coating
- Environment in which the coating must set-up
- Method of application

The coating of the interior of tankships is of interest due to the highly variable nature of the corrosion environment. A tank may contain crude, gasoline, light fuel oils, kerosene, or seawater ballast at any given time. Of additional interest in this environment is the problem of tank washing, where the tank is cleaned in order to take on a different cargo, enable inspection, or enter a yard period. This operation is hard on the coating due to the hydraulic blast of the cleaning jets and the chemical attack due to the application a cleaning medium.

Easily the most important phase in the application of any coating system is the surface preparation. In order for the coating to properly adhere to the steel, it must be clean, dry and corrosion free. However, as any ship yard knows, full compliance with the above conditions are

[33] If a cheap initial system is used, with projected frequent yard periods, the ever rising cost of hazardous waste disposal (Sand Blasting residue, solvents and spray application) must be kept in mind when one considers a cheap short life system.

nearly impossible in the real world given the complexity and sheer size of most ship coating jobs. In order to come as close as possible to this goal, the most effective method of steel preparation is the use of sand blasting followed promptly by the application of a suitable prime coat. The preparation of any steel surface is basically as above with more or less cleaning approaching an ideal level of "white metal". The Steel Structures Painting Council, SSPC, publishes specific guidelines in the level of surface preparation required as a function of the type of coating to be applied, expected durability and the environment in which the system is to operate [36]. It is usually desirable to remove all corrosion from the surface of the steel prior to coating. This may be quite difficult in the case of in-service ships due to heavily pitted regions or inaccessibility to sand blasting equipment, (again design for accessibility problems). Another problem specific to tankship tanks is the waxy build up on the surfaces due to the carriage of heavy crudes. This build up, if not properly removed, can be driven into the metal during blasting making adhesion of the coating nearly impossible. For this reason special care must be taken in the preparation of internal spaces where this cargo has been carried.

The environment present in the vicinity during the application and set up of the coating is also very important. Manufacturer's specifications for humidity, temperature, ventilation and curing time must be met in order to ensure that the expected durability of the coating is realized. All of the above can be controlled artificially in the interior spaces, but are quite difficult to control on topsides surfaces. Once the coating has been properly applied and cured, care must be taken if the coating is applied to the internal surface of cargo carrying tanks to ensure that initial cargos are not detrimental to the new coating. Manufacturers of tank coating systems will normally specify cargoes which will aid or hider curing of newly coated tanks.

VIII.3.1 Coating Types

There are two main types of coatings used in ship building, zinc based coatings and epoxy type coatings. The zinc coatings are comprised of two categories; organic zinc coatings and inorganic zinc coatings: Organic zinc coatings exhibit cathodic protection characteristics combined with epoxy characteristics. Inorganic zinc coatings are most widely used and again provide cathodic protection. The use of a coating with a high zinc content (≈75 w/o Zn by Vol) serves to protect against high corrosion rates in regions of insufficient coating coverage such as bubbles, light spray areas, and areas which are completely missed during application. The coatings may be either solvent or water based with the prime difference being the curing environment required.

Inorganic zinc coatings have a narrow pH range in which they can operate, (nominally neutral: pH=7 +3/-2). The suitability of zinc coatings for exposure to crude is a function of the sulphur content of the oil. Inorganic zinc coatings are tolerant of the solvent characteristics of the full range of petroleum products, as long as the pH requirement is met. Inorganic zinc coating should not be used for continuous sea water immersion due to it's sacrificial nature, however it is an excellent under coating for anti-fouling and topsides paint. The presence of inert gas systems which use stack gas to displace any formation of explosive gas mixtures in cargo tanks[34], has been known to cause rapid deterioration in zinc coatings if high levels of sulfites are present in the gas.[35]

Epoxy coatings can be broken down into 3 categories, amine catalyzed, polyamide catalyzed and coal tar epoxies. Epoxy coatings attempt to prevent corrosion by creating an oxygen tight envelope around the steel isolating it from the oxygen in the air which is necessary for the formation of Iron oxides Fe_2O_3 (Rust). Epoxies are generally two part products consisting of a base and a hardener, the hardener, or curing agent, is the amine or polyamide in the formula. Amine based products are resistant to petroleum products and salt water while polyamide products are susceptible to

---

[34] Required in all tankships over 70,000 DWT

[35] Can be removed through the use of scrubbers

attack by acids and solvents, with both of the afore mentioned drying to form a hard[36] glossy finish. There are of course disadvantages, firstly the epoxies tend to shrink when curing, which can cause the coating to pull away from sharp edges and corners. The second is the tendency of the formation of pinholes which can lead to local corrosion.

Coal tar Epoxies are quite different from the aforementioned types, they are highly water resistant but resistance to solvents is poor and cargo contamination would result from the transport of refined products in a tank lined with coal tar epoxy. As the name implies, coal tar epoxies are dark which implies inspection problems. One of the main reasons for the avoidance of the use of coal tar epoxies is it's potential health hazards, it has been reported to be carcinogenic by many yards which refuse to work with it.

VIII.3.2 Soft Coatings

Soft coatings are, as their name implies, semi permanent coatings which require very little preparation to apply. The level of preparation required can involve as little as the removal of all scale and sludge from a tank. The soft coatings are applied using several methods, they can be applied using conventional spray techniques which require the emptying of the tank, cleaning and then spraying. They can also be applied using the "float" method whereby the coating is poured over the free surface of water in the tank, then the tank is ballasted up and down resulting in the coating the sides of the tank. The "float" method requires more coating than spraying, but it can be accomplished at sea by ship's company, and also ensures that all areas which will come into contact with the seawater are coated.

VIII.4.0 Full Scantlings

Most classification societies now allow a reduction in required scantlings if approved corrosion

---

[36] It has been suggested that the hard finish is advantageous as it will tend to show material cracking more readily than a 'soft' finish; facilitating more successfull crack detection during inspections.

control systems are utilized. The implementation of this reduced scantling requirement dictates that if the corrosion control system should fail, it must be replaced/repaired promptly to prevent the loss of material due to wastage. If it is not, there is a smaller window of time that unchecked corrosion can be allowed to proceed before structural steel replacement is required by the classification society due to the loss of minimum scantlings to wastage [see Figure 1, page 5].

Most owners opt for scantlings which exceed the minimum allowed for a ship with no corrosion control system, so that loss of corrosion control does not imply rapid deterioration of the structure to a point where steel replacement is necessary.

VIII.5.0 Corrosion Rate Prediction; Polarization Rate Methods

The term polarization as it applies to corrosion refers to the change in open circuit electrode potential as the result of the passage of current. In short, polarization is the change in a metal's galvanic potential,(voltage drop), due to current flow from one metal to another of dissimilar potential, (analogous to the voltage 'droop' observed in a heavily loaded DC circuit). Every corrosion process involves a corrosion potential (**e**) and current (**i**), which are VOM[37] measurable quantities (see Table VI). For a given corrosion process, an **i/e** curve can be expressed as a function of the potential of the process where the inverse slope of the generated curve is proportional to the corrosion rate.

$$i = i_c[10 - \frac{P}{B_c} - 10\frac{P}{B_a}] \qquad (33)$$

Eq(34) shows the generally observed form of the curve where;

i=Applied current density
i_c=Corrosion rate expressed as current density
B_a and B_c are Anodic and Cathodic, (-Q,+Q respectively) constants
P is the overpotential, (difference between the open circuit and the polarized potentials)

At low values of P the corrosion rate can be expressed as shown in Eq (35),

---

[37] Volt-Ohm-Meter, usually able to measure voltage, resistance, and current.

$$R=\Delta\frac{P}{\Delta i}=\frac{(B_a)(B_c)}{2.303\ i_c\ (B_a+B_c)} \tag{34}$$

Where R, the slope of the generated curve of E vs. i, has units of resistance and is inversely proportional to the corrosion rate, i_c.

This method is useful in describing the corrosion process but is of limited use in practical applications since the constants which are considered as such in the derivation are in reality variables which are notoriously unpredictable [37].

VIII.6.0 Statistical Rate Prediction Methods

Statistical corrosion rate prediction methods have a wide degree of applicability in industrial, commercial and laboratory applications. Statistical methods characterize the corrosion process in terms of the end result of the process as opposed to deterministic methods which are concerned with the on

Table VI Practical Galvanic Series

Material	Potential (Volts)
Pure Magnesium(Mg)	-1.75
Mg Alloy	-1.6
Al-Zn-In	-1.16
Al-Zn-Hg	-1.1
Zn	-1.1
Pure Al	-0.8
Clean Mild Steel	-0.5 to -0.8
Rusty Mild Steel	-0.2 to -0.5
Cast Iron	-0.5
Pb	-0.5
Mild Steel in Concrete	-0.2
Cu,Brass,Bronze	-0.2
High Si Cast Iron	-0.2
Mill Scale on Steel	-0.2
Carbon, Graphite, Coke	+0.3

going corrosion reactions involved [37]. The beauty of using a statistical frame work lies in the fact that the results of the corrosion analysis can be used directly in the system reliability formulation. For example once a distribution for the corrosion process of a region is determined, the distribution parameters can be combined through methods such as the algebra of normal processes to determine the subsystem reliability index.

VIII.6.1 Corrosion Induced Strength Loss: Probabilistic Model Development

If the mode of failure considered is that of yielding during bending of the hull girder as a "free-free" beam, it can easily be shown that the strength expression is as given in Eq(36), where:

$$\begin{aligned} S &= F(D, t_f, B, t_w, s_y) \\ S &= N*S_y \approx D*(t_f B + \frac{1}{3} t_w D)*S_y \end{aligned} \tag{35}$$

N	=deck or bottom section modulus
s_y	=tensile strength
D	=section depth
B	=section beam
A_f	=flange area
A_w	=web area
t_f	$=A_f/2B$ =equivalent thickness of one flange
t_w	$=A_w/2D$ =equivalent thickness of one web

When corrosion occurs, t_f, A_f, t_w, and A_w all become functions of time or; $t_f(t)$, $A_f(t)$, $t_w(t)$, and $A_w(t)$, as the structure corrodes. The material thickness can be considered to conform to the expression in Eq(37);

$$T(\tau) = T_o - \sum_{i=0}^{i=\tau} R_{c_i} * (\tau_i - \tau_{i-1}) \tag{36}$$

Where;

$T(\tau)$	=plate thickness at $t=\tau$	[mm]
T_o	=original thickness	[mm]
R_{ci}	=corrosion rate for period 'i'	[mm/yr]

(Eq (37) assumes that the corrosion rates over the life of the structure can be subdivided into blocks of different rates of corrosion each with a constant rate, however for simplicity sake a mean value can be used for calculation of temporal performance). As a result of the constant loss of material with time due to corrosion, the strength distribution expression in the reliability expression becomes a function of time, and as a result, so does the system reliability. Accordingly, the probability of failure will increase throughout the ship's life until, when it reaches a minimum scantlings limit,(as shown in Figure 1), and repair costs become too high, the vessel is scrapped. Eq (38), (the familiar 'MVFOSM';Mean Value First Order Second Moment expression), expresses the reliability index as a (normally distributed) function of time since the system strength distribution becomes a function of

$$\beta(t)=\frac{R(t)-S}{\sqrt{\sigma^2_{R(t)}-\sigma^2_S}}$$

If t=Overhaul period, (time separating overhauls);

$$t=\frac{\beta_{MIN}-\beta_{NEW}}{\frac{\partial\beta}{\partial t}} \tag{37}$$

$(\frac{\partial\beta}{\partial t}$ *assumed linear for example sake.*)

time. This relation shows that as the strength diminishes with time, (with increasing uncertainty due to corrosion non-uniformity), the reliability will decrease proportionally.

Alternatively the strength at time t_o can be multiplied by a corrosion rate factor, k_c, (effectively the same procedure as Eq (38)), which is also a random variable, to account for a specific reduction in strength at a certain time in the vessel life.

Another approach is to consider the effect of corrosion which does not result in a time dependant strength is to take the total plate thickness as the sum of the thickness required for limiting stresses, t_n, plus a thickness for corrosion allowance, t_c as shown in Eq (39);

$$t_{min}(@\ BOL)=t_n + t_c \tag{38}$$

which, if expanded about mean plating thickness, yields the COV of the plate thickness over the expected life of the piece as shown in Eq (40).

$$\delta_t^2=(\frac{t_n}{\underline{t}})^2 \cdot \delta_{t_n}^{\ 2} + (\frac{t_c}{\underline{t}})^2 \cdot \delta_c^2 \tag{39}$$

Where the lower case deltas represent the Coefficients of Variation, (COV);

δ_{tn}	=COV of plating thickness due to production tolerances
δ_c	=COV due to corrosion
$\underline{t}_i$	=mean thickness for corrosion condition 'i'

For most ship owners it seems that the addition of a corrosion margin in concert with a high quality corrosion control system is considered an inexpensive method of ensuring that catastrophic failures due to wastage, or loss of revenues due to unscheduled repairs are unlikely to occur.

This Page Intentionally Left Blank

IX.0.0 Corrosion Survey Methodology

The periodic inspection of a vessels structure is necessary in order to determine fitness for continuing service and/or the estimation of the expected time until repairs are required. Although certain structural problems such as cracking are difficult to detect, the detection of corrosion is simple due to its omnipresence and highly visible nature throughout the structure. The difficulty lies in the prediction of average and specific local corrosion rates throughout the structure. Due to the ever changing environment that the ship structure is subjected to, corrosion rates tend to be very erratic. The tanks in a tankship may at any given time contain seawater, crude (sweet or sour[38]), gasoline or light fuel oil, all of which have vastly different corrosive properties.

Inspections are performed in order to satisfy two basic requirements; those as required by a vessels owner in order to access the condition of the ships corrosion protection systems, attain data for estimation of corrosion rates and estimate the time remaining until repairs are required. The other type are the inspections required by a classification society or other regulatory body to determine if the structure (plates and shapes) requires renewal as part of the evaluation of fitness of the vessel to conduct safe operations.

