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SSC-407

OPTIMAL STRATEGIES FOR INSPECTION OF SHIPS FOR FATIGUE AND CORROSION DAMAGE

SHIP STRUCTURE COMMITTEE

1999

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OPTIMAL STRATEGIES FOR THE INSPECTION OF SHIPS

Structural inspections of large ships are difficult and costly because of the sheer size of the task in terms of the area of structure to be inspected. Therefore, there is a need to investigate the development of strategies on how to accomplish the most cost-effective inspection. The current inspection practice of ship structure is dictated by Classification Societies and Flag Administrations in a prescribed manner which is still heavily based on experiences that may have incurred higher cost, or yielded unsatisfactory results and unnecessary inspection.

This report reviews and discusses the three fundamental elements of inspections: where to inspect, what to inspect, and when to inspect. By closely examining each of these elements, a systematic approach has been developed. First, a priority assessment methodology has been developed to rank structural details quantitatively and define the critical areas for where and when to inspect. The methodology is formulated on the basis of a probabilistic risk-based inspection strategy. Second, an inferencing methodology is developed to determine the extent of the structural area that is to be inspected. Third, a fracture mechanics methodology and corrosion rate prediction strategy are applied to determine inspection frequency.

This systematic approach should provide the basis for developing optimal inspection methodology that could enhance the current practice and produce high quality inspections at minimum cost.

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16. Abstract
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CONVERSION FACTORS

(Approximate conversions to metric measures)

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

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1. INTRODUCTION

1.1 Background

In the recent past, aging bulk carriers and VLCCs (Very Large Crude Carriers) suffered many types of structural problems. Corrosion and fatigue cracking are clearly the most pervasive types of problems experienced by them. Each of the problems, if not properly repaired or rectified, can potentially lead to catastrophic failures or unanticipated out of service time. A way to prevent existing ships from structural failures or cargo oil leakage is through properly planned inspections.

Inspection is obviously a critical part of the ship structural integrity assessment process. Its fundamental objective is to maintain a ship's strength and serviceability to some pre-defined levels of safety throughout its life. A primary function of inspection is to give early warning of defects and damage, record and document such defects and damage, define alternatives to manage the defects and damage, choose the best alternative, implement the selected alternative, and then monitor its effects. Because of its importance, inspection is required by classification societies and by some flag administrators. Additionally, owners/operators may also carry out their own inspections in order to optimize the life cycle maintenance cost.

One difficulty associated with inspections is its cost. It is well known that the costs of inspection for these damage categories represent an enormous financial burden for ship owners and operators. Special surveys, for example, require dry docking and the cleaning of tanks/holds. In addition to the usual costs of labor and material, such surveys will require the vessel to be out of service for one to two weeks or more. In cases where permanent access facilities are not installed in the ship, the inspection cost will be further increased due to the high cost of staging.

Another difficulty in adequately inspecting ships, especially Very Large Crude Carriers (VLCCs), is the physical size of the task. The task of conducting structural inspections in those larger ships has become increasingly challenging. For example, on a 250,000 ton dead-weight single hull VLCC, the total area to inspect is around 300,000 square meters and the ballast tank area is about 55,000 square meters. Current double hull vessels of equivalent size have 350,000 square meters of total tank area and over 200,000 square meters of coated ballast tank area. As a result of this difficulty, the percentage of structural defects detected decreases. Due to the large areas involved and the short time frame normally available to carry out inspections, it is necessary to focus on suspect areas to optimize the effectiveness of the survey. However, any attempt to optimize inspections is always subject to the constraint that a certain level of safety is assured.

The consequences of insufficient inspections are severe. In the past few years, casualties of bulk carriers have caused loss of human lives, vessels and cargoes. Similarly, there have been a number of tanker accidents involving structural damage leading to cargo oil spills. Had those ships been inspected more thoroughly or frequently and appropriate repair made, at least some of the accidents would have been avoided.

Although the importance of inspections in regard to structural integrity is so obvious, it is only recently that this topic has been subject to serious research. Cooperative efforts focusing on tanker inspection and maintenance have been carried out by the Tanker Structure Cooperative Forum (TSCF) since 1986 [TSCF, 1986, 1991 and 1997]. A joint-industrial project entitled Ship

Maintenance Project was carried out at the University of California Berkeley from 1989 to 1994. The project has investigated several aspects of tanker Inspection, Maintenance and Repair. Some of its studies were directly related to inspection [Holzman, 1992] [Ma & Bea, 1992]. A Ship Structure Committee (SSC) project on inspection of marine structures was also recently done at University of California Berkeley [Demsetz, 1996a]. The SSC also had another project directly related to inspection [Basar, 1993] and a few others indirectly related to inspection such as [Shinozuka, 1990], [Bea, 1992] and [Jordan, 1978 and 1980]. IACS (International Association of Classification Societies) has developed an Enhanced Survey Program which was aimed at the development of a Unified Requirement to ensure the safety of bulk carriers and tankers [IACS, 1994]. US Coast Guard has also done work on TAPS (Trans-Alaska Pipeline Service) tankers which later led to the implementation of a Critical Area Inspection Plan [Sipes, 1990 & 1991].

1.2 Problems of Tankers and Bulk carriers

1.2.1 Structural Damage in Tankers

Tankers constitute one category of ships that can experience significant structural problems. They can have various types of defects or damage including corrosion, fatigue cracks and buckling. If these defects are not found during inspections, they may grow and result in cargo spill when the hull is penetrated. The hull may be either penetrated by corrosion or cracked by fatigue. If the hull is not properly inspected and maintained, eventual collapse of the hull structure may occur. Therefore inspections play an important role in ensuring the structural integrity of tankers.

Two studies on Trans-Alaska Pipeline Service (TAPS) tankers from 1989 to 1991 revealed that the TAPS tankers experienced more cracks than other U.S. flag oceangoing vessels [Sipes, 1990][Sipes, 1991]. At the end of the first study, three recommendations were made. These recommendations are (for all vessels in TAPS service) to:

(i) conduct structural inspections on more frequent intervals than presently required to satisfy minimum classification and regulatory needs, with at least one internal structural survey performed annually,
(ii) have written Critical Areas Inspection Plans (CAIP), and
(iii) require immediate repairs for all structural failures in critical areas.

These three recommendations were implemented by the U.S. Coast Guard to address structural failures on TAPS vessels.

Table 1.1: Summary of Fatigue Crack Numbers in a Previous Study [Bea, 1992]

Hull Type	DWT	Year Built	Number of Cracks
Double Hull	39,000	1977	168
Double Hull	39,000	1975	24
Double Bottom	188,500	1979	327
Double Bottom	188,500	1980	177
Single Hull	70,200	1972	639
Single Hull	35,700	1973	321
Single Hull	153,200	1977	651
Single Hull	153,200	1977	457
Single Hull	153,200	1977	413
Single Hull	153,200	1976	467

To further show the significance of fatigue problems in tankers, reference can be made to the findings from a joint industry-government sponsored research project [Bea, et al., 1995]. In the study, a fatigue crack database was created based on data from ten tankers with a combined total of 3,629 cracks. A summary of these tankers and the number of cracks found is given in Table 1. From the table, it can be seen that most of these tankers can have up to several hundreds of significant cracks. The large number of cracks imply that inspecting tankers can be an extremely demanding job. In addition to inspecting for fatigue cracks, there is much work in thickness gauging to determine wastage due to corrosion. It is often true that not all the defects can be discovered during inspections. Sometimes a crack can be almost undetectable under normal close-up inspection when the loading condition close the crack at the time of inspection [Ferguson, 1991][Holzman, 1992].

1.2.2 Casualties of Bulk Carriers

The other type of ship experiencing an unusual number of structural problems is bulk carriers. In fact, their problems are, in many cases, more severe than in tankers and have led to disasters involving loss of life. According to data published by IMO (International Maritime Organization), 23 bulk carriers were lost in 1990 [IMO, 1995]. The losses increased to 28 in 1991. The losses were 20 in 1992, 10 in 1993, and 16 in 1994. Over the period of 1990-1994, 97 bulk carriers were lost with a total of 532 lives [IMO, 1995]. The casualty rate of dry bulk cargo carriers (including bulk carriers, ore carriers and ore/oil carriers) has increased to an alarming figure.

The IMO data summarized the bulk carrier casualty in a table listing the name, flag, ship type, year of build, gross tonnage, date and nature of casualty, and the number of lives reported lost. Almost all the lost bulk carriers are old. Ninety-two percent of the lost bulk carriers are equal to or over fifteen years old. Only one bulk carrier is less than ten years old. A histogram of age of the lost bulk carriers is presented in Figure 1.1 to illustrate the trend of the relationship between age and casualty. It can be seen that bulk carriers become high risk structures starting at age of about thirteen years.

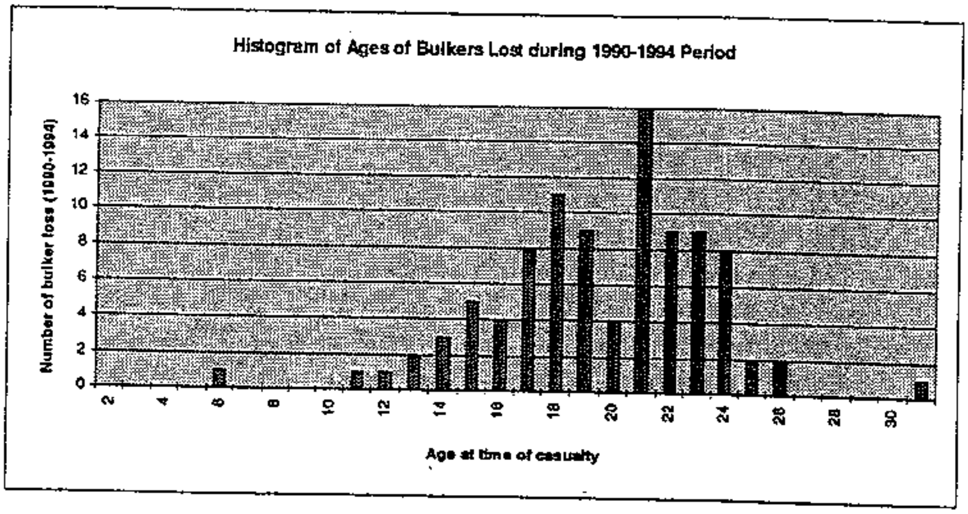


Figure 1.1: Histogram of Ages of Bulk Carriers Lost During 1990-1994 Period.

The casualty data published by IMO has a category in the table entitled, *nature of casualty*, which lists the cause for bulk carrier loss [IMO, 1995]. The causes can be grouped into five categories:

- Lost at sea (Heavy weather/Structural damage) 45 %
- Fire/Explosion 15 %
- Stranding/Grounding 26 %
- Collision 5 %
- Other Causes 9 %

The number accompanying each category is the percentage of bulk carrier loss falling in the period from 1990 to 1994. The cause, *heavy weather/structural damage*, accounts for the majority of the casualties (45 percent). A typical description in this category is "*sustained crack in hull and subsequently sank*". All the descriptions of the entry are short. Some of them do not state a definite cause and are vague, for example, "*presumed sunk*". Some use vague terms such as "*heavy weather damage, sank*" which does not specify what type of damage caused the casualty. However, the results in the table suggest that **structural failure is the major cause for the rising number of bulk carrier casualties**.

An investigation on bulk carrier casualties performed by a classification society in 1990 revealed that most casualties invariably involve the failure of the side structure [Lloyd's Register, 1995]. A good part of the service life of lost bulk carriers had been spent carrying high density cargoes such as iron ore. Some of the bulk carriers sustain excess corrosion because they carry cargoes, such as coal, that tend to accelerate corrosion. The investigation states that evidence from surviving ships indicated that the failure was due to a high level of localized corrosion and consequent structural damage sustained during heavy weather.

One possible scenario for bulk carrier casualties that may be responsible for unexplained losses is described by Liu & Thayamballi [1995]:

(i) Water ingress, because of a propagating hold frame end crack, and subsequent side shell cracking, or water entry because of hatchway damage.
(ii) Collapse of transverse watertight bulkheads at the ends of a flooded cargo hold, and hence progressive flooding and loss of buoyancy.
(iii) Hull girder break up due to the resulting, unfavorable loads. Such breakup may be facilitated by structural degradation. Cargo liquefaction from sea water ingress, and resulting sloshing forces could also be a complicating factor.

The above events can occur with little sign of external damage, making them hard to detect early enough to prevent vessel loss.

A key element in the prevention of the loss of old bulk carriers is through more thorough and/or frequent inspections. In response to the structural problems of bulk carriers, some classification societies have carried out a reappraisal of structural and survey requirements with a view to revising their rules where necessary.

1.2.3 Enhanced Survey Programs

In response to the increasing frequency of bulk carrier casualties and, IACS (International Association of Classification Societies which represents 12 classification societies internationally) developed an Enhanced Survey Program (ESP). The ESP program was aimed at the development of a Unified Requirement and to ensure the structural safety of bulk carriers and oil tankers.

The IACS Unified Requirements amplified their existing requirements in six areas including survey schedules, extent of surveys, preparation for surveys, thickness measurements, reporting and documentation on board. Based on the principles developed for the six areas, a detailed Enhanced Survey Program was developed by IACS. The IACS Council decided that the member societies will phase in these requirements at the earliest possible date, commencing July 1993.

As a result of ESP, survey requirements were tightened for both tankers and bulk carriers. Considering the example of bulk carriers, previously un-coated ballast tanks were not very frequently surveyed. Now, they are surveyed not only at special and intermediate surveys, but also at each annual survey. For cargo holds in bulk carriers, the previous requirement was examination at special surveys, and on an annual basis at a late age. The new rules from ESP required general examinations of bulk carrier cargo holds on an annual basis, commencing after the 2nd special survey. Additionally, bulk carrier special survey requirements are also now more stringent, and specify close-up examination of 25 % of cargo hold framing for the first three special surveys and 100 % for the fourth.

This discussion has indicated that the development of classification society rules on inspection are experience-based. As the performance of ship structures is proven inadequate, the inspection requirements are adjusted accordingly. It also shows that inspection plays the last line of defense in the structural safety of ships.

1.3 Objectives

The overall objective of this study is to recommend methods to minimize in-service inspection cost without compromising the current level of structural reliability. To achieve this goal, several elements of in-service inspections are reviewed or examined. These include:

- Inspection practice;
- Inspection experience in tankers and bulk carriers;
- Critical structural areas for inspection;
- Inspection frequency (or interval);
- Inspection extent; and
- Integrated system of inspection, maintenance, monitoring and repair (IMMR).

All these important elements must be taken into consideration in the development of cost-optimal inspection strategies. Ideally, all the variables that have an effect on the life-cycle inspection cost should be considered as a part of the system for optimization. However, this can not be easily done because of its complexity. To start with something manageable, this study investigates the above listed element individually.

First, the existing practical procedures and technologies employed for ship structural inspections are reviewed and summarized as a precursor to the identification of the major deficiencies in current practice.

In addition, the critical structural details of tankers and bulk carriers specified in the existing literature are gathered and listed to serve as a guide for inspectors.

A methodology developed in this study to rank structural details is introduced. The approach aims to provide rational answers in regard to where inspectors should concentrate on in their search for defects.

This study then reviews inspection extents that are defined in the class society rules, and examines the possibility of narrowing inspection extent without adversely affecting the quality of inspection.

Other aspects such as inspection scheduling are also examined. The frequency and extent of the mandatory inspections/surveys are set up by the flag administrations and class societies. These requirements need to be critically evaluated in terms of their effectiveness. By eliminating unnecessary inspections, significant cost savings can be achieved. However, any revised inspection schedule requirement should be carefully examined to ensure that the current level of reliability is not lowered.

1.4 Overview of Report

Chapter 2 of this report summarizes the current practices of in-service inspections on ship structures especially for tankers and bulk carriers. The definitions of different types of in-service inspections and their frequency and scopes are described. Practical procedures during an inspection from tank preparation to data reporting are introduced.

Chapter 3 collects information on critical structural areas for inspections in tankers and bulk carriers. Information is drawn from the existing literature.

Chapter 4 presents some advanced approaches to optimize various elements of inspections including location, extent and frequency. First, it introduces a rational approach, priority assessment, for ranking structural details accounting for both failure probability and failure consequence. Second, the feasibility for inferring the condition of a large expanse of structure based on inspection results from a limited area of structure is examined. In support of this study, the inspection results from two sample tankers are analyzed. Third, a fracture mechanics-based methodology is introduced as a means for optimizing inspection frequency.

Chapter 5 investigates the various factors affecting the overall IMMR (Inspection, Monitoring, Maintenance and Repair) system.

Chapter 6 presents conclusions and recommendations.

2. CURRENT PRACTICES

After a ship enters service, its hull structure will be monitored by a series of in-service inspections (surveys after construction) to assess the integrity of the hull structure. The goal of these inspections is to ensure that the ships are structurally sound and able to resist all expected loads in their future operations. In-service inspections have a different role from construction inspections which are mainly aimed at ensuring that the ship structure is constructed according to the drawings and appropriate standards of fabrication have been followed. In-service inspections provide a means to evaluate the current condition of steel and coatings, to detect unexpected flaws and damages, and permit appropriate maintenance and repair measures to be taken to preserve the integrity of the hull structure. This chapter reviews the current practice of inspections which can be divided into five phases: **planning, preparation, execution, data reporting & analysis**, and **repairs**. It, then, reviews the practice and strategies used by other industries. This chapter closes with a discussion on the limitations of current practice of ship inspections.

2.1 Inspection Planning

2.1.1 Inspection Objectives - What to Inspect

Classification societies, flag administrators and owners/operators each carry out inspections. Because the objectives of each organization's inspection are different, the procedures and the inspectors themselves are different. For example, prior to scheduled repair in the shipyard, an owner/operator may conduct an underway inspection to determine the approximate scope of repair work so that budget and schedule can be planned. This sort of inspection would be considered successful if areas needing repair were identified.

However, for those mandatory inspections required by classification societies and flag administrators, the inspection objectives can be identified as one or more of the following:

- Detecting defects including fatigue cracks, buckling, corrosion and pitting.
- Reporting present condition of steel plate thickness reduction due to corrosion.
- Reporting present condition of coating and other corrosion protection systems.
- Detecting any other problems such as structural deformation, leakage etc.

2.1.2 Types of Inspection

Inspections can be categorized into two types:

- **mandatory inspections** - those required by classification societies or flag administration, and
- **owner's voluntary inspections** - those performed by owners for their own purposes.

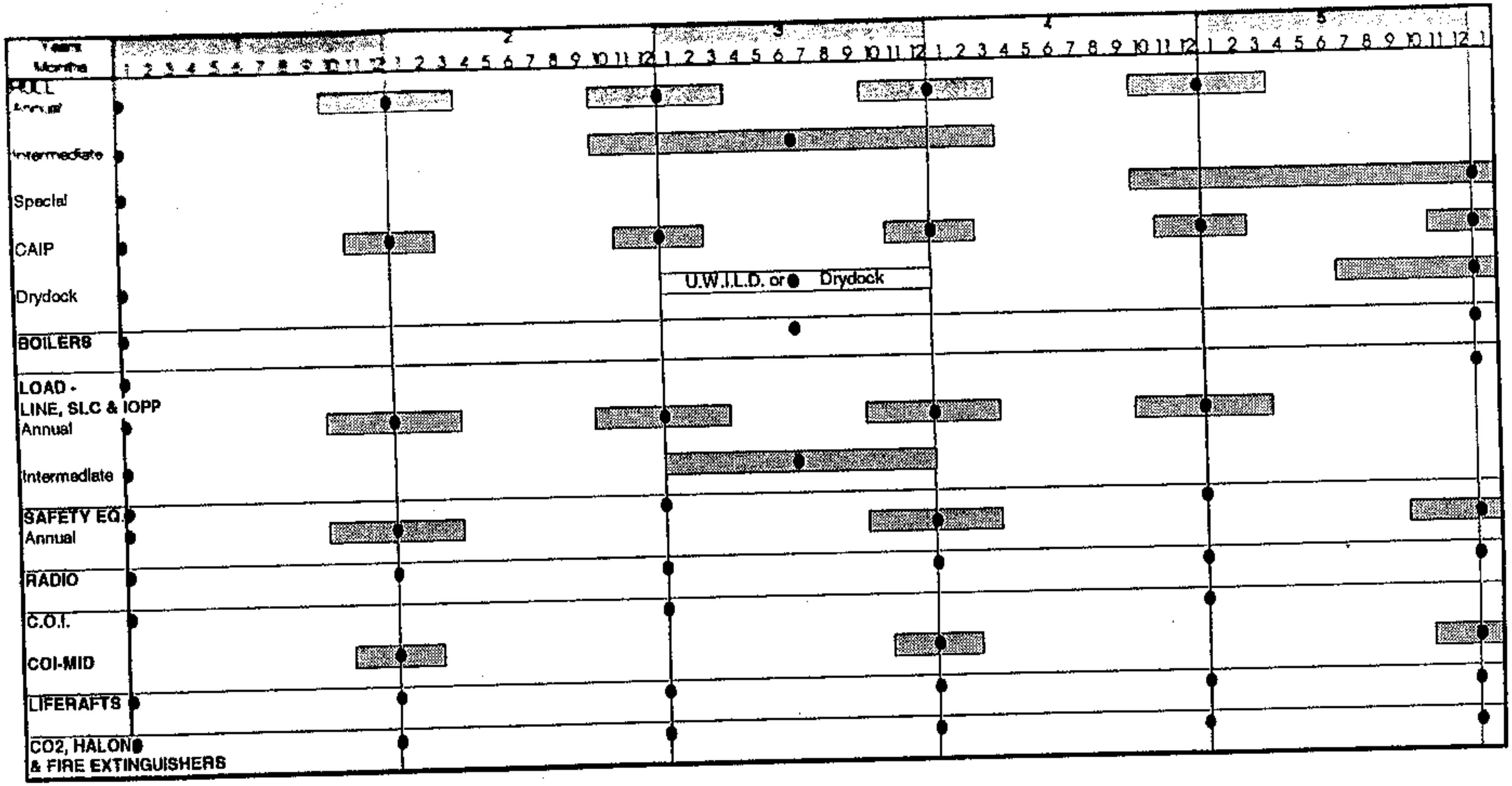
Throughout a ship's life, there will be mandatory inspections periodically required by the classification society. The frequency and extent of these inspections are detailed in the classification society rules. In terms of frequency, marine vessels generally have to be inspected annually except for small vessels under a certain size. These **mandatory inspections** required by class society can be further classified into three types: **annual surveys**, **intermediate surveys** and **special surveys**. Each type of inspection has its specific tasks to be performed.

Annual survey is to be carried out every year within 3 months on each side of the anniversary date of the special survey (see Figure 2.1). Its aim is to ensure that the hull structure and piping are maintained in a satisfactory condition. It typically takes about one to two days to complete. The survey includes an external survey of the hull and piping as far as accessible and practicable. If preceding special survey and intermediate survey reports show that segregated ballast tanks have no coating or the coating is in poor condition, or there are areas of substantial corrosion, internal survey of ballast tanks is required. The detailed requirements of annual surveys are listed in the classification society rules.

Intermediate survey consists of the requirements of an annual survey and an examination of ballast tanks and cargo tanks, the extent being determined by the vessel's age and condition as reported at the preceding special survey. Intermediate surveys are due at the mid-point of the five year special survey/certificate cycle. Its aim is to verify that the condition of the hull structures has not deteriorated at a greater rate than assumed during the preceding special survey. In other words, no unexpected conditions have occurred, in particular with regard to corrosion. All intermediate (hull) surveys can be performed at the second or third annual surveys. Thus these surveys have a nine month window before and after the due date. A "close-up" (which means within reach of a hand) examination of some areas will be carried out. For vessels that are older than ten years, the extent of survey is increased. Thickness measurements may be required. The intermediate surveys take approximately three to four days to complete.

Special surveys are generally required at five year intervals. They can be commenced on the fourth annual survey up to fifteen months before the due date. Its aim is to provide an in-depth look at the structural condition of the vessel. All compartments are subjected to survey. Dry-docking is part of the requirement which will ensure that sufficient access and repair facilities will be available. Special surveys take about one to two weeks to complete. The extent of the special survey requirement increases with the age of the ship. The detailed scope of special surveys are listed in classification society rules.

Although the requirements vary somewhat among the various Classification Societies, in the years since 1980 a considerable effort has been made to improve the minimum standards for the surveys. These are incorporated in the IACS Unified Requirements and form the basis for new IMO Resolution A744 "Guidelines on the Enhanced Program of Inspections during Survey of Oil Tankers and Bulk Carriers". The requirements were first prepared by IACS and agreed by its Council in September 1992 and have later been amended and updated; the latest was 1995 (Rev. 3). The Unified Requirements cover all three types of surveys, i.e. annual survey, intermediate survey and special survey. They specify the minimum extent of overall and close-up surveys, thickness measurements and tank testing, all grouped according to ship age. The updated Requirements include more specific rules with regard to survey planning and reporting.



Legends:

This symbol indicates due date.

Shaded area indicates available window.

- Critical Area Inspection Plan (CAIP) is due for inspection yearly on TAPS trade vessels. There is a two month window available.
- An Under-Water Inspection in Lieu of Dry-docking Survey (U.W.I.L.D.) is considered the equivalent of dry-docking. Consecutive UWILD surveys are not allowed and a UWILD will not satisfy special survey hull requirements.

Figure 2.1: Typical Five-Year Survey Cycle for U.S. Fleet Vessels.

In addition to the rules of class societies, the flag administration, such as U.S. Coast Guard (USCG), may have additional requirements for ships servicing on certain routes. For examples, tankers operating on Trans-Alaska Pipeline Service (TAPS) may have to follow more frequent inspections and have Critical Areas Inspection Plans (CAIPs).

Combining all the mandatory surveys, a typical five-year survey cycle for U.S. fleet vessels is shown in Figure 2.1. Similarly, the same survey cycle for international fleet vessels is shown in Figure 2.2.

Besides the mandatory surveys, some owners have **owner's voluntary inspections**. These inspections are aimed at prolonging the lives of their fleet and to help repair planning. The frequency of owner's volunteered inspections varies widely. Programs range from spot checks of ballast tanks after each voyage, to general surveys of all tanks once a year, to complete internal exams every six months [Sipes, 1990]. Many owners/operators also conduct surveys before scheduled dry-docking, because the cost of repairing cracks found after a ship is already in dock is considerably higher than those listed on a bid specification. They conduct internal surveys of ballast tanks and, to a lesser extent, of cargo tanks 3 to 6 months prior to a vessel's scheduled drydock exam in order to find and document problem areas. Other owners/operators hold to the philosophy that the proper place to find cracks is in the shipyard, and therefore do not conduct pre-drydock surveys.

In summary, the purpose of the mandatory inspections is to meet one or more of the following three requirements:

- Classification societies' statutory requirements
- Flag administration requirements
- Owner inspection requirements

For each inspection, the goal is defined. According to the goal, the extent of areas and the types of defects to be inspected are specified. Generally, four basic defects will be searched for during all types of inspections: cracking, corrosion (including pitting and grooving), coating breakdown and buckling. Note that the term "surveys" often refers to classification surveys, while "inspection" refers to inspections undertaken by others, in particular owners/operators and flag administrations. In this report, however, the two terms are used interchangeably.

2.1.3 Scope of Inspection

For the classification survey, the inspection scope follows the IACS Unified Requirements for annual, intermediate and special survey.

For the owner's survey, the inspection scope depends on the specific inspection type and objectives. The inspection scope is defined prior to each inspection, such as:

- Tanks and spaces to be entered for inspection.
- Extent of thickness measurements.
- Extent of visual inspection for structural defects, corrosion, pitting and coating.

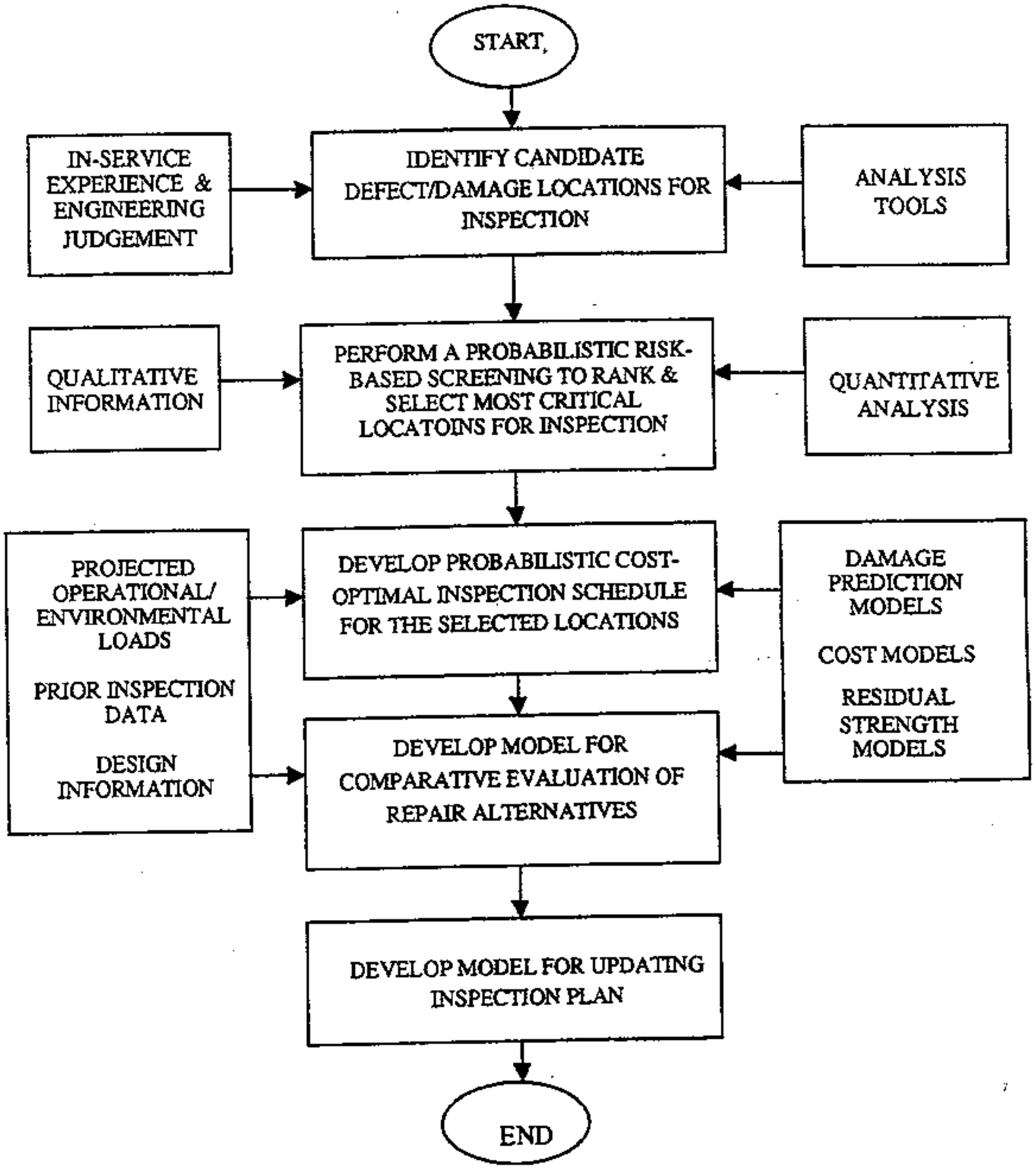


Figure 2.2: Schematic Illustration of Ideal Technical Approach for the Implementation of IMMR Strategies

For each ship, the following technical information is assembled, in order to plan an effective evaluation of the structural condition, prior to the commencement of every survey [TSCF, 1995]:

- (i) Main structural plans.
- (ii) Extent of coatings and corrosion protection systems.
- (iii) Previous structural survey reports and thickness measurement reports, including both Classification Society and Owner's reports.
- (iv) Previous maintenance and repair history.
- (v) Classification Society's condition evaluation reports and status, including any outstanding conditions of class.
- (vi) Updated information on inspections and actions taken by ship's personal with reference to structure and coatings.
- (vii) Critical and high risk areas for corrosion and structural fractures.
- (viii) Survey planning documents (optional).
- (ix) Cargo and ballast loading history.
- (x) Extent of use of inert gas plant and tank cleaning (optional).
- (xi) Trading route history.

With the above technical information, the inspection scope can be defined prior to the commencement of every survey.

2.2 Execution of Inspection

2.2.1 Preparation

After the planning, the tanks or holds subject to inspection are prepared to a condition ready for inspection. Three tasks, namely **tank cleaning, ventilation**, and **lighting**, are completed before inspectors enter tanks. The tanks must be cleaned to allow inspectors to inspect effectively. Ventilation facilities are then installed to prevent gas hazard to the inspectors.

