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Structural Maintenance for New and Existing Ships: Overview, Fatigue Cracking and Repairs

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ABSTRACT

This paper summarizes the objectives, approach, and organization of a joint industry - government sponsored cooperative research project focused on development of engineering technology that can lead to improvements in structural maintenance for new and existing tankers. The project is being conducted by the Department of Naval Architecture and Offshore Engineering in behalf of nineteen participating organizations representing government regulatory bodies, classification societies, new-build and repair yards, and ship owners and operators. Initial results from several of the studies that comprise this project are summarized.

INTRODUCTION

A two-year international Joint Industry Project on "Structural Maintenance for New and Existing Ships" (SMP) was initiated by the Department of Naval Architecture & Offshore Engineering at the University of California at Berkeley (UCB) in June 1990. The project has two technical goals:

> **To develop practical tools and procedures for analysis of proposed ship structural repairs in order to minimize time and materials within the constraints of regulatory and class requirements and prudent engineering practices, and**
>
> **To prepare guidelines for the cost-effective design and construction of lower-maintenance ship structures which also facilitate future inspections and repairs.**

The Joint Industry Project was formed in response to two recent trends in the shipping industry. The first trend is the well-documented ageing of the existing fleet of merchant ships, particularly of tankers. Such ageing is leading to significantly increased scopes of structural repairs and their associated costs and days out of service.

The second trend is the recent boom in ship construction. Many new ships are being designed by shipbuilding yards and are being reviewed by owners, classification societies and government agencies. The heightened interest in double bottom and double hull configurations for ships has generated new concerns related to their structural reliability and future maintenance costs.

In order to better meet the challenges posed by these recent trends, the research in this project has been focused on two primary aspects of structural maintenance:

> **Fatigue effects on the performance of critical internal structural components of existing and new ship hulls (including high strength steel, reduced scantling designs), and**
>
> **Corrosion effects on the critical internal structures of existing and new ship hulls.**

The goal of the SMP is to develop engineering procedures and PC-based computer programs that can assist ship owners, operators, classification agencies, and government agencies in accomplishing effective and efficient structural maintenance and life extension for ageing ships. Each procedure and program will be verified by applying these to real-world problems.

This project is directed toward improving engineering technology to make realistic fitness for purpose evaluations of ship hull structures , and to help answer the two key questions:

> **1) How should I fix critical internal structural components ?**
>
> **2) How can I design better critical internal structural components ?**

In addition to its technical objectives, this project has important organization objectives. The project is intended to provide a common, neutral ground for the constructive interaction between ship owners and operators, ship classification societies, governmental agencies and ship building and repair yards. The development of informed consensus approaches to the problems associated with structural maintenance of existing ships and design of new ship hull structures is expected to provide significant benefits to the ship industry.

This project is one of four inter-related cooperative research projects being conducted by the Department of Naval Architecture & Offshore Engineering. The titles, sponsors, and objectives of the other three projects are as follows:

> <u>Management of Human and Organization Error in Operations of Marine Systems</u> - Sponsored by the Sea Grant Program and seven industrial - government agency sponsors, the objective of this project is to develop and verify engineering analysis procedures to assess alternatives to reduce the effects of human and organization errors in operations of tankers.

Marine Structural Integrity Programs (MSIP) - Sponsored by the Ship Structures Committee, the objective of this project is to develop a procedure for definition of advanced marine structural integrity programs based on current developments in Airframe Structural Integrity Programs (ASIP).

Inspection and Maintenance Impact on Safety and Reliability of Tanker Structure - Sponsored by the Maritime Administration and conducted under the auspices of the UCB National Maritime Enhancement Institute, the objective of this project is to assess the impact of inspection and repair programs on the reliability of tanker structures.

The objectives of these four projects are focused on development of a comprehensive engineering technology for the improved maintenance, design, and operation of shipping fleets, with a specific focus on very and ultra large crude carriers (VLCCs and ULCCs), including both structural and non-structural (e.g. human and organization factors) aspects.

PROJECT ORGANIZATION

There are four major organizational components in the SMP. The first component is the project sponsors and participants. At the present time, there are nineteen national and international organizations including ship owners and operators, ship construction and repair yards, classification societies and government agencies that comprise the first component. Table 1 lists the names of the participating organizations.

The second organization component is the Project Technical Committee (PTC). Each of the project sponsors and participants are represented on the PTC. The PTC is chaired by the American Bureau of Shipping (ABS). The purpose of the PTC is to provide the project investigators with directions on technical goals and objectives, with information and data to assist the project, and to monitor the project budget and schedule.