IX.1.0 Survey Results

Although it is difficult to estimate corrosion rates from historical survey data, it is possible to establish corrosion *patterns* throughout the structure. In specific regions of similar vessels trading on similar routes, and of comparable age, corrosion patterns should be quite similar. The patterns of corrosion can also be correlated to the type of coatings used. These general categories of corrosion observed in ship structures are;

---

[38] The terms "sweet" and "sour" crude refer to the sulfur content of the oil, "sour" crude having a high content of sulfur and thus a "sour" aroma. The effect on corrosion rates has to do with the tendency to form sulfur based acids when exposed to water including: H_2S, HSO_3, and H_2SO_4, these acids having obvious detrimental effects on any lightly protected steel in the tanks.

- General corrosion, or the large scale formation of rust over a significant area;

- Pitting corrosion, which is characterized by the localized attack of the base metal resulting in the physical pitting of the material.

- Crevice corrosion, which occurs along paths of high water flow or along creases or welds in the structure.

Many operators view pitting corrosion as the most detrimental due to the possible of loss of membrane integrity and the possibility of fatigue cracks initiating from pitting sites. The most prevalent general corrosion locations seem to be within the splash zone where seawater continually wets the area yet the complete immersion of the area is slight. General corrosion is prevalently a surface type of corrosion which does not pose significant structural risks unless left unchecked over a long period of time. If this happens deep scaling can occur which can flake away leaving fresh material to corrode again rapidly, this scenario is indicative of a major loss in material which if located in highly stressed regions can lead to major structural failure. Pitting corrosion tends to occur in areas where water is trapped and allowed to stand such as tank tops, side shell longitudinals, bottom shell plating and other horizontal surfaces such as bottom longitudinal flanges.

Local loss of structural integrity in highly stressed areas maybe critical with respect to global integrity especially when local stresses arise from primary loads. For this reason a high degree of scrutiny must be paid to any loss of effective scantlings in the vessel's strength decks or bottom structure which unfortunately are hot beds of corrosion [38, 42].

IX.2.0 Corrosion Data Utilization

The accumulation of corrosion data is the primary tool available to the structural engineer in the estimation of corrosion margins and reevaluation of older structures which have under gone significant material loss to corrosion[39] [38]. The evaluation of corrosion margins is of use in determining the validity of the assumptions made in the design stage, allowing the future use of margins which are more representative of actual corrosion COV's.

Margins are specified by classification societies either as nominal constants or as functions of new steel dimensions. ABS adds a corrosion allowance to the material thickness of the required scantling dimensional formulae and requires hull thickness gagings and renewals based on percentage wastage limits for the various location. The USCG wastage limits are based on an "Average" wastage of 20 percent. Normal wastage allowances before structural steel replacement is required range from between 15 to 30 percent, the exact figure being a function of frame spacing, ship type, age, and the structural component in question. In practice, the plate thickness that the wastage limit is based on the ABS rule required thickness at that location [39].

A more specific use of corrosion data with respect to general corrosion average wastage is the reevaluation of the buckling strength of panels with in plane loading regimes.

$$\sigma_{CR_{BUCKLING}} \approx \frac{\pi^2 * E}{12(1-M^2)} * (\frac{t}{b})^2 * K \tag{40}$$

Eq (41) is the familiar, [37], expression for the critical plate buckling stress where;

t= Plate thickness
M= Poisson's ratio
b= Unstiffened width
k= Plate aspect ratio
E= Young's modulus or the modulus of elasticity

The significant point here is that a reduction in effective material thickness has a second order effect on the ability of the plate to accept in plane compression loads without failing. This example

---

[39] This is a growing area of interest amongst owners of offshore systems which are nearing or have reached the end of their design lives. The re-qualification for service of older structures which are operating in marginally favorable trade can mean high profitability for it's owners since it's value has been depreciated and operating costs are well known.

emphasizes the criticality of any loss of material which is considered effective in the section modulus calculation. Considering that bottom shell and deck plating maybe subjected to buckling loads, and that these areas are highly prone to material loss due to corrosion, (with the bottom plating being the most affected)[40] significant changes in the primary strength can arise due to seemingly small amounts of material loss in these areas.

Only very rudimentary models for the prediction of the loss of strength due to pitting corrosion exist. One of the most intuitive models uses the uniform distribution of an average pit from inspection data to create a mesh arrangement of pits which is analyzed as a homogenous plate of reduced thickness consistent with the mesh model's loss of material as expressed in Eq (42).

$$T_{REDUCED} = \left(\frac{T_o A_{plate} - \rho_{A_{PIT}} V_{PIT}}{A_{plate}}\right) \tag{41}$$

Where;
$T_{REDUCED}$= ***Reduced plate thickness with uniform pit distribution***
A_{plate}= ***Plate area***
$\rho_{A_{PIT}}$=***Average area density of pits***
V_{PIT}= ***Average volume of pits***

Pits are also considered as cyclic stress fatigue failure initiation sites since crevices around the pit can act as notches from which cracks can propagate, an additional important motivating factor in

---

[40] For example a uniform 10% reduction in bottom plating will cause a 30% reduction in it's effectiveness in the section modulus calculation due to the third order effect of the plating's thickness on

$$SM = \sum_{i=1}^{n} \frac{I_{ZZ_i}}{\sqrt{(Z_{NA} - Z_i)^2}}$$

Where;
Z_{NA}=***Height of neutral axis***
Z_i=***Height of i_{th} component***
I_{ZZ_i}=***Second moment of i_{th} component about it's horizontal centroidal axis.***

it's horizontal second moment. This can increase stresses and subsequently significant reductions in the margin to buckling.

the minimization of pitting.

IX.3.0 Corrosion Surveys

Previously three types of corrosion were mentioned, general, pitting and grooving, but in order to be precise, there are actually eight (8) corrosion classifications that can be identified in steels. These include;

- General
- Galvanic
- Crevice
- Pitting/Grooving
- Intergranular
- Selective leaching
- Velocity corrosion (Erosion)
- Stress corrosion cracking

Although there are certain overlaps in the mechanisms of all of the above regimes, definite differences do exist in each, each with specific consequences.

The gathering of corrosion data must be well planned and executed to ensure that pertinent and useful information is obtained. This planning should include but is not limited to;

- Determining the extent and location of inspection
- Logistical plan for minimizing time within the structure
- Detailed emergency plan, with immediate actions required committed to *memory* by all those involved
- All necessary equipment located and on hand
- Peculiarities of the particular vessel reviewed with a company Naval Architect
- Instrument calibration verified

IX.4.0 Corrosion Locations

A.Bottom plating: Experiences the greatest wastage as a result of sea water collection and settling.

Types of corrosion observed include;

- General: In uncoated areas or areas where the coating has been damaged, and in areas where inorganic zinc has been used light general corrosion is observed.

- Pitting and Grooving: In areas where Coal tar epoxy was used, presents a real hazard of bottom penetration.

- Grooving; In areas of high flow due to cutouts and between bottom longitudinals. Heavy pitting is observed on horizontal members or geometries that catch and settle i.e. at the top of the joints between side longitudinal webs and side shell plate near the turn of the bilge.

B. Side Shells: as mentioned above, the most severe corrosion near the side shell plate is in areas where sea water can collect and settle. Corrosion of the side shell is usually initiated at welds and sharp edges.

C. Deckheads: General corrosion usually appears at the connections of the deck longitudinals to the deck. The upper regions of tanks need a coating system since zincs aren't effective in the ullage space, this is a very condusive environment for wastage should the protective system break down. In addition in ships which use a stack gas inerting system in their tanks H_xSO_y's present can form extremely corrosive acidic solutions which can rapidly degrade unprotected steel. For these reasons, the upper sections of cargo tanks need be coated with a high quality coating system resistant to harsh atmospheric conditions.

D. Special Locations: In any particular vessel areas which tend to corrode rapidly will appear requiring extraordinary controls and attention. Many times these areas can be controlled by simply rearranging drainage such that the area loses any tendency to collect corrosive sea water, changing the extent of corrosion protection afforded the area, or reevaluating the expected life of the sub structure.

X.0.0 Inspections

Perhaps the most critical factor involved in the assurance that structural integrity is maintained is the thoroughness with which a vessel is scrutinized by her crew on a routine basis, or by specialized Inspectors during less frequent scheduled or unscheduled inspections. Although the cost of inspections can be relatively high, that cost throughout the ship's life should be more than offset by the savings in unscheduled major repair costs when an assembly actually fails rendering the vessel unserviceable or in need of immediate unscheduled corrective maintenance[41] [40].

The frequency of inspection varies from semi-continuous observation of the ships' performance by her crew to the required periodic inspections by port authorities, classification societies, and the Coast Guard required to ensure specified reliability level over the ships' life.

X.1.0 Design Checks

The inspections carried out during the new-build or overhaul phases are critical with respect to the expected robustness of the structure throughout it's remaining lifetime. The most optimal time for inspection is during the process of assembling a new or repaired detail, since inspections can be performed prior to installation of interferences such as piping, wiring and machinery. Since newly completed structural components have experienced very little, (if any), material loss to corrosion or fouling build up, (which would tend to mask faults in the steel or connections), [41] this is the best time to ensure that high quality, [see section II.2.1[42]], assembly is achieved. In order to minimize the corrosion damage of details throughout the vessel, the quality of the initial application of coatings over bare steel is perhaps the most critical factor involved in the minimizing of the probability of future

[41] The intent of the performance of periodic scheduled preventative maintenance is to detect and monitor possible faults, noting them and preferably scheduling their correction for accomplishment during a scheduled availability of the vessel.

[42] Regarding delays necessary in order to allow any delayed cracking of weldments to occur.

repair costs due to wastage. The preparation of the steel, selection of a proper coating system, a uniformly high quality application, and subsequent inspection of the coating coverage and quality is of paramount importance in the production of a minimum maintenance vessel.

The fitting up of sub assemblies should be given special attention to assure dimensional accuracy, in order to prevent misalignment with adjacent assemblies which when forced into alignment will introduce un-necessary stress.[42]. Many of the inspection responsibilities should, if possible, be delegated to site supervisors in order to minimize work stoppage while waiting for inspectors to approve minor construction completions prior to further work progression. However, certain construction milestones should be Inspected by specifically designated personnel representing the yard, owner or classification society in order to minimize flaws due to "tunnel vision" of on site personnel.

X.1.1 Inspection Milestones

X.1.1.a Planning

During the design, construction and acceptance phase of the vessel's life, a thorough and detailed inspection/QC plan should be designed and approved prior to any actual progress on the vessel's construction. Ideally, in order to minimize possible delays in the initiation of work, a somewhat standardized inspection plan should be established which can be modified in order monitor and assure the quality of any job undertaken by the yard, (with non applicable steps deleted from simpler jobs or details added to larger jobs[43]).

X.1.1.b New Construction

Although not directly related to the maintenance of existing ships, the motivation for an inspection plan in a new-build setting has instructive value amenable to the inspection and repair of existing vessels. The cost involved in any significant structural repair of a vessel dictates that it be

---

[43] As determined by the site level III inspector, (see page 115).

performed as expeditiously, expertly and as permanently as possible.

An analogous concept of an iterative monitoring/inspection system is familiar to the Naval Architect in the iterative design process used during ship design, wherein the design is modified when it is determined that it has fallen short of minimum design requirements. When it is determined that the design meets all the specified checkpoints, i.e. deadweight, speed, strength, constructability, cost etc., it is carefully reviewed and either approved, or sent back to the design department for the indicated revisions. This system is obviously different from a construction scenario in that the design is changed to meet requirements prior to any actual physical structural work. In the yard setting, the design is essentially complete with inspections intended to assure conformance to the design.

This design iteration/review process is of interest to those dealing with existing vessels in that if requirements such as accessibility to welders and inspectors at any time before, during or after work completion, are not met, it should be possible, (and indeed encouraged), that suggestions regarding revisions of the plan be made in an expeditious manner. The attitude that if a structure can be built, it can be inspected should not be assumed, blind spots and sealed voids are to be avoided due to their potential as sites for undetected structural failure[44]. The attitude that plans are to be carried out as specified, even though there are obvious problems which will need attention later, should be discouraged with available channels of communication open between the design office and the shipyard.

Some of the checkpoints that should be met during the design (or refit/repair planning) phase should include [40]:

- Degree of attention paid to accessibility to all details
- Degree of redundancy
- Care in selection, specification, and procurement of materials

---

[44] The term "Structural Failure", indicating any unplanned or potentially damaging condition present or impending within the stress bearing framework, shell plating or ship's machinery. Which is to say it includes anything from coating failure to plastic deformation or fracture of structural members.

- Quality of materials delivered (Receipt Inspection)
- Effectiveness of inspection plan
- Efficiency of defect initiator correction plan (thoroughness of fault analysis)
- Procedure for modification of ship's plans if during construction it is found that modifications are required
- Conformance to Classification Rules
- Proper notification of all concerned bodies
- Effect on adjacent structures
- Logical definition and inclusion of uncertainties in calculations

X.1.2 Structural Analysis

During the evolution of a structural design, the loading preliminary stress analysis should reveal areas of high stress which should, during the next design iteration, result in increases in local scantlings. This strategic increase in local scantlings allows the acceptance of a higher local loadings without unreasonably high stress levels. The goal being the development of similar stress levels in areas of high loading to those experienced elsewhere in the structure[45]. The "Structural Integrity" of the vessel can be expressed somewhat simplistically as a function of the distribution of materials and of structural redundancy, or the degree of indeterminacy built into the ship [43]. Both of these factors are of particular interest when formulating the inspection plan for the vessel, since regions of unavoidably high local stress, (where either space, weight or cost considerations preclude the use of heavier scantlings), are usually the first areas to indicate damage accumulation, which in turn give a good indication of the degree of loading that the ship has experienced up to the time of inspection[46]. The updated level of microstructural damage accumulation can then be used to update the predicted fatigue life of the detail, indicating the need for inspection schedule modification, (updating of

---

[45] Accordingly, in areas that are found to experience low loading levels, scantlings can be reduced. As a result, the total material weight can be kept to a minimum through lightening some and building up other strategic areas.

[46] Indicating the severity of conditions that the ship has experienced up to that time, and as a result the damage accumulation level. Since the initial inspection timetable is based on an assumed loading pattern, the vessel's actual damage level may be indicative of more or less severe loadings requiring either earlier or less frequent monitoring.

probabilistic inspection plan).