The effectiveness of the **tank cleaning** is an important factor contributing to the success of a structural survey. The water in the ballast tanks must be pumped out. There is typically a layer of mud left on all horizontal surfaces which is usually hard to remove. Also, the surfaces in the cargo tanks of tankers can have a layer of wax or cargo residue (sludge) left after cargo oil is pumped out. All the scales, mud, wax or standing water will hide structural defects. Insufficiently cleaned tanks will not only prevent a good visual and ultrasonic survey but will also increase the hazards faced by the inspectors from hydrocarbon levels and slippery structure. In the case of tankers, tank cleaning can be performed with an existing Crude Oil Washing (COW) system. Sediment and sludge may still be a problem in shadow areas and perhaps on the bottom, and in this case crew assistance in sludge removal by using shovels, scrapers and buckets may be necessary.

Ventilation is critical to the safety of inspectors during an inspection into a tank containing hazardous cargo. The risks of hazardous vapors, suffocation, fire and explosions are controlled by conventional gas freeing, cleaning and ventilating. Before entering tanks, gas testing is conducted to ensure that the air in the tanks will not endanger the inspectors. To get rid of these dangerous gases, continuous forced ventilation is supplied to the tank during the inspection. An adequate number of deck fans are used to supply the fresh air. In the case of tankers, the stated cleaning and gas freeing an entire vessel take about seven days and require taking the vessel out of service.

General tank **lighting** is provided by water-turbine lights or air-driven portable lights suspended through deck openings and/or by natural daylight, since all access and tank cleaning holes are opened. Local lighting is provided by the flashlights or cap lights carried by the team members.

After the above three tasks are done, inspectors can then go into tanks to search for defects and assess structural conditions. Inspecting a ship is considered a very dangerous task because of the risks associated with injuries from falling, toxicity of certain cargoes and fire/explosion hazards from residual gas. Different aspects of safety of the inspection personnel during inspection are detailed in various references [see TSCF, 1986, 1997 for example].

2.2.2 Access to Tanks

A fundamental problem that inspectors will meet is obtaining satisfactory access to structural details. The most difficult areas to inspect on large tankers are the upper areas and under-deck structure because of difficult access due to their heights. Popular access methods at the present time are "walking & physical climbing" and "rafting", because they are relatively easy and cost effective. It needs to be noted that no matter what access method is used, the best way to detect cracks is to be within an arm's length and to use visual inspection.

Walking the bottom is commonly used in all types of inspections. This method only allows close-up inspections in the lower region. However, it can be used to assess the overall condition of a tank or a hold. A visual inspection can be performed from the bottom to define suspicious areas such as those containing rust stains or oil leakage patterns. An access method to reach these areas can then be requested by surveyors to further conduct a close-up survey.

Physical climbing is a very common method to inspect critical areas such as side shell longitudinals in tankers. The inspectors use the side longitudinals as a ladder to gain access to upper regions of the tank. Most company policies recommend that the climbing height not exceed 3 meters. In fact, a fall at a height of 3 meters or less could cause serious, if not fatal, injury.

Rafting is one of the more common methods used to survey a tank prior to entering the yard. If conditions and company policy permit, it can be done at sea, with no out-of-service costs, but with pumping and other costs. The method consists of usually two inspectors canvassing the perimeter of a partially ballasted tank in an inflatable rubber raft. An in-depth rafting survey can take 15 to 20 days, resulting in considerable out-of-service costs. If this method is used, the swash bulkheads and centerline girders of the vessels should have large access openings for raft passage. In addition, access to the deckhead is still limited by the depth of the upper portion of the transverse web frames. Although rafting has some risks due to problems with ship motion induced fluid surge in the tank or with unchecked gas condition, it is generally accepted as the best and most cost effective method for surveying the entire tank [Sipes, 1990].

Conventional **temporary staging** within a tank to gain access to deckhead and bulkhead structures is an option that may be attractive in some circumstances but, as the vessel gets older and survey requirements more stringent, the cost of such staging methods could become prohibitive.

Portable staging is a promising method. It uses a portable staging device which works and looks much the same as a window washer device used on tall skyscrapers. The device is easy to disassemble so that access through a manhole is possible. It can usually carry from one to four people. It is air powered. The main difficulty of this method is the initial rigging. If permanent deck plugs are provided in the new construction period, it would greatly improve the rigging efficiency.

A past study performed at U.C. Berkeley [Holzman, 1992] summarized 13 inspection access methods for tanker inspections. Each method has its particular advantages and disadvantages. Table 2.1 summarizes the advantages and disadvantages of alternative internal tank structure inspection methods and techniques. Also, USCG R&D has been conducting and sponsoring work on evaluating innovative inspection techniques such as remotely controlled lights, video cameras, flat plate inspection techniques, imaging systems, thermography and others [Goodwin & Hansen, 1995][Hansen, 1995]. Most of these techniques are not yet widely used in ship structure inspection, but some of them may have the potential to provide a more efficient way of inspection in the future.

The effectiveness of an inspection is dependent on the method of inspection and accessibility. Improving the inspection method, and improving accessibility will increase the percentage of critical structural details that are inspected. Currently most vessels are only fitted with ladders to provide access to the tank bottom. The accessibility to some critical structural details such as side shell longitudinal is poor. It can be greatly improved by simply adding climbing bars, additional horizontal girders, or catwalks with handrails. Accessibility is a key design consideration in current designs.

2.2.3 Data Recording

While the inspection is underway, inspectors will need to record the defects they find. When conducting an internal structural survey, typically the inspector will carry a small pocket size notepad and pen. The defects will be recorded in the notepad and will be reviewed once outside the tank. The inspector records the location, the affected structural member, the type and the size of the defect, and a recommended repair. The inspector will often have to remove one of his/her gloves so that the information can be recorded. The inspector's notepad can be easily stained at this moment. This can make notes difficult to decipher once outside the tank. Rafting poses additional problems; the inspector and all his equipment can become wet. Upon completion of the survey, the inspector is required to transfer the defects list to a clean form so that repair specifications can be made. However, many feel a good old fashioned notebook (hard cover) is still the best alternative. A notebook allows the inspector to write and sketch as the situation demands.

An alternative way of recording data is to use a small tape recorder. This is easier than writing something on a notepad. The inspector does not need to remove his glove. Besides, he/she can keep inspecting while recording. However the difficulty lies in transcribing the information. Once the inspector is out of the tank, there is still a need to review the tape and write down the information. Note that tank interiors are very unfriendly to delicate equipment. If the recorded information cannot be accessed for some reason, the inspection will have to be repeated. Some companies are developing rugged equipment for recording gauging data with ability to transfer the data directly to computers for analysis and print-out.

2.3 Post-inspection Data Reporting and Analysis

2.3.1 Reporting

In accordance with IMO Resolution A. 713, enhanced survey requirements were implemented in the rules for tankers and bulk carriers in 1993. One of the requirements is **Documentation Onboard**. The owner is required to supply and maintain hull survey related documentation onboard, which is to be kept for the lifetime of the ship. The purpose of the document is to identify critical structural areas. Also it is to stipulate the minimum extent, locations, means and access arrangements for close-up survey and gaugings of sections and internal structures, as well as to nominate suspect areas consistent with rule requirements.

In the case of ABS rules, for example, the required onboard document is to contain [ABS, 1995]:

- Reports of structural surveys
- Condition evaluation report
- Thickness measurement report
- Survey planning document

Additional documentation may be required to be placed and maintained on board by the owner such as main structural plans of cargo and ballast tanks, previous repair history, cargo and ballast history and other relevant information.

The inspection report for mandatory survey uses the formats as specified by each individual classification society. Owners/operators sometimes keep track of the ship maintenance condition in a more detailed format. In the case of tankers, many results are presented efficiently on longitudinal elevation drawings of the ship: e.g., Starboard and Port sideshell, longitudinal bulkheads and Centerline (girder or bulkhead as applicable). Supplementary drawings might include horizontal plan views at critical waterlines or girder levels. Usually the least useful drawings are transverse sections at web frames, since comparisons among web frames require tedious flipping through a batch of such drawings [Stanley, 1996]. However, it often is useful to have at least one generalized transverse section, to show details of structural designs and how they fail, particularly if the failures are not neatly confined to the longitudinal elements such as shell or bulkhead stiffeners and their connections to transverse structure.

In general, the survey report contains the following:

- Structural defects such as crack, buckling and indent.
- Pitting and grooving corrosion including pitting intensity diagram.
- Thickness measurement of steel plates.

- Coating condition including percentage of breakdown, peeling, flaking and blistering.
- Condition of corrosion control systems such as sacrificial anode or impressed current cathodic protection systems.
- Effectiveness of previous repairs.
- Crack growth if previously not repaired.
- Drawings or photographs to supplement the above data.

A graphical format is normally preferable for a surveyor to review before commencing an inspection. The surveyor can add an intangible, his/her own prior experience, to reinforce the trends presented. The data reporting will be enhanced if the results can be presented in a form that is easy and simple for surveyors and analysts to use and keep up-to-date (to expand the database).

With the advent of computerized databases, several systems have been developed to facilitate the large amount of inspection, maintenance and repair (IMR) work. A previous SSC report (SSC-380) has summarized the features of four existing commercial IMR software and some other non-commercial ones [Schulte-Strathaus, 1995]. The four software include the CATSIR database systems (developed by CHEVRON in cooperation with OCEANEERING), ARCO's Hull Fracture Database (HFDB), FracTrac (developed by MCA Engineering) and SID (Structural Inspection Database) developed by MIL Systems. All these software have reporting modules to facilitate reporting inspection results.

2.3.2 Data Analysis

When all the necessary survey data and findings, with respect to overall and local corrosion, fractures, and deformations have been collected, the residual strength of the ship can be evaluated and maintenance needs considered for a further period of operation. If the survey coincides with the Special Periodical Survey for Class Society, the further period of operation will be considered to be four to five years. Reference [TSCF, 1986][TSCF, 1997] gives the following guidelines regarding structural integrity in terms of overall hull girder strength, buckling, fracture, general corrosion and local pitting.

The **overall hull girder strength** is confirmed on the basis of the actual hull girder section modulus which may be assessed initially using an allowable area at deck and bottom.

Any **buckling** found during the survey is taken as an indication of areas which require stiffening or renewal of material.

Any **fractures** found are normally to be repaired by part renewal of material or by welding. Structural modifications may also be advisable to avoid repetition of fractures.

Once ultrasonic readings are collected and reviewed, the areas of heavy wastage due to **general corrosion** need to be identified. The integrity of corroded local structure may normally be considered by applying a percentage allowance of the thickness supplemented where necessary by the application of buckling criteria. If wastage is in excess of the allowable limit, steel renewal may be needed.

Local corrosion or **pitting** of the shell can lead to possible hull penetration. Isolated pits are not believed to significantly influence the strength of plates or other structural members, but may cause a potential pollution or leakage problem. When large areas of structure are affected, however, this will influence the strength and must be considered when assessing the residual mean thickness of material. A current on-going project sponsored by Ship Structure Committee (SSC SR-1356) is working on the residual strength assessment of pitted plate panels. Extensive pitting corrosion will reduce the bending capacity of un-stiffened plates significantly. The bending capacity reduction obtained from testing of plates with uniform machined pits suggests that capacity reduction is roughly proportional to the loss of material. The SSC SR-1356 research project has developed a mathematical model to estimate steel reduction from inputs of the number of pits, an average pit depth and an average pit width. Another way of estimating steel reduction is to use the pitting diagrams together with measurements of pitting depths.

As for the coating system, its continuing effectiveness is to be evaluated. The remaining coating life is estimated. The coating repair and maintenance plans can then be developed in conjunction with steel maintenance plan.

Guidelines for corrosion wastage have been developed in a tabular format by TSCF [TSCF, 1997]. The Table lists wastage allowance for different structural components. When corrosion wastage exceeds a certain percentage, assessment or steel renewals will be required according to the Table. Buckling criteria are also given in the same Table. Guidelines for pitting repair are provided as well. See the reference [TSCF, 1996] for more detailed information.

After the inspection data analysis is done, repair and maintenance plans can be developed.

2.4 Repairs

Ideally, several months before the vessel is scheduled for the repair yard, an initial visual and gauging survey will be conducted by owners/operators to evaluate the effectiveness of corrosion protection system and quantify the degree and extent of steel wastage. Based on the results of the survey, a repair plan can be developed. Once the ship enters the shipyard, extensive visual and gauging surveys are again conducted to identify and verify the steel condition in details. These secondary surveys usually reveal additional repair items.

For a fracture type of defect, repair methods vary widely. Consider repairs on fractures for example; they can range from temporary cold patches to stop leaks to complete re-design of the structural detail and replacement of steel nearby the detail. Welding cracks is a popular repair method, but these frequently fail again within a short time. Experience indicates that many of these repairs must be repeated in subsequent dry docking. It is difficult to decide which repair method is most reliable and cost effective. The selection of different repair alternatives usually depends on the location of the crack and the expected life continuance of the ship. More information on advanced fatigue crack repair analyses can be found in Reference [Ma & Bea, 1993].

On the other hand, the repair methods for corroded plate which exceed the corrosion limit is more straightforward. The corroded plate needs to be renewed. Practical maintenance and repair methods for tankers can be found in Reference [TSCF, 1997].

2.5 Inspection Strategies of Other Engineering Structures

Inspection, monitoring, maintenance and repair (herein termed the IMMR process) is a critical part of any structural integrity process. The fundamental objectives of IMMR are the maintenance of strength and serviceability to some predefined levels of safety throughout the life of the structure. This process usually pays attention to efficiency and cost-effectiveness. The manner in which this common objective is achieved varies from one industry to another, and is largely influenced by the degree of sophistication of analytical/computational models or tools, as well as the nature of the inspection equipment. In general, there is a belief that condition-based (rather than periodic) IMMR procedures are more realistic and potentially more cost-effective than existing practices. The application of such techniques to any structural system requires a thorough understanding of the damage/failure mechanisms, the loads, residual strength assessment procedures, as well as definitive damage tolerance guidelines that will serve as the basis for the acceptance/rejection of damaged or degraded structural conditions. Probabilistic risk-based assessment framework is believed to be a rational and systematic strategy for quantitatively implementing such an approach. Several industries have carried out practical applications of such strategies and substantial cost and improved safety benefits have been recorded. In this section, a brief summary of representative approaches utilized in selected industries is presented.

In the nuclear industry, for example, the American Society of Mechanical Engineers (ASME) Center for Research and Technology Development set up a task force in 1988 to develop "Risk-Based Inspection Guidelines" for nuclear structural systems and components. This important effort, which is funded by ASME, the US Nuclear Regulatory Commission and several others has reached an advanced stage of development (ASME, 1981). The results of the recommendations and guidelines developed from this study have been successfully applied in the nuclear industry to power plants.

In the aerospace industry, inspection programs and requirements are largely driven by the specifications of the Aircraft Structural Integrity Program (ASIP) introduced by the United States Air Force (USAF, 1974). ASIP is used worldwide by many commercial as well as military establishments for the maintenance of sound aircraft structural integrity. Under the application of ASIP for inspection/planning of damage-tolerant aircraft structures, analysis are conducted to estimate the time, T_c, required for a crack (at a critical structural location) to grow to a critical size, based on projected mission profiles. ASIP requires an inspection for such a flaw/defect to be conducted at half this time, i.e. $T_c/2$. The ASIP guideline is predominantly geared towards the fatigue crack damage category and has no similar quantitative guidelines or requirements for corrosion damage. Field applications of ASIP in inspection planning have been largely deterministic. There are, however, ongoing research and development efforts both by the United States Air Force and the Canadian Air Force to move towards the application of probabilistic risk-based strategies in this connection.

For offshore structures, the merit of the application of probabilistic techniques for inspection planning has long been recognized. As of now, probabilistic inspection strategies are being successfully employed in the field - especially by the Norwegians to North Sea offshore platforms. Noteworthy research and development investigations that paved the way for current practical applications include the works of Madsen et al. [20], Lotsberg and Kirkemo [22], Paliu et al. [21], Skjong, (1985) and

Skjong and Torhaug, (1991). Wirsching and Torng (1989) have also recommended optimal strategies for the inspection/repair of fatigue-sensitive marine structural systems using risk-based economics. The application of these concepts to ship structures requires similar principles. However, very limited attempts (for example, Schall and Öestergaard (1991) have been made (even at the research stage) to apply probabilistic inspection planning strategies to ships.

We believe that the ideal technical approach to realize a truly optimal strategy for the inspection, monitoring, maintenance and repair process is as schematically illustrated in Figure 2.2. However, for ship structures in particular, several technical challenges must still be overcome in order to realize the full benefits that a quantitative probabilistic risk-based approach has to offer. Examples in this connection include: (i) accurate definition of loads, (ii) accurate and efficient computation of stresses/strains at local hot spots, (iii) robust damage tolerance and residual strength assessment that are capable of accounting for the effects of load shedding and redundancies present in the structure, and (iv) and accuracy of damage (particularly corrosion) growth rates. Even though ship structural technology limitations do not permit us to apply the full-blown procedure shown in Figure 2.2, the strategy that has been employed in this study represents a realistic compromise that utilizes the essence of the concept along with the practical realities and constraints of current ship inspection practices.

2.6 Limitations of Current Practices

The current practices of ship inspections are heavily based on experience. Take the inspection interval (or frequency) for example. Regardless of the limited extent in an Annual Survey, ships can generally be considered to have an inspection interval of one year. The choice of this one-year interval is arbitrary or, to some extent, based on experience. It is not based on a rigorous engineering analysis. As a result, it may create an inefficient inspection program in which a better maintained ship has to be subjected to the same degree of inspection as a poorly maintained one. The experience-based inspection interval establishment has the disadvantage of possibly wasting surveyor labor and causing down time by conducting unnecessary inspections for ships in good conditions.

If rules on inspection intervals are calibrated from experience, they will then be improved or revised only after sufficient amount of experience or lessons have been learned. The inspection interval specified in the codes may be shortened, after a class of ships are experiencing an extraordinary failure rate. This has happened to certain classes of TAPS tankers. In 1990, the U.S. Coast Guard published the result of a study which revealed that the TAPS tankers experienced a substantially higher number of fatigue cracks than the rest of the U.S. flag tankers. As a result of this study, the Coast Guard proposed an inspection program which requires some classes of TAPS tanker to survey their critical areas in a shorter interval [Sipes, 1991]. The U.S. Coast Guard also requires all TAPS tankers to have Critical Area Inspection Plans. The actions taken by the U.S. Coast Guard showed a good example of establishing inspection interval based on newly learned experience.

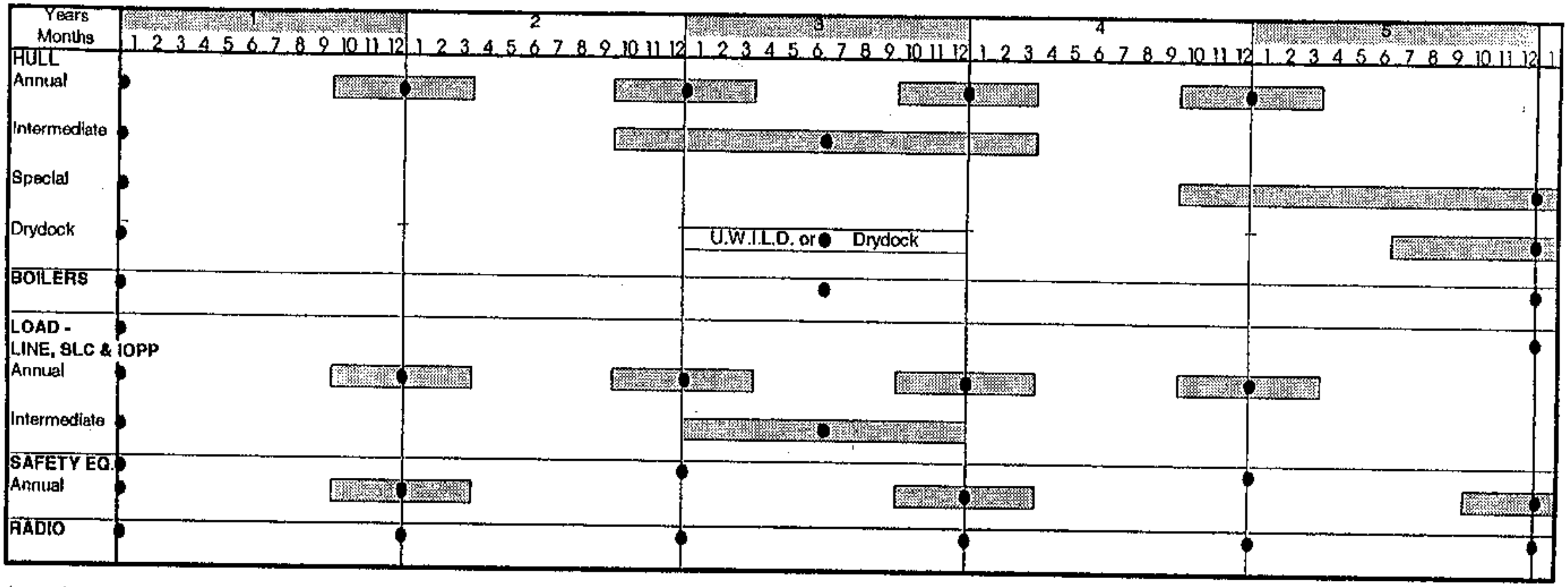
The experience-based approach has some drawbacks. If it is not used with careful and thorough examination, the inspection interval can become so short that unnecessary inspections are conducted. A simple rule to check if an added inspection is necessary is that the cost of the added inspection should be less than the expected failure loss due to not detecting defects in time. In other words, the reward from the increased inspection frequency should be worth more than the cost of extra inspections.

Another drawback is that the inspection interval may have the danger of becoming so long that a major structural failure can occur before the next inspection. This has happened to bulk carriers in the recent past. Nearly one hundred bulk carriers have sunk over the period from 1990 to 1994. A high percentage of these casualties is due to structural failures, especially those associated with side frame fractures. The class survey requirement in the past did not include close-up examination of side frame structures in their annual surveys. The inspection interval of side frame structure was 5 years at special surveys and on an annual basis at a late age. After the series of the bulk carrier casualties, major class societies have tightened their rules together through the IACS unified requirements prepared in 1992. All aging bulk carriers (older than 10 or 15 years old depending on different class societies) now are required to be close-up surveyed in Annual Surveys. The inspection interval for side frame structures, then, has been effectively shortened to one year. Additionally, intermediate survey requirements are also more stringent, and specify close-up examination of 25 % of cargo hold framing. The extent of close-up surveys has been expanded.

Beside inspection frequency, the requirements on other aspects such as inspection extent and location all have been based on experience. Chapter 4 of this report will introduce advanced approaches that can be used to optimize these aspects.

Table 2.1: Summary of Access Methods [Holzman, 1992].

Methods	Advantages	Disadvantages
1. Tanker design	Safety, increased accessibility	Cost, weight, maintenance, unwanted structural detail
2. Walking the bottom	Inexpensive	Poor accessibility, only line of sight view
3. Climbing w/o fall safety device	Increased accessibility, inexpensive	Unsafe, impossible to climb central tanks
4. Physical climbing with fall safety device	Increased accessibility, inexpensive	Initial rigging difficult, physically demanding
5. Access to side member with ascender	Increased accessibility, inexpensive	Initial rigging difficult, training required
6. Fixed Staging	Access available to all members in party	Expensive, labor intensive
7. Rafting	Can be accomplished underway, inexpensive	Considered unsafe by some, expensive, time consuming
8. Binocular with high intensity light	Can be accomplished underway	Hands on inspection not possible, only line of sight view
9. Portable staging	Light repairs possible, relatively safe	Expensive, difficult initial rigging
10. Mechanical arm	Increased accessibility	Difficult initial rigging
11. Divers	Can be accomplished underway	Diver inexperienced in ship inspections, time consuming, expensive, unsafe
12. ROV	Can be done underway, gas freeing tank not required if equipment is intrinsically safe	Expensive, easy for operator to become disoriented
13. Acoustic emission	Can be accomplished while vessel is in service provided equipment is intrinsically safe	Only tank top area currently feasible



Legends:

● This symbol indicates due date.

▭ Shaded area indicates available window.

- An Under-Water Inspection in Lieu of Dry-docking Survey (U.W.I.L.D.) is considered the equivalent of dry-docking. Consecutive UWILD surveys are not allowed and a UWILD will not satisfy special survey hull requirements.

Figure 2.3: Typical Five-Year Survey Cycle for International Fleet Vessels.

3. INSPECTION EXPERIENCE IN TANKERS AND BULK CARRIERS

A common question for surveyors is where to inspect in a huge structure such as a VLCC or a Capesize bulk carrier. It is almost impossible to conduct a close-up survey for every square foot in structures of such a size. A good strategy is to concentrate efforts on Critical Structural Details (CSDs). Many studies have defined CSDs in different ship categories based on past experiences gained from inspections. This chapter has collected and compiled a list of critical structural areas in tankers and bulk carriers in terms of fatigue, corrosion and operational wear from the existing literature.

3.1 Tanker Critical Areas

With the introduction of large tankers such as VLCCs (Very Large Crude Carriers), the task of conducting structural inspections has become increasingly problematic. On a 250,000 ton deadweight single hull VLCC, the total area to inspect is around 300,000 square meters (see Figure 3.10 and 3.11 for the mid-ship configurations of a double hull tanker and a single hull tanker, respectively). Due to the large areas involved, it is necessary to focus on suspect areas to optimize the effectiveness of surveys. For tankers, it appears that substantial information regarding fatigue and corrosion critical areas is already available in various forms through the efforts of previous studies by various organizations [Bea, et al., 1995][TSCF, 1992, 1995 & 1997][Sipes, 1990 & 1991][Ferguson, 1991a]. This section summarizes the results of these studies.

3.2 Fatigue Critical Areas

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

A more recent study, Ship Maintenance Project (SMP), was undertaken at the University of California at Berkeley [Bea et al., 1995]. This study created a crack database based on data gathered from 10 tankers including 2 double hulls, 2 double bottoms, and 6 single hulls (4 of which were sister ships). The data base consisted of 3600 cracks, of which about 2000 were in the 4 sister ships. The study indicated that 40 % of the total 3600 cracks occurred in **connections of side shell longitudinals to transverse bulkheads or web frames**. About 10 % of all cracks were found in the bottom longitudinal end connections. A further 10 % were in horizontal stringers. Figure 3.1 shows the crack distribution by tanks along the vessel length, for the four sister ships. There is a trend for more cracks to occur in the mid body region for this class of vessels. However, this trend

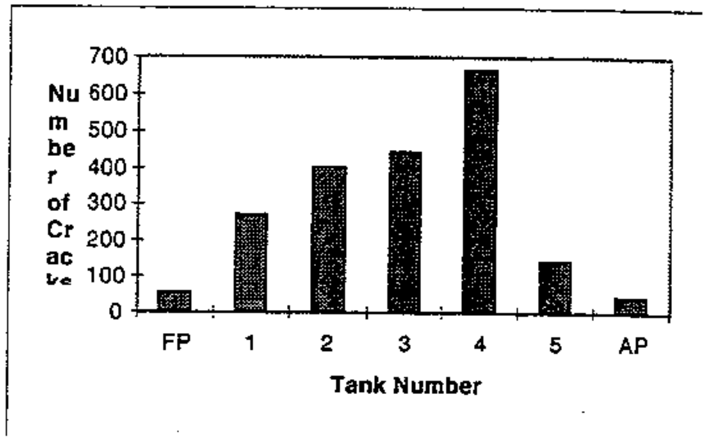


Figure 3.1: Crack Distribution Along the Vessel Length of 4 Tankers in the Same Class [Schulte-Strathaus, 1991].

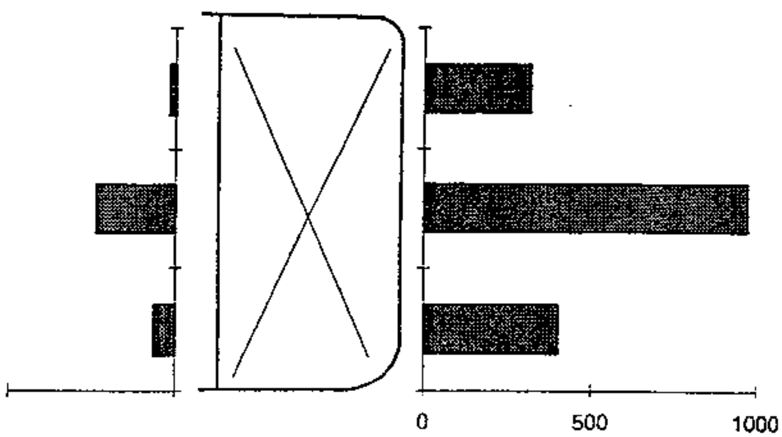


Figure 3.2: Crack Distribution Along the Longitudinal Bulkheads (Left) and Side Shells (Right) of 10 Tankers [Schulte-Strathaus, 1991].

is formed partly because of the smaller sizes of the fore-peak tank and aft tank. While all factors being equal, smaller tanks should have less cracks than larger ones. If the number of cracks in each tank is normalized according to its tank size, the trend shown in Figure 3.1 becomes less clear. The study also presented the crack distribution along the vessel height which was divided into three regions. Most side shell cracks and longitudinal bulkhead cracks tend to occur in the middle third of the vessel height (see Figure 3.2). The side shells have significantly more cracks than the longitudinal bulkheads in these 10 ships.

A study examining general trends was also performed and is reported in this report using the data of 2 VLCCs in the same class. The two vessels are both 15 years old at the time when the survey data were collected. Each has around 500 cracks. Most of the cracks are located in the side shell and longitudinal bulkhead areas. Their crack distribution along the vessel length is presented in Figure 3.3. Tank no. 1 was excluded because its data was not available for one of the two vessels. All tanks have 9 transverse web frames except tank no. 3 and no. 6 which have 7 and 11 frames respectively. In order to make a fair comparison, the crack numbers of these two tanks are normalized according to their sizes. Note that the distribution covers only the cracks found in transverse web frames and in adjacent structure. Cracks elsewhere are not many and are excluded to facilitate normalization of the results. The result shows that the water ballast tanks (tank no. 3 and no. 5) have more than 250 cracks, while the cargo oil tanks (tank no. 2, 4 and 6) each have around 150 cracks. There is no obvious trend along the vessel length. The tank type seems to be an important factor affecting cracking rate. It was noticed that some cracks in the ballast tanks are located in areas with heavy corrosion. Therefore, it may be concluded that the corrosion in water ballast tanks of these two vessels accelerates fatigue cracking.

The crack distribution along the vessel height is presented in Figure 3.4. A distinct crack trend of four problem areas can be seen probably as a result of poor designs of the struts. Instead of using a continuous flange connecting to the flange of the web frame, the struts use two small brackets in each end. This design results in large loads on the adjacent flat bar stiffeners and for this reason almost all have failed. This highlights the fact that many fatigue failures are caused by poor design. Side shells have more cracks than longitudinal bulkheads. The distribution of cracks along the vessel height is consistent with the conclusion reached by many studies that most cracks fall in the region from the load water line to about 8 meters below.

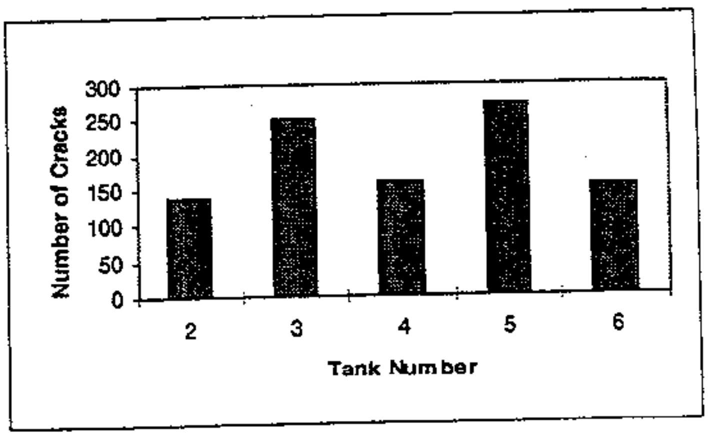


Figure 3.3: Crack Distribution Along the Vessel Length of 2 Tankers in the Same Class.