The third organization component is the Office of Research Services and Sponsored Projects Office at the University of California at Berkeley. This component is responsible for the contracting, invoicing, and project accounting.

The fourth organization component is the project investigators. Table 2 summarizes the names and responsibilities of the project investigators.

BACKGROUND

Since the turn of the century, ship hull design has seen significant progress. Examples of this progress include materials technology, seaway loading technology, and computerized loadings and structural analysis. The economic benefits of this progress to ship owners and operators have been far-reaching.

The advancement of shipbuilding technology also been significant. Automated plate cutting and welding, CAD/CAM, zone outfitting, and modular construction are some of the tools available to shipbuilders that were not available in the past, and that have resulted in the shipbuilding revolution.

In stark contrast to the two success stories of design and construction is the field of ship repair and maintenance. Today's vessels are repaired pretty much the same way as their predecessors were at the turn of the century. Steel weights and coating areas are mostly calculated by hand. Most ship maintenance records are kept on paper. Much inspection, maintenance, and repair is still done by "rule of thumb."

From this history, one might conclude that ship maintenance and repair is a relatively less expensive and less important undertaking than ship design or construction. Anyone in the marine business knows that just the opposite is true. A ship is built and constructed in a very short period of time, but it still needs to be maintained for 20 years or more. As the ship gets older, the maintenance requirements and costs increase significantly. In the later years of a ship's life, many difficult questions are raised with regard to the desirability and feasibility of extending its life.

Given the present state of ship design and construction technology and the present state of the world's ageing fleet of ships, it is time to further develop and upgrade the technology of structural maintenance of new and existing ships. The following factors influence these developments.

A large proportion of the world's tanker fleet is approaching the age of 15 years. Steel renewal requirements are increasing with a consequent increase in time out of service. The process of inspecting a vessel, writing the repair specification, making repair drawings, calculating the steel weights and coating areas, etc., is very labor intensive. The workload is increasing with each passing year as the fleet grows older.

Life extension of existing ships beyond 20 years is becoming more attractive as the cost of new buildings skyrockets. Yet, it is difficult to conduct a proper economic analysis of the two alternatives because estimating the future repair requirements and costs for existing ships is a time-consuming task.

There is increased public scrutiny of ship operations, particularly tanker operations. There is no such thing as an insignificant oil leak in today's world.

Tanker structure information data bases are difficult to assemble, analyze, and retrieve to detect and monitor dangerous trends in pitting, cracking, corrosion, and coating failures.

Given a decision to build new ships, there are significant concerns that the standards and procedures used to design and construct these ships will result in a vessel that can be efficiently and effectively maintained. Even in some recently constructed ULCCs, there are unsettling indications that in the quest for lower structural weights and initial costs that reasonable levels of durability have been sacrificed.

The more general use of higher tensile steels, use of lighter scantlings of higher tensile steel, and the requirements for hull structures that will have greater degrees of safety against cargo losses given groundings and collisions indicate a greater need to pay more attention to detail design, design to facilitate inspections and maintenance, providing sufficient structural reserve, and providing robust hull structures that can tolerate defects and damage without significant losses in capacity and safety.

The SMP seeks to bring ship structural repair technology to a level commensurate with today's engineering needs and capabilities. It is intended to help equip organizations with powerful, yet practical, analytical tools for ship repair and maintenance. Based on the experience with the past generation of ships, the project also is intended to help develop guidelines for new builds that can result in hull structural systems that will have higher degrees of inspectability, maintainability, and durability.

Most importantly, the project is intended to provide a common ground for the interaction between ship owners, ship classification societies, governmental agencies, and ship building and repair yards (ship industry). The experience of these groups will provide the basic starting points for this project. The development of informed consensus approaches to the problems associated with repairs to existing ships and design of new ship hull structures to facilitate inspections and maintenance is a key objective of this project.

A principal objective of this project is to better equip the ship industry to extend the useful lives of existing ships and to define the characteristics for design of new builds that will profit from the lessons of the past. To realize this objective, the industry needs to pull together toward a common set of goals. Ship owners and operators must take the initiative to manage and not be managed. Public initiated "legislated naval architecture" must be avoided. Development of guidelines for improved design and repair are key aspects of this management, and will be a key aspect of this project.

Naval architects and ship maintenance-repair engineers need to have better guidelines and tools to accomplish their work. Development of improved guidelines for both existing ships and new builds to help better minimize corrosion and fatigue cracking problems, and development of computer programs to assist these engineers are a key aspect of this project.