The structural redundancy increases the reliability, in that failure of the entire system is highly unlikely as a result of the failure of a single element. However, if damage is detected in a redundant member, adjacent load sharing members should be closely examined in order to determine if they too have been damaged requiring either reenforcement or replacement.

When a Probabilistic design format is used, a target reliability level is specified which defines the maximum acceptable risk level, (Probability of Failure), at which it is considered acceptable to operate the ship. Since the strength of the ship slowly decreases with time, (due to corrosion, fatigue damage accumulation and general wear), accordingly the reliability level also decreases. When the reliability is determined to have reached the afore-mentioned minimum level, the ship must undergo a structural survey, (and overhaul if required), which will allow a reevaluation of the reliability through the reduction of uncertainty of the structural condition of the vessel [Figure 1]. This procedure extends the life by shifting the reliability level upward, above the minimum, due to the determination of structures actual vs. predicted level of soundness. This new reliability level will never be as high as when the vessel was new, which means that at some point when it is determined that the cost of overhauling an old ship to maintain it's viability as a commercial venture becomes too high it is simply scrapped.

Of critical importance in the performance of a numerical structural analysis, is the review of the results of involved computations. If the model, the analysis method, the imposed loads, or mathematics are in error the value of the work is nil. In particular, the FEM which has gained acceptance as the standard by which details are analyzed can easily be misused by the introduction of errors in the assumption of boundary conditions, mesh size, or material properties. Thus the proper procedure in the use of sophisticated structural analysis methods such as the FEM must include [44];

- Verification of loads

- Verification of boundary condition assumptions
- Checking that geometry is correct
- Appropriateness of mesh size, (are regions of stress concentration likely to be "hidden" in a coarse mesh?)
- Verification of material properties
- Testing the accuracy of analysis programs with benchmark problems

In summary the performance of a structural analysis consists of the adoption of a geometry, the determination of the geometry to applied loads and the evaluation of the response with respect to acceptable standards. This is a crucial step in the design/planning process, however without careful scrutiny of the steps involved, a GIGO[47] loop can be easily established with possibly disastrous results. The results of an accurate structural analysis provides a good basis for an initial in service inspection plan, in that critically high stressed regions can be identified for routine inspections.

X.2.0 Construction Phase

X.2.1 Receipt Inspection

Prior to commencing with the cutting of plate and framing elements, and the erection of modules, a receipt inspection of delivered materials must be carried out. The cost of receipt inspection can be minimized by utilizing random sampling methods on specific "Lots" or "batches" of material and statistically predicting the variability of material properties about specified nominal values. The material should be color coded so as to minimize the incorrect use of material once it has been accepted from the mill. Receipt inspection checkpoints should include;

- Dimensional Accuracy
- Surface Defects
- Plate Lamination
- Grade

X.2.2 Construction/Overhaul/Modification Inspection

The inspection plan should identify as specifically as possible the frequency and scope of

[47] Garbage In Garbage Out

inspections to be performed throughout the yard/construction period. Over inspection of construction will slow progress and drive costs up unnecessarily, however under inspection of the process may allow flaws to leave the yard undetected and impose unplanned repair costs on the vessel far costlier than the correction of errors while the ship was still in the yard with equipment and yard personnel on board[48]. As mentioned previously, the self inspection philosophy should be used to the maximum extent possible given the yard's record of quality and the size and type of vessel being built.

Specific customer needs should also be addressed in the inspection plan, as nearly all owners will have "Pet" requirements which may seem trivial to the yard and designers, but may mean the difference between a cordial and adversarial relationship between the two parties. If early problems are identified and corrected expeditiously, the confidence level that the owner has in the yard will increase, which will tend to persuade the owner to place more responsibility in the yard's hands further expediting construction and reducing costs.

In process inspection during subassembly, assembly and erection should in particular check for the following [38, 42]:

- Completeness of details,
  (Welds: Slag removal, Fusion, Complete;
  Structure: Correct scantlings, Correct geometry, Correct Placement; Coatings: Preparation, Coverage, Type)
- Materials are correct
- Accuracy of fitup (all assemblies within tolerance, minimum of "jacking" of components into place)
- Preparation: Preparation is of paramount importance with respect to any operation to be performed, be it welding, cutting, fitting up, equipment installation or especially the application of the coating system.
- Welding: Weld Type/Method/Quality
- Detail Conformity with Plans
- Proper Support for Construction Equipment
- General Workmanship
- Calibration of Cutting Equipment
- Clear definition of Datums used to align sub assemblies
  (Actually this should be ensured during planning stages)

---

[48] Very critical with regard to yard reputation, one of the intangible costs of doing business.

o Application and curing of coatings per manufacturer's specifications

X.3.0 Inspection Archiving

A continuous log of inspection results should be maintained as part of the ship's record. Results of structural inspections should be distributed to the ship's owners, the yard and the classification society charged with classing the vessel. Of primary importance in the assurance of structural integrity, is the prompt transmission of inspection results to the cognizant structural engineer. When structural deficiencies are found this information is imperative in order for prompt expert advise regarding recommended corrective action in light of the results of analysis of the failures effect on the global structural safety.

All inspection results should be statistically analyzed in order to detect trends in the performance of certain details and enable the design office to track the efficiency of all aspects of the design.

X.4.0 In Service Inspection Program

At the vessel's completion of a yard period, be it post newbuild or overhaul, the inspection plan should be reviewed and updated to reflect any changes in the vessels structure which may weaken or strengthen it, dictating more or less frequent inspection intervals. Changes in the inspection plan should in particular give instructions to the crew identifying critical areas to be watched and logged during all ship's operational periods. This is an important point since, as mentioned previously, the ship's crew is able to continuously monitor the behavior of the ship in it's element and is thus most able to note subtle changes in it's characteristics. When the crew is unable to access a suspect area, they are the people best suited to schedule inspection during availabilities such that ship operations are interrupted as little as possible.

X.4.1 Specific Detail Inspections

X.4.1.a Longitudinal Stiffeners

Longitudinals are joined using two different joints, firstly the joint between the plating and the stiffener is a fillet weld, and secondly the joints between stiffener sections are butt welds. Historically the butt welds are very robust and have not been known to fail [45]. The fillet welds have been known to fail due to the tripping of the longitudinal, (transverse shear failure, in vertical planes adjacent to the welds-see chapter IV), and due to secondary bending of the plating structure between transverse members, (Longitudinal shear failure and vertical sear failure depending on the severity of the secondary deflection).

Considering the above statements, the inspection of hull longitudinals should concentrate on the fillet welds between the longitudinals and plating, especially if heavy plate is used such as that in the box girders of container ships.

X.5.0 Survey Results

Although it is difficult to estimate corrosion rates from historical survey data, it is possible to establish corrosion patterns throughout the structure. In specific regions of vessels of common type route and age, corrosion patterns are quite similar. The nature and patterns of corrosion can also be correlated to the type of coatings used. The typical types of corrosion observed are those of general corrosion, or the large scale formation of rust over a significant area, pitting corrosion which is characterized by the localized attack of the base metal resulting in the physical pitting of the material, and thirdly, crevice corrosion which occurs along paths of high water flow, along creases, or welds in the structure. Many operators view pitting corrosion as the most detrimental due to the possibly of the loss of membrane integrity and possibility of fatigue cracks initiating from pitting sites.

This Page Intentionally Left Blank

XI.0.0 Non Destructive Testing

XI.1.0 Purpose

The performance of Non Destructive Testing (NDT) would not be necessary if it could be proven that 100% of all the materials, connections, and design assumptions used in the design and construction of a structure were flawless. Since this is not the case, it is necessary to test components of a structure to ensure that specifications and requirements are met. NDT is accomplished by using a wide variety of methods and equipment ranging from simple visual checks to sophisticated high energy particle testing of critical welds in a structure.

XI.2.0 Scope

The degree or thoroughness with which a particular subassembly is inspected is in direct proportion to it's perceived criticality in the structure and/or the type and frequency of flaws commonly encountered in the particular detail type [46]. The degree of confidence required of a particular subassembly, dictates the inspection method(s) used to evaluate the detail since the cost of inspection can be quite high when highly skilled inspection personnel are required to perform complicated inspections, i.e. radiography.

In a welded steel structure the most critical and thus most inspected part of the structure are of course the welds. There are literally miles of welded joints in a modern vessel, with a large percentage being critical to the structural and watertight integrity of the vessel.

Since the emphasis of this report is directed towards maintenance of existing ships, the inspections of interest are those performed either as preventative, post abnormal loading, (collision, storm, post-fracture etc.), or post repair. The inspections carried out on a routine basis would fall primarily into the preventative category. This type of inspection is performed somewhat continuously by an alert crew operating the vessel. Scheduled preventative maintenance is usually performed on subsystems which are heavily loaded, inaccessible during normal operation or on assemblies which have been recently repaired or modified in order to evaluate the performance of the repair over time. Scheduled preventative maintenance is done in such a way that specific personnel must take responsibility for the results of the inspections and are thus held accountable for inspection results. Corrective maintenance inspections should be conducted in an even more formal manner than that of preventative maintenance inspections. In this case, more documentation is required, more steps are required, and higher authorities must be notified of the results. The procedure should include at least three (3) separate inspections [47];

- A *pre-repair inspection* should be performed to determine the extent of damage, the condition of surrounding components and any other conditions pertinent to necessary failure analysis.
- The structure should be *inspected prior to actual repairs*, but after all preparations have been completed. This condition being met by the removal of all damaged steel, all corrosion and coatings, insulation, machinery and interferences removed, and necessary materials needed to complete the repair present. Depending on the cause of damage, the proposed repairs should also be approved by qualified personnel,(engineering analysis completed), prior to the actual repair being initiated, (this being absolutely necessary if the failure was as a result of normal loading resulting in the need for the addition of material to reenforce the area).
- Lastly a post repair inspection should be completed including all inspections necessary to verify the soundness and conformity of the repair, a verification that all the pertinent information has been recorded in the vessel's records, that the classification society has been notified and approves of the repair and post repair checks, and finally that all equipment or structure removed has been replaced and properly preserved.

XI.3.0 Personnel Qualification

As in most jobs which require the completion of tasks requiring definitive levels of skill and competence, certain personal qualification requirements must be met by NDT personnel. This in itself is a form of preventive maintenance, ensuring that personnel performing the testing have been tested and certified to perform according to the standards of the most recent published standards as set forth by the ASTM [48].

There are three levels of NDT qualification for Inspectors depending on experience and knowledge level [48, 49]:

- NDT level I Level I personnel are certified to perform the testing only, he is responsible to a level II or III inspector.

- NDT level II Level II personnel are also qualified to perform tests but in addition he is certified to set up and calibrate the equipment, evaluate the test results and compare them with established codes or specifications as set forth by the level III inspector.

- NDT level III A level III inspector can in addition to the above, is qualified to interpret codes, establish techniques and design a particular set of inspections in order to satisfy particular codes. He is responsible for supervising level II and III personnel, and ensuring the establishment of maintenance of their proper qualification levels. Usually a shipyard will have only one or two level III personnel responsible for all of the above, with the title of NDT manager or head.

XI.4.0 Methods of Non Destructive Testing

The focus of this chapter, as mentioned above, is the testing for the level of integrity of the materials and welds in the structure. The inspection of the condition of steel and corrosion control systems is discussed in chapter VII.

The goal of NDT for welded connections is the assurance that the strength of the welded connection is as close as possible to that of the surrounding material, and more specifically that defects which might initiate cracking are minimized [49]. Specifications and checkpoints for proper weld profiles are the main assurance of the strength of a weld and are discussed in chapter II. Thus the main goal of weld NDT is to check for the existence of cracks which are not visible or may not be at the weld surface. The following is a brief discussion of the basic methods of NDT for welds, assuming that the weld beads meet the standards of the American Welding Society guidelines for the connection in question. Several excellent guides have been published by the SSC for the interpretation of inspection results provided by qualified NDT personnel, most notably; SSC177/213/245 [48, 49, 50, 51], which contain excellent summaries of joint types, flaws and the inspection methods used to detect them.

XI.4.1 Radiography

The methods used for Radiography should always conform to the latest published guidelines of the American Society for Testing and Materials, (ASTM). All activities certified to perform radiography should have the latest copies of the guidelines available for review and "in hand" when radiography is being performed. In addition to the actual testing procedures, all applicable radiological precautions must be strictly adhered to as specified by 10 CFR 20[49] and the cognizant activities' local radiological controls instructions.