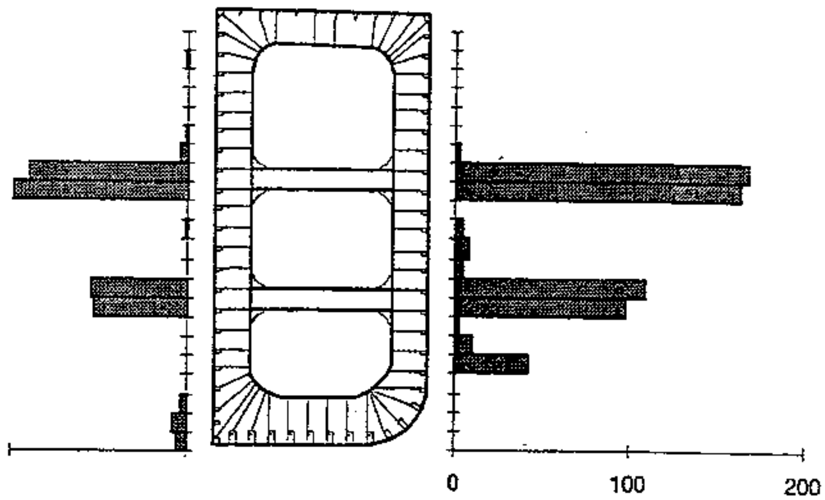


Figure 3.4: Crack Distributions Along the Longitudinal Bulkheads (Left) and Side Shells (Right) of 2 Tankers in the Same Class.

A study conducted by NK [Yoneya, 1993] has investigated the hull cracking of relatively young 2nd-generation VLCCs built with a considerable amount of high-tensile steel. These vessels experienced cracks at the intersection of side longitudinals with transverse bulkheads. The cracks start at the flange of side longitudinals and propagate into the longitudinal's web plates toward the side shell. If not found in time, they may lead to cargo oil spill from wing oil tanks. The study surveyed 18 vessels thoroughly. An average of about 10 cracks was found in each vessel. The crack trend is shown in Figure 3.5 and Figure 3.6. Nearly 80 % of the cracks were found in the mid-body tanks. Cracks are concentrated within the range of 2-5 meters under the full load waterline [Nakajima et al., 1993].

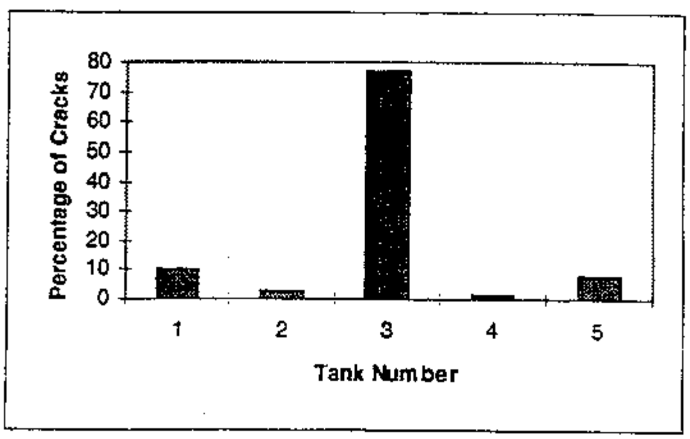


Figure 3.5: Crack Distribution Along the Vessel Length of Some 2nd-Generation Vlccs [Yoneya, 1993].

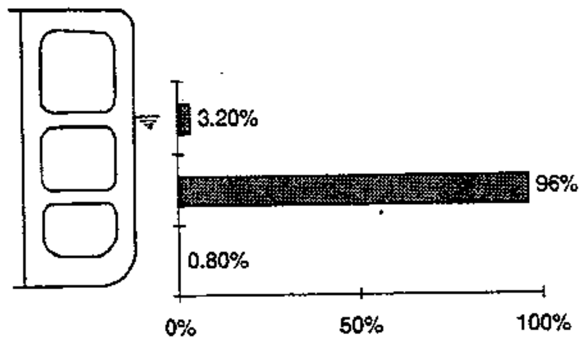


Figure 3.6: Crack Distributions Along the Side Longitudinals of 2nd-Generation VLCCS [Yoneya, 1993].

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

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

According to one of the Berkeley SMP studies [Ma and Bea, 1992], fatigue critical areas in tankers that are of concern to the inspector were summarized as:

- Intersections of longitudinal stiffeners (particularly side shell longitudinal) with transverse bulkheads or transverse web frames, particular, in the region between full load and ballast waterlines (see Figure 3.7);
- Bracketed end connections of primary and secondary supporting components;
- Discontinuities in high stressed face plates, stiffeners, and longitudinal members; and
- Openings and cut-outs in primary structures.

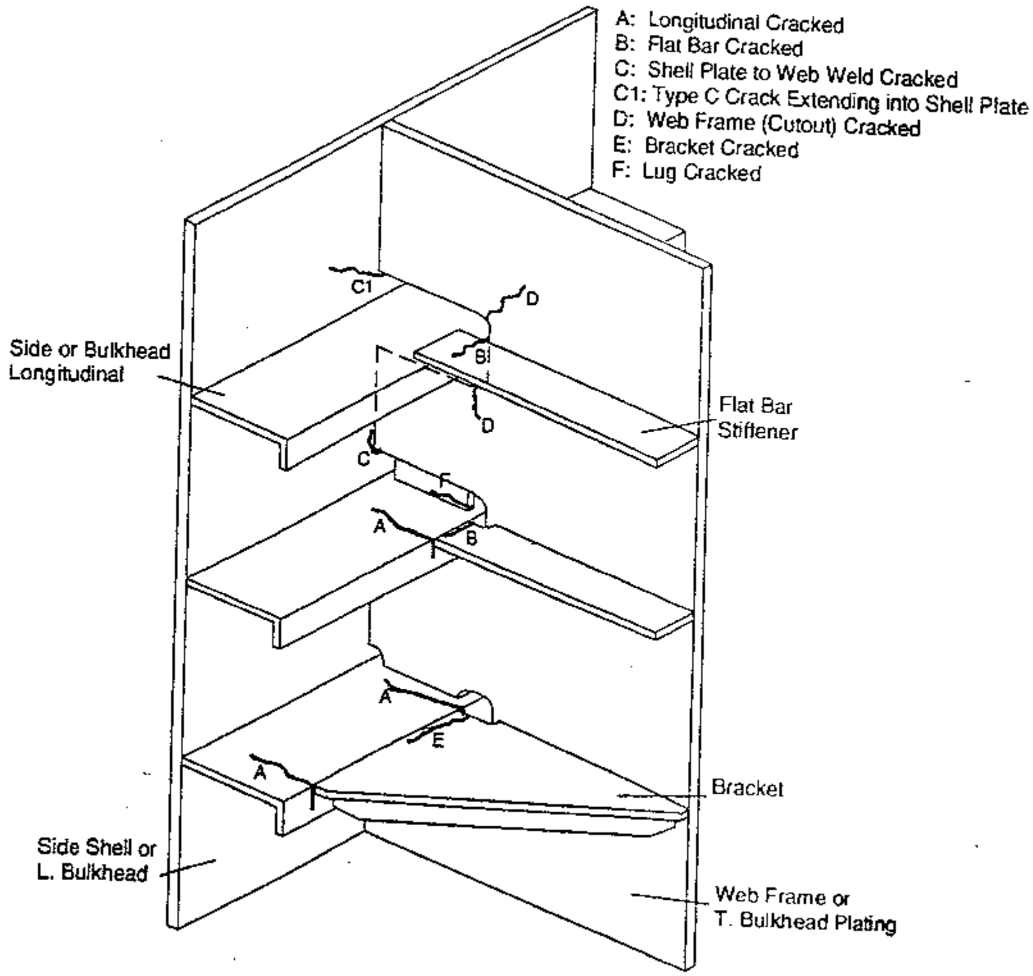


Figure 3.7: Typical Cracks in Side Shells or Longitudinal Bulkheads [TSCF, 1992].

Figure 3.7 shows the typical cracks experienced at side shell longitudinal connections to transverse frames or bulkheads. The basic mechanics of these typical cracks can be explained by considering the load transmission path. The cyclic load on side shell plates is mainly transmitted through longitudinal stiffeners to web frames. This load is then conveyed into the web frames by the flat bar stiffeners and lugs (collar rings). In some designs, the longitudinal cutout is left open without an attachment of a lug. Then the load has to be transmitted through the small footage of a flat bar stiffener. This creates a high stress that causes crack initiation in the flat bar toe or heel. The crack (type B in Figure 3.7) will then grow along the flat bar weld. After the flat bar stiffener is completely cracked through and detached from the longitudinal, a progressive redistribution of loading takes place and normally results in another fatigue crack (type D) initiated in the cutout corner of the web frame. If these two cracks are left un-repaired, the web frame crack may grow into the shell plate or new cracks will initiate in the web frame weld to the shell plate (type C and C1). Eventually a shell plate collapse, possibly together with a cargo spill, will occur. This crack sequence, however, is favorable, because type A, which is a more serious crack, comes late in the sequence. This type of crack starts from the toe or heel of a flat bar stiffener or a bracket into the web of a longitudinal. The crack can quickly grow into the side shell and lead to an oil spill. In most tankers, this crack sequence is more common. However, some designs such as those in the

2nd-generation VLCCs in the NK study tend to create an unfavorable crack sequence where the type A cracks occur first. More attention may need to be paid on ships of these designs.

3.2.1 Corrosion Critical Areas

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

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

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

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

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

A TSCF publication entitled "Condition Evaluation and Maintenance of Tanker Structures" provides detailed descriptions on corrosion suspect areas in tankers [TSCF, 1992]. It notes that the corrosion problems are different for each vessel. Even among sister ships there can be significant differences in findings. However, a number of common problems that are found on many ships are summarized These problems are summarized in terms of three general areas: tank bottom structures, side shell and bulkheads, and deckhead structures. Readers are referred to this reference for more information.

3.3 Bulk Carrier Critical Areas

Bulk carriers are generally grouped into 3 categories in accordance with their size. These are Capesize, Panamax and Handy bulkers, from larger to smaller. A typical Capesize bulk carrier has 9 or more cargo holds and dead weight in excess of 100,000 tons. Each hold has up to 25 frames on each side with a depth of around 23 meters from the tank top to the top of the hold (see Figure 3.12 for the mid-ship configuration of a typical bulk carrier). To give only their side frames, which are considered one of the most critical members, a very thorough inspection, would require, as a minimum, at least two inspectors for one day per hold. Due to the physical size involved, it is necessary to focus on critical areas. Thus, it is important for inspectors to know where the critical areas are, so more efficient inspections can be performed. This section summarizes the fatigue and corrosion critical areas defined in the existing literature [IACS, 1994][USCG et al., 1995][Grove et al., 1992][Lloyd's Register, 1995][Ferguson, 1991b].

3.3.1 Fatigue Critical Areas

The particular configuration and service of bulk carriers create some typical fatigue critical areas. These include

- Side frames,
- Hatchway corners,
- Hatch coamings,
- Intersections of hopper plates/stool plates and inner bottoms, and
- Intersections of corrugated bulkheads and stools.

Transverse **side frames** and associated end brackets in the cargo holds (see Figure 3.9) are areas that experience significant levels of failure [Grove et al., 1992]. A particular concern stems from the potential for these frames to become separated from the top and hopper tanks and, more significantly, from the side shell. Cracks usually develop from the bracket toes and can be the beginning of a possible scenario in bulk carrier casualties, as stated in Chapter 1. The exact location and extent of cracks depend on the type of bracket configuration [IACS, 1994]. Where separate brackets are employed, the fracture location is normally at the bracket toe position on the frames, whereas with integral brackets the fracture location is at the toe position on the hopper and topside tank (see top portion of Figure 3.9).

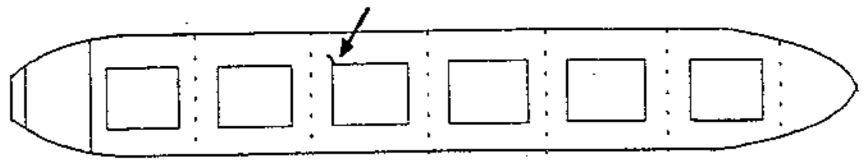


Figure 3.8: Hatchway Corner Cracks.

Bulk carriers have cargo hatchways for the convenience of cargo handling facilities. These large cargo hatchways reduce the ship's torsional strength and invite concentrated stress at the hatchway corners on the upper deck. A longitudinal bending moment causes an axial force on the upper deck that may cause cracking of the deck plate at the locations where the stress is concentrated. In this regard, upper deck plating at **hatchway corners** are one of the focal points for cracking (see Figure 3.8). Those cracks propagating from the cargo hatchways are generally considered serious to the ship's safety. Particular attention is required for these areas during inspection. Various metal fittings are welded to the upper deck plating. These installations may also cause stress concentrations at the welded joints or have defects in the welds. Deck platings in vicinities of manholes, hatch coaming end brackets, bulwark stays, crane post foundations and deck house etc. are to be carefully watched for cracking.

Hatch coamings are subjected to hull girder stress. Although they are not critical longitudinal strength members, they should be watched carefully to ensure that these cracks do not spread. Cracking may be initiated at defects in welded joints and metal fittings to the coamings that will invite stress concentration. Such cracking is considered serious to ship's safety because it may be the initiation of a fracture on a large scale.

Bilge hopper plating around the knuckle line may be cracked along the bilge hopper transverse webs (see Figure 3.9). These cracks may be caused by the cyclic deflection of the inner bottom induced by repeated loading from the sea.

In cargo holds, fractures occur at the **boundaries of corrugated bulkheads and stools**, particularly in way of shelf plates, shedder plated, deck, inner bottom etc. (see Figure 3.9). In bulk carriers having combination cargo/ballast holds, cracks may often be found at or near the connection of the stool of the transverse bulkhead and the inner bottom. All the Capesize and Panamax bulk carriers and some of Handy bulkers have combination cargo/ballast holds to maintain the necessary draft in heavy weather conditions. The bulkhead boundaries of the spaces are designed to comply with the requirements for deep tank bulkheads. In these holds cracks may often be found at the connection between the transverse bulkhead and the tanktop. These cracks can be detected by visual inspection or by noting leakage from the double bottom tanks.

In double bottom tanks, cracks may be found in the side, bottom and tanktop longitudinals at intersections with solid floors or bilge hopper transverses. Cracks also may be found in the floors or transverses occurring at the corners of the slots cut for longitudinals. In hopper tanks, cracks may be observed in transverse webs in bilge hoppers initiating from the slot openings for longitudinals and at the knuckled corners of the lower ends of the hoppers. On large bulk carriers such as Capesize and Panamax bulkers, bilge hopper plating around the knuckle line may be cracked along the bilge hopper transverse webs. This is considered to be caused by insufficient local reinforcement.

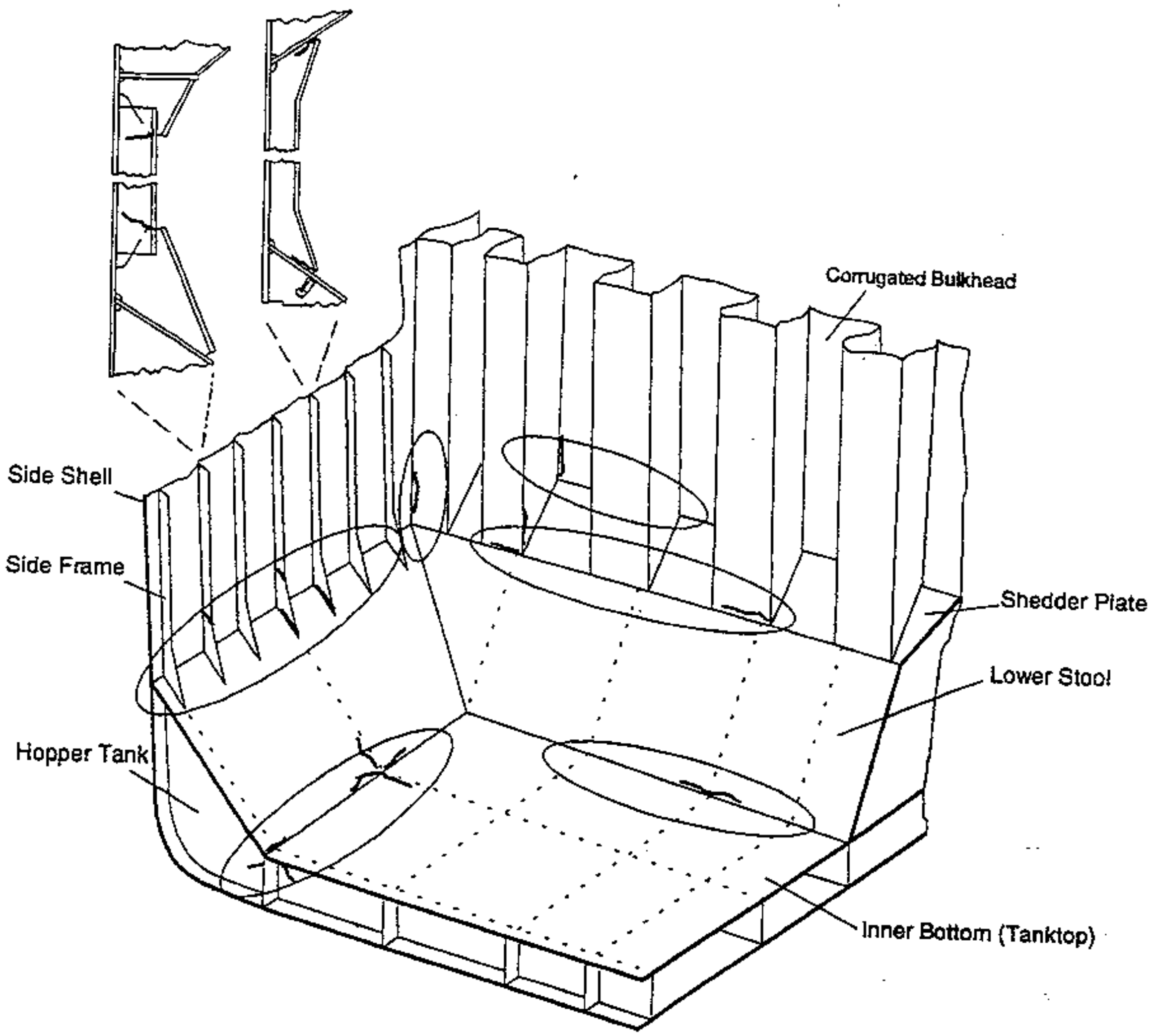


Figure 3.9: Fatigue Critical Areas in Side Frames, Bulkhead Stools and Hopper Platings of a Bulk Carrier [IACS, 1994].

3.3.2 Corrosion Critical Areas

Corrosion is a major concern in bulk carriers. In ballast tanks, the frequent ballasting tends to allow a humid atmosphere to remain in empty tanks thus contributing to wastage. Likewise, some cargo holds carry high sulfur coal which accelerates corrosion. High temperature cargoes, such as pelletized iron ore, also promote a humid environment through condensation on the vessel side from the cooler surrounding water.

The focal points for corrosion includes

- Side frames,
- Topside tanks,
- Ballast tanks (especially those adjacent to heated fuel oil tanks),

- Cargo holds carrying corrosive cargoes, and
- Transverse bulkheads.

Among the various members that comprise cargo hold structures, the **side frames** are usually the thinnest structures especially at the web plates. In addition, the side frames also have more surface area exposed, in that both surfaces of the plate are susceptible. This may mean accelerated corrosion in the hold frames, the thinnest among all the members in cargo holds. If corrosion and waste become excessive, failure of hold frames invites additional loads to the adjacent ones, which may lead to failure throughout the side shell structure. Since the consequence of a side shell frame failure is usually critical, the condition of side shell structures and their reinforcements may be the most important aspects during cargo hold inspections. Special attention should be paid to the condition of hold frames and their connection to the shell plating.

The worst area of the **topside tank** is its top and bottom. Though the water ballast tanks of newer bulk carriers are well protected against corrosion, the upper portion is susceptible to corrosion because the protective coating will easily deteriorate due to heat from the upper deck and the cyclic washing effect of sea water. Therefore, the upper part of the topside tanks should be carefully watched. On the other hand, its bottom contains the vital connection between the longitudinal framing of the ballast tank and the transverse framing of the cargo hold. Unfortunately, the brackets and adjacent structures in the bottom portion of the tank may be under mud and other debris and it may not be readily apparent that they may be severely wasted. As pointed out by Grove [Grove, 1992], this severe wastage can lead to cracking and detachment of the brackets in the tank bottom leaving the adjacent bracket or frame in the hold unsupported. Therefore, this wastage has serious implication on the safety of bulk carriers.

Corrosion must be carefully watched in water **ballast tanks** particularly in older bulk carriers over 10 years of age. In general, the condition of the steel and protective coatings will be in satisfactory condition much longer in the double bottoms than in topside compartments. However, even double bottom tanks will deteriorate in time due to the continual ballast of the ship.

In ships with fuel oil heating systems, heavy corrosion can be expected to occur in double bottom water **ballast tanks adjacent to the heated fuel oil tanks**. In many cases, the corrosion is worse in areas closer to the fuel oil tank boundaries. The fuel oil heating system was adopted to increase the viscosity of fuel oil. The heat can increase the temperature in the tank to 80° C or more. Such high temperatures can accelerate corrosion of the steel in the tanks. In one case, the heavy corrosion of the internal structure in the stool of a bulk carrier due to heat from fuel oil tanks caused a collapse of the transverse bulkhead between holds no. 8 and 9 [DNV, 1992]. Inspection after the collapse revealed that the internal longitudinal stiffeners in the stool were seriously corroded locally at the tank top, particularly in locations where the stool passed over heated fuel oil tank in the double bottom. Elsewhere the stool and the original coating remained in good condition.

Regarding the corrosiveness of cargoes, coal is among the most **corrosive cargoes** carried on board the bulk carriers. Thickness measurement surveys reveal that bulk carriers which have been employed in carriage of coal suffer more serious corrosion to their cargo holds than those engaged in the carriage of other cargoes.

Bulk carrier watertight **transverse bulkheads** at the ends of dry cargo holds are constructed in various ways which in general can be categorized as either vertically corrugated, double plated, or plane bulkheads vertically stiffened. They may also be susceptible to accelerated corrosion, particularly at the mid-height and at the bottom. Special attention should be given to the following areas [USCG et al., 1995]:

- Bulkhead plating adjacent to the shell plating.
- Bulkhead trunks which form part of the venting, filling and discharging arrangements between the topside tanks and the hopper tanks.
- Bulkhead plating and weld connections to the lower or upper stool shelf plates.
- Weld connections of stool plating to the lower or upper stool shelf plate and inner bottom.
- In way of weld connections to topside tanks and hopper tanks.

3.3.3 Local Structural Deformation

Because of the large hatchway openings on the deck, the cross deck strips have to carry high axial compression loads in the transverse direction. This sometimes results in buckling. If the cross deck strip is designed with a longitudinal stiffening system instead of a transverse one, it will be very susceptible to buckling.

Another type of deformation is the local structural damage created from loading or unloading process. Local structural damage can be caused by grabs and pneumatic hammers used to knock or vibrate cargo residues from hold surfaces. Deliberately swinging grabs against the ship's frames to shake residues free may damage the structure. Using a pneumatic hammer at the bottom of a frame to shake free residues from the top of the frame can be harmful to the structure. Local structures can be easily damaged by these procedures.

The puncturing of hopper tanks and the indenting of hatch coamings by contact with the corners of grabs is also a common occurrence. The buckling of frames and the tearing of brackets can occur in a similar manner. Such damage often remains un-repaired upon sailing because the port usually lacks the resources or the motive to make the repair.

The focal points for deformation can be summarized as follows:

- Buckling of the cross deck strips
- Grab or bulldozer damage to the lower part of side frames
- Grab damage to the inner bottom, hopper and stool platings

These damages should be carefully watched during inspections.

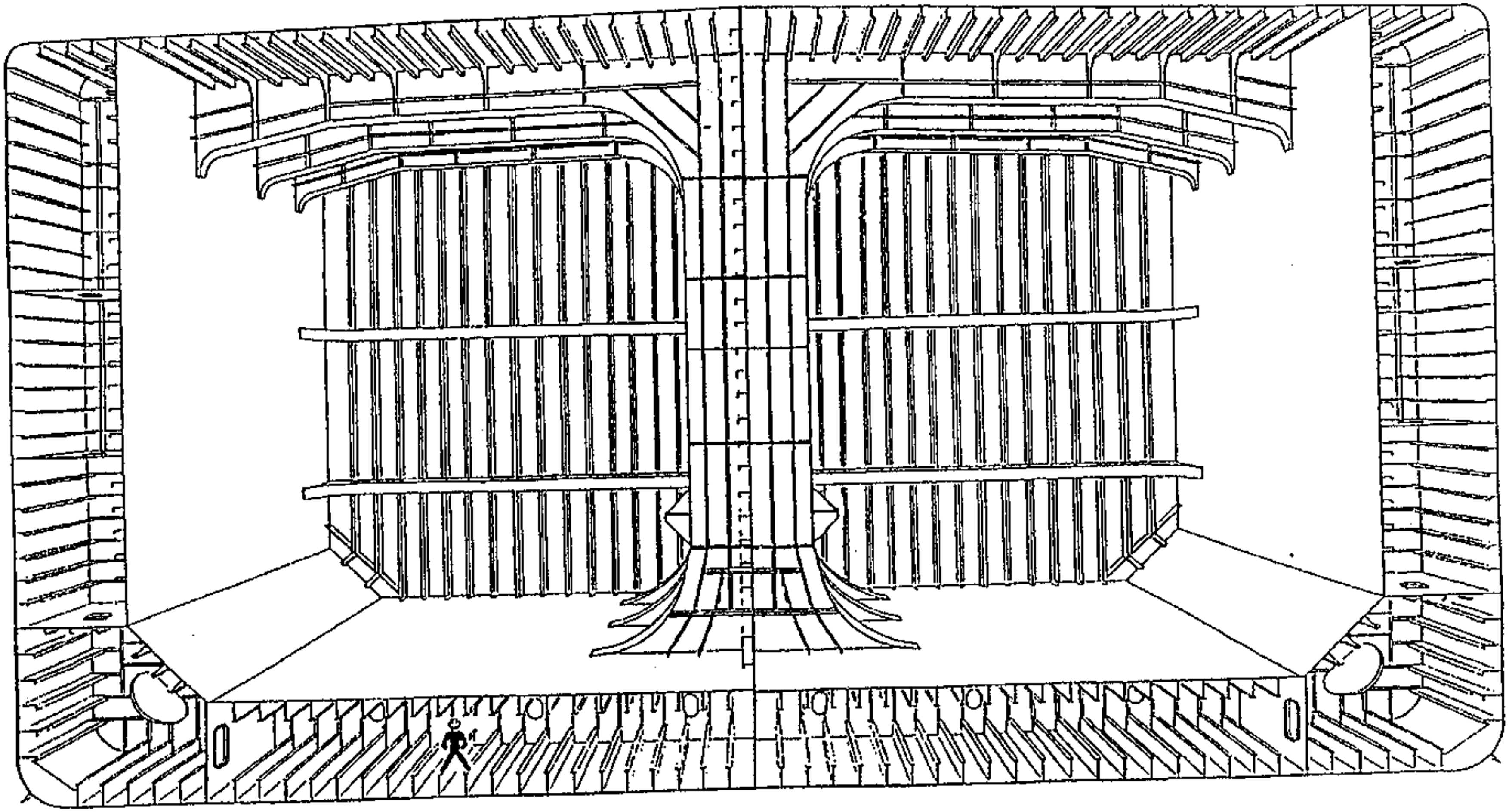


Figure 3.10: Typical Mid-Ship Structural Configuration for a Double Hull Tanker.

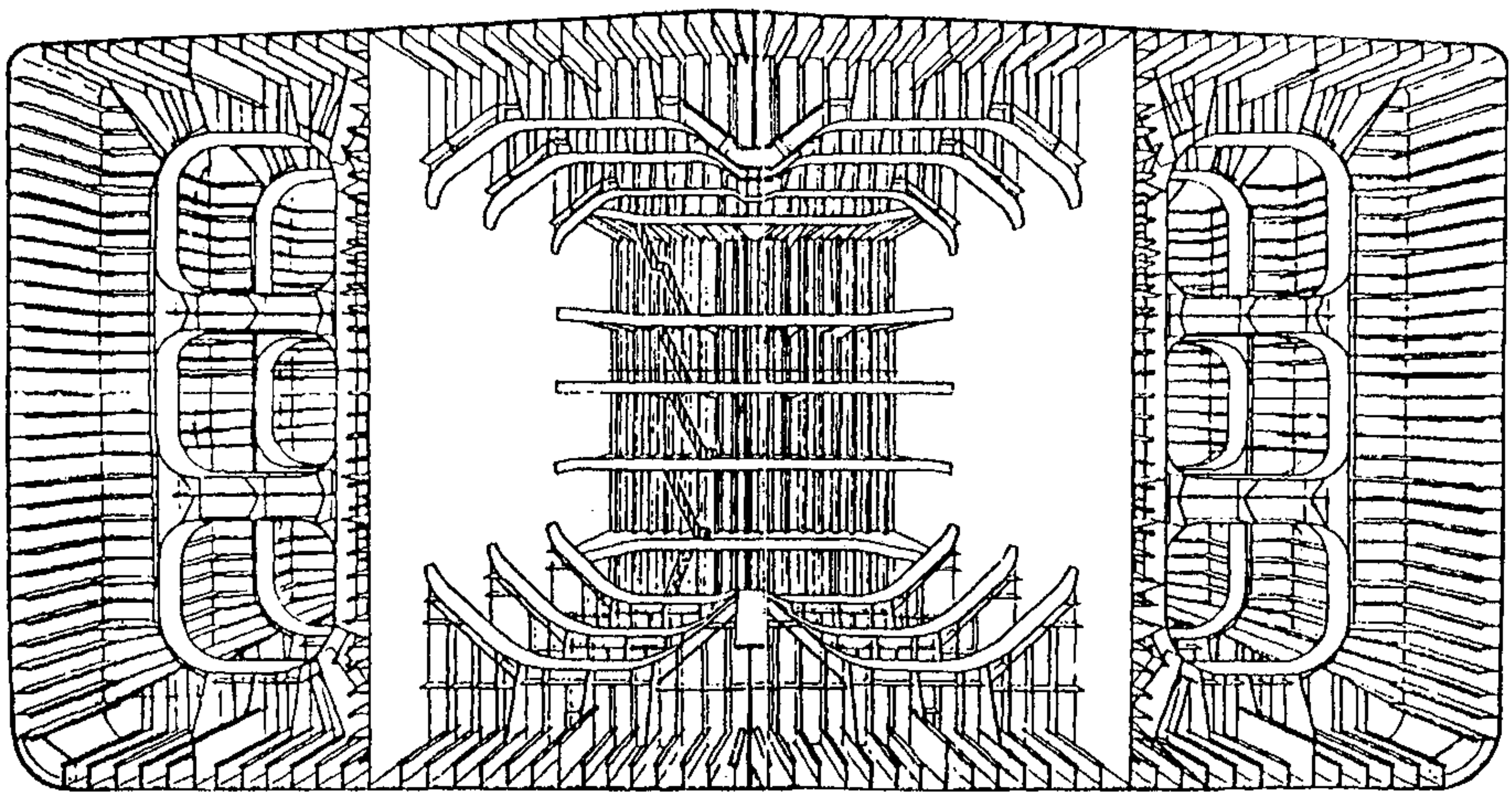


Figure 3.11: Typical Mid-Ship Structural Configuration for a Single Hull Tanker.