Ship builders and repair yards have responsibility for quality construction and repair. They must have the technical tools and other resources required to deliver the necessary quality. This project is intended to provide some of the technical tools that can assist in improvements in repairs and design of critical structural components in new builds.

Ship surveyors, classification agencies, and governmental agencies have responsibility for quality inspection, verification, and encouragement of the ship industry to do what is right for the industry and the societies that it serves. This means helping maintain the economic viability of a critical industry, and defining those guidelines and requirements that will result in acceptable performance by the industry. This project is intended to contribute to the development of such guidelines and requirements.

Experience with the maintenance and life extension of existing ships has indicated that there are two key problems that must be addressed if maintenance costs are to be managed within acceptable limits, and if the structural reliability of the hulls are to be maintained:

1) Corrosion of critical internal structural components, and

2) Fatigue cracking of critical internal structural components.

In many cases, fatigue and corrosion have been inter-related. In some cases (in particular in many high tensile steel, lighter scantling, HTS/LS , ships), design and construction methods have exacerbated fatigue and corrosion problems.

Fatigue cracking and corrosion are a major concern because of their potential effects on hull and tank leak integrity, and their potential effects on the structural capacity of the hull. Repairs are costly , and sometimes, are ineffective. Evaluating how to best repair cracks, and how and when to repair corrosion in the most cost effective manner is not an easy task. More definitive guidelines and analytical tools that can help the surveyor, inspector, and repair engineer make such decisions are badly needed. Development of such tools is a primary objective of this project.

While fatigue and corrosion maintenance have some very important ramifications with regard to life extension of an ageing fleet, they also have some potentially critical implications with regard to construction of new ships. If properly and well understood, experience with older ships can provide some important insights into improved engineering and construction methods for newbuilds. Development of guidelines for the improved design of critical structural details and components of hulls is a primary objective of this project.

A substantial base of technology pertaining to the objectives of this project has been developed by organizations such as the International Ship Structures Congress [1,2], the Tanker Structure Co-operative Forum [3], the Ship Structures Committee [4-10], the American Bureau of Shipping [11-15], and others [16-39].

In addition, many ship owners and operators have developed advanced methods for maintaining their fleets [24,25, 39]. A starting point for each of the efforts in this project is this base of technology; fully utilizing available engineering and operating experience. For example, the American Bureau of Shipping and other organizations have developed some very sophisticated analytical tools to perform fatigue and strength analyses. Several ship owners and operators have developed and implemented advanced inspection and maintenance data archiving software.

A major problem in ageing vessel maintenance is locating structural failures and severe corrosion. Timing of inspections, access to critical areas, and coverage of critical areas with rust and cargo residues provide other obstacles to disclosing cracks and corrosion. This project is intended to address, but not necessarily solve such "realities." One of the benefits of the development of condition survey data bases on ship hulls that have common characteristics is to improve insights on when and where such problems might exist, and how they might be most effectively found. Analysis of the hull structure can indicate which structural components need to be watched most closely.

Experience with life extension of marine structures indicates that the most severe problem is usually the lack of definitive information on the current condition of the structure. This is a problem of how, when, and where to inspect. This is a problem of starting and maintaining a complete and accessible data bank on the structure. This experience also indicates that if the structure cannot be effectively inspected, then it is highly likely that it cannot be effectively maintained. It is not possible to realistically evaluate the needs for repairs and evaluate the safety and integrity of the hull structural system without definitive information on the condition of the critical components that comprise the system. The greater the knowledge about the critical components, then the more realistic is the evaluation, and the more effective the repairs and maintenance.

TECHNICAL APPROACH

Six inter-related studies define this research project (Table 3). The fatigue and corrosion damage evaluations constitute the basic studies in the project. These evaluations, however, cannot be completed without defining the boundary loading and fixity conditions of the local details where damage has occurred. Such boundary loads and conditions will be developed in Study 3.

Based on results from Studies 1 - 3, repair strategies and guidelines will be developed in Studies 4 and 5. Finally, software packages for personal computers with documentation will be developed in Study 6. The following sections will describe in more detail the content of each of these studies

Study 1 - Fatigue Damage Evaluations

The objective of this study is to develop and verify engineering approaches to assess fatigue effects on the performance characteristics of critical structural details in tanker hulls, including the effects of inspection, maintenance and repair. This study is addressing both mild steel and HTS/LS steel hull structural elements and systems. This study is organized into six tasks (Table 3).

Study 2 - Corrosion Damage Evaluations

The objective of this study is to develop and verify engineering approaches to evaluate internal corrosion effects (general and pitting) on the structural strength and leak integrity characteristics of critical (to strength and leak integrity) components comprising existing ship hulls and new builds.