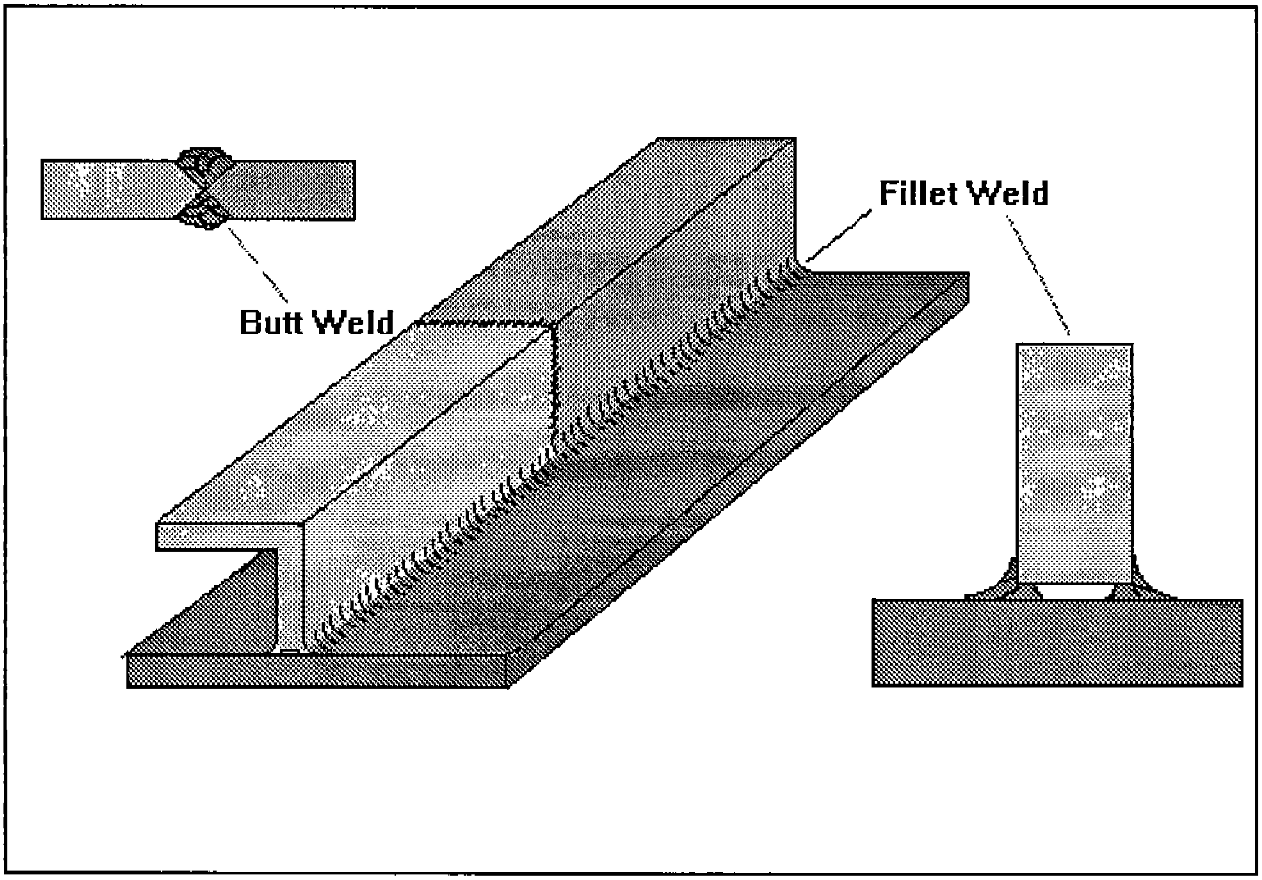


Figure 19 Weld Joint Geometry Sketch

Radiographic testing enables the inspector to see "inside" the interior of the weld and to check

[49] Federal Guidelines for Exposure limits for Radiation and Non-Radiation workers.

for possible failure initiation sites. The method is quite expensive and demands very tight controls due to the use of high energy particle emitting isotopes or powerful electromagnetic fields. For these reasons the method is usually used to examine the most critical welds.

Radiographic inspection is accomplished by placing a radiation sensitive film cartridge on one side of the weld, and a radiation emitting isotope source or "X-ray" generating device on the other side of the weld. The source or machine is subsequently exposed/energized for a predetermined time, dependant on the material thickness, generating an image of the interior of the weld on the film cassette. This enables the inspector to determine weather flaws exist within the weld with almost absolute certainty. SSC245 [48, 49] contains photographs of common flaws to be aware of when examining Radiographic images of welds. The inspector should be well trained to identify any abnormalities in the images.

XI.4.2 Magnetic Particle Testing

This method is used to identify near surface or surface cracks in welds of ferro-magnetic materials. The method involves the scattering of ferrous powder over the area to be inspected and observing the patterns that result when a magnetic field is generated in the test specimen. Flaws are detected by the formation of distinctive patterns on the surface indicating the existence of near-surface or surface flaws, these patterns being formed by the migration of the particles to the location of discontinuities attracted to the strong leakage of the magnetic fields in these areas [52].

The magnetic field is generated in the test specimen using either magnets or high current low voltage probes [50] in contact with the metal. Most often a portable high voltage generator with attached electrical probes are used due to their portability and ability to adjust output to vary the

---

[50] The leads of an arc welding unit can be used to generate the magnetic field needed to perform Magnetic Particle Testing, Ref *SSC195 Emergency Welding Procedures for Temporary Repairs of Ship Steels.*

magnetic field to suit the test conditions. The probes generate a magnetic field which is perpendicular to a line between the probes, which allows the detection of flaws parallel to the line between the prods. In order to detect longitudinal flaws, the probes are positioned along the weld bead, and for transverse flaws the probes are positioned on either side of the bead. Electrode voltage and prod spacing is set in accordance with approved test procedures and is as a function of the material thickness and composition.

Some high strength low alloy steels may exhibit false flaw indications, however, unnecessary repairs can be avoided by light exploratory grinding followed by retesting. Again this method requires specialized equipment and personnel, so it is used only for relatively critical welds. This method is less costly and not as technically demanding as radiography, however, it can miss deep discontinuities in welds.

XI.4.3 Dye Penetrant Testing

This method, aside from simple unassisted visual inspections, is the easiest of the 3 commonly used tests. It is useful for the detection of surface discontinuities only. The method uses a bright dye which seeps into cracks and pits, making them more obvious to visual inspection. The method is simple meaning that yard personnel can be quickly trained and qualified in it's use. Like the other tests, the surface to be tested must be cleaned to bare metal. However, with this test, care must be taken to avoid the inadvertent peening of the material resulting in the closure of cracks. Therefore, chemical or high pressure water blasting is preferred for pre-test cleaning of a test specimen[51].

---

[51] For all NDT it is preferable to clean the material in a manner which produces the smallest possible disturbance in the base and weld metal. Therefore, better methods include; chemical, high pressure washing (care must be taken in the use of this method as it can cause some deformation in metal), and methods to be avoided include; needle gunning, grinding or chipping. All of which tend to highly deform the surface of the sample.

XI.4.4 Visual Inspection

Visual inspection is by far the simplest and most easily performed mode of NDT. Usually the welder will self inspect his work prior to calling the job complete and ready for any more extensive testing. Common checkpoints for visual checks include bead size, bead shape, pitting, slag inclusions etc. Visual inspections are perhaps the most subjective type of inspection available, relying heavily on the experience and judgement of the person performing the inspection. A good welder will inspect multi-pass welds thoroughly after the completion of each pass, since remediation of defects are most easily accomplished if they are surface or near surface defects. The complete removal of slag between each pass is perhaps the most important self inspection task that the welder performs.

As mentioned above, the inspection of an assembly which has been fitted up and is ready to be welded is quite important. This step can ensure that unnecessary stresses are not introduced by improper fit and forcing members into alignment. In addition the proper preparation of joint gaps and condition is checked, ideally just prior to actual welding.

Assurance of conformity to minimum bead size and geometry can be accomplished using template type gauges for quick go-nogo checks of finished welds, the welder will usually carry several of these gauges for self inspection.

XI.5.0 Specialized Non Destructive Testing

XI.5.1 Inspection of Heavy Sections

The non destructive testing of heavy section weldments, forgings and castings demand differing inspection techniques to detect flaws unique to these type of specimens. Thick sections have a greater chance of flaws due to the larger amount of material present, castings and forgings in particular are prone to flaws resulting from cooling effects [53]. Castings are also prone to inclusions of porous point defects due to entrained gasses in the molten material. The criticality of surface defects in large castings and forgings is lower since catastrophic crack migration is less likely due to the random crystalline orientation present.

The ASTM and ABS both publish a set of standards and guidelines for testing heavy sections. The shipyard is given a high degree of freedom in the establishment of standards for these heavy sections due to the historical reliability of these types of sub assemblies.

XI.6.0 Underwater Testing

On occasions when it becomes necessary to examine the condition of submerged portions of a vessel's hull, historically it has been necessary to expose the hull through dry docking or grounding in an area with a large tidal range. In the offshore oil industry the above options are not available, which has encouraged the development of technology for underwater inspection and repair utilizing both manned and unmanned methods [54]. If under water repair and more specifically underwater inspections, can be done in such a manner that underwriters and classification societies accept the procedures as semi-permanent to permanent repairs, the large costs involved in unscheduled dry-docking may be avoided.

XI.6.1 Techniques

Of the five methods used for non-destructive testing, (visual, magnetic particle, radiography, ultrasonic and dye-penetrant testing), all but the dye penetrant test have been successfully used in underwater applications.

Visual inspection can be performed using either direct reporting, photographic equipment or video equipment. For all of these methods, the visibility in the water must be good, this can be achieved by either the continuous pumping of clean water to the site or the isolation of the site using a boundary filled with clean water. In addition, all methods require that the region must be cleaned to bare metal[52]. This is achieved using high pressure water jets, mechanical methods, such as needle guns, or for small regions, manual means, such as scrapers or wire brushes. The preferred method is the water jet, since mechanical means can slightly peen the welds which tends to mask defects.

Magnetic particle inspection is performed using the ferrous particles suspended in a slurry with the rest of the procedure performed in the normal manner. Superior results have been obtained using florescent particles in conjunction with ultraviolet light, providing much more apparent results. This method is actually a more sophisticated visual inspection, since the results must be recorded as mentioned above, e.g. directly reported, photographed or transmitted via video camera [55] to personnel in a remote locale.

Radiographic inspection for underwater applications also requires some procedural deviations from those carried out in a dry environment. Firstly since a radiation source and a film cassette must be placed on opposing sides of the weld, the alignment of the source and the film cassette presents a unique challenge. Electronic probes have been the most successful method of alignment, where one probe is placed inside of the hull, and a diver has the other which, when moved to within a predetermined distance, emits a signal which alerts the diver to mark the spot. Either component (the source or film cassette), can be placed within the hull. Although, if room allows, it is preferable to place the source inside the hull in order to maintain maximum control of radioactive material[53]. Using this arrangement, the film can be attached to the outside of the hull using magnets holding a lead backing sheet to the hull, which when complete allows the diver to leave the area. This method gives the best results. However, it is the most costly and hazardous method.

Ultrasonic inspection is perhaps the most readily adapted method of underwater inspections.

---

[52] The reapplication of a coating system is imperative once the inspection(s) have been completed, requiring the use of a coating system which can be applied underwater.

[53] This also allows the use of a less highly qualified diver since if the source is placed outside of the hull, the diver must be qualified to have custody of the radioactive material.

seawater is an efficient couplant for the ultrasonic probe and the diver's mobility around the three dimensional hull cannot be duplicated in the drydock. There are numerous battery powered portable ultrasonic inspection devices available which only need to be sealed for underwater use. A more efficient method would be the use of a recorder topside with the actual device connected by cable to the diver operated probe. Again remote video equipment carried by the diver can be monitored/recorded topside and used to direct the diver to exact locations on the hull.

XII.0.0 Instrumentation

At some point in the development of theory which is meant to predict the behavior of a dynamic system, the theory must be calibrated against the actual physical behavior of the system it is meant to model. Once actual data is obtained, the theory can be modified in order to reduce bias present in the prediction process. For marine structures, actual motions data is important due to the larger amplitude forces and motions experienced with respect to other large structures. The vessel motions and accelerations along with concurrent measurements of the forcing mechanisms, (Ocean waves, wind and currents), must be recorded in order to verify design assumptions and determine if structures should be built or modified according to revised standards [56]. In addition, with the aforementioned more highly stressed nature of modern ship structures, their instrumentation can serve as an additional safeguard against overloading. Which is to say that in addition to the collection of data, the system can serve as a monitoring system for the crew, thus creating an increased level of awareness of the vessel's structural performance[54].

The accurate recording of wave properties is important to oceanographers whose ultimate goal is the accurate prediction of ocean behavior according to season and existing conditions. The ability to accurately forecast the average and maximum severity of conditions directly affects the ultimate and fatigue loading uncertainties and subsequently the strength and cost of structures.

The rational design of ship structures must be based on knowledge of the magnitudes and combined effects of the loads to which the ship is subjected in service. Some of these loads arise from locked in stresses, diurnal temperature variations, local heating or cooling, still water cargo loading, low frequency wave bending load, slamming, and local vibratory effects. Rather than attempt

---

[54] The provision of such information as midship bending moment, impact pressures, vibration amplitudes... etc., will be of little use to the crew if some basic training regarding the significance and meaning of the data is not accomplished. This can be somewhat circumvented by the provision of tables of nominal, severe, and dangerous levels of these parameters, or simply installing alarm circuitry.

a simultaneous study of the effects of all of the above loads, and because of the statistical nature of some of them, it is most convenient to investigate each type of loading in detail and then establish the effects of combined loading.

With the ever improving level of technology with regard to instrumentation and data processing and recording devices, the cost and complexity of instrumentation packages continues to fall. Where once the existence of an instrumentation system on a vessel was highly unusual, and probably the centerpiece of an expensive research project, it is now becoming an integral part of normal ship's operational equipment. These packages, once they gain acceptance by owners and operators, could become to the field of structural damage avoidance what radar, satellite navigation, and computers have become to the ancient art of navigation.

XII.1.0 Data Types

The data attained from instrumentation programs carried out on seagoing structures can be divided into two general categories, environmental and structural response data. Environmental data consists of wave height, period and shape, wind speed, direction and variation, current (speed, direction and temperature), and barometric pressure and variability. This data is recorded for use by engineers in the verification of structural response to environmental conditions, and by oceanographers as previously mentioned. Response data is measured within the structure as strains, stresses, vibrations, displacements and accelerations. The response data is used by engineers to verify that the structure is behaving as designed or to detect conditions that indicate possible trouble. Perhaps the most useful application of the data is that of the verification of model accuracy and subsequent bias[55] determination as mentioned above.

[55] Bias is defined as the true value of a variate divided by the calculated or predicted value of the variate. In the event that the bias is very non-proportional or large, the model used for predictions may need extensive modification or complete redefinition.

In most instances modern recording equipment will process analog signals through a A-D converter and store the data in digital form. The data is then easily analyzed using a digital computer either on board or ashore.

XII.2.0 Measuring Equipment

In any structural response study it is desirable to obtain simultaneous cause and effect information, in order to establish the proper correlation between loading and structural response. For this reason response instrumentation packages developed for use in the marine environment, tend to consist of a rather extensive array of triggering, detection, signal processing, and data recording devices to comprise a system which yields valuable data. Of prime concern when selecting the components for such a system is the robustness of the equipment. It must be corrosion resistant, it must not interfere with normal ship's operation, it must be somewhat autonomous, since most modern commercial vessels sail with very small crews (unless the body sponsoring a short term data gathering program wishes to embark personnel to monitor the performance of the equipment).