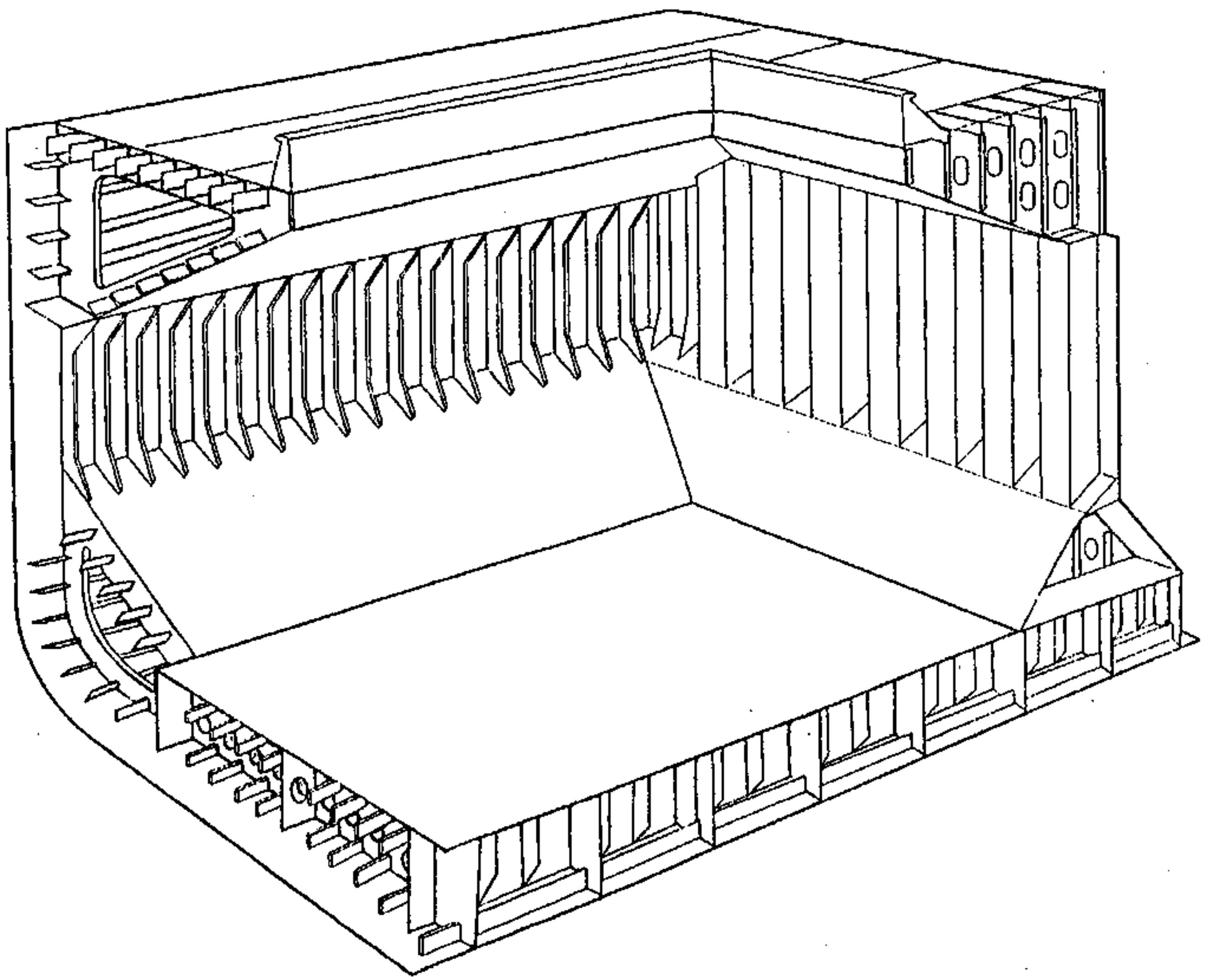


Figure 3.12: Typical Cargo Hold Structural Configuration for a Bulk Carrier [IACS, 1994].

4. TOWARDS OPTIMIZING INSPECTIONS

The optimization of a complex process involving a large number of variables is problematic. The structural inspections of large vessels such as VLCCs and large bulk carriers are no exception. In the present context optimization is taken to mean the minimization of the cost of inspection while satisfying various constraints such as maintaining a minimum level of safety. This section outlines methods which go some distance towards a systematic methodology for optimizing inspections.

4.1 Elements of Inspection Optimization

The ideal overall goal for commercial ships is to maximize the revenue generated while ensuring safety, legal, environmental and other requirements and obligations are met. The complexity of the process of acquiring, building and operating a ship, the numerous variables that influence the cost of the exercise, and the interrelationships between many of the variables precludes a direct attack on the optimization. The practice is usually to isolate elements of the problem and then to optimize within one element without regard to others. An attempt is made to minimize cost of a particular element without compromising safety, legal, environmental and other requirements.

The optimizion of inspection costs should ideally be performed within the context of the maintenance process. This requires that costs of items such as drydocking the ship, materials, repairs of defects, labour should be included. In a broader sense, the optimizing exercise should be within the context of the operations of the ship. Clearly this is not practicable in the present case. The approach proposed here is to break down the inspection into its essential elements and attempt to minimize their cost while satisfying the relevant constraints.

The essential elements that comprise the inspection process have been discussed in detail in earlier chapters of this report. They are:

- Where to Inspect - Critical Areas
- When to Inspect - Interval
- What (How Much) to Inspect - Extent

The following sections discuss methodologies which can be used to optimize each of these elements of the inspection process.

4.2 Where to INSPECT - Critical Areas

Critical areas are those structural members more susceptible or critical to defects and damages. Transverse web frames in tankers and side frames in bulk carriers are some of the typical critical areas. Take bulk carriers for example, certain side frames may be more critical than others in terms of the loads or stresses they bear. Certain areas within the hold of a bulk carrier may be more likely to experience cracking, corrosion or damage due to loading and discharge. For planning inspections, it is important to know which Critical Structural Details (CSDs) are more important than the others so that inspection priorities can be established. Given the constraint of having to inspect a certain small percentage of the frames, an optimal inspection strategy should be developed which will focus on those areas that are most critical or most likely to experience damage. This section introduces a methodology which prioritizes CSDs based on risk assessment.

At present, surveyors for the most part depend on their own experience and knowledge to qualitatively prioritize the structure for inspections. They usually lack the theoretical background with which to rank the priorities of structural details. It is up to managers and analysts to develop guidance to direct the surveyors to areas of high risks [Stanley, 1996]. Eventually, the surveyors will learn to make effective use of guides for critical structural areas.

Ranking or prioritizing of CSDs quantitatively is difficult because many factors have to be considered and many of the relevant factors have a high degree of uncertainty associated with them. The classical systematic approach is to use "Risk Assessment" procedures which are used in other industries. CSDs should be prioritized or ranked in terms of consequences of defects/damage (**Criticality**) and likelihood of defect/damage (**Susceptibility**). However, the application first principles quantitative risk assessment procures is difficult to employ in ship structures because of the lack of data and lengthy procedures involved in computing failure probabilities. To overcome this difficulty, a simplified approach called **priority assessment** has been developed. A priority assessment can be broken down into three steps as follows:

(i) Rate the criticality of structural details.
(ii) Rate the susceptibility the structural details to damage.
(iii) From the criticality and susceptibility ratings, evaluate the priority.

Figure 4.1 presents a schematic overview of the prioritization process.

The criticality evaluation is essentially focussed on rating the structural details, elements, and components (assemblies of details and elements) that define a CSD according to the consequences of failure. Evaluation of the potential consequences may be based on historical data (experience) and analysis to define details critical to hull structural integrity.

The susceptibility evaluation essentially focusses on rating the likelihood of a CSD experiencing damage or defects. Again, experience and analysis are complementary means of evaluating susceptibility to corrosion, fatigue cracking and other forms of in-service damage (e.g. deformation due to accidental damage, berthing damage, loading / unloading). The determination of criticality and susceptibility ratings is discussed further in Sections 4.2.1 and 4.2.2.

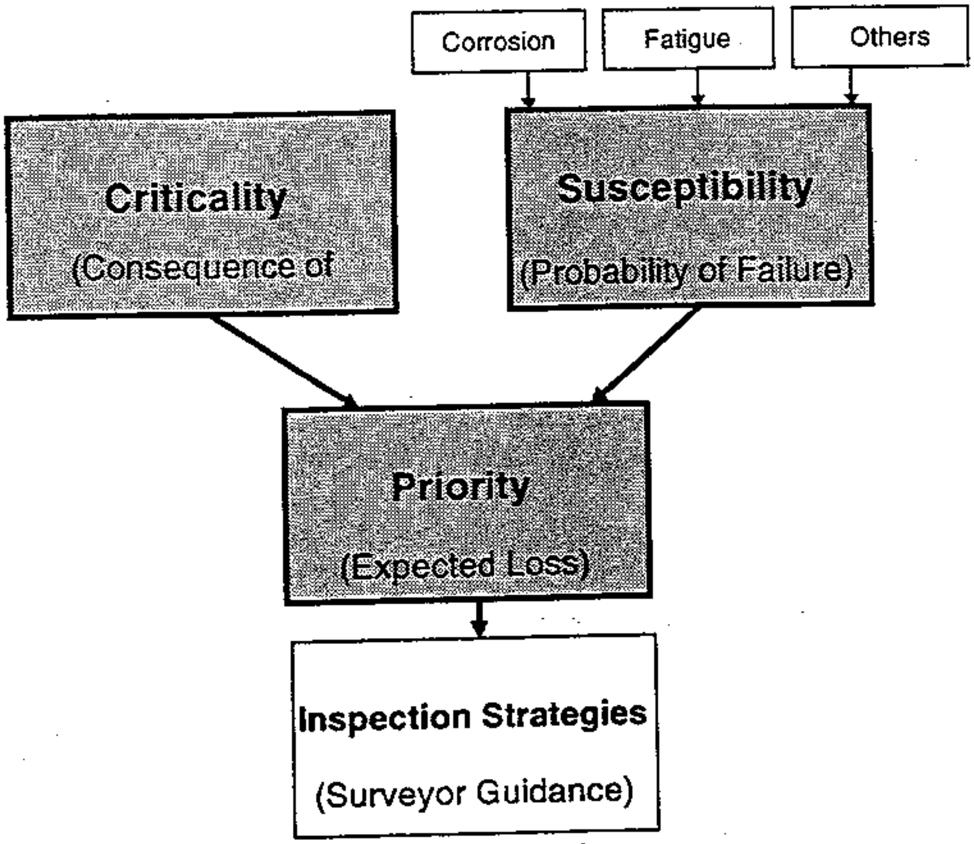


Figure 4.1: The Relation Between Priority, Criticality and Susceptibility

The rating of the priorities of CSDs for inspections is subsequently evaluated from the product of the criticality and susceptibility ratings. Quantitatively, the priority is evaluated as follows :

$$P = S \cdot C \tag{4.1}$$

where P is the Priority rating,
S is the Susceptibility rating, and
C is the Criticality rating.

Note that the above equation is analogous to the concept of "risk" which is defined as follows :

$$Risk = (Probability\ of\ Failure) \bullet (Consequence\ of\ Failure) \tag{4.2}$$

The use of the priority ratings to establish inspection strategies is illustrated qualitatively in Figure 4.2. Structure with both high criticality and susceptibility ratings have high likelihoods of experiencing damage and potentially serious consequences of failure. As such, they should be given the highest priorities for close up inspections. Structures with low criticality ratings and low susceptibility ratings have relatively minor failure consequences and the likelihood of experiencing damage is low. Such structures should be given the minimum priority for inspection.

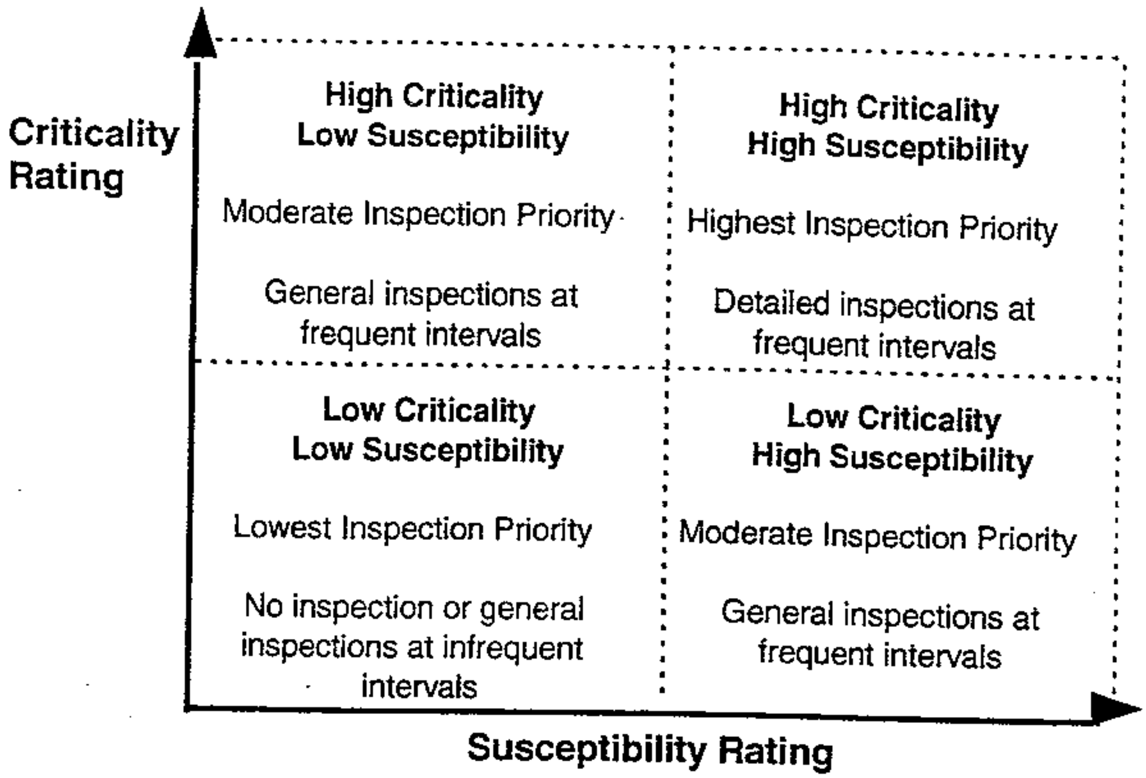


Figure 4.2: Use of Criticality and Susceptibility Ratings in Developing Inspection Priorities.

This concept of prioritizing structure for inspections is, intuitively, relatively straight-forward. However, in order to make such a concept practical for application, a systematic methodology is required to rate any structure in terms of its criticality and susceptibility, and to somehow combine these ratings to rank the structure in terms of its priority for inspections. The following sections outline the methodology that has been developed for prioritizing ship structure CSDs.

4.2.1 Criticality Ratings

The **criticality** rating is a measure of the consequence of failure. It is an important factor in ranking the priority of a CSD since similar details at two different locations can have dramatically different consequences of failure. For example, a crack in the side shell of a cargo oil tank may have much more serious consequences than the same crack in a water ballast tank because the former can cause pollution potentially.

The potential major consequences of failure include the following :

- Loss of vessel, lives and cargo
- Pollution
- Effects on Personnel Safety
- Repair cost and down time
- Loss or reduction of serviceability

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

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

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

The more common failure consequence is simply **unscheduled maintenance or repair.** As many of the fatigue cracks tend to stop or grow at a slow pace, their consequences constitute only local repairs. Veeing and welding which is one of the most common temporary crack repair methods has relatively low cost. If a design modification or a plate insert is involved, their costs may be higher, but still relatively low comparing to the other two consequences, i.e. vessel lost and pollution. The total cost of a repair should include material, labor, dry dock charge, tank cleaning, staging and down time. Some of the items such as dry dock charge, tank cleaning and staging may not be applicable to some repairs depending on the location of the crack and other circumstances. Liu and Thayamballi have illustrated a sample of the charge rates:

1. Dry dock charges: for vessels above 150,000 GRT, the minimum charge for the first two days is about $ 0.5 GRT. The charge for each subsequent day is about $ 0.2 GRT.

2. Tank cleaning: ranges from \$ 2 to \$ 12 per metric ton capacity, depending on type and location of tank, gas freeing and ventilation excluded.
3. Steel renewal: for mild steel, about 4000 to 5000 \$ per ton of steel renewed.
4. Staging: about \$ 5 per cubic meter of volume covered.

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

In a risk assessment, the consequence of failure can be measured by a monetary value which is the sum of the consequences caused directly or indirectly by the failure. The monetary costs of a severe failure will generally include costs other than those associated with the repair of the damage to the ship. In the case of oil spills there may be costs associated with oil spill clean up and with the payment of compensation. There may be various costs of a societal nature that may need to be included; the most difficult to assess in this category of costs are failures involving the loss of life.

For the purposes of this project, notional criticality ratings have been assigned for each criticality category as shown in Table 4.1. These ratings can be considered to be a very rough measure of the consequential costs of a failure, and ideally they would be based on the actual estimated costs for the category concerned. Of course, the actual figures must be appropriate to the nature of the loss. For example, the consequential loss of an oil spill in coastal waters in the vicinity of a highly populated area will be much more expensive than a loss in the high seas. If the cargo lost is of a toxic nature the consequential costs will be higher than cases where the cargo is more benign. These are just two of many factors that need to be considered in the process of assigning quantitative criticality ratings.

Table 4.1: An Example of Structure Defect Criticality Classification.

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

The notional criticality ratings are chosen merely for demonstration purposes, and should not be used as a reference. Different companies or organizations may develop their own rating systems. Their assigned rating numbers may be different for the same type of consequence of failure depending on the function, size and condition of their ships and the nature of their cargo. For instance, loss of ship has a more serious consequence for companies running passenger ships than others running dry bulk carriers. Oil spills from a small vessel may have a milder consequence than the one from a VLCC. Companies should design their own rating system to fit their service and operational profile.

4.2.2 Susceptibility Ratings

The next step in the prioritization procedure is to determine how prone the structure is to damage. Susceptibility is defined as the likelihood of damage. In this regard a CSD may be prone to one type of damage mode, or several damage modes, and in some cases they may be related (e.g. fatigue cracks in areas experiencing corrosion). Susceptibility is equivalent to the likelihood of failure, a concept widely used in a risk assessment. As an alternative to a rigorous analysis, simple statistical analysis combined with engineering judgment can be used to estimate its susceptibility. This scheme avoids the difficulties associated with computing failure probabilities.

For the purpose of this project, notional susceptibility ratings have been assigned for each susceptibility category as shown in Table 4.2. Susceptibility is categorized into four classes: extreme, high, moderate and low. Engineers may design a rating system according to their requirements. For demonstration purposes, structures that are highly susceptible to damage are assigned an annual susceptibility (probability of failure per year) of 10^{-2}, while those unlikely to experience a failure are assigned an annual susceptibility of 10^{-5}. Table 4.2 also summarizes the approximate relation between the susceptibility rating and the likelihood of experiencing damage.

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

ASME (The American Society of Mechanical Engineers) has developed a table to convert qualitative statements to equivalent numerical probabilities, in an effort to apply a probabilistic risk assessment to mechanical systems such as nuclear power plants [ASME, 1991]. The table gives some definitions to failure probability from 10^{-1} to 10^{-8}. It notes that converting qualitative assessments of an expert to a probability value is a process with potential pitfalls and should be approached most carefully. These conversions can be used as a guide when developing a susceptibility classification table such as the one in Table 4.2.

Assigning a susceptibility rating for a CSD is usually considered more difficult than assigning a criticality rating. In cases where substantial in-service (experience) records of damage are available, simple statistical techniques may be applied in conjunction with engineering judgment to estimate the likelihood of damage for a given CSD. For example, if a record shows that the fatigue failure rate of a CSD is roughly once in the design life of 25 years, it then has an extremely high annual susceptibility of $4x10^{-2}$. This CSD should be rated "Extreme" susceptible as defined in Table 4.2. Other CSDs of the same design at similar locations should then be assigned this same level of susceptibility.

Past experience or in-service data is valuable in helping determine the susceptibilities of structural details that are prone to several forms of damage. For instance, experience has indicated that tankers tend to have fatigue cracks in the intersection of transverse webs and longitudinals in side shell areas between high and low water lines. In bulk carriers, cracks can often be found in the corners of hold openings, side frames, welds of corrugated bulkheads and stools. Therefore, these areas are considered highly susceptible. A few past studies have compiled collections of CSDs with high failure rates [IACS, 1994] [TSCF, 1995] [Jordan, 1978] [Jordan, 1980]. They are summarized in Chapter 3.

Table 4.2: An Example of Structure Defect Susceptibility Classification.

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

If a ship is newly designed, its designers should be able to identify highly stressed areas. A rigorous analysis such as a fatigue analysis can be performed to obtain a numerical probability of failure. Several procedures for fatigue analysis have been documented in the literature [Wirsching, 1983] [Munse et al., 1983] [Wirsching & Chen, 1987] [ABS, 1992] [DNV, 1995] [Bea, 1995].

Susceptibility assessments should be evaluated independently for each of the main failure modes which normally include fatigue cracking and corrosion. In determining corrosion susceptibility, operating-environment factors such as the exposure to salt water, heat, and caustic elements are key factors. Structural configuration and condition of protection systems are also important. Corrosion rates of different conditions have been studied and published by Tanker Structure Co-operative Forum [TSCF, 1992]. Past experiences provide valuable information on CSDs that are prone to corrosion. These are summarized in Chapter 3 which addresses the performances of CSDs in tankers and bulk carriers.

4.2.3 Priority Ranking

After both susceptibility and criticality ratings have been determined, the priority rating of each CSD can be readily obtained using equation 4.1. **Priority** is defined as the expected loss due to damage which is the product of criticality and susceptibility. If criticality is expressed in terms of monetary value, priority is expressed in terms of monetary value as well.

A CSD with a high priority rating implies a high expected loss, and should receive frequent and/or extensive inspections. A good example of a high priority CSD is the side frames of bulk carriers, because they have both high susceptibility (to fatigue cracking) and high criticality (loss of ship and crews).

An example of the priority rating system has been developed in Table 4.3. Priority is classified into four classes: Extreme, High, Moderate and Low. CSDs with extreme priorities are recommended for inspection most frequently, while those with low priority ratings can be surveyed less frequently. The rating numbers chosen in Table 4.3 are, again, for demonstration purpose only and not to be used as a reference.

Table 4.3: An Example of Critical Structural Detail (CSD) Priority Classification.

Priority	Priority Rating	Inspection Frequency
Extreme	100,000 or above	CSDs should be given the highest priority for surveys. They are recommended to be inspected most frequently. All of them should be subject to a close-up survey, if possible. Improved designs should be adopted for the new builds of the next generation.
High	1000 - 9,999	CSDs should be given the second highest priority for surveys. They are recommended to be inspected frequently.
Moderate	10 – 999	CSDs should be given a moderate priority for surveys. They should be inspected at normal frequency.
Low	Below 10	CSDs should be given the lowest priority for surveys. Surveys for these CSDs should be conducted at a minimum frequency.

To demonstrate the use of a priority assessment, two simple examples are given here. For the first example, consider two typical CSDs in a tanker, named Detail A and Detail B. Assume that Detail A is located in the side shell area of a cargo wing tank and Detail B is in a similar location of an adjacent water ballast wing tank. Assume that this tanker is relatively young so that corrosion has not had much effect on accelerating fatigue in the ballast tanks. Thus, the susceptibilities of both details are on the same level, say 10^{-3}. Since Detail A has a potential for oil spill, a criticality rating of 10^{6} is assigned to it according to Table 4.1. Detail B is assigned a moderate criticality of 10^{4} assuming that its failure constitutes only an unscheduled repair. As a result, the priority of detail A and B are 1000 and 10, respectively. According to the CSD priority classification in Table 4.3, Detail A should receive a higher inspection priority than Detail B. Based on this result, an inspection program can be designed to allow more inspections for Detail A.

For the second example, consider the same two details when the ship is 15 years old. Because of the fatigue damage accumulation with time, both details have higher susceptibilities now. Assume that their susceptibilities are estimated to be 10^{-2} and $2x10^{-2}$. Detail B has twice the likelihood of experiencing fatigue because of the effect of corrosion. This assumption is supported by Figure 3.3 which shows that ballast tanks have roughly twice the number of fatigue cracks as cargo tanks for a particular class of tankers at age 15 years. By giving Detail A and B the same criticality ratings as in Example 1, Detail A will have a priority rating of 10,000 which is again higher than Detail B's 200. As a result, Detail A should also receive higher priority for inspections.

On the basis of the results of the two examples, a modification to the current inspection practice may be recommended. The current class rules concentrate close-up surveys in ballast tanks, while the two examples suggest that the side shell details in cargo tanks have a higher priority than water ballast tanks, because of the possible oil spills. However, a more thorough assessment is needed to validate this recommendation. These examples show that a priority assessment provides a rational way to improve inspection practice.

It should be noted that the outcome of a priority assessment is sensitive to the design of the criticality rating system. If the criticality rating system is not scaled properly, the result can be misleading or wrong. This can be shown by using Example 2. If an oversimplified criticality rating system is employed using, say, 1, 2, 3 and 4 to represent the four classes (Low, Moderate, High and Extreme), Detail A and B in Example 2 will have susceptibility ratings of 3 and 2. Detail A will turn out to have a lower priority rating of $3x10^{-2}$ than Detail B's $4x10^{-2}$. This is the opposite result to that obtained earlier. This serves to illustrate that this procedure must be applied with care. Hence arbitrary assignment of numerical values to ratings is not recommended. The numerical values should reflect, as far as possible, actual estimated monetary values.

4.3 What (How Much) to INSPECT - Inspection Extent

Inspecting the total areas of VLCCs and large bulk carriers is clearly not practicable. The practice has been to concentrate a close-up inspection on limited areas in ship structures. By implication, the condition of structure not surveyed is inferred from the condition of other areas that has been surveyed. This raises a question as: To what degree this "inference" can be applied? In simple words, whether the condition of a structural member reflects that of another similar one? This section investigates this issue by performing analyses of two inspection reports. If this inference is applicable, the extent of inspections may be reduced.

4.3.1 Current Practice in Establishing Extent of Inspection

A major difficulty in inspecting ships, especially large ships such as VLCCs and Capesize bulk carriers, is the physical size of the task. William and Sharpe note that the size of one tank in a ship is the order of that of a gymnasium [William & Sharpe, 1995]. Not only are tanks large, but there are also many of them in a tanker. A typical single hull VLCC has about 20 or more tanks. Given the size and number of tanks, the tasks that inspectors face when seeking cracks is challenging. Clearly, it is impossible to inspect all the area thoroughly. In practice, only a limited extent of the large internal areas are subjected to close-up inspections.

Similar considerations apply to bulk carriers. A typical large bulk carrier will have up to 50 frames per hold with a depth of around 23 meters from the tank top to the hatch coaming. To give this a very thorough inspection will require as a minimum at least two inspectors for one day per hold. A typical bulk carrier has about 7 holds and each hold has two topside tanks, two bilge hoppers and a double bottom. Again, it is not feasible to inspect all the areas thoroughly. The difficulty associated with the physical size suggests the question: what is the minimum area that can be inspected to ensure a given larger area is satisfactory.

Before considering this question, it would be useful to review the current practice regarding inspection extent. Inspection extents are mainly regulated by class societies which use a combination of overall surveys and close-up surveys to cover the hull to a sufficient extent.

An **overall survey** is a survey intended to report on the overall condition of the hull structure. Surveyors visually inspect the hull structure at a distance from the structure. At Special Surveys, overall surveys are to be carried out in all cargo tanks/holds, ballast tanks, pump rooms, pipe tunnels, cofferdams and void spaces bounding cargo tanks/holds, decks and outer hull [ABS, 1995]. Normally, no detailed data on defects is expected to be gathered. Instead, it is used to determine where the problem areas are and this is used to plan additional close-up surveys.

A **close-up survey** is a survey in which the inspector is able to conduct inspections in close proximity of the subject structure; generally it is preferred that the subject structure is within the reach of the inspector. Data on cracks and other defects are expected to be measured and recorded. Because close-up surveys are time- and labor-consuming, only limited extent of the hull structure can be practically covered. The extent is established based on the results of overall surveys and the minimum requirement of the class society rules. The ABS rule requirements on the minimum extent of close-up surveys of oil tankers are listed in Table 4.4. Other major class societies have similar requirements.

Table 4.4: Requirements For "Close-Up" Surveys at Special Survey Of Oil Tankers [ABS, 1997].

Special Periodical Survey Number 1 (Age ≤ 5 Years)	*Special Periodical Survey Number 2 (5 < Age ≤ 10 Years)*	*Special Periodical Survey Number 3 (10 < Age ≤ 15 Years)*	*Subsequent Special Periodical Surveys (Age > 15 Years)*
1. One complete transverse web frame ring including adjacent structural members in a ballast wing tank, if any, or a cargo wing tank used primarily for water ballast. 2. One deck transverse including adjacent deck structural members in a cargo wing tank. 3. Lower part of transverse bulkhead including girder system and adjacent structural members - in one ballast tank - in one cargo oil wing tank - in one cargo oil center tank	1. All complete transverse web frame rings including adjacent structural members in a ballast wing tank, if any, or a cargo wing tank used primarily for water ballast. 2. One deck transverse including adjacent deck structural members - in each of the remaining ballast tanks, if any - in a cargo wing tank - in two cargo center tanks 3. Both transverse bulkheads including girder system and adjacent structural members in a wing ballast tank, if any, or a cargo wing tank used primarily for water ballast. 4. Lower part of transverse bulkhead including girder system and adjacent structural members - in each remaining ballast tank - in one cargo oil wing tank - in two cargo center tanks	1. All complete transverse web frame rings including adjacent structural members - in all ballast tanks - in a cargo wing tank 2. One complete transverse web frame ring including adjacent structural members in each remaining cargo wing tank. 3. One deck and bottom transverse including adjacent structural members in each cargo center tank. 4. All transverse bulkheads including girder and stiffeners systems and adjacent members in all cargo and ballast tanks. 5. Additional complete transverse web frame rings as considered necessary by the Surveyor.	1. All complete transverse web frame rings including adjacent structural members - in all ballast tanks - in a cargo wing tank 2. One complete transverse web frame ring including adjacent structural members in each remaining cargo wing tank. 3. One deck and bottom transverse including adjacent structural members in each cargo center tank. 4. All transverse bulkheads including girder and stiffener systems and adjacent members in all cargo and ballast tanks. 5. Additional complete transverse web frame rings as considered necessary by the Surveyor. 6. Any additional tanks and structure as considered necessary by the Surveyor.

As can be seen in Table 4.4, the requirements gradually become more demanding while ships get older. For example, one web frame ring is required to be inspected at 5 years old (Special Survey No. 1). Later at 10 years old (Special Survey No. 2), all web frame rings in one wing ballast tank are subjected to inspection. The requirements increase to all web frame rings in all ballast tanks and one cargo wing tank for ships 15 years old or over. It can be seen that none of the special survey requirements covers all of the web frame rings in an entire ship. Even the requirements for the third and later special surveys cover only all ballast tanks and one cargo tank, which represent only a small portion of a single-hull tanker. The inspection extents listed in class rules are clearly limited, although surveyors may extend the close-up survey as deemed necessary. This suggests questions such as: do these requirements cover a sufficient extent to ensure the structure is adequate for safe operation through the next inspection interval or, on the other hand, are the requirements excessive.

A good way to approach these questions is to look at the past execution of the inspection requirements. Past experience has shown that very few ships have suffered catastrophic failures due to structure-related causes (The only exceptions are the bulk carrier casualties in the recent years). Furthermore, most major failures are the result of non-structural causes. This may be a indication that current hull inspection practice seem to work well in terms of maintaining a safe structure. However, the inspection requirements should be constantly reviewed to eliminate unnecessary inspection and reduce inspection cost.

4.3.2 Inference from Inspecting Limited Areas

As mentioned earlier, the physical size of ships limits the extent of hull structure inspection. This implies that the conditions of areas not surveyed have to be inferred from those of inspected areas. In this regard, it would be useful to investigate whether this inference can be made reliably. If it can be made, its effectiveness need to be established.

Take a tanker for example: one web frame ring is subjected to inspection during the first special survey according to the rules of class societies (see Table 4.4). Even in the second special survey, only the web frame rings in one tank will be subject to a close-up inspection. Accordingly, a large number of web frame rings will be left un-inspected. While a medium size tanker can have a total of more than 100 web frame rings in its wing tanks, only one web frame is inspected during the first special survey. The condition of one web frame ring serves as an index to those of all the other web frames in the vessel. In other words, the conditions of large extent of the ship are inferred from that of a limited extent. The validity of this kind of inference needs to be investigated.

The data in many inspection reports shows that most ships do have their patterns of fatigue cracking. The same type of failures can often be expected in other tanks/holds after a particular failure is sound in one tank/hold. In fact, it has been a common tactic in which inspectors perform a very thorough inspection in one tank, and then spend somewhat less time in the second and subsequent tanks. On the basis of limited data, inspectors note whether there are trends. In the case of other tanks, the inspector can then go directly to the problem areas to look for structural failures. It would be interesting to check if the above tactic taken by many inspectors is effective. The following section performs simple analysis on actual inspection data gathered from two tankers to determine the effectiveness.

4.3.2.1 Sample Tankers

In the example presented here, the inspection reports of two 70,000 DWT single hull tankers are used. The two vessels are in the same class and, therefore, have identical structural layouts. The two vessels were selected because both have inspection reports in a graphical format which clearly mark the location and type of cracks. The vessels have six center cargo tanks and six wing tanks on the port and starboard sides. Wing tanks 3 and 5 are water ballast tanks. Figure 4.3 shows the general arrangement and tank locations of the vessels.