Greatly accelerated corrosion rates have been observed in localized areas of low structural rigidity in ship hulls. This appears to be due to the corrosion products (rust scale) being flaked off by the flexing of the component. This effect is believed to be particularly important in HTS/LS ships. This study is investigating the relationship between local flexure of hull structures and corrosion rates with the goal of recommending limits to local flexibility for both mild and HTS/LS. The study is organized into nine tasks (Table 3).

Study 3 - Interaction of Details with Adjacent Structure

This study plays a key role in that it provides input and support to the fatigue and corrosion damage effects elements of the project . The over all objective is to develop a reliable but simplified and practical analytical tool that will enable the engineer to make the necessary structural system performance evaluations rapidly and with accuracies sufficient to make good engineering decisions on repairs and maintenance strategies.

The analysis of the interaction between critical internal structural details, e.g., brackets, and adjacent structural components, e.g., webs and stiffened plate panels, must provide (a) an accurate and efficient model of the load-displacement behavior of the detail in conjunction with the adjacent structural components, and (b) the stress distributions at the element level for the fatigue, corrosion and repair evaluations. The study is organized into two principal tasks (Table 3).

The successful completion of Task 1 and Task 2 will provide the foundation for the the development of: (a) a library of typical generic structural detail modules consisting of the detail and the adjacent structure of sufficient extent to model the detail's boundary conditions, (b) a corresponding library of module loadings, and (c) the PC software necessary to implement the analysis. These steps will be carried out during following stages of the project.

The objective of this work is the development of simple and reliable procedures. To this end, much effort is being devoted to proving and calibrating the simplified models.

Study 4 - Fatigue and Corrosion Repair Assessments

The objective of this study is to develop and verify with ship service data engineering guidelines for the evaluation of fatigue and corrosion repairs to critical structural components of existing ships, and to develop general guidelines for new builds to help maximize inspectability and minimize repairs.

The fatigue and corrosion studies will provide analytical abilities to project future crack propagation and corrosion rates and effects. The corrosion study also will provide background on limits that should be placed on the flexibility of components to reduce corrosion rates.

The work of the Tanker Structural Co-operative Forum (TSCF) provides a valuable starting point for this effort [3]. As well, the special reports developed by Committee V.3 (Service Experience - Ships), of the International Ship & Offshore Structures Structures Congress [1, 2, 36] provide important direction for this effort. In particular, the TSCF has documented frequently occurring fatigue damage, and strategies to repair that damage. An objective of this study will be to continue and extend the TSCF developments. The study of fatigue and corrosion repair assessments for existing ships is organized into five task (Table 3).

Study 5 - Durability Guidelines for New Ships

The Ship Structures Committee has initiated a research project being conducted at UCB on the topic of development of Marine Structural Integrity Programs (MSIP) for ships. The project is addressing new build ship life-cycle phases, structural and non-structural (operational) aspects, inspections and quality control, and inter-relationships of design of new VLCCs and ULCCs and MSIP.

In addition to a practical approach that can be used to develop life-cycle MSIP for new builds, the project is intended to define a general purpose computer based information and evaluation system to assist in the life-cycle management of the structural integrity of ships.

As a basis for the development of MSIP, the study is reviewing the U.S. Air Force's Airframe Structural Integrity Program and the comparable program of the Federal Aviation Administration. Results from the Ship Structures Committee sponsored research project will be incorporated into this project as appropriate to the objectives of this project.

This study is organized into four tasks that are focused on improving the durability characteristics of critical structural elements (Table 3).

Study 6 - Development of Software and Applications Examples

This study, unlike the other technical studies, is focused at providing the background, standards and support so that the computer codes developed by many programmers will be of uniformly high quality, will permit easy modification and be user friendly. As such, this study will provide a uniform foundation and standard interfaces which will serve as a reference for all of the studies.

There are important reasons for developing these standards early and adhering to them strictly. In the past 15 years we have experienced at least 5 different generations of computer technology and there appears to be no end in sight of this rapid development. This means it is certain that the coding developed on the current generation of machines will be used on future generations of faster and more powerful machines. It is imperative, therefore that the code have portability and not be dependent on quirks or specialized features of any particular hardware configuration.

Further, it is anticipated that the computer programs produced as part of this study will be "living" documents. That is the first version delivered will be a baseline to modified, expanded and improved with time. This means that in all likelihood several different programmers will contribute to the code. Setting of standards prevents a code from becoming programmer dependent and therefore lost when he leaves (or graduates). It should also be recognized that programming to a standard requires considerably more effort than programming in one's own style and that the initial programming costs are therefore higher.