XII.2.1 Triggering Devices

In order to avoid the accumulation of large masses of data of little interest to researchers, or subject equipment to long periods of expensive unnecessary operation, triggering devices are used to start the equipment only when certain conditions are satisfied. The onset of bow slamming is commonly a condition for which recording equipment is automatically switched from standby to record[56] (or in an operations system, warning the crew of the slamming condition). The environmental conditions recording instrumentation can also be used to switch the equipment from standby to operate. (e.g. wave height, wind speed, and barometric pressure trends are all examples of environmental).

[56] This condition is sensed by either bow displacement, acceleration, or vibration sensing equipment which actually senses the slamming.

The operation of these triggering devices is quite simple, the signal from the signal conditioning unit is simply fed to a bistable amplifier which is in turn used to operate an electronic switch which places the equipment on line. The triggering mechanism may have several levels of operation;

- During periods of very mild conditions it may align the system such that most of the equipment is off.
- When conditions reach a moderate loading level, the system may switch on various equipment, placing it in a standby mode, with circuitry energized and thus "warmed up", internal calibration carried out.
- When conditions become more severe, the system may go into a "reduced" data gathering mode, e.g. wave height sensing on, recorder off, standby for slamming data with accompanying indications on the bridge.
- Fully operational, all sensors on, all recorders on indication of conditions.

XII.2.2 Detectors

The types of detectors available for measuring quantities of interest on board a ship are as numerous as the possible quantities and ranges they are intended to measure. They range in sophistication from simple strain gauges to complex RADAR [57] wave height sensing equipment consisting of many complex components which must be expertly installed, calibrated, and maintained.

The information provided by the detectors is only useful if their location has been carefully selected to correspond to regions of high variation of parameters, (a detector intended to measure shear load would reveal little if it is attached on the deck center-line!). Detectors must be compensated if they are measuring quantities that are relative in nature, e.g. absolute wave height signals may be compensated by ship motion signals, depth sounder signals, and ship trim.

Detectors should be mounted in such a way as to minimize the possibility of their interference with normal shipboard operation. Devices such as strain gauges, accelerometers, and pressure cells are usually mounted in locations (on the shell plating or internal framing members) where the chances of interference with machinery or personnel movement is small[57]. Topside exposed detectors such as wave height sensors and outer shell strain gauges should again be clearly marked, and preferably be protected by an enclosing cage. The protective "cage" should be designed so as to prevent fouling of cables, lines, or equipment with the detector. The immediate area around the detector should be painted with warnings to attempt to instill some caution in those working nearby.

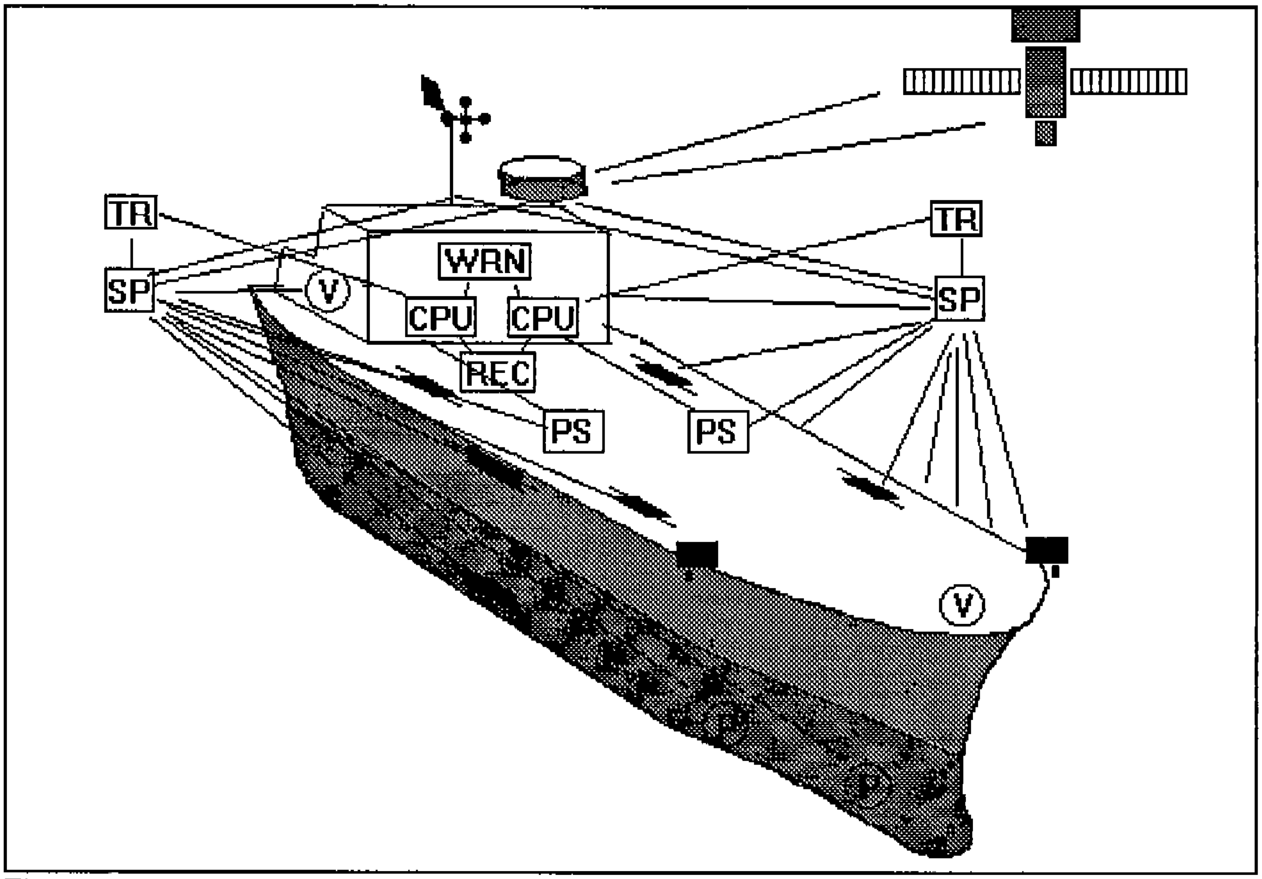


Figure 20 Instrumentation Block Representation

XII.2.3 Component Connection (Cabling)

As shown in block form in Figure 20, the interconnection of the components in an instrumentation system is not a trivial matter. All the components of an instrumentation system are

[57] These detectors should be clearly marked for inspection or repair teams, so that when accessing a space, damage is not done to the detector, (or Inspector), due to stumbling over the detector or cabling.

widely dispersed throughout the vessel, are located in many differing types of environments, and produce signals which can easily be masked by radio frequency interference emitted by various machinery throughout the vessel.

The loss of detector signals is most often due to cabling failure, and most often in severe conditions when the data is most informative. For these reasons the guidelines shown in Table VII should be observed in order to ensure maximum reliability of the system.

Table VII Instrumentation System Cabling

1. Cabling
   - Shielded, thermally rated, heavily armored.
   - Spare cable runs to remote detectors.
2. Installation
   - All cable terminations completed & TESTED per standard.
   - Minimize cable terminations.
   - Penetrations completed through insulated stuffing boxes.
   - Follow ship's cable runs, {ensure distinction between}.
   - Maintain clearance between machinery.
   - If cable must bend around plating, provide saddles.
   - All cabling permanently clearly labeled, if permanent entry in ship's machinery history and drawings.
   - Connections should be made within sealed junction boxes, securely mounted to the vessel.
3. Maintenance
   - If the above guidelines are adhered to, none should be required.

XII.2.4 Signal Processing Equipment

Due to the wide variety of signal types and levels supplied by the various detection components in the system, there must be a system of signal conditioners or pre-amplifiers which provide signal isolation, amplification, demodulation, and general conditioning. This equipment connects one end to the coaxial shielded cabling from the detectors and at the other end provides the signals as analyzed, displayed, and stored by the computer system. The preamplifiers are used during the initial alignment of the system to coarsely tune the signals from the detectors, clamping the signal levels for use by the A-D converters in the computing system.

XII.2.5 Computing/Display System

With the availability and ever increasing capabilities of commercially available personal computers, this onetime costly and complex component of the instrumentation system has become it's most reliable and easy to understand. The computing needs of a complete ship structural instrumentation system can now be easily met by using standard high performance PC's.

This Page Intentionally Left Blank

XIII.0.0 SSC Database System

In addition to this report, the research project sponsors, (MARAD SR-1347), requested that a database of SSC reports be developed for use by the maritime industry. The database code and report data fields were programmed/entered using the commercially available FOXPRO V 2.0 database package[58]. As a result, a user must have this package loaded on his IBM compatible PC in order to utilize the *SSCDBASE* package. However, due to the low cost of the package it is felt that the utility of the system is well worth the cost. An operator's manual, (Appendix I), details all the operations possible with the system, the *SSCDBASE* code is provided on floppy disk as part of this report package.

XIII.1.0 Data Format

All reports published by the SSC as SSC XXX reports have been entered into the database with the following information included;

- SSC report number
- General subject classification
- Author(s)
- Date of publication
- Abstract
- National Technical Information Service (NTIS) order number, (all of these reports are kept by the NTIS on microfilm, and can be ordered in hardcopy for a nominal fee[59].

A utility for the entering of new reports has been incorporated into the system allowing any user to either add commentary, pertinent references, or new SSC reports.

XIII.2.0 Database Usage

A complete users manual is included in the appendices of this report, detailing the usage of the

---

[58] The complete package is available from;
Fox Software, 143 W. South Boundary, Perrysburg, Ohio 435521
As of spring 1993 the package sold for approximately $125 U.S.

[59] U.S. DEPARTMENT OF COMMERCE, National Technical Information Service, Springfield, VA 22161, PHONE: (1-800-553-NTIS), FAX: (1-703-321-8547), TELEX: (89-9405)

package, it's capabilities and limitations.

XIV.0.0 Conclusions

In the course of reviewing SSC reports for this project, it became quite clear that a full review of *all* aspects of ship maintenance would be impossible to complete in the allotted time frame. Even the areas discussed in this report are only considered to be overviews of the currant state of the art as defined by the related SSC reports. For a structure as complex and variable as that of a ship, it is clear that only general conclusions and guidelines can be given to aid the ship owner/operator in his goal of performing the best maintenance that resources allow.

The reviewers recommended that this project be continued with new efforts directed in areas not covered or not completely covered by this report. Some suggested topics include;

- Operational Guidelines
  - Ship handling effects on ship structures, (maneuvering effects).
  - Guideline for data reporting by ship's company.
  - Quick reference guide for operators in the event of grounding/ stranding.
- Guidelines
  - Emergency repairs.
  - Data archiving, maintenance system.
  - Detail surveys, [273].
  - Numerical models of details for direct use by standardized FEM routine.
  - Failure correlation study, [262], quick reference for welders to aid in their understanding of weld flaw consequences.
- Design
  - Ergonomic design methods, design for accessibility during construction and subsequent inspections.
  - Probability Based Design
  - Further elimination of error regarding COV's for wave loading, (COV's for large waves currently err by 10-20% [331, mans]).
  - Effects of vessel form on vibratory loadings; fatigue effects.
  - More work with regards to whipping behavior of ships [330].
  - Further investigation regarding plastic behavior of metals, for use in non-linear mechanics.
- Welding
  - Intermittent vs. continuous welding guidelines.
  - Effect of neglecting corrosion allowances on cost and strength.

As seen by the above list, the topics which relate to ship maintenance are widely varied, effecting the vessel's integrity in direct and indirect manners. The maintainability of a structure is a function of many variables, ranging from decisions made in the early planning stages of a design to procedures used when failures occur.

SSC Database, *SSCDBASE*, User's Guide

1.0 Introduction

This database system has been developed in response to the need for a method of rapid access to the wealth of information that has been published by the SSC over the past 50 years. The system is to be issued as part of the final product of the MARAD sponsored research project entitled Maintenance of Marine Structures; a State of the Art Summary, (SR-1347)[60].

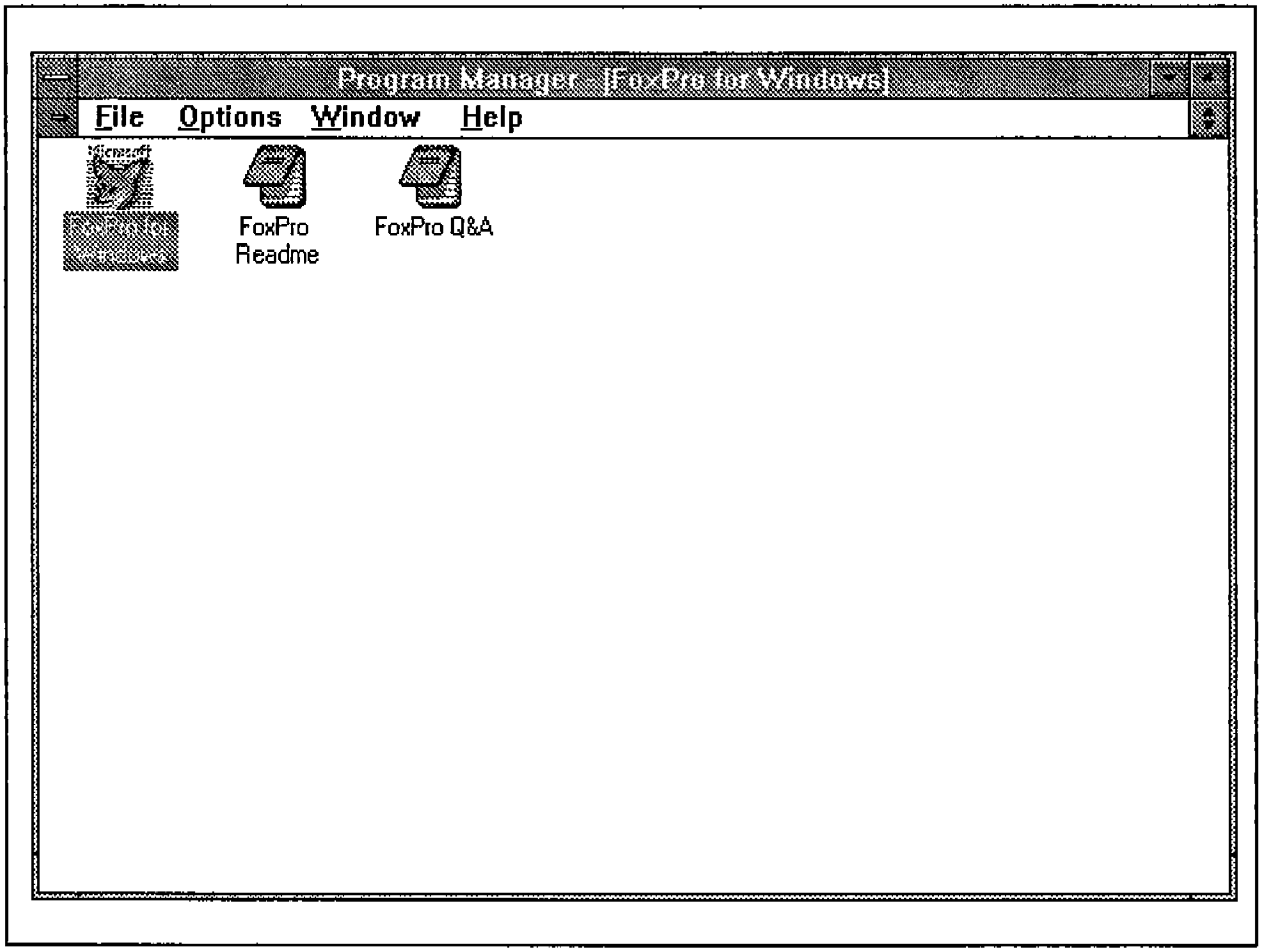


Figure 21 Foxpro icon in windows environment

The system has been designed to allow a user to access any of the 367 SSC reports issued as of publication of this report, (May 1993), with provisions for the entry of additional SSC or outside

[60] Marad Report DTMA91-92-CA-200096

reports as they become available.