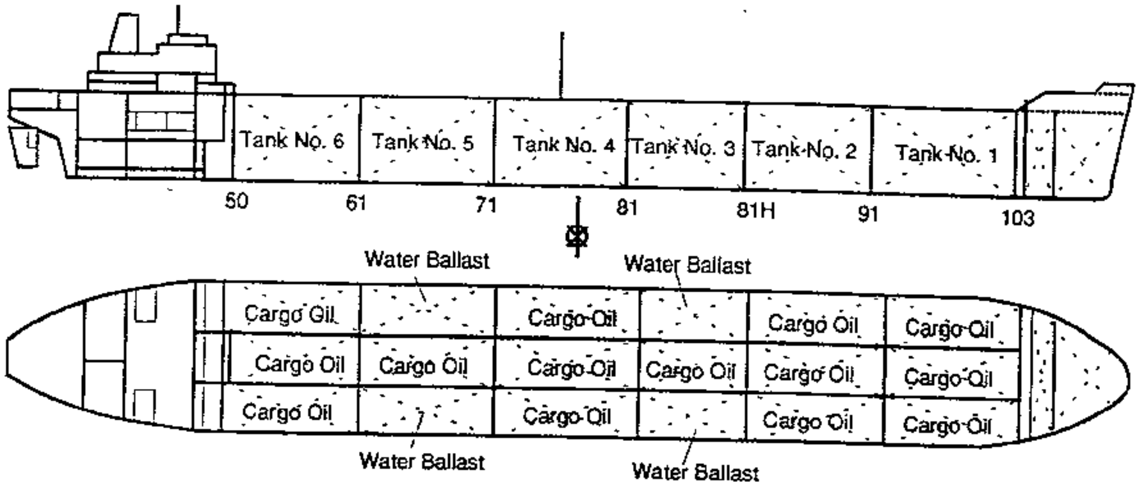


Figure 4.3: General Arrangement of Ships.

Table 4.5 shows the vessel particulars. The midship section is shown in Figure 4.4. The vessels have a standard single-hull construction. The port and starboard wing tanks are supported by two struts. The two vessels were both built in 1972. The 1987 inspection reports represent their conditions at 15 years of service.

Table 4.5: Characteristics of the Two Vessels.

Year Built	1972
Length (O.A.)	810 ft
Length (B.P.)	786 ft
Breadth (MLD)	57 ft
Depth (MLD)	105 ft
Gross Ton	35,589 tons
Net Ton	29,439 tons
Dead Weight Ton	70,213 tons
Segregated Ballast Tanks	Yes
Cargo Type	Crude Oil
Scantlings Reduced	No

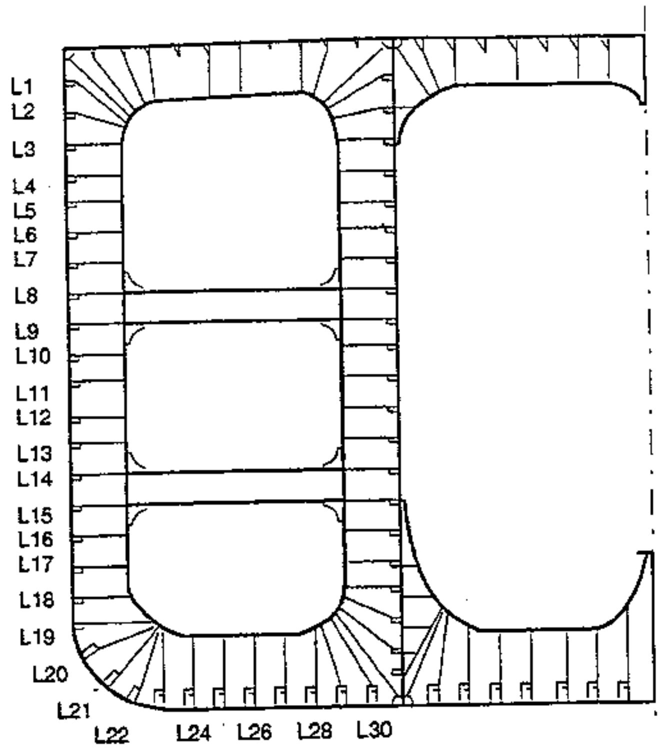


Figure 4.4: Midship Section.

4.3.2.2 General Approach

The objective of the analysis is to determine whether the condition of one sampled area reflects the conditions of other areas. This is a situation often faced by inspectors and owners/operators. After a thorough close-up inspection in one tank, inspectors and owners/operators will be interested to know how similar the conditions of the other tanks are. Assuming that the condition of any two tanks are highly correlated and an inspection has shown a good condition for one tank, then, it would be reasonable to assume the other tanks are in good condition and the decision may be taken to waive their inspections. On the other hand, if the first tank is in a poor condition, the other tanks can be expected to be in poor conditions according to this assumption. Therefore, they should be further inspected.

In an attempt to prove or disprove this logic, the inspection reports of in-service vessels are used to perform a statistical analysis and to make comparisons. It is first assumed that the actual structural conditions of the two sample tankers can be represented by their inspection reports. In other words, their inspection reports reflect the true condition of the two vessels at the time when they were inspected. The two reports were made in 1987 after dry-dock inspections were carried out by commercial inspectors for the owner, so they should contain data which is close to the true conditions of the ships. This assumption may not be true, because an underway inspection carried out three years later found a few more cracks. Some of these cracks may have been missed in the earlier dry-dock inspection. However, the number of missed cracks is relatively small compared to the total number of cracks. They should not affect the outcome of the data analyses.

The approach is to perform a simple statistical analysis for one tank and compare the result with those of the other tanks using the data contained in the inspection report. This is done by imagining that an inspector has entered and inspected one tank. The crack distribution along web frame rings in the tank is, then, obtained. This crack distribution is compared with those of the other tanks which are documented in the inspection report. The result of the comparisons can show how effectively inferences can be made, and therefore provide some insights on how such inferences can be used to define an inspection extent.

4.3.2.3 Data Analyses

There are many ways to compare two web frames. It can be done between starboard and port, between cargo tanks, between ballast tanks or between sister ships. The goal of the analyses is to define some indicators which can predict the degree of similarity of two tank conditions. The candidates of indicators may include the side (starboard or port), the location (tank number), the tank usage (cargo oil or water ballast) and the vessel class.

To simplify these analyses, only fatigue cracks in the connections of longitudinals and transverse web frames are considered. A high percentage of the cracks in the two vessels occurred at these locations. Other types of defects and the fatigue cracks at other locations are excluded. The numbering sequence of the longitudinals is rearranged for easy display of the crack distribution. Longitudinals starting from the top of a side shell to the top of a longitudinal bulkhead are numbered from 1 to 53 (see Figure 4.5). Each number represents a connection of a longitudinal and a transverse frame except the number 31 and 53 which represent the circular cutouts for construction welds. The deck portion is excluded because few cracks were reported there. This numbering system allows the charting of the crack distribution along the transverse web frame ring. Common crack types are found in the following locations: flat bar weld, cutout corner, lug, longitudinal flange, longitudinal web and shell plate. In some cases, one local connection area can contain two or three cracks of different types. Each of these locations with multiple cracks is counted as one fatigue failure, even though they physically have more than one crack. This simplification makes the comparison of two frames (or two tanks) easier.

After statistical analyses were performed, crack distributions were prepared in a series of charts (see Figure 4.6 to Figure 4.15). The first five charts present the crack distributions of Tank No. 2 to Tank No. 6 in Ship A. The latter five charts are for Ship B. Tank No. 1 was not included, because no data were recorded in the inspection report of Ship B. It is suspected that the tank was not inspected at all during the dry-docking. Each chart contains two sets of crack distributions which were plotted using two 3-D ribbons with starboard in the front and port in the rear. The use of the 3-D ribbons is to make a visual comparison between starboard and port easier. All tanks have 9 web frame rings except that Tank No. 3 and 6 which have 7 and 11 rings respectively. The numbers of cracks of these two tanks were normalized to allow comparisons to be made on the same baseline. As a result of the normalization, all the Y-axes in the charts have a maximum crack number of nine.

As can be seen in the charts, the most obvious feature is that most of them have at least four distinct peaks. The first peak corresponds to Longitudinal Nos. 8 and 9. The second peak corresponds to Longitudinal Nos. 14 and 15, the third to 38 and 39, and the fourth to 44 and 45.

Figure 4.15 gives a clear example of the four peaks. According to the inspection reports, all of these areas experienced flat bar weld cracking and some of them had additional cracks in other nearby hot-spots. Comparing these four problem areas with the midship section drawing, it can be seen that they are all at the ends of the two struts. The upper and lower flanges of the struts directly connect to the flat bar stiffeners of the four problem areas. When the struts are subject to axial tension, compression or out-of-plane bending induced by wave or internal pressure, these forces will be transmitted to the flat bar stiffeners and result in fatigue cracking in the flat bar welds. Therefore, the cause of these cracks can be related to an improper design of the strut ends. If the struts had been designed with wider ends with flanges connecting to web ring flanges instead of using brackets, the loads should have been shared by more flat bar stiffeners. It is reasonable to speculate that such a design would have performed better.

Another observation is that the two problem areas on side shell are more severe than the other two on longitudinal bulkheads. A possible reason for this is that the cyclic wave pressure is more severe than the internal pressure loads which derives from cargo oil or ballast water.

The objective of this analyses is to determine the similarity of crack distribution between tanks. The first comparison performed was between **starboard and port** tanks. Since the structure of the vessel is symmetrical along the center line, the fatigue crack distribution of both sides should be similar assuming their loads are about the same. This statement should also be valid for the two sample ships. In most charts, the crack distributions along the transverse ring of two sides have very similar trends. However, there are minor differences between two sides in some cases. Take Tank No. 2 of Ship A for an example (see Figure 4.6), while the starboard has 4 cracks in both longitudinal No. 14 and 15, the port side has none. If a surveyor inspected the starboard tank and used it exclusively as an inspection guide for the port tank, cracks in Longitudinal No. 14 and 15 may have been missed.

A comparison between **ballast and cargo** tanks shows that all ballast tanks are in a much worse condition than cargo tanks. They have more cracks than cargo tanks and the cracks are more randomly distributed. Apparently, corrosion plays an important role in both increasing the failure rates and randomizing the crack sites. The inspection reports show that some cracks are located in heavily corroded areas while the equivalent locations of cargo tanks have no cracks. This implies that some cracks are a result of heavy corrosion. The comparison indicates that the conditions of water ballast tanks can not be used as an index for those of cargo tanks.

A comparison between **cargo tanks** of different locations shows that their cracking trends are very similar, although their locations are different along the vessel length. Tank No. 2, 4 and 6 are cargo tanks. Most cracks are in the four strut-related problem areas. The similarity implies that the location along the vessel length is not an important factor to crack distribution in a tank, at least for this class of tankers.

In comparing two **ballast tanks** of the same vessel located at different positions along the vessel length, it was found that their degree of similarity of crack distributions is far less than those of cargo tanks. Corrosion appears to make the cracking trend less predictable.

The last comparison was between the two vessels. The two vessels are in the same class and operate in the same route. They have similar fatigue problems in the strut ends. The ballast tanks have the worst condition in both vessels. The high degree of similarity suggests that the inspection reports of vessels in the same class can be used to predict the condition of the same tanks in sister ships.

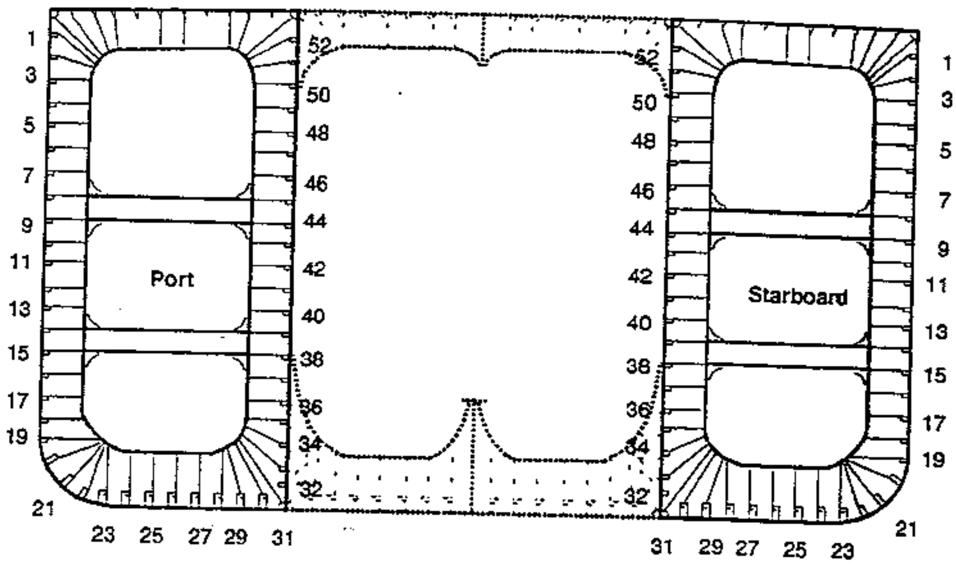


Figure 4.5: Numbering Sequence for the Crack Data Analyses.

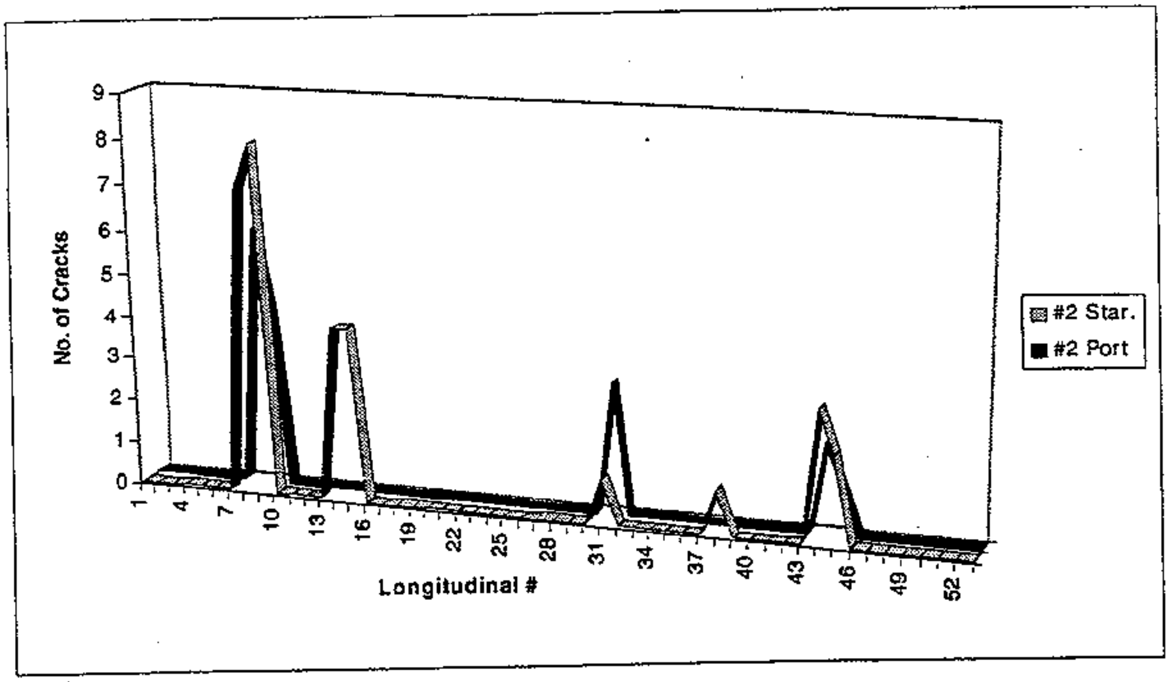


Figure 4.6: Crack Distributions in No. 2 Wing Tanks of Ship A.

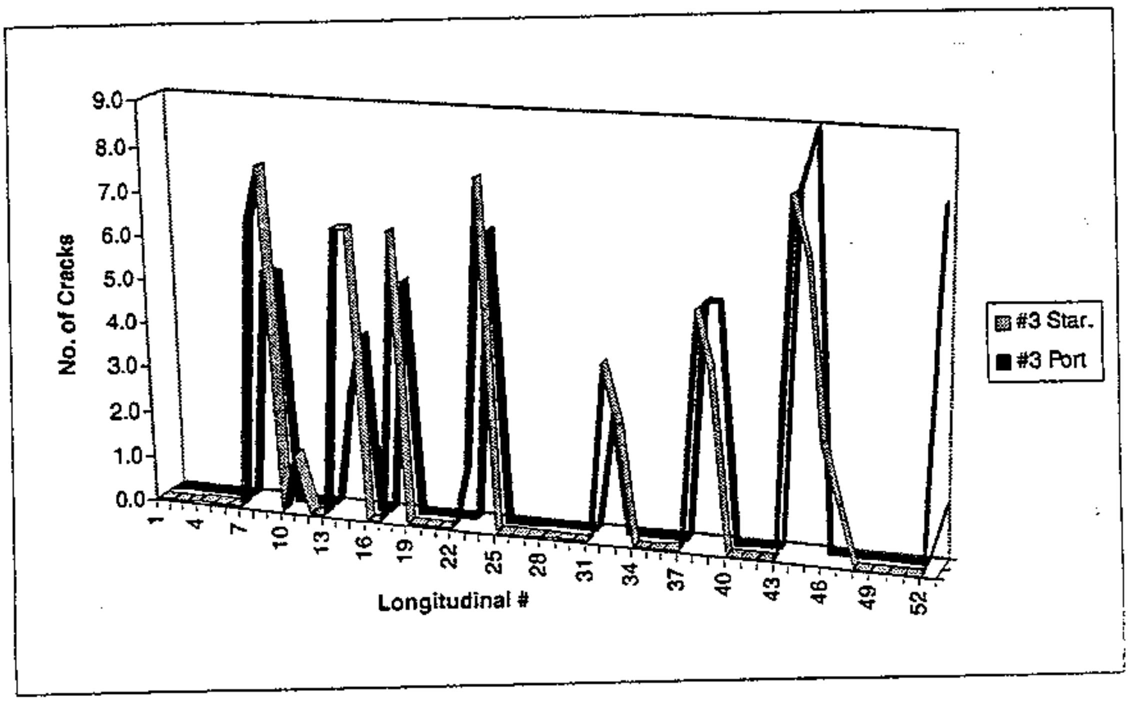


Figure 4.7: Crack Distributions in No. 3 Wing Tanks (Water Ballast) of Ship A.

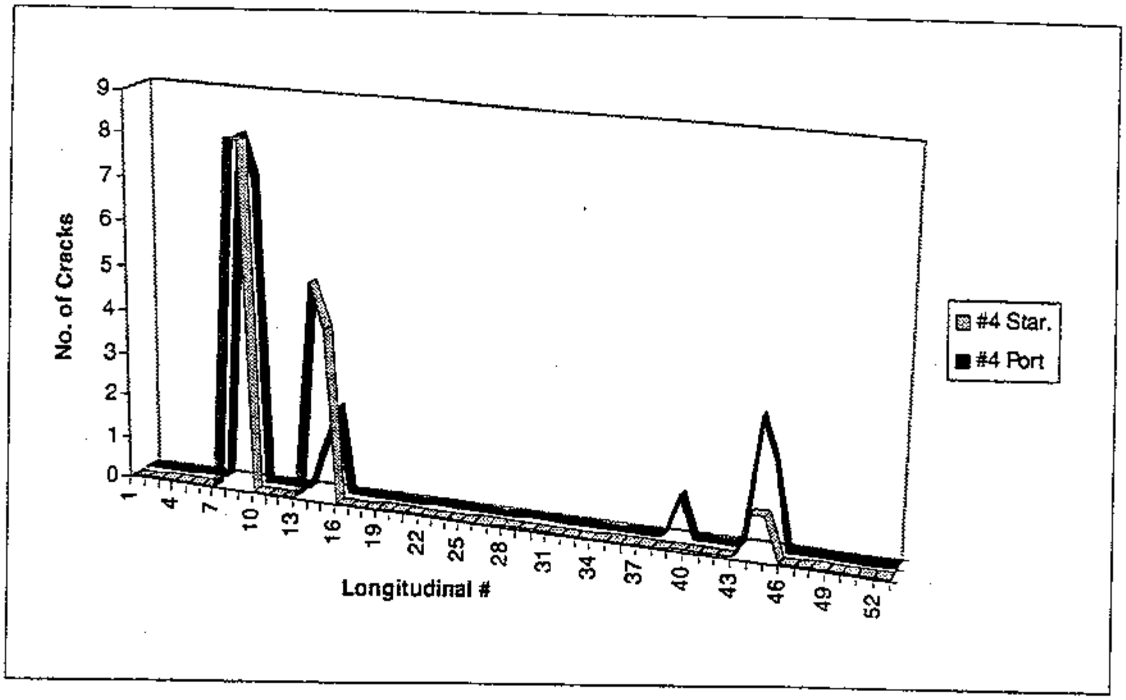


Figure 4.8: Crack Distributions in No. 4 Wing Tanks of Ship A.

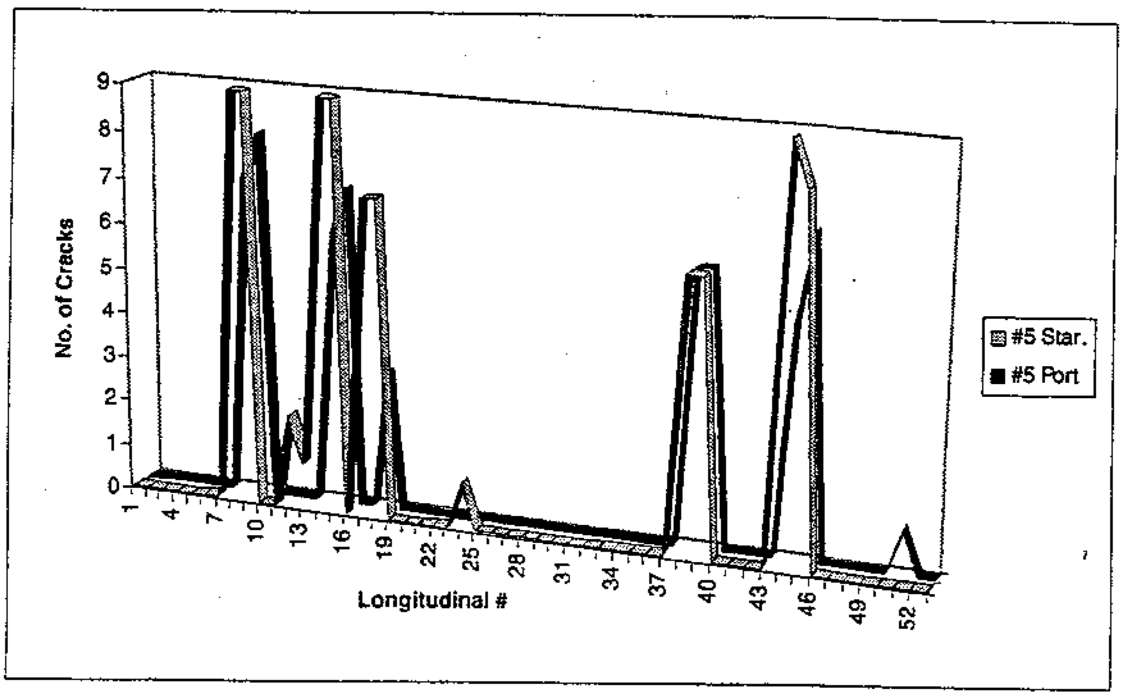


Figure 4.9: Crack Distributions iln No. 5 Wing Tanks (Water Ballast) of Ship A.

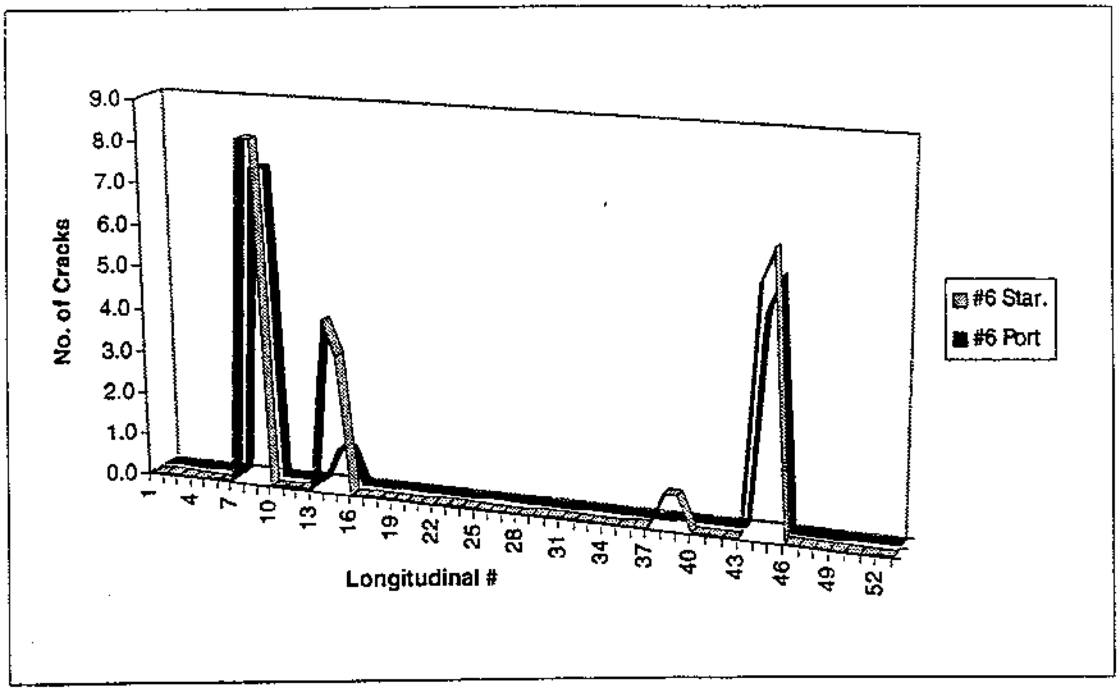


Figure 4.10: Crack Distributions in No. 6 Wing Tanks of Ship A.

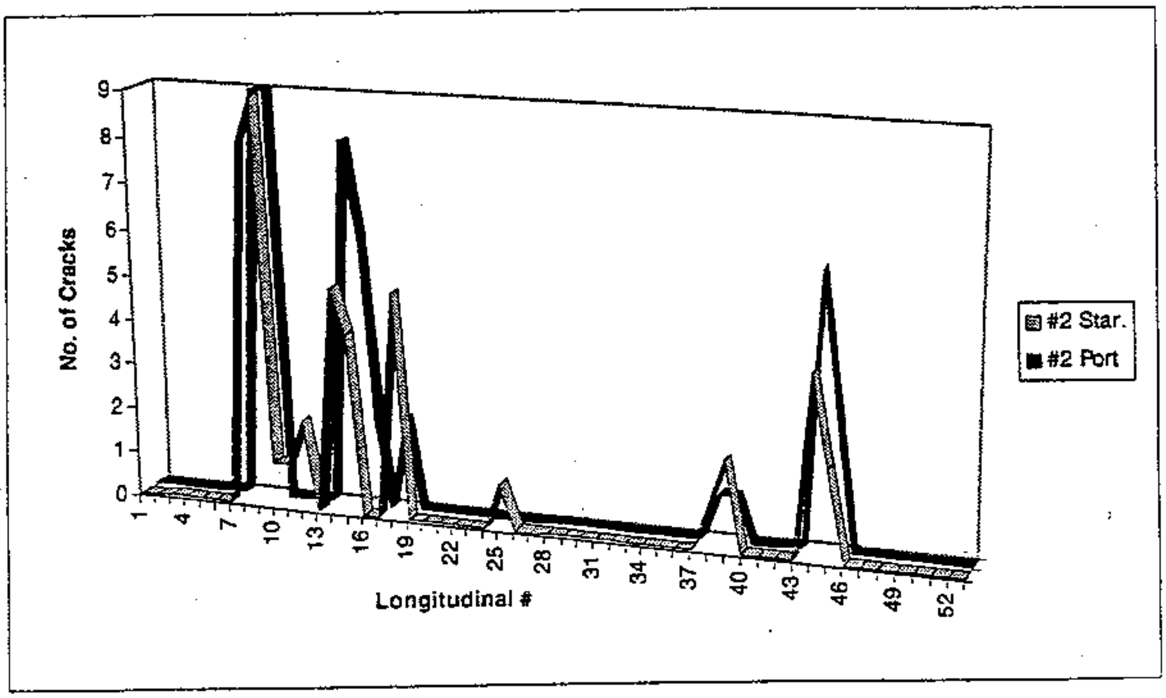


Figure 4.11: Crack Distributions in No. 2 Wing Tanks of Ship B.

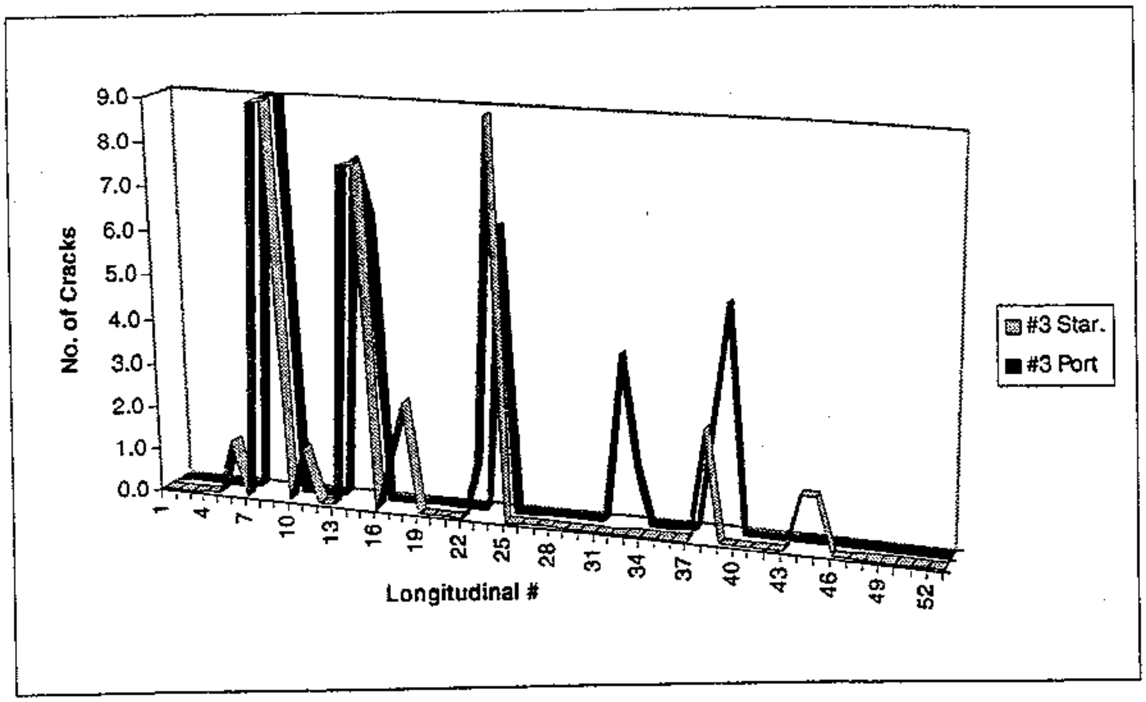


Figure 4.12: Crack Distributions in No. 3 Wing Tanks (Water Ballast) of Ship B.

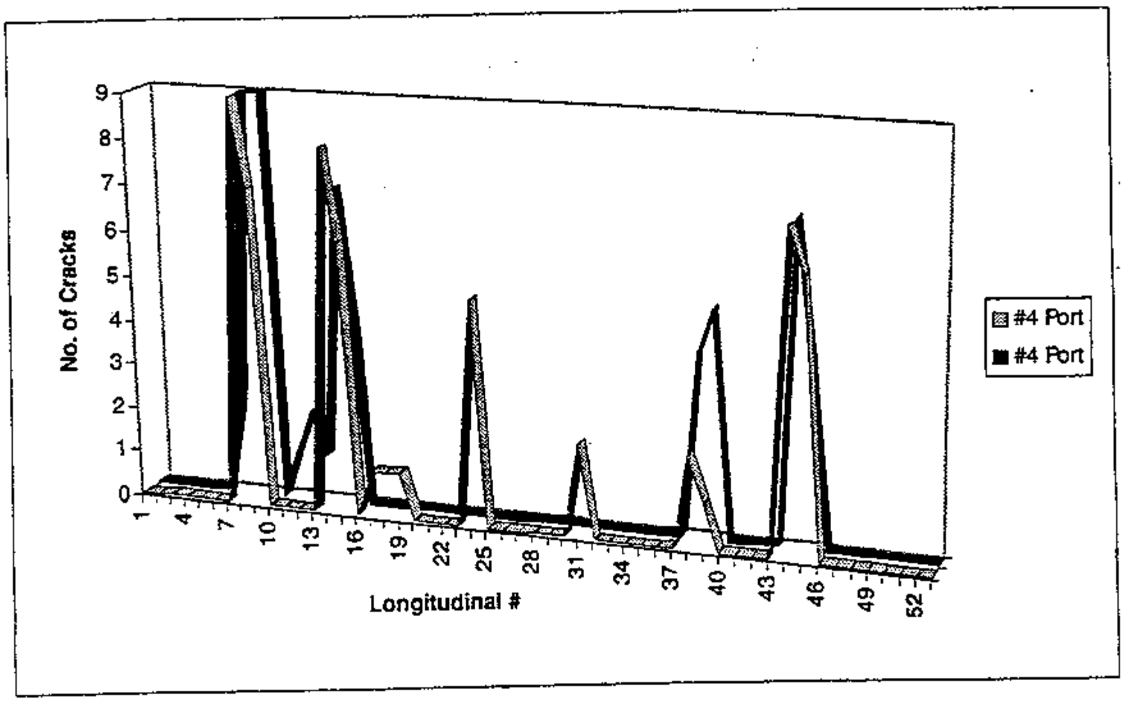


Figure 4.13: Crack Distributions in No. 4 Wing Tanks of Ship B.