As a result, several global aspects of these standards have been defined. The programs will be written in the FORTRAN language, using the constructs embodied in the 1977 revisions (also known as FORTRAN/77). None of the many machine dependent additions to this language will be included. The use of this "plain vanilla" FORTRAN is essential to solving the portability issue and, for instance, will allow usage of the codes on both current IBM PC and Apple Macintosh equipment . This study is organized into two tasks (Table 3).

TECHNICAL RESULTS TO DATE

The following sections of this paper summarize some of the important results developed during the first six months of the project .

As an initial step in all of the studies that comprise this project, a significant number of field trips have been made to participate in unscheduled surveys and repair operations, scheduled surveys, and scheduled drydock repair operations involving VLCCs and ULCCs. Understanding the realities of what goes on inside the ballast and cargo tanks of a VLCC or ULCC has been a sobering experience for the project research investigators and research assistants alike.

Examples of important observations include:

• Corrosion can interact with welded stiffeners, coatings, and tank wall flexibility to cause fatigue cracking.

• Drainage holes intended to prevent ballast water accumulations in tanks can become clogged with corrosion products, debris, and sediment. Concentrated areas of corrosion develop in these areas. Anodes in the bottom of ballast tanks frequently are covered with sediment, reducing their effectiveness. This sediment severely hampers inspections of the critical structural elements in the bottoms of ballast tanks.

• Inspections of cargo and ballast tanks to determine the locations and causes of fractures and corrosion are extremely challenging, particularly when rafting the cargo tanks wearing breathing apparatus must be used. The quality of inspections is very dependent on the experience and diligence levels of the surveyor and on the time and facilities devoted to the survey.

•It is impossible to perform inspections that will reliably disclose the presence of all significant cracks. Survey reports are frequently lacking information on cracks in highly corroded areas, which are replaced in a major overhaul. The probability of detection (**POD**) curves used in present fatigue analyses [e.g. 13, 34] are not realistic for present inspections of critical structural details in VLCC and ULCC tanks.

• Many severe corrosion and fatigue cracking problems can be directly traced to bad initial design, construction, and maintenance practices. Our surveys indicate that problems with high strength steel elements seem not to be a problem with the material, but rather with its proper use (design), construction (welding, fitting, cutting), and maintenance (corrosion prevention).

• Repairs to critical internal structural details is a difficult and demanding task for ship owners, operators, repair yards, surveyors, and inspectors alike. There is no reasonable consensus on what, how, and when to repair. The general lack of readily retrievable and analyzable information on repairs and maintenance frustrates repair and maintenance tracking. Many fracture repairs appear to be ineffectual. Veeing and welding cracks that have occurred early in the life of the ship seems to be ineffective; they quickly develop again. Attempts to make temporary repairs (e.g. cold patching) serve too long can result in costly down time due to unexpected cargo losses.

Database development has been a key aspect of the initial phase of three of the studies (Fatigue, Corrosion, Repairs). In this development, a general purpose computer program, FoxPro, has been used. The databases developed with this software have been designed to be fully compatible with the more comprehensive tabular and graphics capabilities of the CATSIR 3.0 (Computer Aided Tanker Structure Inspection and Repair) system being developed by several of the participants in this project [40, 41].

Study 1 - Fatigue Damage Evaluations

Development of Database Formats. The fields included in the fatigue database are summarized in

Table 4. The development of this database format identified several important problems and constraints:

- At the present time it is not feasible to use a general coordinate system for all the different classes of tankers involved. Since such a coordinate system would resolve most of the encountered problems especially in combination with the use of CAD/CAM systems, this topic will be addressed in future research.

- Within the scope of this database, the reoccurrence of a crack cannot be determined. Ineffective repairs cannot be documented. This is a major drawback for the repairs database.

- The type of crack and the location within a detail have to be described by a set of key words. These key words were developed with the help of ABS and are also used in the corrosion database.

The location, type, and characteristics of a crack are determined as follows:

- **Longitudinal position**: Frame number.

- **Vertical position**: Definition of three zones (lower third, middle third, upper third) of Side shell, Longitudinal Bulkhead, and Transverse Framing.

- **Horizontal position**: Port or Starboard and zones.

- **Detailed position**: Key words for description of cracks.

Data Input. Ten ships with a total number of 3,629 cracks have been included into the database. A summary of these ships and the number of cracks found is given in Table 5.