The system runs as an application within the Microsoft Foxpro for Windows environment, meaning that a user must obtain a copy of Foxpro for windows, (and windows in the unlikely case that windows is not running on the user's machine). This is a reasonably priced, commercially available program which runs well on an 80386 based PC.

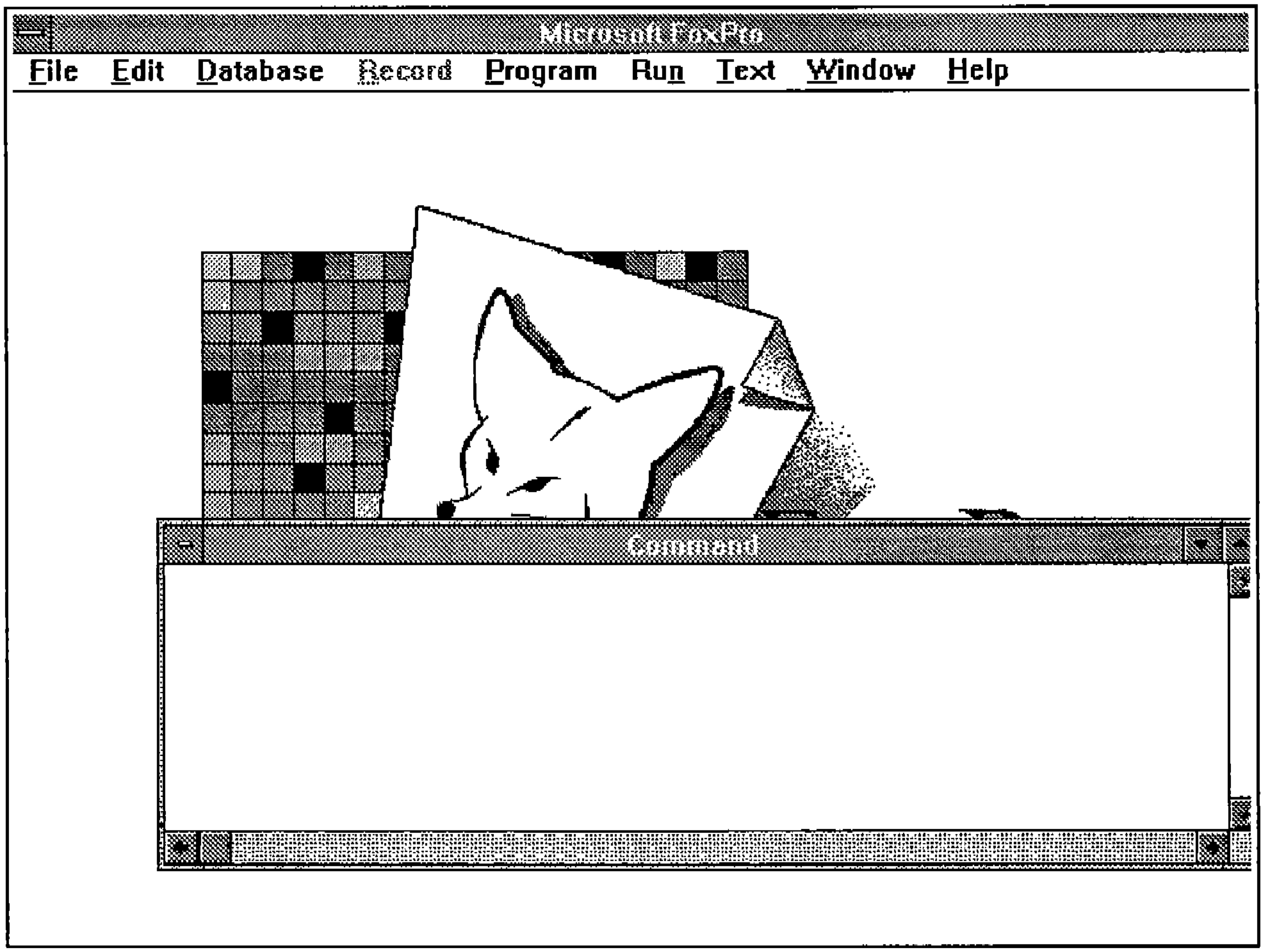


Figure 22 Foxpro main program screen

1.1 Database Contents

The database has been designed to enable the user to continue the classification, evaluation and cross referencing begun by the authors after the completion of a workable database system. The additional classification of the reports in terms of their contents has been accomplished through the addition of keywords entered in addendum to the report abstract fields, and their entry by subject into specific categories. These keywords are intended to facilitate the listing of reports whose abstracts may have left out indications as to the contents of text contained in the body of a report. The additional keywords are entered in the abstracts below a heading which appears as follows:

SMRP Commentary
****

All of the reports published by the SSC have been entered into the database in terms of their apparent subjects as inferred by their titles and abstracts. The addition of commentary is limited to the reports cited as references in the end of this report.

2.0 Installation

The application is supplied on one (1) 1.44 MByte 3.5" floppy disk, with installation accomplished by simply copying all of the files on the supplied floppy to whatever directory the user desires. It is suggested that the following procedure be carried out;

- Boot computer or change to the target directory using the standard DOS *CD_Target* command; Foxpro for windows is loaded into a directory called Foxprow by default, and it is recommended that the SSCDBASE files be loaded into a sub-directory created as *C:\foxprow\SSC.*
- Copy all files from the supplied floppy by inserting it and typing COPY B:*.* while in the target directory.
- Start windows in the usual way
- Load foxpro for windows by double clicking on the fox icon as shown in Figure 21.

3.0 Program Loading

Once the foxpro/w program has been loaded and started as described above, the screen will appear as shown in Figure 22. The SSCDBASE program is started by clicking on the 'SSC' icon, which will bring up the screen shown in Figure 23. The data base is now ready for use.

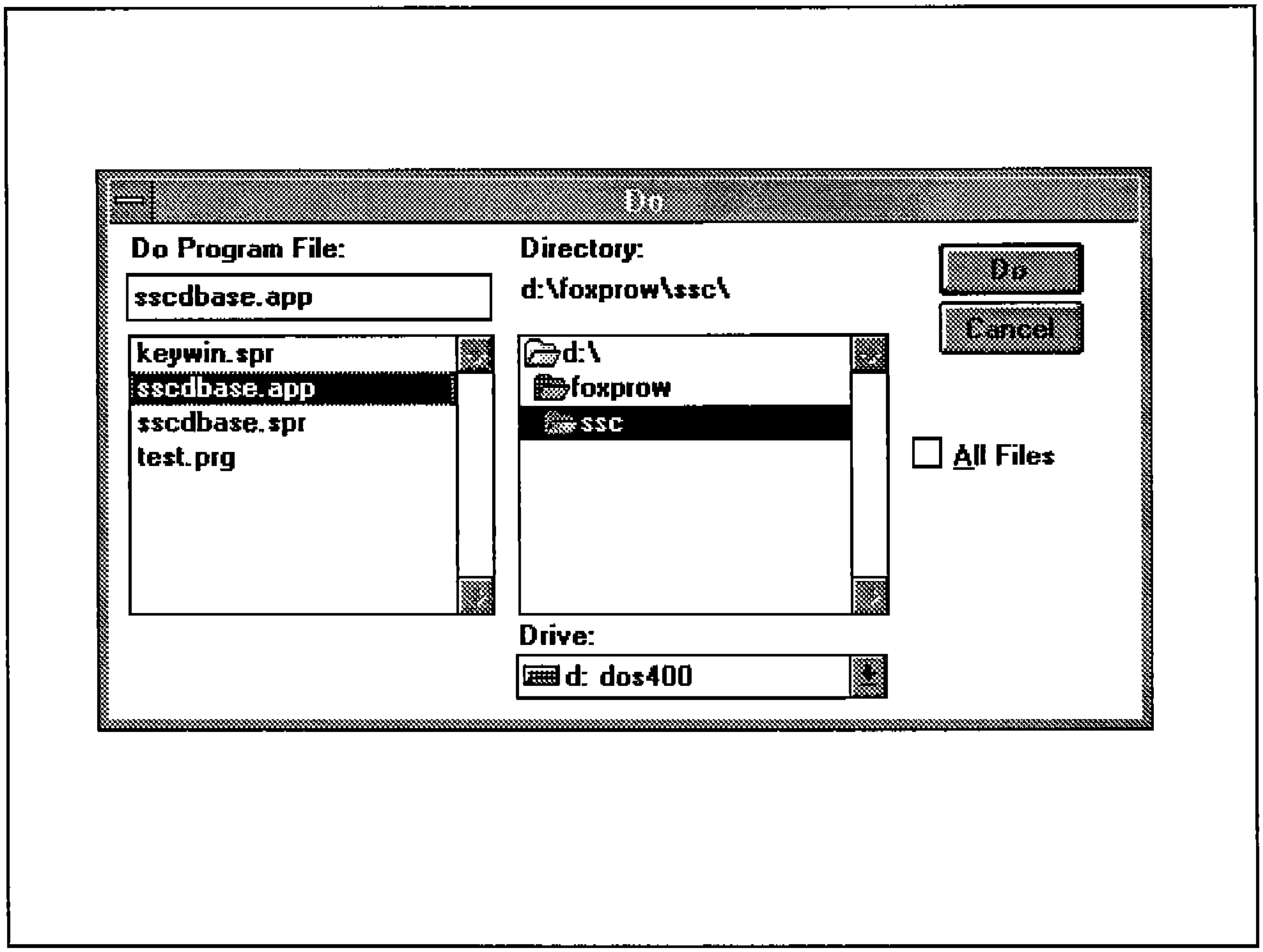


Figure 23 SSCDBASE program selection window

4.0 Database Layout

The SSCDBASE system is organized into two basic blocks, an upper editing block, and a lower search block. In this section the user is taken on a tour of the main screen in order to familiarize himself with the basic operation of all the 'buttons' in the program.

4.1 Editing Block

The editing block, starting from the upper left-hand corner down, consists of:

- Report number block: Displays current report number of record displayed.
- Title Block: Displays Title of current record.
- Subject Block: Displays category of current record.
- NTIS Cat #: Displays National Technical Information Service, (NTIS), catalogue number for ordering complete reports.