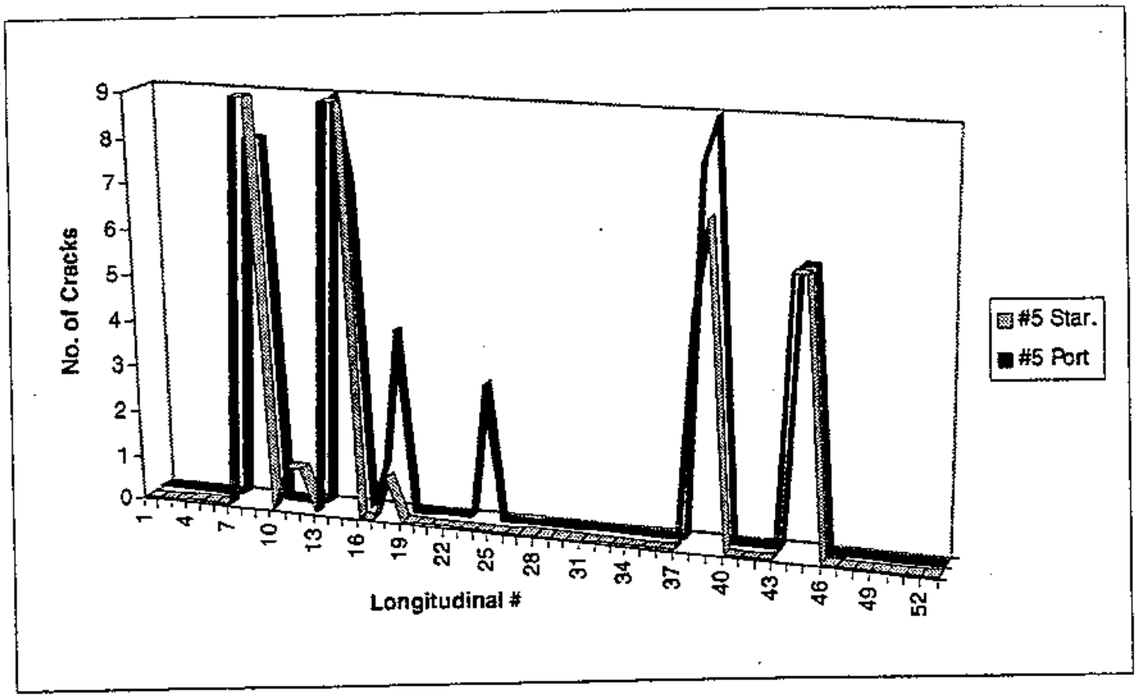


Figure 4.14: Crack Distributions in No. 5 Wing Tanks (Water Ballast) of Ship B.

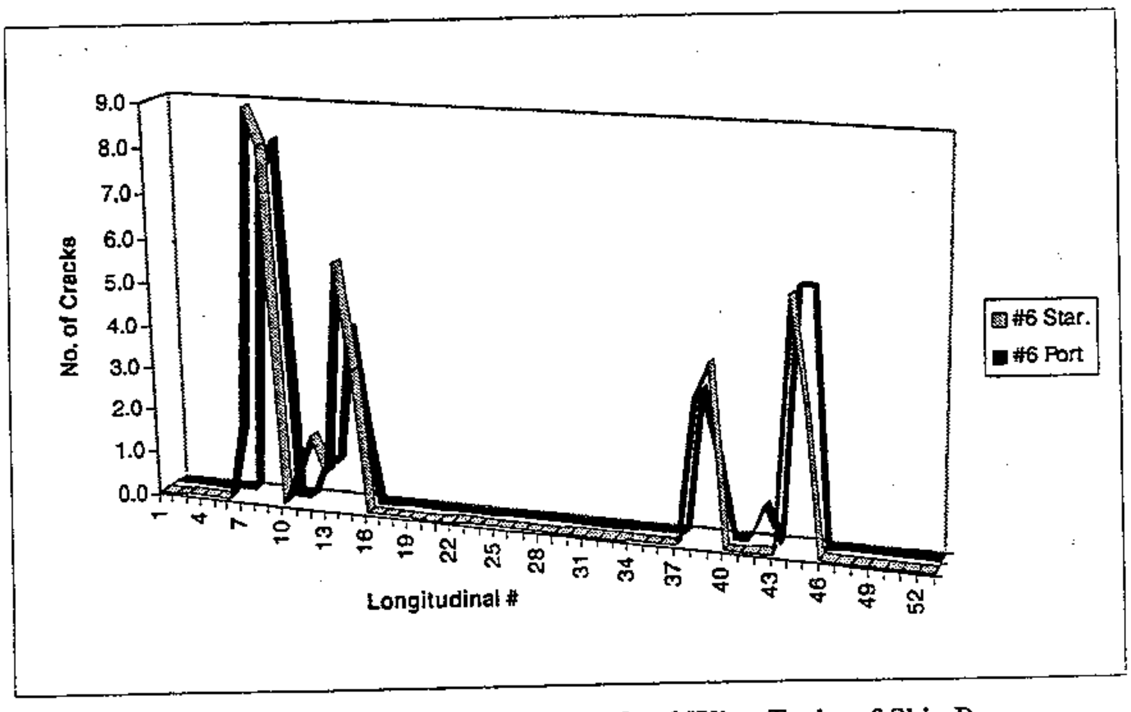


Figure 4.15: Crack Distributions in No. 6 Wing Tanks of Ship B.

4.3.2.4 Summary of the Results

The comparative analyses carried out here show that the crack patterns of a tank can be inferred from other tanks of the same type in most cases. The analyses were performed on two tankers of the same class and the same age, so the conclusions drawn from them may not be valid for other situations. The results of the comparison can be summarized as follows:

- The strongest correlation appears to occur between starboard and port tanks.
- Ballast tanks have the worse cracking conditions because they are prone to corrosion which tends to accelerate fatigue cracking (see Figure 4.16).
- Cracks in ballast tanks are more widely and randomly distributed than those in cargo tanks.
- Most cracks in cargo tanks are the direct result of poor design. Since all wing tanks have a nearly identical layout and configuration, they all contain the same design deficiency and, hence, suffer the same type of cracking problems.
- The trend and condition of the two sister ships are very similar. Therefore, it is always beneficial to have sister ships' inspection reports onboard for reference.

Some of the conclusions complement the findings of a study conducted by Nippon Kaiji Kyokai (NKK) on the distribution of cracks in 2nd-generation VLCCs [Yoneya, 1993]. The study carried out detailed field surveys in cooperation with ship owners, operators and shipbuilders after a new type of hull cracking was found in many young VLCCs. The new type of crack is different from the typical flat bar weld cracks which are frequently found in 1st-generation VLCCs. The cracks start at the flange ends of side longitudinals and propagate into their webs toward the side shell. The study concluded that many cracks were seen in cargo oil tanks, especially in the midship tank, and cracks in water ballast tanks are few. These conclusions differ in three respects from our conclusions.

First, our statistical analysis shows that ballast tanks have more cracks, while the NK study concludes the opposite. This can be explained by the heavy corrosion in aged ballast tanks. Ballast tanks in aging tankers usually have heavy corrosion which tends to accelerate fatigue cracking, while those in new tankers are protected by coating. Second, our analysis shows that the numbers of cracks in starboard and port sides are similar, while the NK study shows a more severe cracking problem in starboard side (79% starboard and 21% port). The unbalanced crack distribution in those VLCCs was explained as a result of their sea route. According to the study, it was found that the wave pressure on the starboard side is about 10% higher at 10^{-4} of the probability of exceedence than the port side. It was understood that the waves from the southwest direction are predominant in the Indian Ocean and they act on the starboard side of the ship navigating from the Persian Gulf to Japan under fully loaded condition. Third, the NK study shows that cracks were concentrated in the midship tank. About 77% of the cracks are in the midship tank. Our analysis shows that cracks are quite evenly distributed along the vessel length.

The above discussions indicate that the conclusions drawn from the analysis are valid only for the specific class of tankers of the same age and operating on similar routes. Generalized conclusions can be made only after data analyses based on a sufficient large number of ships have been performed. However, the results from limited samples of ships can be useful, and can be applied to other circumstances if the analysis is performed with skill and care.

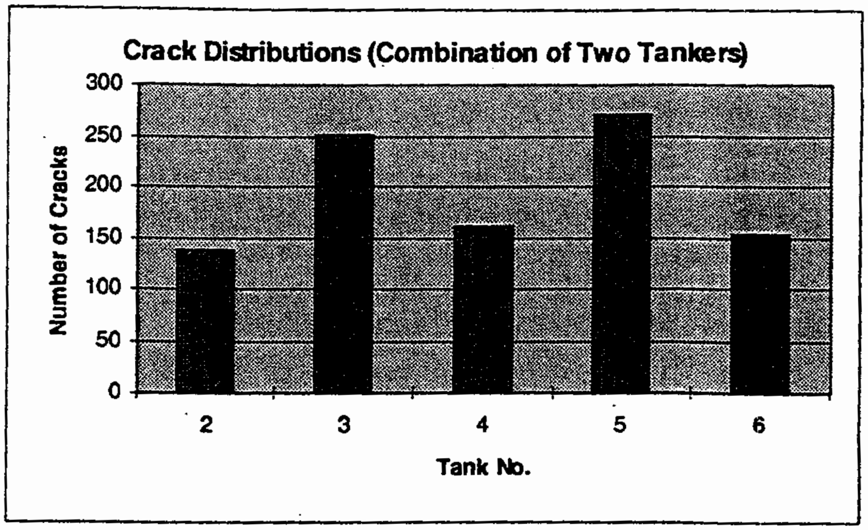


Figure 4.16: Crack Distributions Along the Vessel Length of Two VLCCS of The Same Class.

4.3.3 Strategies to Optimize Inspection Extent

As mentioned earlier, it is economically prohibitive to inspect all the internal areas of a large ship. Inspection extent, therefore, will always be an element to be defined. To determine how much to inspect in a ship survey is a difficult task because inspection extent is related to many other aspects including frequency, techniques, design, maintenance, repair and human factors. This complexity has made a direct quantitative attack on the problem not practicable, and it has been necessary to rely on experience to guide the development of inspection rules. Class Society rules are usually revised as a result of experience of poor performance in service or catastrophic failures. On the other hand, if a ship type is historically safe, the corresponding rules will likely stay the same, or even be relaxed. This experienced-based process is usually quick in tightening rules but slow in relaxing them. Thus, the inspection practice of the ship industry may tend to be conservative.

While it is difficult to create an analytical model to optimize inspection extent, some general strategies can be used to optimize the existing inspection extent. According to the results of the data analyses in the preceding sections, at least two improvements can be incorporated in current practices. First, instead of inspecting all the transverse web frame in a tank to identify problem areas, a "jump search" can be performed on every other frame or a multiple of frames. Very often, when a crack is found in one ring, other rings will have the same type of crack. If the failure of a structural detail is due to fatigue, the other details of the same configuration that subject to the same load should likely fail in the same manner. This is why inspection reports often show a series of fatigue cracks of a certain type lining up in a tank. Therefore, a jump search should be able to identify problem areas. When a jump search is used, inspection time and cost can be reduced. Alternatively, the inspection extent can be extended to more tanks by using the saved time.

The second strategy is to recognize the time dependence of corrosion growth. The current inspection rules emphasize ballast tanks. While this may be good in identifying coating break down or corrosion, it can be misleading in terms of fatigue. For ships with coated ballast tanks, a cargo tank should have an equal chance of getting fatigue cracks, assuming that they have similar structural layouts. Some single hull VLCCs have experienced higher fatigue failure rates in cargo tanks than in water ballast tanks.

The third strategy is to concentrate inspections in the areas of high priority (or high risk). The current inspection practice does not systematically take failure consequence and failure probability into account, when planning the extent and area to be inspected. As a result, effort and resources may have been used inefficiently, because some areas of low failure consequence are regularly inspected.

The experience-based approach will probably remain the main approach for defining inspection extent in the future. However, some improvements may be made by applying a mix of experience and some of the strategies outlined above. This is best accomplished by also considering several other related aspects such as repair practice and human and organization factors.

4.4 When to INSPECT - Inspection Frequency

Currently the Class Society rules dictate, to a large extent, the required frequency of surveys of hull structure. The inspection frequencies have been established through the years based on in-service experience of various classes of ships, and represent a balance between the requirements for safety and ship operational availability. One method of optimizing inspection frequencies within these constraints is to use the priority analysis as illustrated in Figure 4.3. The priority analysis can identify the CSDs that are susceptible to damage and critical to the structural integrity of the ship. Annual surveys can then focus on those structures with high priority and susceptibility ratings (likelihood of experiencing damage). At intermediate surveys, areas with high priority and criticality ratings should be considered for close-up inspections, whereas less attention need be given to structure with low criticality ratings.

Different analytical procedures have been developed in other industries, notably the aircraft and offshore structures industries, to determine inspection intervals for components which are subject to time dependent failure modes such as fatigue and corrosion. Recently, there has been much interest in applying these techniques to ship structures.

A rational method of determining an optimal inspection interval for fatigue cracks is through the application of a fracture mechanics methodology. Fracture mechanics theory can be employed to predict a crack propagation curve for a particular CSD under consideration. Figure 4.17 shows schematically a crack propagation versus time.

other types of structures are, in many respects, different from ships. They are mainly composed of many separate parts or components. These parts, if cracked, tend to have a crack growth trend of an accelerating trend like the one in Figure 4.17. Ship structures are large complex structures with a high degree of redundancy. Therefore, they do not behave as independently as the components in an aircraft or an automobile. Failure of a detail in a ship structure does not necessarily cause overall collapse; in many cases local failure merely results in a load redistribution in the proximity of the failure. This is often referred to as a **load shedding** effect. As a result of load shedding, the crack propagation may have a decelerating trend at the end of its growth period. Also, the crack may come nearly to a stop or may grow at a very slow rate in the end. Figure 4.21 shows schematically the crack propagation curves of different types.

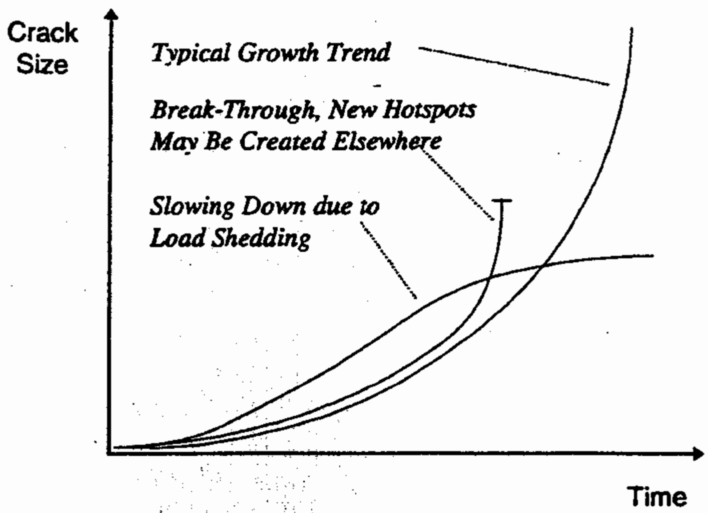


Figure 4.21: Different Types Of Crack Growth Trends.

In some other cases, a crack may break through a structural component. Crack growth curve of this type is also shown schematically in Figure 4.21. Once the break-through occurs, the neighboring structures may accommodate the excess load if there is a built-in redundancy. Thus, no serious consequence will necessary follow the failure. A good example is the flat-bar weld cracks often seen in the intersection of a transverse web and a longitudinal of a tanker. The breaking-through of one flat-bar weld usually does not constitute a complete structural failure. If there are stress concentrations in the neighboring area, new cracks will consequentially be initiated. Also, the adjacent web frames may develop the same type of cracks. If many neighboring structures fail subsequently and the problem is left untreated, eventually the local structure may collapse. However, observations have been made in some tankers where these types of cracks have existed for years without causing major collapse. Some of them have escaped detection from surveyors. This illustrates the high degree of redundancies in ship structures. The classical crack propagation model shown in Figure 4.17 may not be a realistic model for some structural configurations.

On the other hand, the typical crack propagation model is suitable for the catastrophic side frame failures of bulk carriers in the recent years. Over the period of 1990-1994, 97 bulk carriers were lost according to data published by International Maritime Organization (IMO) [IMO, 1995]. Approximately 45 percent of these casualties are due to structural related causes. Most of them invariably involved the failure of side shells and their hold frames. Most possible failure scenario is suspected as a propagating hold frame end crack and subsequent side shell cracking. A crack initiated in the hold frame welds can grow into the side shell plate. The side structure is the weakest link in the cross section of hull. There is no redundancy in the neighboring structure to shed the load, so it can grow at an accelerating pace into adjacent frames. In the end, the crack will reach a critical length. Water ingress and structure collapse can occur quite suddenly. According to the IMO report, it seems that some of these casualties came so suddenly that ship crews were unable to issue distress calls or escape. To prevent this kind of failure, the defects have to be detected early enough while they are still small. Alternatively, a better inspection strategy has to be implemented.

The second constraint comes from the difficulties in applying fracture mechanics methodology in practice for the large number of CSDs associated with a ship. As addressed earlier, the procedures to develop a crack growth curve can be broken down into several well-defined steps. Some of these steps are very tedious and time-consuming. One run of the complete procedure will only generate a result for one CSD in one location of one class of ship. The amount of effort to carry out the steps may be cost or time prohibitive. The example demonstrated in Rolfe's paper represents one of the simplest cases in which the local stress of the bottom shell can be calculated by using beam theory with an assumption on a simplified load combination. Even with the simplified method, the whole procedure may still be time-consuming. One possible solution for resolving this problem is to develop an automated program to integrate all the subroutines so that the crack growth curve can be computed from a simple set of data including ship route, loading pattern, location of the crack, fracture toughness database, etc.

Beside the lengthy process, the large number of CSDs existing in a ship also presents a problem. In a VLCC, the number of fatigue cracks can easily reach several hundred. Even if many of them can be classified into several types, their different locations still require an individual assessment for each. Fracture mechanics methodology should be applied judiciously. In this regard, the priority assessment approach described earlier can be used to prioritize which CSDs should be treated.

4.4.4 Other Strategies to Optimize Inspection Interval

4.4.4.1 Accelerating Inspection Frequency

So far in this chapter, only fixed inspection intervals have been discussed. An inspection program which varies its inspection intervals may be a superior alternative to the ones with fixed intervals. Ship structures degrade with time because of corrosion and fatigue. Their failure rates increase as they become older. This can be proved by a data analysis from an insurance company which indicated that ships of 15 to 20 years old contributed the most number of structure-related claims [Liu & Thayamballi, 1995]. Apparently the probability that a minor crack turns into a major one is greater for the older vessels which tend to have more cracks. Ship age is a critical parameter in the rate of casualty. It is, therefore, logical to arrange more frequent inspections (or shorter intervals) for older ships.

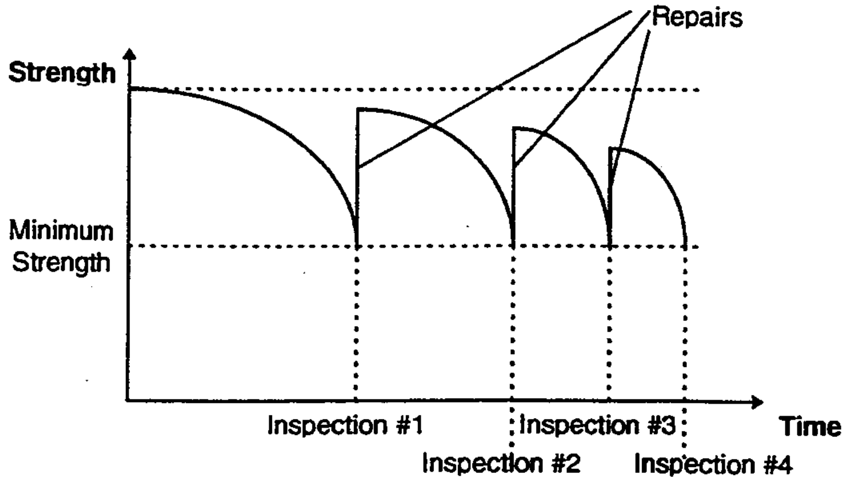


Figure 4.22: Shortening Inspection Intervals Along Time.

Figure 4.22 shows that the original strength of a ship structure decreases till it reaches the minimum strength limit. At this time, inspection and repair should be conducted to restore the condition or strength of the ship to a higher level for the next period of a safe operation. However, it is normally difficult to restore its strength to the original as-built state. In the second degrading period, it will take less time to reach the minimum strength limit. A second inspection and repair will be needed then. As the process continues, the inspection interval shortens.

Class Society rules are based on a fixed inspection interval. Annual, Intermediate and Special Surveys have fixed frequency of once every one year, 2.5 years and 5 years, respectively. This may create a inconsistency in which younger ships are subject to the same degree of inspections as older ships. A strategy used by class societies to cope with this problem is to require a larger extent of structure of older ships to be inspected while retaining the same inspection interval. Fixed frequencies may have certain administrative advantages. It may be also easier for the owners/operations to arrange their periodic maintenance. However, the use of an accelerating inspection frequency can provides a finer inspection program. A balance between adopting an accelerating frequency and using an expanding extent should be seek to provide an optimal inspection program.

4.4.4.2 –Condition Driven Inspection

The ideal way for conducting inspections is to determine the interval and extent based on the condition of the ship after repair following the previous inspection. This can be called a condition-driven inspection compared with a flat inspection, which strictly follows rule requirements no matter the ships' actual conditions. In a condition-driven inspection, the requirement is determined based on the condition of the ship recorded during the previous the organizational factors, the structure, the procedures and hardware used to perform the inspection, the environments (external, internal, social), and the interfaces between these categories of factors (Bea, 1994a).

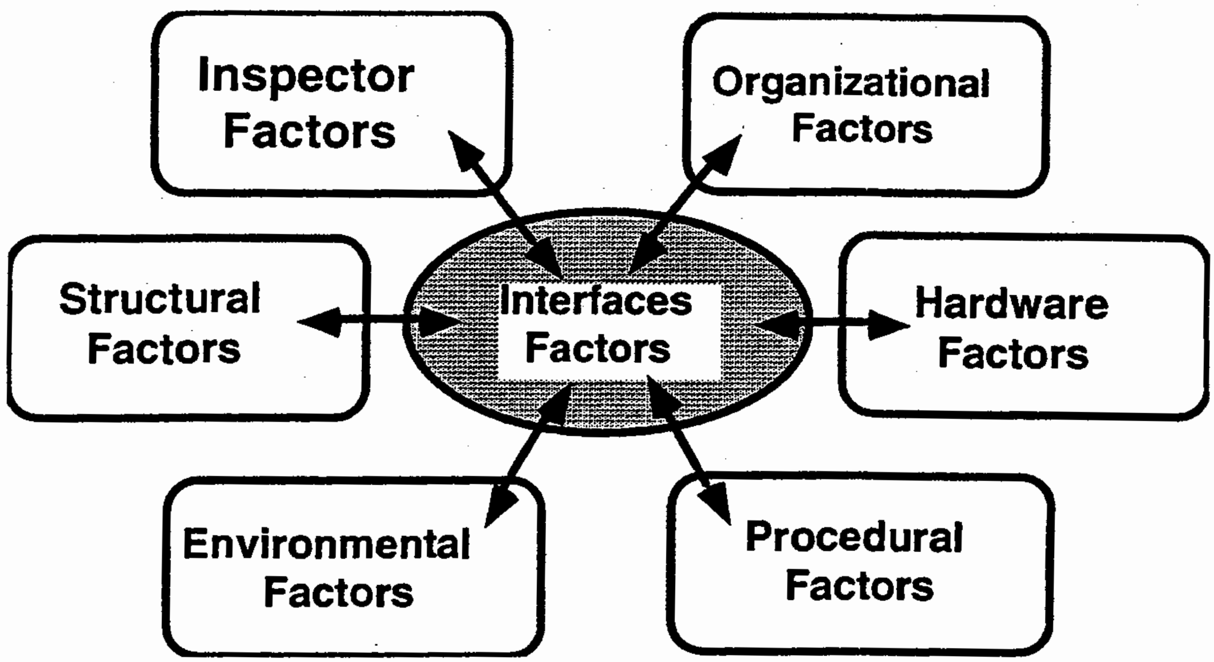


Figure 5.2: Factors Influencing Inspection Performance and Quality

Ship structure factors can be divided into two categories: design factors, and condition and maintenance factors. Design factors, including structural layout, size, and coatings are fixed at the time of initial design or through the redesign that may accompany repair. Condition/maintenance factors reflect the change in a structure as it ages, including the operation history and characteristics of individual damages/defects such as the type of defects/damages (crack, corrosion, buckling, denting), its size, and its location.

The person (inspector) who carries out an inspection can greatly influence the inspection performance (Demsetz, et al, 1996). Performance varies not only from inspector to inspector, but also from inspection to inspection with the same inspector based on mental and physical conditions. Factors associated with the inspector include experience, training, fatigue, and motivation.

Equally important are the organizational influences exerted on the inspector (Bea, 1994a). These include the procedures and processes mandated by the organization, resources provided to perform the inspections, communications, incentives, conflict resolution processes, and culture. In ship structure inspections today, there are many negative organizational influences that have dramatic effects on the quality of ship structure inspections. The lack of prestige and recognition given to ship structure inspectors, the provision of minimal facilities and measures to assure the

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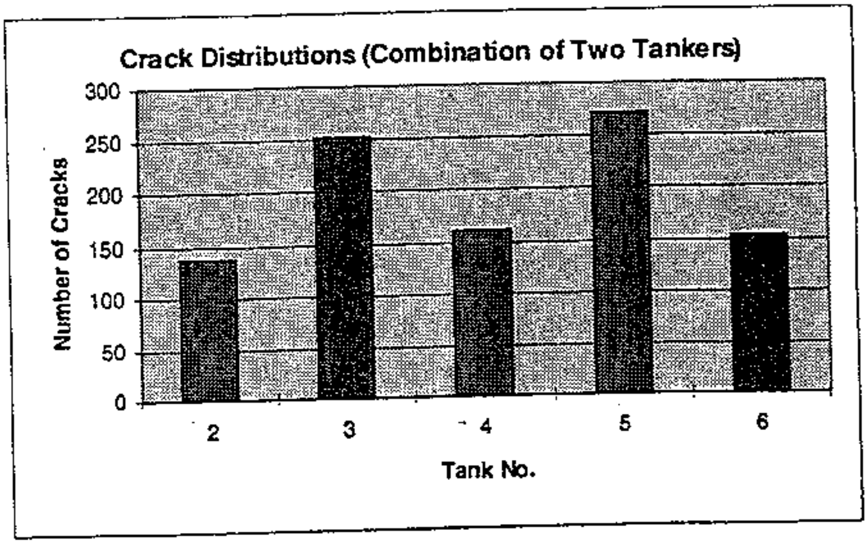

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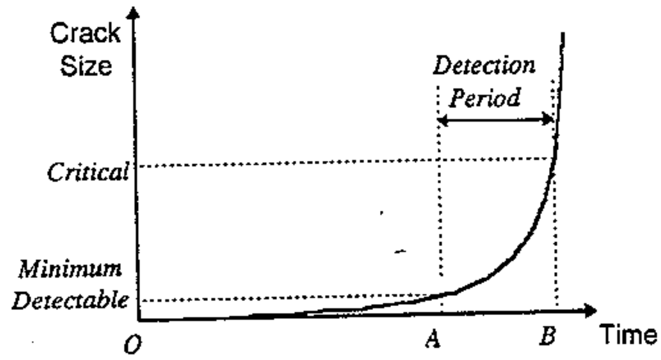

Figure 4.17: Crack Propagation Curve.

The curve presents the growth of a crack length as a function of time. It is assumed that the curve in Figure 4.17 represents the crack growth behavior of a highly stressed location (hot spot) in a CSD. After a certain service period, a crack is initiated at the hot spot at time "O" as shown in Figure 4.17. The crack is too small to be detected by a visual inspection at this time. It will grow due to fatigue until at time "A" when it reaches a size that allows detection, which is called the minimum detectable size. The minimum detectable size using visual means may vary widely depending on lighting, accessibility and many other factors. The crack will eventually grow to a critical size at time "B". At this time, the crack becomes unstable and failure may soon occur. The period from time "A" to "B" is available for crack detection, so is called the **detection period.** Inspection should be scheduled within this period. Preferably, there should be more than one inspection, since a crack of the minimum detectable length may just escape detection during one inspection.

The first step in establishing an inspection interval is to identify critical structural details that need special attention in terms of fatigue or corrosion. This can be done by performing a priority assessment as shown schematically in Figure 4.18. The CSDs with high priorities are selected and are then analyzed using fracture mechanics and/or corrosion mechanics to establish the inspection interval.

4.4.1 Procedures to Establish Inspection Intervals

For CSDs with high priorities in terms of fatigue, their crack growth curves need to be developed. This may be more difficult for ship structures than other types of structures. In aircraft, most of its components are moderate in size and can be tested in a lab to calibrate their crack propagation curves. Most of the critical components may have accumulated large amount of crack growth data from past operations of the aircraft of the same model. The crack growth curves can be calibrated from those data. In the case of ships, each is designed individually and there only be a few ships in the same class. Gathering fatigue crack growth data for ship structural details in laboratory conditions is expensive and their large size are such that only a few facilities can accommodate them. Furthermore, their structural details are too large to be economically tested in a lab. As a result, very limited data can be obtained. Therefore, it becomes a challenge to develop this curve for a ship CSD. Conservative assumptions often have to be used.

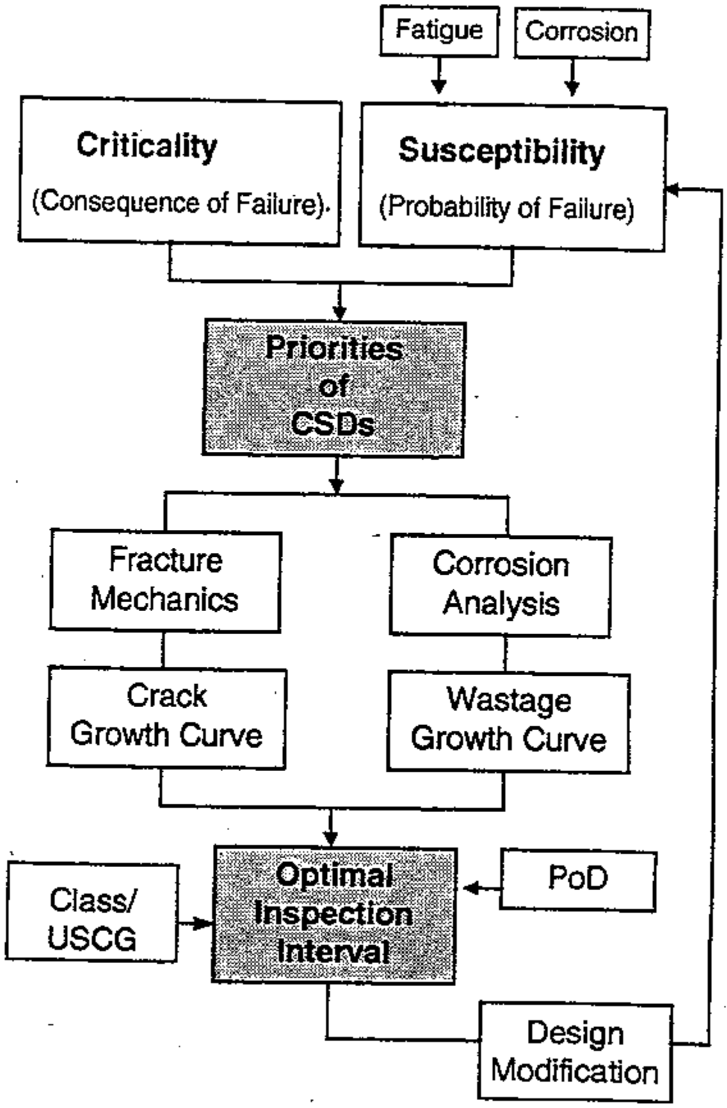

Figure 4.18: Flow Chart For Establishing an Optimal Inspection Interval.