For 6 ships, survey reports submitted by the participants have been analyzed in order to achieve the necessary information for the database input. These survey reports varied greatly in the amount and detail of information included. For some of the database fields the survey reports did not contain sufficient information. A database submitted by one participant included 4 ships of the same class with a total number of 1989 cracks.

Due to the relatively small amount of data included in the present database, only basic statistical analyses were performed to show analysis approaches and data trends. This analysis has been performed first for all ships included in the database and then for the 4 ships of the same class, which are mentioned above.

Results. One important result of the database development has been to give operators as well as survey companies a better understanding as to what should be included in future survey reports. In order to find trends and the most probable locations of cracks the percentage of occurrence of cracks in different types of structural components has been evaluated:

- **Cracks in the Side shell Longitudinals accounted for about 42% of all cracks. About 10 % of all cracks were found in each the Bottom Longitudinals and in the Horizontal Girders.**

Figure 1 shows the number of cracks as a function of the time until detection (date of survey - date of delivery of vessel) for all ships. This graph shows that a relatively high number of cracks occurs early in the life of the vessels. These cracks can be related to bad initial design. Later in the lifetime of the vessels the effects of fatigue begin to show.

The number of cracks per tank is presented in Figure 2 for the 4 ships of the same class to show the longitudinal distribution of the cracks. Most cracks occur aft midships in tank no. 4.

The distribution of cracks over the height of the ships can be seen in Figure 3 for all ships and in Figure 4 for the 4 ships of the same class. Here the number of cracks is shown for the different zones, which are established in the database. For side shell cracks most cracks are found in the middle third of the height.

In general the chosen format of the database has proven to be sufficient to enable detailed analysis of the input data.

Fatigue Analysis Approaches. A review of the existing approaches to fatigue and fracture mechanics has been started. In this review, a primary emphasis has been given to analyses associated with defective or damaged welded details. A summary of both the conventional stress range - numbers of cycles to failure (**S-N**) curve approach and the fracture mechanics (**F-M**) approach has been prepared.

The work has addressed development of a hybrid S-N / F-M analysis that would permit practical analyses of defective or damaged welded details. For the calculation of the residual life of cracked details a fracture mechanics approach will be used to establish a set of S-N curves for different crack lengths. This set of curves will be compatible with the design S-N curves for uncracked details. The main effort of the next months will be to determine the details of this approach. Professor Stig Berge, a visiting professor working on this project (Table 2), has provided significant guidance to development of this approach.

As a part of the fatigue study, the use of predicted fatigue crack growth behavior in the updating of fatigue design life has been investigated [42]. Based on experience and experimental fatigue crack growth tests, the relationships between developed crack size and remaining fatigue life has been characterized. These analyses have established a definitive link between a conventional S-N fatigue analysis model and a fracture mechanics analysis model. This has particularly important ramifications in development of acceptability criteria for cracked internal structural details, avoiding the zero tolerance syndrome.

The analyses have demonstrated the critical importance of defining realistic probability of detection (**POD**) curves based on practical ship inspection methods. The work has been extended to include a cost - benefit model to evaluate alternative strategies for inspections, maintenance, and repair (**IMR**) [43].

Study 2 - Corrosion Damage Evaluations

The data for this study was provided by the project participants in the form of the gauging report portion of surveys conducted on the vessels during their service lives. Surveys are typically conducted every three to five years, as dictated by classification societies, or the operators own internal maintenance philosophy (which ever is sooner). The reports can range in detail from simple belt girth gaging, to full surveys of major details in all tanks. The number of gagings might range from a few hundred to several thousand. These are then compiled in binders, typically ordered by tank or detail type.

Factors Examined. The corrosion rate is determined by the environment that the element is exposed to. What is important is more than just the relative amount of salt present in the water. The composition of the corrosive, while certainly important, is not necessarily the most important factor in determining the corrosion rate. For ballast tanks one might say that over a large sample of vessels in the same trade the composition of the ballast is the same. Yet we can expect to see vastly different corrosion rates in ships which have heated cargo and those without. There are in fact innumerable differences in the conditions in which corrosion takes place, some crucial, some less so.

When confronted with this problem, the only recourse was to turn to the literature for an outline of what was considered important in the determination of corrosion rate. From the literature and consultation with industry, a list of the important factors was compiled.

The next step was to consult with industry representatives to determine, of the factors considered important, those one might expect to find reasonable amounts of data. This was accomplished by means of a questionnaire which was sent to each of the participants. This questionnaire asked only what types of data the participants had and could release to the project. For example, it is of interest to know the humidity of the ballast tanks when the tanks are not in ballast. An estimate can be made, but accurate, high quality data is generally not available.