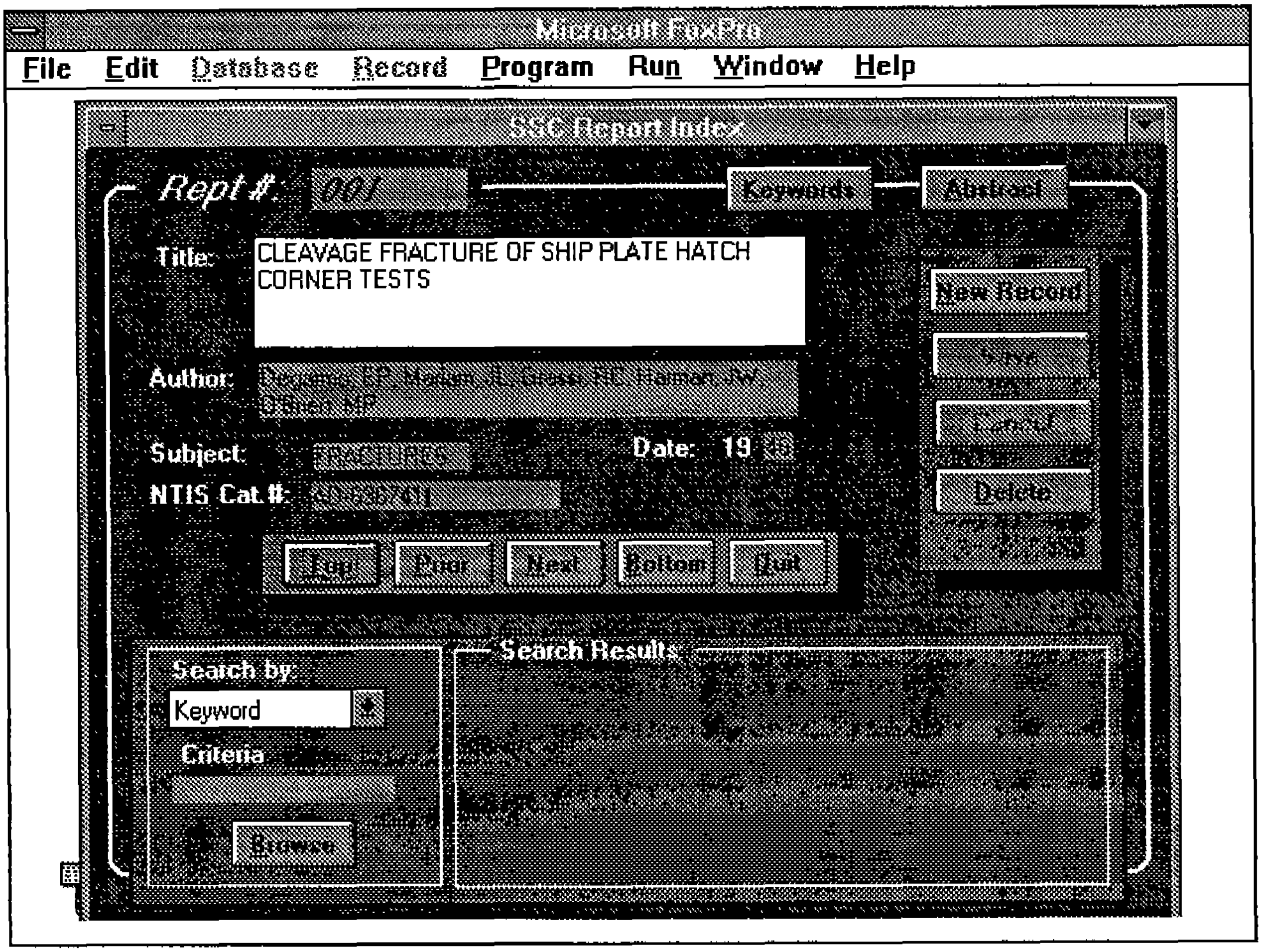


Figure 24 *SSCDBASE* Main Screen

- Scan Bar: Allows moving through the database by:
  - *Top: Moves pointer to the first record in the database
  - *Prior: Moves pointer back one record in the sequence
  - *Next: Moves pointer forward one record in the database.
  - *Bottom: Moves pointer to the last record in the database.
  - *Quit: Quits the application

- Date: Displays the publishing date of the report.
- Editing Box: Allows editing of records including:
  - *The addition of new records
  - *Saving new records to the database file, (SSCDBASE.DBF)
  - *Canceling an editorial session.
  - *Deletion of records from the database file.
- The Keywords button allows the user to define keywords for permanent association with the currently displayed record, (page VI: §4.2). The popup which appears for inputting new keywords by the user is shown in Figure 25.

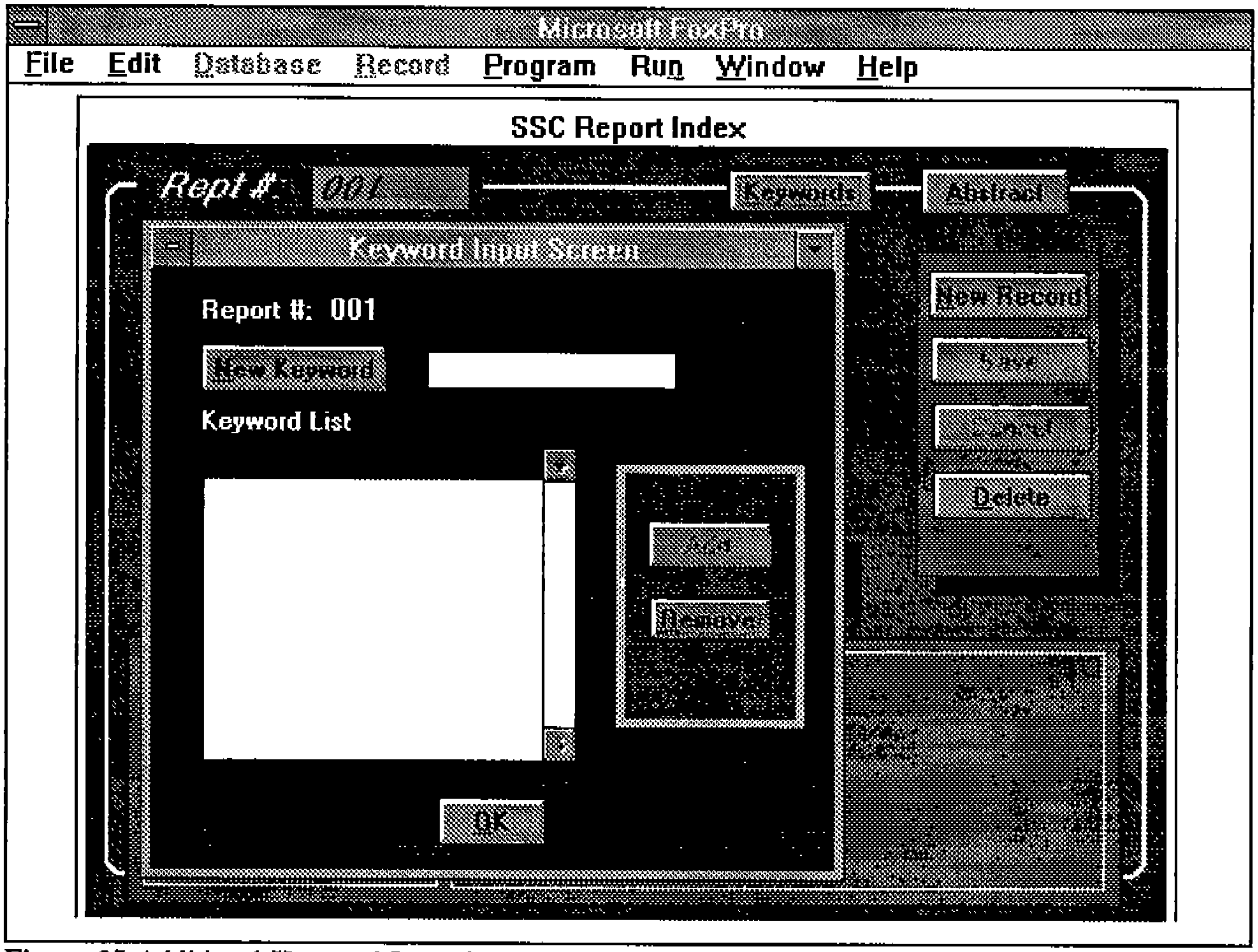


Figure 25 Additional Keyword Input Screen

- The Abstract button displays the abstract of the current record, as shown in Figure 26.

4.2 Search Block

The search block consists of a left side criteria block, and a right side results block. The search criterium is defined in the search block by selecting on of the options displayed when the 'Search By' down arrow is clicked on. The options include:

- $Abstract: Searches through all abstracts for keywords entered by user in the **Search By** box.
- Subject : Searches for reports under pre arranged groups of records, e.g. corrosion, fatigue, damage etc.
- Author: Searches for report(s) by specific authors.
- Keyword: Searches for records that have been linked to particular keywords as defined in the Keyword button in the upper right region of the main screen, (see Figure 27).

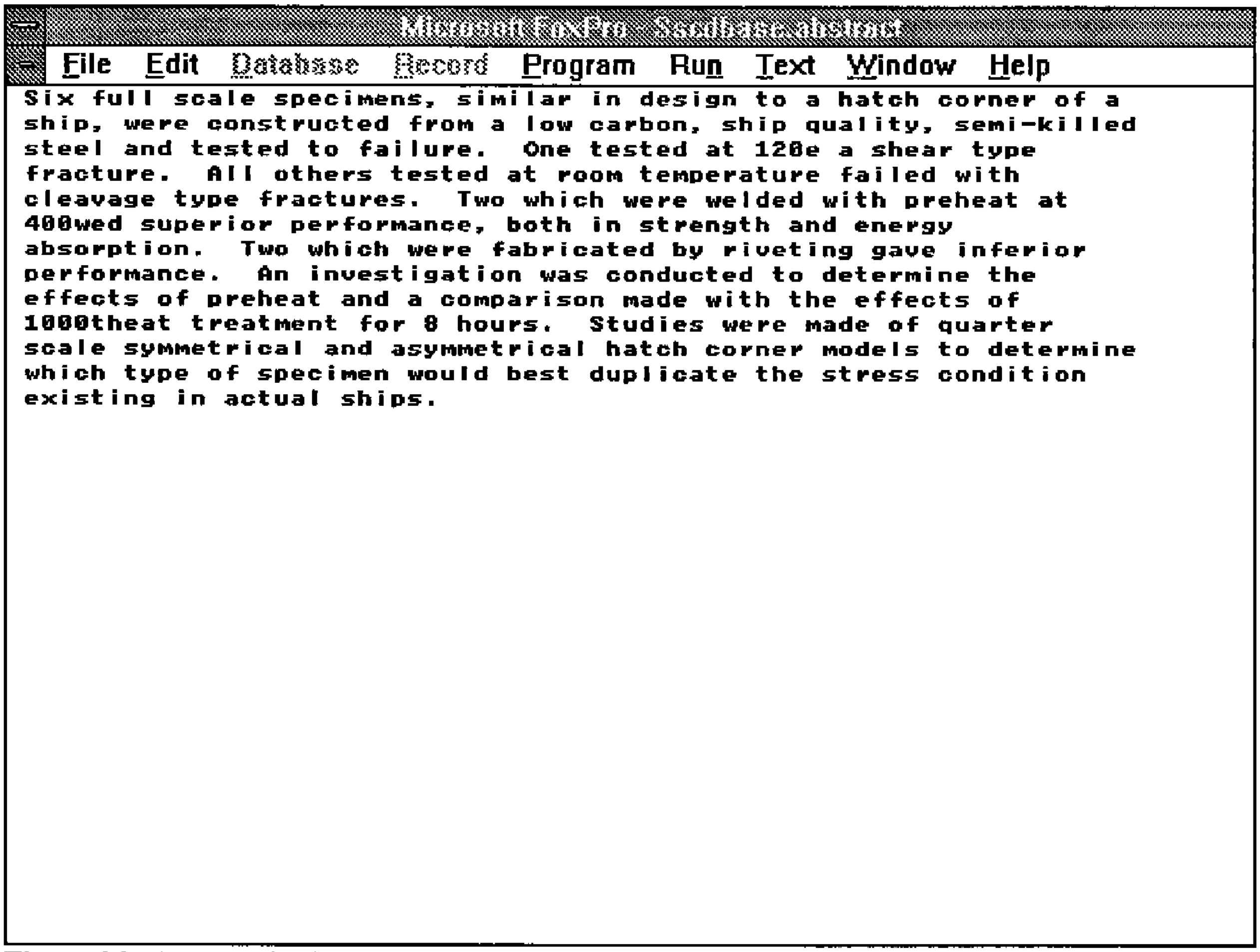


Figure 26 Abstract Viewing Window

The actual initiation of the search routines in the program is accomplished by clicking on the **Browse** button positioned at the bottom of the criterium block.

5.0 Database Operation

The following section will run the user through several example searches in order to familiarize himself with the basic operation of the system.

5.1 Searches

- Keyword Search:
  - The system is started as described above
  - The **Search By** down arrow is clicked on
  - The desired keyword is entered in the **Criteria box**
  - The search is initiated by clicking on the **Browse** button

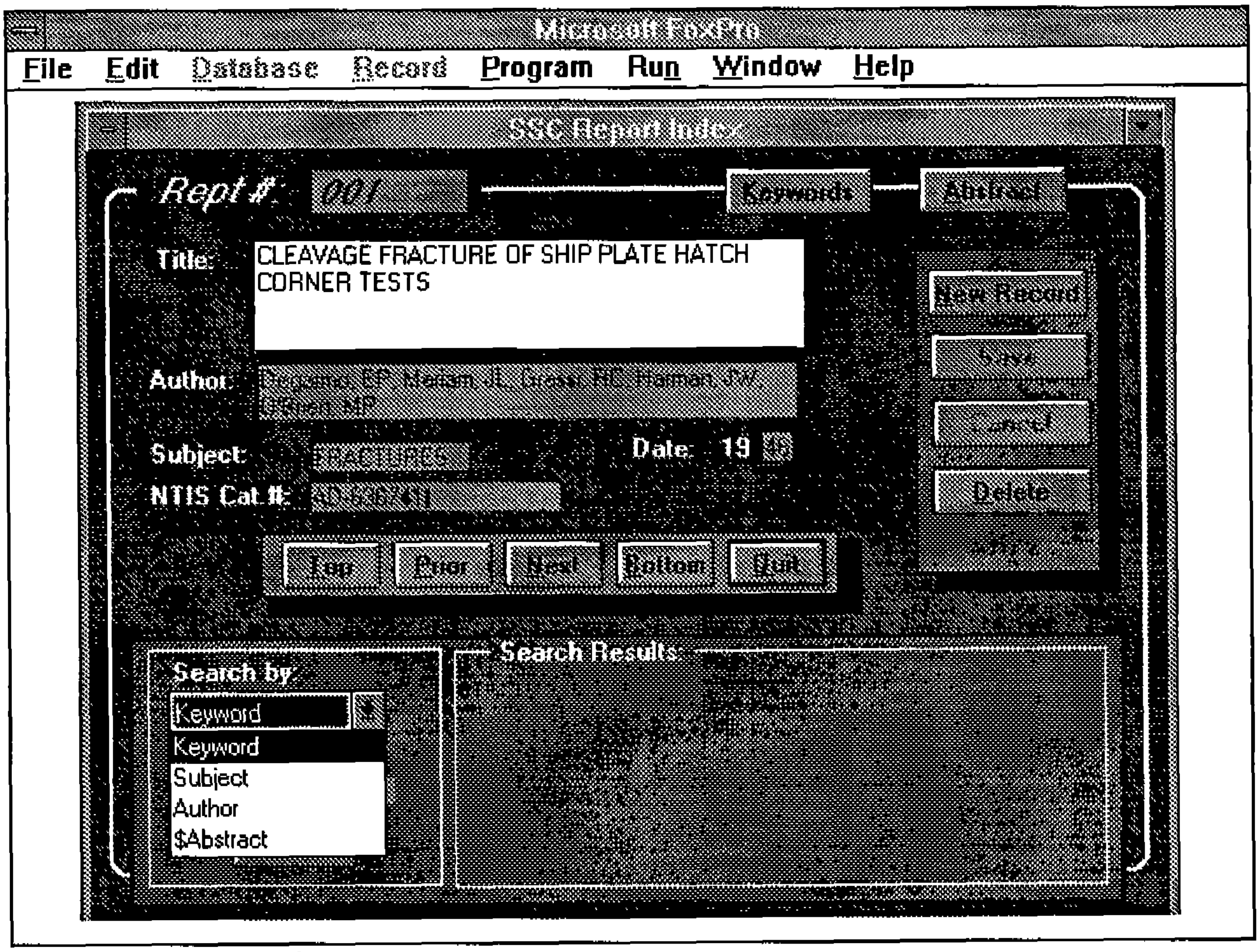


Figure 27 Search criterium pull-down

- o The records retrieved as a result of the search are displayed in the **Search Results** box
- o When a particular record is selected in the **Search Results** box, the details regarding the record automatically appear above in the editing section.

o Subject Search:

- o As above except Subject is selected from the **Search By** Pull Down

o Author Search:

- o As above except Author is selected from the **Search By** Pull Down

o $Abstract Search:

- o As above except Abstract is selected from the **Search By** Pull Down

6.0 Maintenance

The system has been designed so as to allow a user to continuously update the

SSCDBASE.DBF and KEYWORD.DBF database files through the editing section, all updating of the system should be accomplished through the utilities available in the main screen. Changes to the database file(s) are permanently accomplished upon exiting the program.