Rolfe et al. demonstrated the use of **fracture mechanics** methodology for establishing a reasonable inspection interval [Rolfe, 1993]. He applied the methodology to the bottom shell of an oil tanker of a particular class. The methodology can be broken down into the following steps:

1. Develop a stress intensity factor relationship, K_I, for the chosen detail.

2. Estimate the **minimum detectable size** with a high probability of detection. This is the initial crack size, a_0.

3. Calculate the maximum stress to which the detail is subjected. Estimate the fracture toughness, K_c, by conducting fracture tests. Use the toughness, the maximum stress and the K_I relation from step 1 to calculate the **critical crack size**, a_{CR}.

4. Calculate a histogram displaying stresses that the critical area will experience over the time period of interest. Use the load histogram to develop a **crack growth curve**.

5. Determine the **detection period** from the curve. Establish reasonable inspection intervals.

The above procedures use fracture mechanics methodology to establish a reasonable inspection interval for one CSD in one ship. It should be noted that this approach may not be applicable for some types of cracks that tend to be arrested by the robustness of the local structure. Constraints like this are further discussed in the following sections.

The critical crack size calculated using the above procedures is the size at which unstable crack growth is about to occur. Beyond this size, the crack can grow rapidly with potentially a serious consequences. Figure 4.19 shows a crack initiated in the bracket toe on a bottom longitudinal of a cargo oil tank. The critical crack size thus predicted may be greater than the crack size that allows oil to spill. Hence, this is constraint that will need to be applied in any analysis to determine the maximum allowable crack size. Other situations are less obvious. For example, if the crack in Figure 4.19 is in the bottom or side shell of a water ballast tank, it will propagate into the bottom plate and continue to grow. There is no danger of oil spills. In this case, the critical crack size should be defined as the size which is about to cause an unstable growth. The fracture toughness of the bottom plate will have to be estimated in order to calculate the critical crack size.

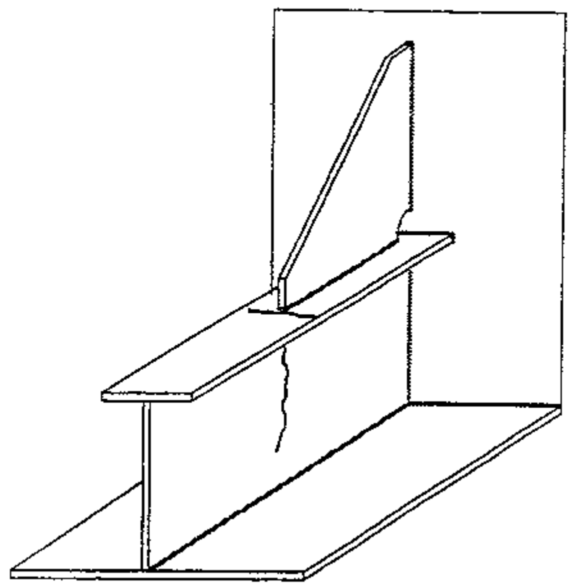

Figure 4.19: A Crack Initiated From a Bracket Toe Developing into Longitudinal.

The minimum detectable size in Step 2 may be difficult to define. Rolfe el al. indicated that 3 inches appears to be the minimum detectable crack length based on estimates made by U.S. Coast Guard inspectors [Rolfe, 1993]. However, this value is controversial because many inspection reports regularly record small cracks down to about 10 millimeter in size (0.4 inches). In fact, one of the inspection reports used for the data analysis in Section 4.3 records three 5 millimeter cracks (0.2 inches). On the other hand, the minimum detectable size can also be large in cases where the critical areas are covered with mud, debris or wax. Therefore, the value of the minimum detectable crack size should be determined on the basis of a number of factors. These factors include lighting, condition of coating, rust, existence of sludge, water or wax, inspection techniques used, inspector experience level and familiarity with the vessel class, vessel loading condition, and the location of the CSD in the ship, etc. For these reasons, the use of a generalized definition is questionable in practice.

The above procedures can be used to establish a safe inspection interval, as well as determining if the determent of a crack repair is safe. Fracture mechanics has been successfully applied to different type of CSDs [ABS, 1996]. In one case, a small through-thickness crack was found in the bottom shell plating of a medium sized tanker. The crack was detected while the vessel was in port where its cargo had been unloaded, and it was necessary to determine if the vessel could safely sail to another harbor where it could then be dry-docked and for appropriate repairs. With pessimistic analysis assumptions, it was determined that the crack would only grow by a small amount during the voyage. Thus for the owner, there was no need to attempt to make expensive temporary repairs. In the same article, three more examples of using fracture mechanics were given. In one case, fracture mechanics was applied to a side shell fracture created from a contact incident. It was determined that there was no likelihood of a through-thickness crack developing through the side shell, which would have led to a potential pollution problem. Another case dealt with a flaw within a rudder horn casting. It was determined that the flaw was unlikely to grow significantly in size for a long period of time. Therefore, instead of being repaired, it will only be inspected at each dry-docking. The last case dealt with cracks in a bulk carrier where fracture mechanics analysis was used to demonstrate that standard weld repairs were satisfactory.

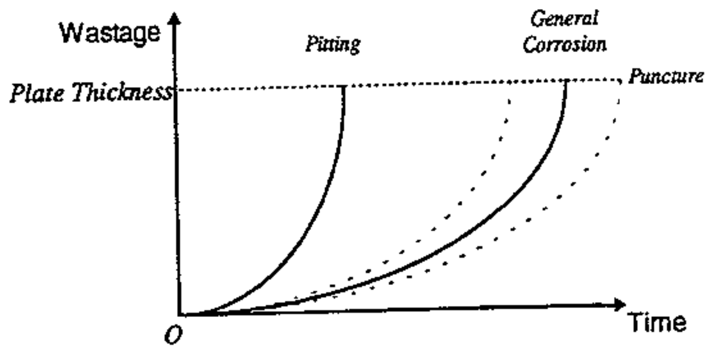

Figure 4.20: Corrosion (Wastage) Growth Curve.

So far, only fatigue cracking has been discussed. The other major failure mode, corrosion, can be treated in a similar way. A corrosion wastage growth curve similar to a crack growth curve could be developed. Figure 4.20 shows schematically a corrosion wastage growth curve. Typical corrosion growth curves for different environments developed by TSCF can be used [TSCF, 1992]. Depending on the location of the CSD, the tank type, the existence of anodes and the use of a heating device, a suitable curve can be selected. The most difficult aspect of developing a corrosion growth curve is likely to determine the allowable wastage (or the maximum corrosion limit). To ensure that the reduced plate thickness will not result in a ship structure failure, global and local strengths have to be reassessed which may include longitudinal strength, transverse strength, grillage buckling strength, and panel buckling strength. Based on these strength analyses, the allowable wastage can be defined.

Pitting corrosion should be treated differently than general corrosion in regard to determining its inspection interval. Generally speaking, localized pitting is not considered a threat to structural strength. Rather, it is more of a pollution risk which has the potential to cause a cargo spill when the plate is penetrated. The residual thickness of the pitted plate should be sufficient to sustain further corrosion wastage until the next scheduled inspection. Otherwise, the pitting should be repaired. This minimum can be estimated by multiplying the pitting growth rate by the amount of time before the next scheduled inspection. However, if the pits are not in the boundary of cargo tanks, and have no potential to cause cargo spills, the minimum reserve may be relaxed.

4.4.2 Safe Inspection Interval

The available period for successfully discovering a crack is the detection period which is defined as the duration from the time when the damage is detectable until it reaches its critical dimension. Typically, one half of the detection period is considered to be a reasonable inspection interval for the structures with a high Probability of Detection (POD). However, a shorter interval might be appropriate for fatigue cracking in ship structures because of the low POD and the high degree of uncertainty in the crack propagation curves.

The POD of a crack varies from inspection to inspection and is dependent on a variety of factors. These include degree of surface cleanliness, existence of sludge, water or wax, lighting, inspection techniques used, inspector experience level and familiarity with the vessel class, condition of the coating system, vessel loading condition, and the location the CSD in the ship.

A low POD implies that more inspections are needed to achieve a certain safety level. To improve the quality of inspections of the structures with low PODs, multiple inspections should be arranged in the detection period. The probability of missing a defect in all inspections during the detection period can be calculated as:

$$P_{miss} = (1 - POD_{t1})(1 - POD_{t2})\ldots(1 - POD_{tn}) = \prod_{1}^{n}(1 - POD_{ti}) \tag{4.3}$$

where P_{miss} is the probability of missing a defect in all inspections during a detection period;
POD_{ti} is the probability of detection of the inspection at time *ti*.

The combined POD of all inspection during the detection period is:

$$POD_{combined} = 1 - P_{miss} = 1 - \prod_{1}^{n}(1 - POD_{ti}) \tag{4.4}$$

The combined POD can serve as a safety measure of the chosen inspection interval. A shorter inspection interval (more frequent inspections) will give a higher value of the combined POD, and vice versa. Note that the POD at time t_n has a larger value than the one at time t_{n-1}, because the crack size grows larger and therefore becomes easier to detect. Unfortunately, no POD curves were currently available for ship structures. Work is underway in the direction of developing POD curves from in-field experiments [Demsetz, 1996b]. Also, work has been done on how to develop a POD curve for vessel inspection [Holzman, 1992]. This procedure may be used to evaluate the POD of various lengths of fractures for the particular structure being evaluated.

4.4.3 Constraints of Applying Fracture Mechanics

There are a few constraints in using fracture mechanics methodology to establish inspection intervals. The first arises from the special characteristics of crack growth in structures with large redundancy. The foregoing discussion is based on a hypothetical crack propagation curve which has an accelerating trend with time. In many types of structures such as aircraft, this is often true. It is especially true for specimens of simple geometry used in labs. Aircraft, automobile and some

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The environment in which the inspection is carried out has a major influence on performance. The environment factors can be divided into two categories: external factors which can not be modified by inspection procedures and procedural factors that can be modified. External factors include weather and location of the ship, that is, whether the inspection is performed while underway, while in port, or while in dry-dock. Procedural factors reflect the condition during the inspection (lighting, cleanliness, temperature, ventilation); the way in which the inspection is conducted (access methods, inspection methods, inspection strategies, crew support, and time available), and the overall specifications for inspection (inspection type) (Demsetz, et al, 1996).

In the author's experience, ship structure inspectors are generally very capable and highly motivated. Their primary problems are associated with safe and adequate access to the ship structure (try inspecting a ship while it is underway using rafting methods or when the temperature inside the ship is 120° F), provision of adequate resources to perform and record the inspections (scheduling, time, support services, efficient recording devices), and provision of efficient and effective planning and follow-up (analysis, reporting) systems. Ship structure design for inspections, access, and safety can go a long way to make ship inspections more efficient and effective. Further, design of the ship for adequate durability, and not depending on inspections to provide acceptable durability, can further improve the effectiveness and efficiency of inspections. Then inspections can be performed to disclose unexpected or unusual durability problems.

5.4 An Integrated IMMR System

A fundamental purpose of in-service inspections is to identify structural integrity problems and assess the capability of the structure to remain safe until next inspection, and to accomplish the necessary corrective measures to maintain this capability. An 'optimum' in-service inspection program should have four functions:

- to assess the condition of the in-service characteristics of the ship structure.
- to confirm what is thought; to addresses damage that can be predicted based on results from technical analyses.
- to disclose what is not known before the inspections; to address damage that can not be predicted based on results from technical analyses. The forth fundamental function is to control the predictable and unpredictable damages; to develop high quality maintenance and repair program

Quantitative IMMR analyses can help address the first, second, and third functions; providing insights into when, where, and how to inspect and repair. Such analyses can not be relied upon to provide information that addresses the third purpose.

An optimum IMMR method starts with a survey to determine the locations and extents of expected and unexpected defects and damage (Bea, 1993). Based on the analysis results and historical experience, the inspection for expected damage can be conducted in a rational way.

other types of structures are, in many respects, different from ships. They are mainly composed of many separate parts or components. These parts, if cracked, tend to have a crack growth trend of an accelerating trend like the one in Figure 4.17. Ship structures are large complex structures with a high degree of redundancy. Therefore, they do not behave as independently as the components in an aircraft or an automobile. Failure of a detail in a ship structure does not necessarily cause overall collapse; in many cases local failure merely results in a load redistribution in the proximity of the failure. This is often referred to as a **load shedding** effect. As a result of load shedding, the crack propagation may have a decelerating trend at the end of its growth period. Also, the crack may come nearly to a stop or may grow at a very slow rate in the end. Figure 4.21 shows schematically the crack propagation curves of different types.

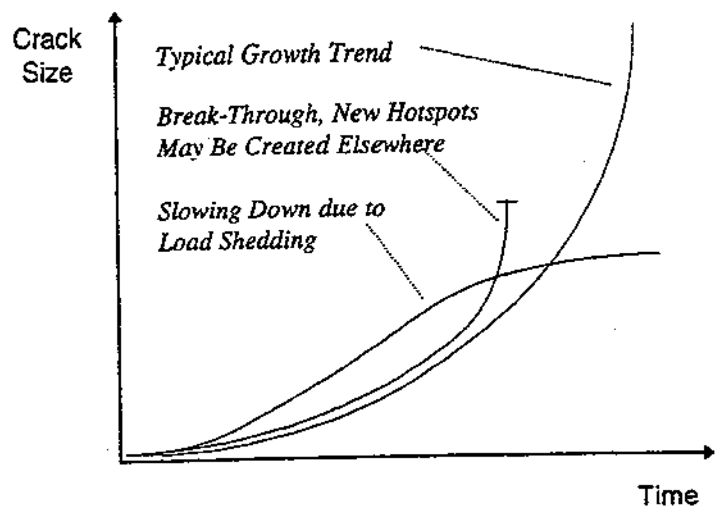

Figure 4.21: Different Types Of Crack Growth Trends.

In some other cases, a crack may break through a structural component. Crack growth curve of this type is also shown schematically in Figure 4.21. Once the break-through occurs, the neighboring structures may accommodate the excess load if there is a built-in redundancy. Thus, no serious consequence will necessary follow the failure. A good example is the flat-bar weld cracks often seen in the intersection of a transverse web and a longitudinal of a tanker. The breaking-through of one flat-bar weld usually does not constitute a complete structural failure. If there are stress concentrations in the neighboring area, new cracks will consequentially be initiated. Also, the adjacent web frames may develop the same type of cracks. If many neighboring structures fail subsequently and the problem is left untreated, eventually the local structure may collapse. However, observations have been made in some tankers where these types of cracks have existed for years without causing major collapse. Some of them have escaped detection from surveyors. This illustrates the high degree of redundancies in ship structures. The classical crack propagation model shown in Figure 4.17 may not be a realistic model for some structural configurations.

On the other hand, the typical crack propagation model is suitable for the catastrophic side frame failures of bulk carriers in the recent years. Over the period of 1990-1994, 97 bulk carriers were lost according to data published by International Maritime Organization (IMO) [IMO, 1995]. Approximately 45 percent of these casualties are due to structural related causes. Most of them invariably involved the failure of side shells and their hold frames. Most possible failure scenario is suspected as a propagating hold frame end crack and subsequent side shell cracking. A crack initiated in the hold frame welds can grow into the side shell plate. The side structure is the weakest link in the cross section of hull. There is no redundancy in the neighboring structure to shed the load, so it can grow at an accelerating pace into adjacent frames. In the end, the crack will reach a critical length. Water ingress and structure collapse can occur quite suddenly. According to the IMO report, it seems that some of these casualties came so suddenly that ship crews were unable to issue distress calls or escape. To prevent this kind of failure, the defects have to be detected early enough while they are still small. Alternatively, a better inspection strategy has to be implemented.

The second constraint comes from the difficulties in applying fracture mechanics methodology in practice for the large number of CSDs associated with a ship. As addressed earlier, the procedures to develop a crack growth curve can be broken down into several well-defined steps. Some of these steps are very tedious and time-consuming. One run of the complete procedure will only generate a result for one CSD in one location of one class of ship. The amount of effort to carry out the steps may be cost or time prohibitive. The example demonstrated in Rolfe's paper represents one of the simplest cases in which the local stress of the bottom shell can be calculated by using beam theory with an assumption on a simplified load combination. Even with the simplified method, the whole procedure may still be time-consuming. One possible solution for resolving this problem is to develop an automated program to integrate all the subroutines so that the crack growth curve can be computed from a simple set of data including ship route, loading pattern, location of the crack, fracture toughness database, etc.

Beside the lengthy process, the large number of CSDs existing in a ship also presents a problem. In a VLCC, the number of fatigue cracks can easily reach several hundred. Even if many of them can be classified into several types, their different locations still require an individual assessment for each. Fracture mechanics methodology should be applied judiciously. In this regard, the priority assessment approach described earlier can be used to prioritize which CSDs should be treated.

4.4.4 Other Strategies to Optimize Inspection Interval

4.4.4.1 Accelerating Inspection Frequency

So far in this chapter, only fixed inspection intervals have been discussed. An inspection program which varies its inspection intervals may be a superior alternative to the ones with fixed intervals. Ship structures degrade with time because of corrosion and fatigue. Their failure rates increase as they become older. This can be proved by a data analysis from an insurance company which indicated that ships of 15 to 20 years old contributed the most number of structure-related claims [Liu & Thayamballi, 1995]. Apparently the probability that a minor crack turns into a major one is greater for the older vessels which tend to have more cracks. Ship age is a critical parameter in the rate of casualty. It is, therefore, logical to arrange more frequent inspections (or shorter intervals) for older ships.

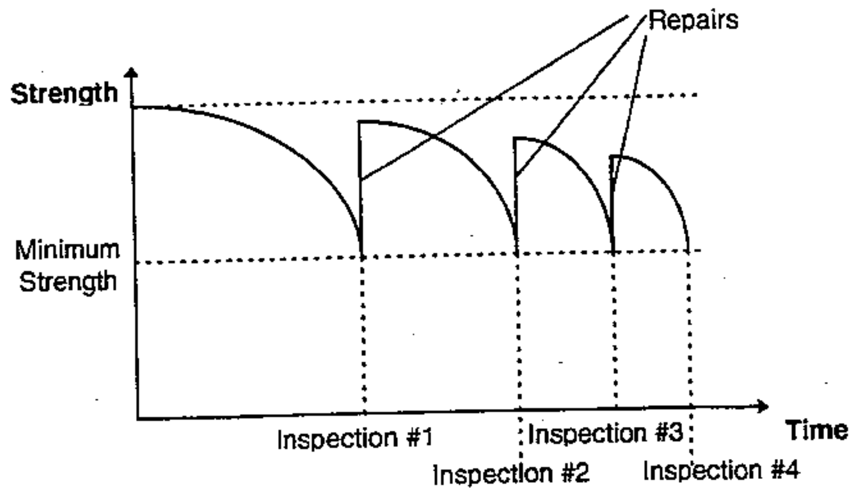

Figure 4.22: Shortening Inspection Intervals Along Time.

Figure 4.22 shows that the original strength of a ship structure decreases till it reaches the minimum strength limit. At this time, inspection and repair should be conducted to restore the condition or strength of the ship to a higher level for the next period of a safe operation. However, it is normally difficult to restore its strength to the original as-built state. In the second degrading period, it will take less time to reach the minimum strength limit. A second inspection and repair will be needed then. As the process continues, the inspection interval shortens.

Class Society rules are based on a fixed inspection interval. Annual, Intermediate and Special Surveys have fixed frequency of once every one year, 2.5 years and 5 years, respectively. This may create a inconsistency in which younger ships are subject to the same degree of inspections as older ships. A strategy used by class societies to cope with this problem is to require a larger extent of structure of older ships to be inspected while retaining the same inspection interval. Fixed frequencies may have certain administrative advantages. It may be also easier for the owners/operations to arrange their periodic maintenance. However, the use of an accelerating inspection frequency can provides a finer inspection program. A balance between adopting an accelerating frequency and using an expanding extent should be seek to provide an optimal inspection program.

4.4.4.2 –Condition Driven Inspection

The ideal way for conducting inspections is to determine the interval and extent based on the condition of the ship after repair following the previous inspection. This can be called a condition-driven inspection compared with a flat inspection, which strictly follows rule requirements no matter the ships' actual conditions. In a condition-driven inspection, the requirement is determined based on the condition of the ship recorded during the previous inspection. The determination can be assisted by an analysis such as a damage tolerance assessment that can predict the fitness-for-service of the ship. If a ship is found in a satisfactory condition, then it will be subject to an inspection in a longer period. The condition assessment can adopt a rating system with some fuzzy terms such as excellent, good, fair and bad. A similar rating system has been used in practice for coating condition rating.

A condition-driven inspection program has the advantage of eliminating unnecessary inspections or unnecessary extents of an inspection, and therefore reduce inspection cost and labor for all parties including owners/operators, class societies and flag administrators. However, a program of this type has to be carefully designed so that uncertainties from human and organizational factors can be reduced to a minimum level.

The current class society rules have a limited usage of condition driven rules. A few examples from LR rules are listed as follows [Lloyd's Register, 1996]:

> 2.2.19 (In Annual Surveys) The surveyor is to carry out a Close-up Survey and thickness measurement of structure identified at the previous Special Survey as having substantial corrosion.
>
> 3.2.5 For independent double bottom tanks where substantial corrosion or other defects are found, the examination is to be extended to other ballast tanks of the same type.

The first rule requires that the inspection frequency be increased to once every year, if there is substantial corrosion. The second example shows that the inspection extent is expanded, if substantial corrosion or other defects are found. These are the two typical examples of many condition-driven rules existing in a class society rule. A condition-driven rule requirement should be superior to flat requirements, since only necessary inspections will be mandated.

5. RE-ENGINEERING THE IMMR PROCESS

This section addresses an integrated Inspection, Maintenance, Monitoring, and Repair (IMMR) system. This IMMR process is initiated and defined during the design phase, and conducted throughout the remainder of the life-cycle phases of a ship. The IMMR process is integrated with a ship Life-Cycle Management Information System (LCMIS). The LCMIS system should take full advantage of current and near-future developments in information technology. To be efficient and effective, the IMMR system should be 're-engineered' to eliminate unnecessary and low productivity tasks and activities. Streamlining to improve efficiency in processes is critical to reduce costs and provide resources that can be used to develop and implement an integrated IMMR system.

5.1 Objectives

The objective of an IMMR system is to provide information and knowledge on the present, and future integrity of a ship structure. Given this knowledge, a ship owner / operator is given adequate guidelines and incentives to keep the ship structure at a desirable and acceptable level of quality (serviceability, durability, safety, compatibility). Inspections, data recording, management, and data analysis should all be a part of a comprehensive and integrated IMMR system. Records and thorough understanding of the information contained in these records are key aspects of IMMR programs. Quality assurance and quality control (QA/QC) are part of a successful IMMR system. The IMMR systems should be focused on:

- determination of condition of structural elements and structural system,
- disclosure of defects and damage (design, construction, operation, and maintenance),
- assurance of conformance with plans and specifications, guidelines and rules, and quality requirements,
- definition of adequate maintenance programs to manage fatigue and corrosion damage,
- definition of efficient and effective repairs for corrosion and fatigue damage, and
- development of information to improve design, construction, operation, repair, and maintenance procedures.

5.2 IMMR System

Ship structure in-service inspections, maintenance, monitoring, and repairs are components in an IMMR system (Figure 5.1) that is intended to help disclose the presence of 'anticipated' and 'unanticipated' defects and damage to the ship structure that result from corrosion and fatigue (Bea, 1992). Development of in-service IMMR programs should address:

(i) elements to be inspected (where and how many),
(ii) defects, degradation, and damage to be detected (what),

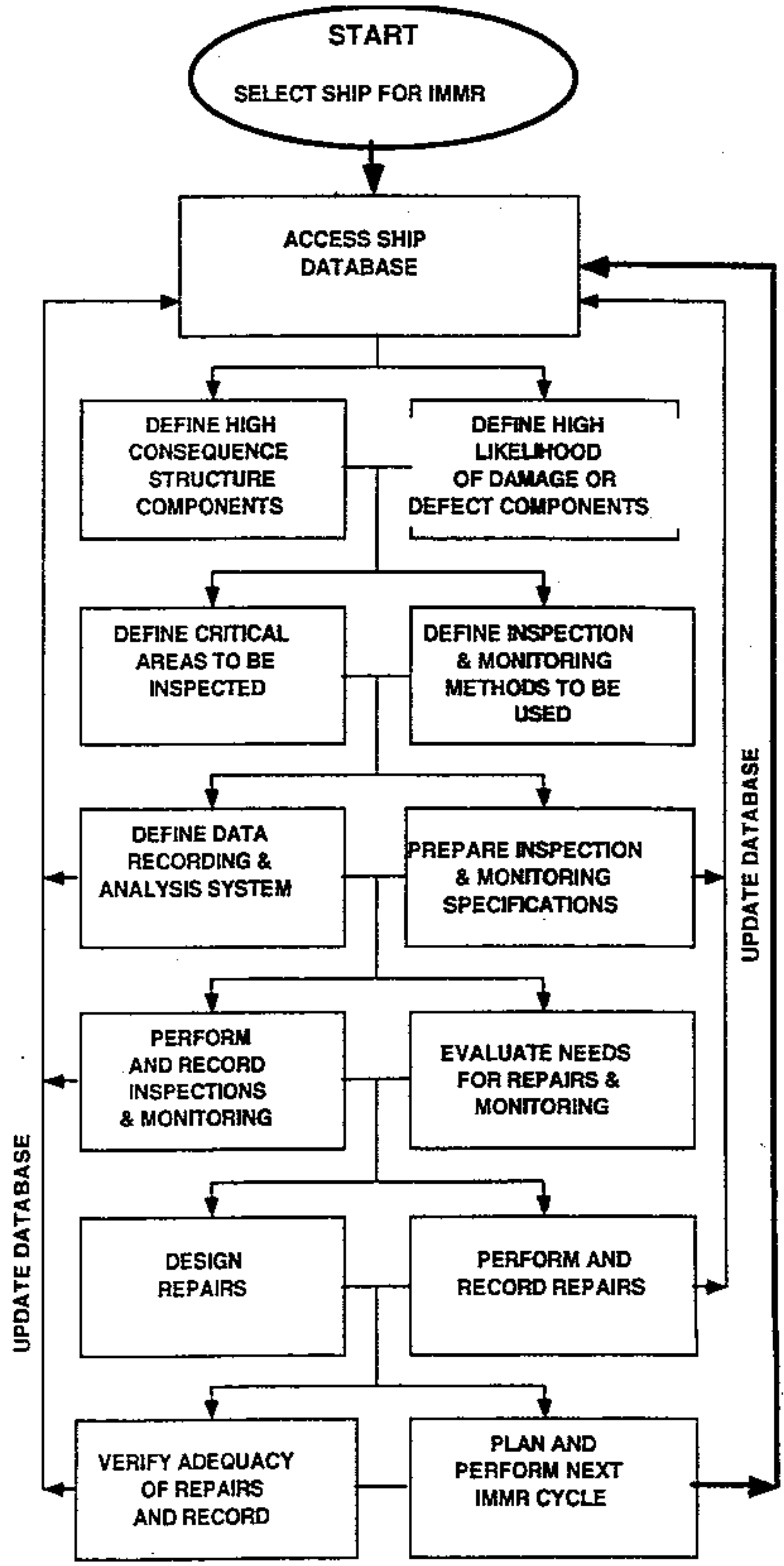

Figure 5.1: Components of IMMR System

(iii) methods to be used to inspect, monitor, evaluate, record, archive, and report results (how),
(iv) timing and scheduling (when),
(v) organization, selection, training, verification, conflict resolution, and responsibilities (who), and
(vi) objectives (why).

An IMMR system is a critical part of the maintenance of in-service quality (serviceability, safety, durability, compatibility) of a ship structure. The IMMR process must be in place, working, and being further developed during the entire lifetime of the ship structure. The IMMR process is responsible for maintaining the quality of the structure during the useful lifetime of the ship. A fundamental and essential part of the IMMR process is knowledge. The IMMR process can be no more effective or efficient than the knowledge, data, and experience that forms the basis for the process.

The IMMR process must be diligent and disciplined and have integrity. There must be a focus on the quality of the performance of the process; quality of the structure will be a natural by-product. The IMMR process should investigate a wide variety of alternatives to accomplish its fundamental objectives (maintenance of strength and serviceability). Inspections can range from general to detailed, visual to acoustic, periodic to continuous (monitoring). Maintenance can range from patching to complete replacement. Repairs can range from replacement as-was to re-design and replacement; temporary to permanent; from complete and comprehensive to judicious neglect.

The IMMR process can be proactive (focused on prevention), or it can be reactive (focused on correction). The IMMR process can be periodic (time based), or it can be condition oriented (occasion based). Combinations of proactive, reactive, periodic, and condition based approaches can be appropriate for different IMMR programs. A major challenge is to find the combination that best fits a particular ship structures, their operations, and the organizations responsible for their integrity.

An IMMR process should define the combinations and permutations of IMMR that will produce the lowest total costs (initial and future) and optimize the use of resources without compromising minimum quality and reliability requirements (Bea, 1994a; 1994b; 1994c; Yang, 1976; Fujimoto, et al, 1991).

5.3 The Critical Link - The Inspector

5.3.1 Influences

Each inspection represents a unique combination of ship structure, personnel, and environment. Inspection performance and quality are influenced (Figure 5.2) by the inspector.

the organizational factors, the structure, the procedures and hardware used to perform the inspection, the environments (external, internal, social), and the interfaces between these categories of factors (Bea, 1994a).

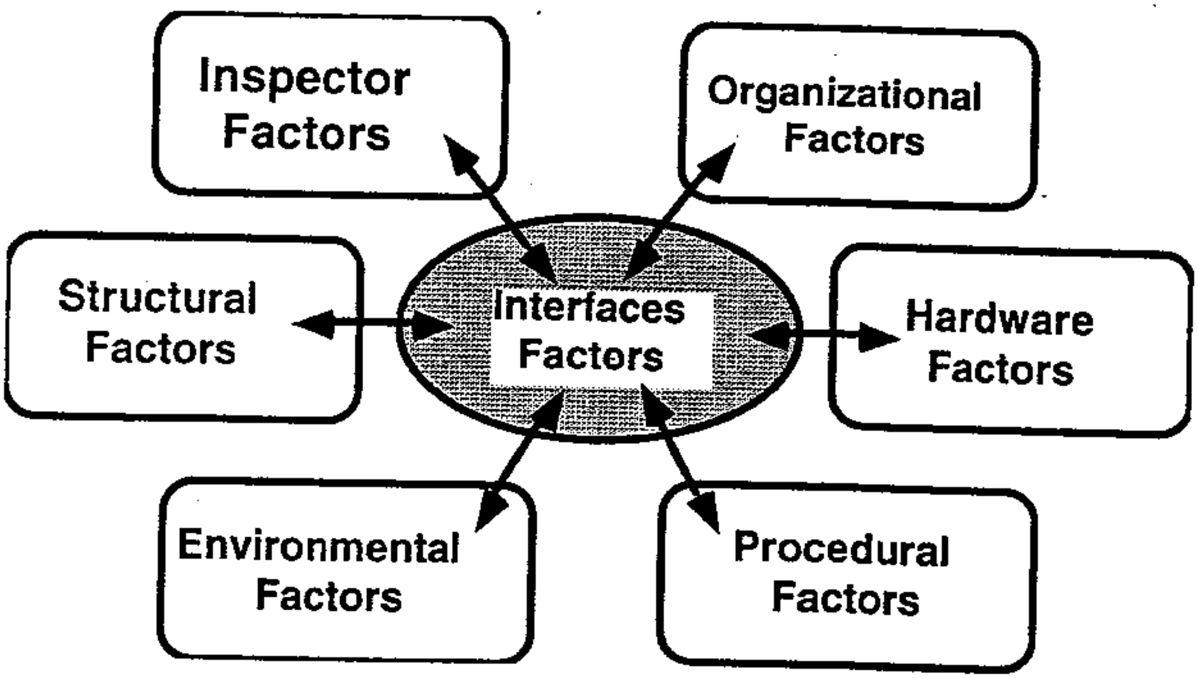

Figure 5.2: Factors Influencing Inspection Performance and Quality

Ship structure factors can be divided into two categories: design factors, and condition and maintenance factors. Design factors, including structural layout, size, and coatings are fixed at the time of initial design or through the redesign that may accompany repair. Condition/maintenance factors reflect the change in a structure as it ages, including the operation history and characteristics of individual damages/defects such as the type of defects/damages (crack, corrosion, buckling, denting), its size, and its location.

The person (inspector) who carries out an inspection can greatly influence the inspection performance (Demsetz, et al, 1996). Performance varies not only from inspector to inspector, but also from inspection to inspection with the same inspector based on mental and physical conditions. Factors associated with the inspector include experience, training, fatigue, and motivation.