Table 6 summarizes the list of the important factors for which reasonable amounts of quality data exists. These factors became the basis for development of the corrosion data base.

We next developed a second questionnaire. We asked the participants to provide the investigators with exactly the information they indicated they could provide, for each of their ships they wished to see in the database. From this, a list of the ships for which sufficient amounts of data were available was compiled, and the effort made to obtain the gauging reports. The resulting database includes those ships for which we were able to get these reports.

Data Base Development. The amount of corrosion data on even a single ship makes the development of a data base a large bookkeeping problem; the sort of problem that is best suited to a database management system. If the data is organized in a rational fashion, analysis can be performed by simple search and average routines. Once the relevant data is input then, work can begin on an analysis. This is where the difficulty in this sort of work lies. It is vital in the beginning the database is constructed in such a way that all the important data is in fact included, and included in such a manner that it lends itself to analysis.

The corrosion related factors were separated into three main types: Ship specific data, Tank specific data, and Incident specific data.

Ship specific data - data which are assumed to apply to all gagings in all tanks for all surveys of a single ship. They include: ship size, date of build, cargo type (crude or product), double side, double bottom, class society, trade route (it is true that this may change over the life of the ship), and the units the surveys are taken in.

Tank specific data - including tank type, time in ballast (for ballast tanks), time in cargo (for cargo tanks), corrosion protection system, fresh or salt water ballast, clean or dirty ballast, sulphur, water, and wax content of cargo, presence of heated cargo, IGS gas quality (% sulphur), and method of tank washing.

Incident data - an incident of corrosion is defined as a location where a gauging was taken. Thus every gauging represents a corrosion incident, and every gauging from the survey is included in the data base. The incident data includes: ship age at survey, the type of corrosion, the type of detail the corrosion is gauged at, and some relative location in the tank of the gauging.

Detail Types. Table 7 lists the types of details which were considered in this study. Depending upon the level of complexity one wished to consider, the list might be either longer or shorter. This particular list was decided upon as it closely matched one which was used by the TSCF [3]. In developing this list, one of the considerations was that the list must be compatible with that used in the fatigue portion of this project. The list of details that study used was much more exhaustive than the one used here. For example, brackets of any type are not included, nor are some details such as centerline girders. It was felt that the large increase in the degrees freedom implied by the larger list of details would mean a diminished sample size for each of the analysis, and so diminished confidence in the results. It is important in this type of study, because of the variable nature of corrosion, to obtain the largest possible sample size, so that any statistics developed accurately reflect reality. The TSCF list of basic details was chosen as a basis for one which would satisfy both the requirements of brief generality, as well as compatibility with the fatigue study.

Incident Location. The location of the gauging is given simply in the longitudinal, and vertical frames as either forward-middle-aft or upper-middle-lower respectively , a format which is used in the fatigue study, and was chosen here for that reason. Any more detailed, or rather specific, manner of identifying location would have meant the same increase in degrees of freedom as discussed above in reference to the detail types, and so was limited for this reason. Even still, the list of 22 standard details, along with this code of 9 locations, implies 198 possible detail/location pairs

Corrosion Rates. There are a large number of possible combinations of all the factors included in the database. The example that will be developed here will be the combinations of what were indicated by the participants to be the most important factors: tank type, detail type, and location.

These factors were separated into two groups of 'keys'. The first, KEYI was a combination of the tank type and detail type. The second, KEYII was a combination of the tank type and location. KEYI has 88 possible combinations (4 tank types x 22 detail types), while KEYII has 36 possible combinations (4 tank types x 9 location pairs) KEYI allows one to examine the relative expected corrosion rates over a set of details throughout the tank, where KEYII allows one to examine how one might expect those corrosion rates to change as location in the tank changes. For example the corrosion rate of Longitudinal Bulkhead Stiffener Webs (LBLW) in ballast only tanks might be a concern.

After determining the expected corrosion rate over all LBLW's in the tank (Figure 5), one would examine the KEYII curves to determine how corrosion changes as one moves either forward, aft, down, or up in the tank (Figure 6).

Data Quality. The data for the corrosion portion of the study came, for the most part, from the gauging portions of survey reports. These reports are intended to reflect the current condition of the structure in the tank. The reports are often not intended to allow one to understand how the condition of the structure is changing with time. The owner/operator may not be interested in understanding how corrosion rate is changing, having more than enough to worry about in simply maintaining the vessel. Because of this, no consistent, coherent effort has been made to insure that the data, the gaging portions of the survey reports, are collected to further this effort. Often gagings are not taken at the same location in each survey, giving no time continuity to the data making it difficult to understand then how the corrosion will vary through time.