The usual backup copies of the disk should be made using the DOS *Diskcopy* command. The program will be archived permanently by the Department of Naval Architecture on the University of California at Berkeley.

XV.0.0 References

1. **SSC-365** MARINE STRUCTURAL INTEGRITY PROGRAMS (MSIP)
Bea, RG
Department of Naval Architecture
University of California, Berkeley

2. **SSC-337 (Part 1)**
SHIP FRACTURE MECHANISMS INVESTIGATION
Stambaugh, KA, Wood, WA

3. **SSC-363** UNCERTAINTIES IN STRESS ANALYSES ON MARINE STRUCTURES
Nikolaidis, E, Kaplan, P

4. **SSC 328** FRACTURE CONTROL FOR FIXED OFFSHORE STRUCTURES
Besuner, PM, Ortiz, K, Thomas, JM, Adams, SD
Failure Analysis Associates

5. **SSC 323** UPDATING OF FILLET WELD STRENGTH PARAMETERS FOR COMMERCIAL SHIPBUILDING.
Krumpen, Jr., RP, Jordan, CR
Newport News Shipbuilding

6. **SSC 296** REVIEW OF FILLET WELD STRENGTH PARAMETERS IN SHIPBUILDING
Tsai, CL, Itoga, K, Malliris, AP, McCabe, WC Masubuchi, K
Massachusetts Institute of Technology

7. **SSC 273** SURVEY OF STRUCTURAL TOLERANCES IN THE UNITED STATES SHIPBUILDING INDUSTRY.
Basar, NS, Stanlcy, RF
Rosenblatt (M) and Son, Incorporated

8. **SSC262** PREVENTING DELAYED CRACKS IN SHIP WELDS
Mishler, HW
Battelle Columbus Laboratories

9. Derucher & Korfiatis, Materials for Civil Engineers, Prentice Hall, Englewood Cliffs, NJ 1988

10. **SSC 260** A SURVEY OF FASTENING TECHNIQUES FOR SHIPBUILDING
Yutani, N, Reynolds, TL
Boeing Commercial Airplane Company

4

11. **SSC 356** FATIGUE PERFORMANCE UNDER MULTIAXIAL LOADING
Stambaugh, KA, Van Mater, Jr., PR
Columbia Research Corporation

12. **SSC 249** SHIP VIBRATION PREDICTION METHODS AND EVALUATION OF INFLUENCE OF HULL STIFFNESS VARIATION ON VIBRATORY RESPONSE.
Kline, RG, Daidola, JC
Rosenblatt (M) and Son, Incorporated

13. **SSC292** REPORT ON SHIP VIBRATION SYMPOSIUM '78
Dillon, HS

14. **SSC330** PRACTICAL GUIDE FOR SHIPBOARD VIBRATION CONTROL AND ATTENUATION
Noonan, EF, Antonides, GP, Wood, WA
NKF Engineering Associates, Inc.

15. **SSC281** BIBLIOGRAPHY FOR THE STUDY OF PROPELLER-INDUCED VIBRATION IN HULL STRUCTURAL ELEMENTS
Bumside, OH, Kana, DD, Reed, FE
Southwest Research Institute; Littleton Research & Engineering

16. **SSC-291** A DESIGN PROCEDURE FOR MINIMIZING PROPELLER-INDUCED VIBRATION IN HULL STRUCTURAL ELEMENTS
Bumside, OH, Kana, DD, Reed, FE
Southwest Research Institute

17. **SSC-318** FATIGUE CHARACTERIZATION OF FABRICATED SHIP DETAILS FOR DESIGN
Munse, WH, Wilbur, TW, Tellalian, ML, Nicoll, K, Wilson, K
Department of Civil Engineering

18. **SSC-358** INFLUENCE OF PRIOR DAMAGE BY CYCLIC LOADING BELOW THE YIELD STRENGTH ON SHIP STEELS IN MARINE ENVIRONMENTS
Leis, BN
Battelle, Columbus Division

19. **SSC-356** FATIGUE PERFORMANCE UNDER MULTIAXIAL LOADING IN MARINE STRUCTURES
Stambaugh, KA, Van Mater, Jr., PR
Columbia Research Corporation

20. **SSC 337** SHIP FRACTURE MECHANISMS INVESTIGATION
Stambaugh, KA, Wood, WA
Giannotti & Associates, Inc.

21. **SSC-232** STUDY OF THE FACTORS WHICH AFFECT THE ADEQUACY OF HIGH-STRENGTH, LOW-ALLOY STEEL WELDMENTS FOR CARGO SHIP HULLS
Norris, EB, Pickett, AG, Wylie, RD
Southwest Research Institute

22. **SSC-354** STRUCTURAL REDUNDANCY FOR CONTINUOUS AND DISCRETE SYSTEMS
Walsh, WJ, Leis, BN, Yung, JY
Battelle Institute

23. **SSC-332** GUIDE FOR SHIP STRUCTURAL INSPECTION
Basar, NS, Jovino, VW
M. Rosenblatt & Son, Inc.

24. **SSC-346** FATIGUE CHARACTERIZATION OF FABRICATED SHIP DETAILS FOR DESIGN - PHASE II
Park, SK, Lawrence, FV
Department of Civil Engineering, University of Illinois at Urbana-Champaign

25. **SSC-334** STUDY TO DETERMINE THE INFLUENCE OF WELD POROSITY ON THE INTEGRITY OF MARINE STRUCTURES
Walsh, WJ, Leis, BN, Yung, JY
Battelle

26. **SSC-307** EVALUATION OF FRACTURE CRITERIA FOR SHIP STEELS AND WELDMENTS
Pense, AW
Lehigh University

27. **SSC-322** ANALYSIS AND ASSESSMENT OF MAJOR UNCERTAINTIES ASSOCIATED WITH SHIP HULL ULTIMATE FAILURE
Kaplan, P, Benatar, M, Bentson, J, Achtarides, TA
Hydromechanics, Inc.

28. **SSC-266** REVIEW OF SHIP STRUCTURAL DETAILS
Glasfeld, R, Jordan, D , Kerr, MJ, Zoller, D
General Dynamics Corporation

29. **SSC-272** IN-SERVICE PERFORMANCE OF STRUCTURAL DETAILS
Jordan, CR Cochran, CS
Newport News Shipbuilding

30. **SSC-294** FURTHER SURVEY OF IN-SERVICE PERFORMANCE OF STRUCTURAL DETAILS
Jordan, CR, Knight, LT
Newport News Shipbuilding

31. **SSC-265** A STUDY OF CRACK ARRESTER SYSTEMS
Kanninen, M Mills, E Hahn, GT Marschall, C Broek, D Coyle, A
Masubuchi, K Itoga, K

32. **SSC-195** RECOMMENDED EMERGENCY WELDING PROCEDURE FOR TEMPORARY REPAIRS OF SHIP STEELS
Lowenberg, AL, Watson, PD
Southwest Research Institute

33. **SSC-296** REVIEW OF FILLET WELD STRENGTH PARAMETERS FOR SHIPBUILDING
Tsai, CL, Itoga, K, Malliris, AP, McCabe, WC Masubuchi, K
Massachusetts Institute of Technology

34. **SSC-345** Part 1 ELASTIC-PLASTIC FRACTURE MECHANICS - A CRITICAL REVIEW
Anderson, TL
Texas A & M Research Foundation

35. **SSC-312** INVESTIGATION OF INTERNAL CORROSION AND INTERNAL CORROSION CONTROL ALTERNATIVES IN COMMERCIAL TANKSHIPS
Herling, LC, Titcomb, AN
Newport News Shipbuilding

36. **SSC-326** LONG-TERM CORROSION FATIGUE OF WELDED MARINE STEELS
Burnside, OH, Hudak, Jr., SJ, Oelkers, E, Chan, K, Dexter, RJ
Southwest Research Institute

37. **SSC-348** CORROSION EXPERIENCE DATA REQUIREMENTS
Stambaugh, KA, Knecht, JC
Giannotti & Associates, Inc.

38. **SSC-332** GUIDE FOR SHIP STRUCTURAL INSPECTION
Basar, NS, Jovino, VW
M. Rosenblatt & Son, Inc.

39. **SSC-301** PROBABILISTIC STRUCTURAL ANALYSIS OF SHIP HULL LONGITUDINAL STRENGTH
Daidola, JC, Basar, NS
Rosenblatt (M) and Son, Incorporated

40. **SSC-136** ON VARIOUS PROBLEMS OF IMMEDIATE INTEREST TO A SHIP CLASSIFICATION MAN
Vedeler, G
Norske Veritas

41. **SSC-220** A LIMITED SURVEY OF SHIP STRUCTURAL DAMAGE
Hawkins, S, Levine, GH, Taggart, R
Taggart (Robert), Incorporated

42. **SSC-332** GUIDE FOR SHIP STRUCTURAL INSPECTION
Basar, NS, Jovino, VW

43. **SSC-322** ANALYSIS AND ASSESSMENT OF MAJOR UNCERTAINTIES ASSOCIATED WITH SHIP HULL ULTIMATE FAILURE
Kaplan, P, Benatar, M, Bentson, J, Achtarides, TA

44. **SSC-313** SL-7 RESEARCH PROGRAM SUMMARY, CONCLUSIONS AND RECOMMENDATIONS
Stambaugh, KA, Wood, WA

45.**SSC-295** NONDESTRUCTIVE INSPECTION OF LONGITUDINAL STIFFENER BUTT WELDS IN COMMERCIAL VESSELS
Youshaw, RA

46. **SSC-332** GUIDE FOR SHIP STRUCTURAL INSPECTION
Basar, NS, Jovino, VW

47. **SSC-253** A GUIDE FOR THE NONDESTRUCTIVE TESTING OF NON-BUTT WELDS IN COMMERCIAL SHIPS. PART 1
Youshaw, RA Criscuolo, EL

48. **SSC245** GUIDE FOR INTERPRETATION OF NONDESTRUCTIVE TESTS OF ORDINARY-, MEDIUM-, AND HIGH-STRENGTH, LOW-ALLOY STEEL BUTT-JOINT WELDMENTS IN SHIP HULL STRUCTURES
Ship Structure Committee

49. **SSC-262** PREVENTING DELAYED CRACKS IN SHIP WELDS (PART II)
Mishler, HW

50. **SSC-177** GUIDE FOR INTERPRETATION OF NON-DESTRUCTIVE TESTS OF WELDS IN SHIP HULL STRUCTURES
Ship Structure Committee

51. **SSC-213** A GUIDE FOR ULTRASONIC TESTING AND EVALUATION OF WELD FLAWS
Youshaw, RA

52. **SSC-332** GUIDE FOR SHIP STRUCTURAL INSPECTION
Basar, NS, Jovino, VW

53. **SSC-300** SUMMARY OF NONDESTRUCTIVE INSPECTION STANDARDS FOR HEAVY SECTION CASTINGS, FORGINGS, AND WELDMENTS
Youshaw, RA

54. **SSC-293** UNDERWATER NONDESTRUCTIVE TESTING OF SHIP HULL WELDS
Youshaw, RA, Dyer, C

55. **SSC-189** THE VIDEO TAPE RECORDING OF ULTRASONIC TEST INFORMATION
Youshaw, R Dyer, CH Criscuolo, EL

56. **SSC-274** DEVELOPMENT OF AN INSTRUMENTATION PACKAGE TO RECORD FULL-SCALE SHIP SLAM DATA
Band, EGU, Euler, AJ

57. **SSC-238** DESIGN AND INSTALLATION OF A SHIP RESPONSE INSTRUMENTATION SYSTEM ABOARD THE SL-7 CLASS CONTAINERSHIP S.S. SEA-LAND MCLEAN (SL-7-1)
Fain, RA

Project Technical Committee Members

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

Mr. Frederick Seibold –Chairman	U.S. Maritime Administration
Mr. John Garside	American Bureau of Shipping
Mr. Zbigniew Karaszewski	U. S. Coast Guard
LT Rob Holtzman	U. S. Coast Guard
Mr. Richard Norris	American Bureau of Shipping
Dr. Neil G. Pegg	Defence Research Establishment Atlantic– Canada
LCDR Doug O'Reilly	National Defence Headquarters– Canada
Mr. William Siekierka	Naval Sea Systems Command, Contracting Officer's Technical Representative
Mr. Alex Stavovy Dr. Robert Sielski	National Academy of Science, Marine Board Liaison
CDR Mike Parmelee CDR Steve Sharpe	U.S. Coast Guard, Executive Director Ship Structure Committee