Equally important are the organizational influences exerted on the inspector (Bea, 1994a). These include the procedures and processes mandated by the organization, resources provided to perform the inspections, communications, incentives, conflict resolution processes, and culture. In ship structure inspections today, there are many negative organizational influences that have dramatic effects on the quality of ship structure inspections. The lack of prestige and recognition given to ship structure inspectors, the provision of minimal facilities and measures to assure the safety of the inspectors, and the lack of sufficient organizational support to help assure the efficiency, effectiveness, and quality of inspection processes are examples.

The environment in which the inspection is carried out has a major influence on performance. The environment factors can be divided into two categories: external factors which can not be modified by inspection procedures and procedural factors that can be modified. External factors include weather and location of the ship, that is, whether the inspection is performed while underway, while in port, or while in dry-dock. Procedural factors reflect the condition during the inspection (lighting, cleanliness, temperature, ventilation); the way in which the inspection is conducted (access methods, inspection methods, inspection strategies, crew support, and time available), and the overall specifications for inspection (inspection type) (Demsetz, et al, 1996).

In the author's experience, ship structure inspectors are generally very capable and highly motivated. Their primary problems are associated with safe and adequate access to the ship structure (try inspecting a ship while it is underway using rafting methods or when the temperature inside the ship is 120° F), provision of adequate resources to perform and record the inspections (scheduling, time, support services, efficient recording devices), and provision of efficient and effective planning and follow-up (analysis, reporting) systems. Ship structure design for inspections, access, and safety can go a long way to make ship inspections more efficient and effective. Further, design of the ship for adequate durability, and not depending on inspections to provide acceptable durability, can further improve the effectiveness and efficiency of inspections. Then inspections can be performed to disclose unexpected or unusual durability problems.

5.4 An Integrated IMMR System

A fundamental purpose of in-service inspections is to identify structural integrity problems and assess the capability of the structure to remain safe until next inspection, and to accomplish the necessary corrective measures to maintain this capability. An 'optimum' in-service inspection program should have four functions:

- to assess the condition of the in-service characteristics of the ship structure.
- to confirm what is thought; to addresses damage that can be predicted based on results from technical analyses.
- to disclose what is not known before the inspections; to address damage that can not be predicted based on results from technical analyses. The forth fundamental function is to control the predictable and unpredictable damages; to develop high quality maintenance and repair program

Quantitative IMMR analyses can help address the first, second, and third functions: providing insights into when, where, and how to inspect and repair. Such analyses can not be relied upon to provide information that addresses the third purpose.

An optimum IMMR method starts with a survey to determine the locations and extents of expected and unexpected defects and damage (Bea, 1993). Based on the analysis results and historical experience, the inspection for expected damage can be conducted in a rational way.

Existing probability-based inspection methods provide a framework for expected damages and defects.

For the unexpected damages and defects, the problem is more complex. A knowledge-based inspection method must be applied (Xu, Bea, 1996). A major component of this development is the inquisitive, intuitive, judgmental element of 'diagnosis' (something doesn't sense 'right'). A physician uses this element to diagnose an injury or disease in a patient. A physician uses inspection instrumentation and systems to confirm a diagnosis; rarely, is it done vice versa. In in-service inspection practice, knowledge is generally used in a quite specific way to detect the unexpected damage and defects. The specification of such a problem solving method (problem by problem) requires a precise, unambiguous formalism. Here, logic techniques are better suited for this purpose, because reasoning can be described in a declarative way, i.e., in terms of relations among logical tasks.

An integrated IMMR program can be proactive (focused on prevention) or it can be reactive (focused on correction) (Yang, 1985; 1993). It should have the following functions:

- Assess the general condition of the ship structure,
- Identify intrinsic damages/defects to confirm what we know,
- Detect extrinsic damages/defects to disclose what we don't know,
- Evaluate intrinsic and extrinsic damage/defects to identify appropriate measures to remedy the damage/defects, and
- Implement the measures, record the results, and identify future IMMR measures, and
- Provide QA / QC to assure that the objectives of the IMMR program are satisfied.

The integrated IMMR program should be started with the design of the ship (conception), proceed through the life of the ship, and conclude with its scrapping (life-cycle). The integrated IMMR program should include not only the hull structure, but as well, its equipment and its personnel (full scope). The integrated IMMR program should provide the means to assess the general condition of the ship structure. The integrated IMMR program should provide are means to detect and remedy predictable (inherent causes) and unpredictable (human error causes) flaws and damages to the structural elements, and permit appropriate measures to be taken to preserve the safety and integrity of the structure. The integrated IMMR program should provide the means to assure that all is going as expected, that the structural elements are performing as expected, and that corrosion protection and mitigation (e.g. patching pits, renewing locally excessively corroded plate) is maintained.

The integrated IMMR program differs from many existing programs such as those based solely on probability-based or risk-based programs in several ways. First, the existing IMMR strategy focused on the intrinsic damage which can be predicted based on the technical studies. In the integrated IMMR method, not only the intrinsic damage/defects are considered, but also the extrinsic damage/defects are addressed. In-service experience with ship structures has adequately demonstrated that extrinsic damage and defects are a major source of maintenance effort and many times are more important in terms of the structural safety and integrity. Existing IMMR techniques mainly deal with the individual ship as a representative of a class of similar ships. They are developed to deal with the common problems such as fatigue cracks of the side longitudinal in the class of the ships. However, the integrated IMMR method not only treats the individual ship as the representative of the class of ships, but also deals with the ship individually.

The integrated IMMR method starts with a survey to detect, identify, and assess intrinsic damage. Based on experience, the IMMR program for intrinsic damage can be conducted in a rational manner. The probability-based or risk-based inspection method provides a framework for intrinsic damages/defects. For the extrinsic damage for each individual ship, the problem is more complex (Itagaki, et al., 1983). A knowledge-based, inductive / deductive logical diagnostic method should be used.

Development of an integrated IMMR program should include following steps:

- Developing a standard task checklists to ensure that relevant data and tasks are not omitted because of distractions or routine workload.
- Global survey to develop general situational awareness (skill and rule based actions).
- Inspection of high likelihood of damage or defect 'parts' and high consequence parts.
- If something 'suspicious' is found, intensify the inspection based on semantic relationships and causal model (knowledge-based diagnosis) until root causes (not symptoms) are determined (knowledge based actions).
- Inspect periodically decreasing the time between inspections as the rate of degradation or likelihood of defects and damage increase. Inspect after accidents or 'early warning' signals are sensed.
- Be independent from the circumstances that cause potential defects and damage.
- Use qualified and experienced IMMR personnel that have sufficient resources and incentives to perform quality work.

The integrated IMMR plan should be an integral part of a life-cycle design, construction, operation-maintenance strategy for the ship structure for its expected service life. The master plan through the life-cycle should be defined during the design phase to achieve the acceptable quality at the minimum total (initial and future) cost. The detailed plan before a specific IMMR activity should encompass the different activities necessary for monitoring the ship structure and corrosion protection systems to ensure continued fitness for purpose.

For each ship structure, standard checklists and procedures should be established from the ship Life-Cycle Management Information System (LCMIS), in order to carry out an effective evaluation of the structural condition, prior to the commencement of any general survey and include:

- Structural drawings,
- Operating history and conditions,
- Previous cracking and corrosion inspection results,
- Condition and extent of protective coatings
- Classification status, including any outstanding conditions of class,
- Previous repairs and maintenance work,
- Previous information on possible damage/defects, and
- Relevant information from other similar types of ships.

With this information and previous inspection guidelines regarding critical elements in the structures considered to be sites of potential damage/defects based on historical data, analysis results, and the expert's judgment, it should be possible target the appropriate areas within the structure for general survey and determining the initial scope of inspection.

After the initial inspection to determine the general condition of the structure, the inspector can develop situation awareness identify unpredictable critical damage/defect sites. Further logic-based diagnosis should be conducted for these suspicious areas.

The inspection resources (time, personnel, equipment) should be allocated based on the life-cycle cost concept and value of the inspections. Inspection results may change the maintenance and repair plans to result in the saving of the life-cycle cost. IMMR plans should be updated based on the results of the general surveys and the results from maintenance and repairs.

5.5 Re-Engineering The IMMR System

Results from a confidential report that summarized interviews and meetings with some 80 experienced ship surveyors and inspectors has been reported (Bea, Schulte-Strathaus, Dry, 1996). The responses contained in this report summarize meetings and interviews with surveyors and inspectors at 14 locations around the world. The purpose of the interviews and meetings was to have ship surveyors and inspectors define 'off-the-record' and on a confidential basis what they thought could and should be done to improve the efficiency and effectiveness of ship structural (and mechanical) surveys. The report defines 130 major suggestions to improve efficiency and efficiency.

It is noteworthy that not one of these suggestions addresses details of surveying and inspection procedures and equipment. The vast majority of the suggestions address the needs for improvements in automation, use of computers and computing technology, communications between surveyors, auditing and quality control, billing and invoicing, scheduling, equipment acquisition, resolution of conflicts, standardization of assessment and evaluation procedures, standardization of repair procedures, reporting writing, data recording, data access, and elimination of unnecessary questions, re-processing of data and forms, and paper.

This information from experienced surveyors and inspectors indicates that the process of in-service inspections needs to be 're-engineered' if owners and operators of marine structures are to realize significant improvements in the development of optimal strategies for inspections. The results of the interviews and meetings with experienced surveyors and inspectors indicates that problem is not fundamentally one of improving the where, when, and how of ship inspections. Rather, the problem is finding out how to eliminate unnecessary and unproductive efforts and steps in the process and finding out how to take full advantage of modern computing, communications, and information technologies.

Experience indicates that 'tweaking' how, when, and where inspections are made likely will not result in the cost efficiencies that are desired and necessary to see advanced inspection strategies implemented. It is not likely that major breakthroughs can or will be made in the near future in inspection methods and equipment. Ship structure, probability / risk, and cost-benefit analyses should not be expected to produce significant breakthroughs. Improved organization and management of the overall ship inspection, maintenance, and repair 'system' can be expected to result in significant benefits. Given the present 'overloads' on people and organizations, anything that requires significantly more effort and cost likely can not or will not be done.

Experience with re-engineering inspection processes clearly indicates that organization of work should be developed around the process required to produce something. Most people are not process oriented; they are task oriented. Compared with process oriented organizations, task oriented organizations tend to be slow, error prone, fragmented, and relatively unresponsive to changes. Generally, the problem does not lie with the people performing the tasks or even with the tasks themselves, but in the structuring of the people and the tasks (Bea, Schulte-Strathaus, Dry, 1996).

The single weakest component that has been found in present inspection systems for ship and offshore structures regards the data and information that is developed during and from inspections. Typically, little thought has been given to the efficient gathering of data and information, even less thought to what is done with this data and information when it is obtained, and far less thought given to the archiving, analysis, and reporting of the data. The interfaces in the data gathering, archiving, analysis, and reporting activities also have received little systematic thought. Our work has not been able to identify a single coherent and integrated IMMR data system for ship structures (Schulte-Strathaus, Bea, 1995).

Advances in information technology have resulted in better ways to use information for the management of safe and efficient ship structures. The integration of stand-alone systems combined with improved information recording, organization and communication offers substantial benefits for the life-cycle management of ship structures. Technology is rapidly changing the way both information and work is managed within a business. Radical change is achieved today by many organizations through re-engineering existing processes. Key to this change is the utilization of technology to manage information and work, and the order in which work activities are organized to make efficient use of technology.

Process flows are descriptions of how information and work is organized. This technique details both inputs and outputs, and involves ordering work activities across time, place and company functions. Process Re-engineering involves taking an overall view of a system and completely re-organizing the process flow.

5.5.1 Re-Engineering

Re-engineering goes back to fundamentals of processes and how they are organized and conducted and offers a radical and dramatic change to process efficiency. Documentation of the existing process flows highlights where improvement is required and changes are implemented in the new re-engineered process. These changes are enabled through the use of technology, information and organizational re-structuring.

Business process re-engineering, has been used by a large number of companies to improve their performance radically. This improvement is measurable in terms of financial and quality goals, as well as customer satisfaction. Process innovation involves re-designing the way processes are planned, organized, lead, and controlled. It therefore involves organizing the activities in terms of processes that are used to fulfill user or 'customer' requirements.

Experience with re-engineering processes clearly indicates that organization of work should be developed around the process required to produce something. Most people and organizations are not process oriented; they are task oriented. Compared with process oriented organizations, task oriented organizations tend to be slow, error prone, fragmented, and relatively unresponsive to changes. Generally, the problem does not lie with the people performing the tasks or even with the tasks themselves, but in the structuring of the people and the tasks.

Experience with re-engineering systems indicates several key themes to achieve major improvements in efficiencies including: a) process orientation, b) aiming for breakthroughs, c) discarding old traditions, and d) creative use of Information Technology (IT).

5.5.2 Information Technology

IT include things such as: a) shared databases, b) expert or knowledge based evaluation and decision support tools, c) telecommunications networks, d) automatic identification and tracking technology, e) high performance computing and data storage, and f) interactive video systems.

Information Technology (IT) has revolutionized international business. A modern IMMR system must take full advantage of IT. A clear distinction must be made between information and IT. Information is manipulated or handled by information technology. Information is recorded, stored, analyzed and reported by IT. IT is a combination of hardware, software, and communication technologies, plus information used together to control and/or manage processes.

IT is used to integrate information within a process flow. One form of IT, automation which is the replacement of human-power by technology, has been used extensively by industry to increase efficiency. However, it has been introduced with a focus on improving the efficiency of explicit functional activities rather than improving the overall process flow. Automation of functional activities may only yield small benefits since technology is introduced without being integrated across the process flow.

In the past, the tendency of software development has been to support a functional view of business activities. This has resulted in programs written to support activities in a process that cannot share the same inputs and as a result data has been trapped within functional activities. With the implementation of a process view the information requirements must support the process flow.

It has been identified above that information technology and the use of information must be implemented across functional divisions to achieve innovation. Therefore, the introduction of information technology within a process must be supported by organizational changes.

Advances in communication technologies, such as the increasing use of networks, has now made integration of information technology feasible. A ship at sea can transfer vast amounts of information to and from shore quickly and easily. The use of land, cellular and satellite links has resulted in truly world wide communications making the effective electronic transfer and integration of information possible.

The aim in the management of IT is to develop systems which integrate information on a process level. Traditional views of software development has taken a functional approach to information requirements. Information processes are largely unstructured and moving to structured process is itself an innovation for many companies.

The use of IT in process innovation is maximized with the incorporation of organizational changes to boost process and business performance. The introduction of information management systems that do not take advantage of organizational changes to collect, analyze and utilize process information are, at best, only automation improvements of functional activities. The identification of business processes, the information used therein and the related organizational changes are therefore essential to develop a useful and effective information management tool.

5.6 Reliability Centered Maintenance

Deficiencies in probability based inspection methods were summarized by Jones (1995):

> "My studies in the theoretical world of reliability once gave me what I thought were powerful analytical tools for solving real-world problems with accuracy and precision. The elegant logic engines developed around the pure rigors of mathematics, probability and statistics were extremely attractive to an applied mathematician. Unfortunately, my little bubble of numerical security popped every time I set foot in a chemical plant, refinery, discrete manufacturer, paper mill, and, in fact, basically any type of real-life situation. The reliability papers I had relied on were built largely with a mathematical elegance that exists primarily the rarefied air of theory. Although they offered tremendous intellectual challenge and have advanced the sate of the art in reliability theory, the often missed the marked where "the rubber meets the road." I found that, in most cases, the models I'd embraced were running on empty. That is, they were built with little real data, using assumptions that could not be verified. Most maintenance and operations people were inclined to look at them, as I came to, as houses of straw."

Such recognition lead to development of Reliability Centered Maintenance (RCM) in complex structures such as airframes and nuclear power plants. RCM developed in the late 1960's by the commercial aviation industry is a method for developing and selecting maintenance alternatives based on safety, operational, and economic criteria. RCM employs a system perspective in its analyses of system functions, failures of the functions, and prevention of these failures (Jones, 1995).

Application of the RCM approach lead to development of a decision tree logic system that is employed in development of maintenance programs for airframes (Figure 5.3). The RCM methodology focuses on what should be done by only recommending IMMR tasks on those component failure modes which are critical to maintaining important system functions. It provides a documented basis for the elimination of preventative maintenance tasks on components which do not support critical system functions. This approach not only eliminates the costs associated with the maintenance, but also reduces the risks of human errors developing during maintenance (maintenance errors often result in subsequent premature failures following restoration to service).

The airlines have found that this approach leads to greater effectiveness in providing a standardized justification process for doing and not doing maintenance. RCM has reportedly lead to a reduction in the amount of time an aircraft spends in the shop, more operational time, and fewer aircraft that have to be mobilized to provide the scheduled service. There are five major steps in RCM:

(i) definition of the system and subsystem boundaries,
(ii) definition of the subsystem interfaces, functions, and functional failures,
(iii) definition of failure modes for each functional failure,
(iv) categorization of the maintenance tasks, and
(v) implementation of the maintenance tasks.

In the first step, the system is divided into mutually exclusive subsystems. Elements that cross the subsystem interfaces are identified. Each subsystem has 'in-interfaces' that represent inputs to the subsystem and 'out-interfaces' that represent outputs from the subsystem.

In the second step, the inputs and outputs of each subsystem are linked with quantitative functional characterizations. Functional failures are then characterized for the subsystem (how the subsystem can fail to perform its functions termed a functional Failure Analysis, FFA) (Yang, 1993).

In the third step, specific element failures that can cause each functional failure are identified. Generally, the dominant failure modes are developed from a failure modes and effects analysis (FMEA). The FMEA identifies conditions that must be prevented by maintenance actions.

In the fourth step, for each failure mode, a type of maintenance task is characterized: scheduled or unscheduled. Scheduled maintenance is generally assigned to all functions that can lead to safety related failures. If an effective scheduled maintenance task can not be defined, then the element / subsystem is either redesigned (to remove the failure mode or change the criticality) or the risk accepted. Unscheduled, condition based tasks are assigned to element / subsystem failures that affect operational capabilities or have a significant influence on costs. Qualitative or quantitative evaluations of likelihoods and consequences can be utilized to assist the evaluations.

In the fifth step, the tasks are grouped and coordinated with available resources (equipment, personnel, time, etc.). If the current resource allocation is not sufficient or too sufficient, then cost/benefits can be estimated and decisions made on developing acceptable balances of costs/benefits of RCM.

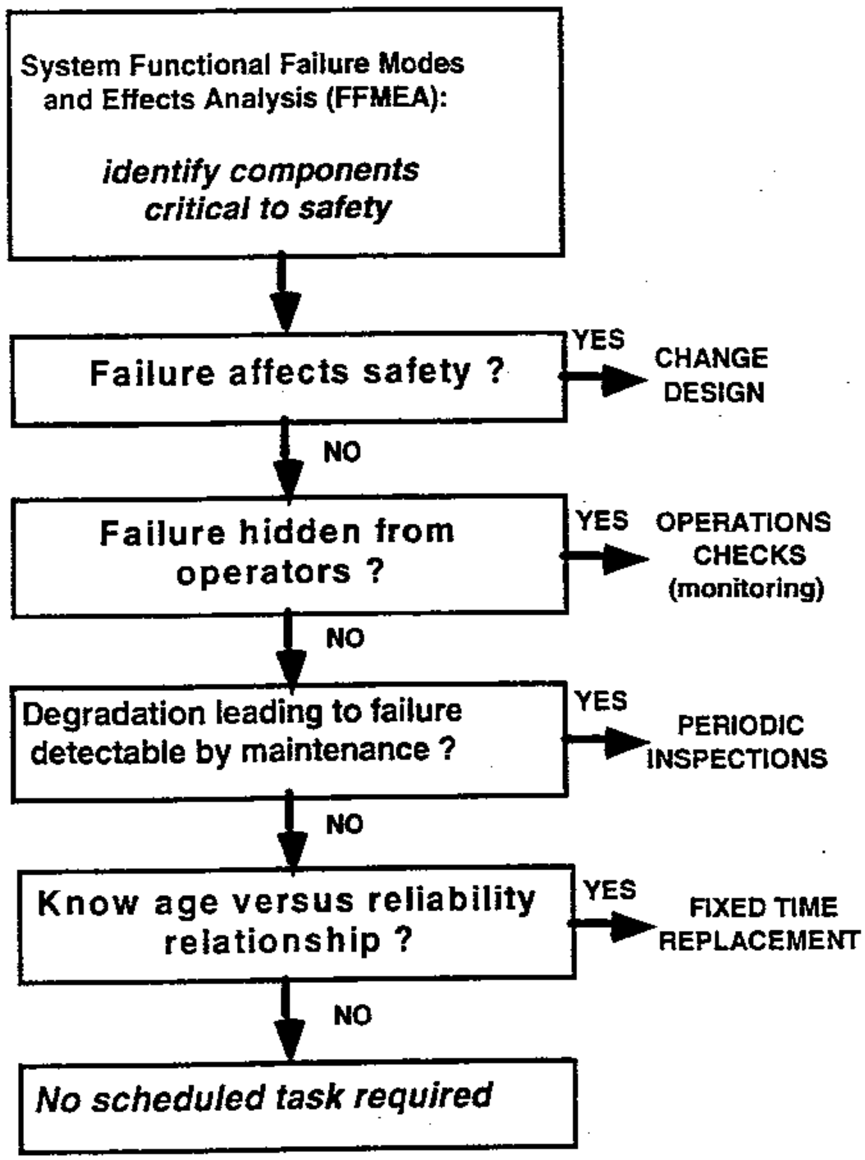

Figure 5.3: Reliability Centered Maintenance Strategy

Figure 5.4 summarizes the logical development of RCM IMMR alternatives. The alternatives consist of:

- Period **Verification,**
- Time Based Maintenance,
- Modification (re-design),
- Condition Based Maintenance, and
- Break-down Maintenance.

In development of RCM the potential for 'secondary maintenance' has been recognized (Bea, 1994a; Itagaki, et al, 1983; Jones, 1995). Secondary maintenance addresses damage and defects that develop due to the occurrence of human and organizational errors. Experience reported by Jones (1995) indicates that 20% to in excess of 50% of the total maintenance effort is due to secondary maintenance. Comparable results have been developed for ship and offshore structures (Bea, Xu, 1997). RCM methods address this category of maintenance. For example, the inspections of commercial aircraft include development of 'ergonomic interventions' such as socio-technical systems (management, team work), training (diagnosis, simulator training), information systems design (input, archiving, output), error controls, and improvements in inspection systems (lighting, access, etc.) (Dury, Lock, 1996).

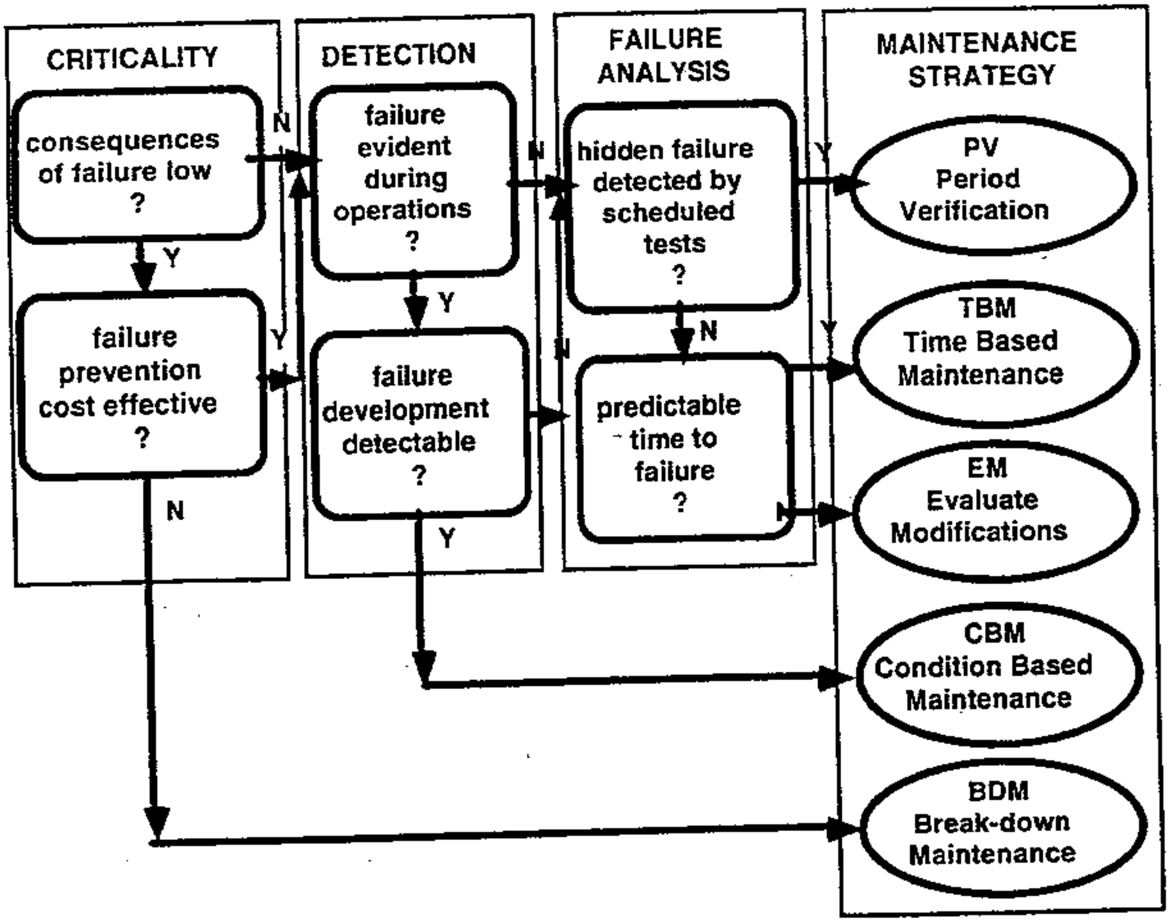

Figure 5.4: Development of Alternative IMMR Programs

6. CONCLUSIONS AND FUTURE DIRECTIONS

6.1 Conclusions

This report has reviewed four important aspects of inspections : current practices, critical structural areas, inspection interval (or frequency) and inspection extent. These aspects cover the four key elements of the structural inspections of ships: how, where, when and how much to inspect. By closely examining each of these aspects, methodologies for optimizing the process of inspections have been proposed.

A comprehensive review of **current practices** is presented in terms of the time phases that describe a complete survey : planning, preparation, execution, data reporting & analysis, and repairs. Each phase is reviewed in turn. Types of inspections are introduced which include mandatory inspections and owner's voluntary inspections. The procedures for tank cleaning, ventilation and lighting are described. Access methods, data recording and reporting are also reviewed.

The primary focus of this project has been on tankers and bulk carriers as ship types that could most benefit from optimized inspections. Hence, a detailed investigation was undertaken into the nature of the structural defects these types of ship typically suffer. The areas of tankers and bulk carriers that are particularly prone to fatigue and corrosion damage are identified and the discussion is supported by extensive references to the published experiences of owners, operators, class societies and other agencies. The information presented in this section provides valuable information in support of the next section which addresses the topic of optimization of structural inspections.

The problematic nature of optimizing inspections is discussed. The key difficulty is that any optimization involving a large number of variables, particularly when many of them are interrelated, is highly complex and of doubtful value. Strictly speaking the optimization of inspections should not be undertaken independently of other aspects of maintenance such as the repair process. And this perhaps should also apply to various other operational parameters which are also related, however indirectly, to the inspection process. In the face of these difficulties the strategy in this project has been to identify the essential elements of the inspection process, and to optimize each element independently. The essential elements are identified as:

- Where to Inspect - Critical Areas
- What (How Much) to Inspect - Extent
- When to Inspect - Interval

The large size of modern tankers and bulk carriers make it impracticable to survey the total ships. This raises the question of which structure should be selected for inspection.

In this regard, an approach called priority assessment has been developed to rank quantitatively the priorities of structural details. Priority assessment is based on the concept that structural details with high failure rates and serious failure consequences should receive a high priority for inspection. The priorities of structural areas can be evaluated and then used as guidance to direct surveyors or owners/operators to areas of high risks. Tankers and bulk carriers are two types of ships that have experienced many severe structural problems in the recent past. Their **critical structural areas** are documented in many sources. These were compiled, analyzed, and summarized. This will be useful to surveyors as a guide on where to concentrate on in inspections.

Ideally, an inspection should cover the whole ship structure. However, **inspection extents** are always limited because of the sheer sizes of ship structures. The results from the limited inspection extent are used to infer the state of the structure as a whole. The validity of this inference is questionable and needs to be proved. Hence, a data analysis was undertaken to examine the feasibility of the approach and to expose any potential problems. In this regard, the degree to which the results of limited inspection data can be used to infer the state of the structure in the rest of ship is examined. Two sample tankers were selected and their inspection reports were used for the data analyses. The approach and results are presented. It was concluded that cargo oil tanks have very similar cracking trends for the two sample tankers. A larger database is needed to draw more generalized conclusions that are statistically meaningful.

Inspection interval (or frequency) may be the most influential factor in optimizing the life cycle inspection cost. A fundamental question is when (or how often) should inspections be carried out during the long period of about 20 to 30 years of a commercial ship's life. A rational approach to define an optimal inspection interval may be through the application of a fracture mechanics methodology or using damage tolerance assessment principles. The concept has been used by certain other industries for many years, but rarely in ships. Its procedures and applications, adapted for ship structures, are introduced.

In conclusion, the current practice of conducting ship inspections is still heavily based on experience alone. On the system level, the current requirements on inspection frequency and extent are also based experience gained from past failure experiences. The lack of the application of systematic and rational approaches for both planning and conducting inspections may have resulted in an inefficient allocation of resources to the inspection of ships. The approaches presented in this report should provide the basis for a new and advanced inspection system that can produce a high quality inspection at minimum cost.

6.2 Future Directions

6.2.1 Implementing Priority Assessment

The priority assessments concept presented in this report is mainly for demonstration purpose and has not been applied in practice. The rating system of susceptibility for each Critical Structural Detail (CSD) may need to be calibrated based on statistics of a large database. Also, the rating system of criticality may need to be refined. Further efforts will be required to implement a complete priority assessment for CSDs of tanker, bulk carriers and other types of ships.

6.2.2 Failure Report System

While some ships have been lost without trace, there are also a substantial number of vessels which have survived serious structural damage. In many instances, no detailed failure/damage reports have been made public. Classification societies and flag administrators have the responsibility for informing the public about the causes, the lessons learned, and developing guidelines from study of earlier incidents. News letters such as Surveyor by ABS and Casualty Information published by Det Norske Veritas (DNV) are good examples of providing the marine industry with the lessons learned from incidents of ship damage and more serious accidents. The news letter contains descriptions on ship type, course of events, extent of damage, probable cause and lessons to be learned. Through the news letter, many similar occurrences of structural failures and casualties may be prevented.

6.2.3 Surveyor-Friendly Designs

Poor accessibility has been well known as one of the main obstacles to attaining high quality in inspections. In the past, most new built ships were designed without carefully considering accessibility for inspection or maintenance. Some of them were fitted with vertical ladders or other access facilities during construction as an afterthought. These ships, of course, were built with very poor accessibility. There are cases where inspectors or repairers have lost their lives or were seriously injured. Until recently, people realized the accessibility should be considered in details during the design process. Accessibility is now given more serious attention as a design parameter. Improved access will assist in the overall effectiveness of in-service inspection activities.

IACS has recommended the provision of means to enable the surveyor to examine the tank structure in a "safe and practical" way, but there are no specific classification rule requirements at present. Therefore, it has become a responsibility for owners to work with shipbuilders at the time of construction or design to develop proper access arrangements for the future inspection and maintenance of tanker structures.

Improved accessibility should be provided where the probability of structural failure is high. The methods of improving accessibility considered here are listed as follows:

- Install both forward and aft inclined ladders, (i.e. at each end of the tank);
- Fit vertical ladders or climbing bars to the less critical areas;
- Fit permanent walkways;
- Attach permanent clips or lugs on the internal structural members for use of temporary staging or attaching ropes;
- Install extended longitudinal every fourth or fifth longitudinal:
- Provide continuous stringer levels within the side ballast tanks in double hull tankers; and
- Design sufficiently large access openings.

Surveyor-friendly designs may not only make inspection easier for the surveyor, but they may also make maintenance, over time, less costly for the owners. Permanent access facilities such as inclined or vertical ladders and horizontal stringers only increase the initial cost slightly. These are best built during construction of the ship. For ships without appropriate access facilities, staging must be set up for repairs and inspection each time at an extremely high cost. Over the life of the ship, it is probably more economical to have a permanently installed structure component to gain access rather than stage for inspection and repairs.

6.3 Acknowledgments

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