As well, data for localized corrosion is somewhat muddled. Different firms, depending upon their maintenance philosophies regarding localized corrosion, collect data on the various forms of corrosion (pitting, grooving) in different manners, whether it is simply counting the number of pits in a tank, or identifying one gauging as taken in a pit. No industry standard method of evaluating the corrosion damage by localized is used. This has made the effort to analysis localized corrosion in the same manner as general corrosion difficult, if not impossible. An alternate method to deal with localized corrosion must be developed.

Study 4 - Fatigue and Corrosion Repair Assessments

The general strategy used in repairing a vessel is based on the following considerations.

The design life of the vessel. Typically for tankers this is approximately 20 years. As the vessel approaches the end of economic life, the operator general will spend less money for repairs and maintenance. The emphasis will be on making minimal repairs needed to keep the vessel in class.

Second hand values as determined by the supply and demand for tonnage for a vessel of a particular size. The current and anticipated demand for tonnage is dictated by the domestic and international oil markets. Another major factor is the cost for new builds which has had an economic substitutional effect on second hand values which has recently received a lot of attention. The rise in second hand values encourages ship owners to invest more in maintaining their current ships and taking a longer term approach toward repairs. The object of this effort is to delay the purchase of expensive new builds.

Future plans of the company for retention of the ship. Marketing and refining logistics change with time. Maintenance expenditures for steel and coating repairs are reduced when the operator decides that the vessel may no longer fit in their logistics strategy. Oil companies with U.S. flag tanker operations are faced with the projected decline of the Alaska North Slope crude oil trade due to decreasing production in that field. Independent tanker operators of U.S. flag vessels also face this issue.

Availability of funds for maintaining and repairing vessels. During the first half of the 1980's the tanker owners and operators faced economic crisis. Huge financial losses by both oil company and independent operators alike reduced the availability of cash for repairs and maintaining their vessels. Owners were forced to make minimum investments for repairs and maintenance.

Environmental issues. Increased international concern over environmental issues particularly tanker oil spills have prompted ship owners to increase their efforts in maintaining hull structural integrity.

Repair Data Bases for Steel and Coating Repairs. The initial efforts in this study were focused on development of a tabular and graphic computer data base system for recording and analyzing steel and coating repairs. Two general observations have developed during the efforts to compile repairs data bases on six tankers:

1) Data on repairs is extremely difficult to retrieve and evaluate, and

2) There is a wide diversity of practices in accomplishing repairs.

Development and analysis of the data base can make problem areas readily apparent by reducing large amounts of repair data into types of structural members repaired and by location in the vessel. Figure 7 shows a comparison of two double hull tankers of the same class. The data base indicates the location and types of structural member repaired. This gives a graphic summary to the ships operator of the areas that need the most attention in future inspections.

At the initiation of this study three operators had developed crack / steel repair data bases for tracking fractures. The sophistication of these data bases varied from a relatively simple paper file system to a computer data base with graphical displays containing ships drawings. Only one operator was tracking coating repairs data in a data base.

Tanker operators in general are not making full use of computers as tools in tracking their repair expenditures and maintenance documentation. Generally, there is the lack of organization in engineering files for retrieving information quickly on steel and coating repairs. Much information including visual and ultrasonic surveys reports is missing or extremely difficult to retrieve due to poor record archiving.

Many ship owners and operators have very informal systems for tracking the details of maintenance of a given ship. Documentation ranges from a coherent history of reasonably detailed shipyard repair reports on crack repairs, steel renewals, and coatings and anodes maintenance to scattered shipyard invoices that define gross tonnages and areas. The documentation varies widely as a function of the diligence of the owner and operator, and as a function of the ship's life. Maintenance documentation developed during the first five years of a ship's operation frequently cannot be retrieved by the fifteenth year.

Documentation of crack repairs frequently cannot be tracked from one repair to another repair cycle. Thus, it becomes impossible to evaluate the effectiveness of given types of repairs. The problem of documentation of crack repairs is further complicated by corrosion. In many cases, if corrosion is extensive, cracking will not be noted; it will only be noted that the detail or section needs to be replaced. In several cases, we have found that cracks that were to be repaired in a certain manner were not repaired at all or were repaired in a manner different from that specified in the repair report.

Similar problems exist with regard to maintenance of coatings and anodes. Details of locations and the coating break downs and the procedures used to repair the break downs are frequently not documented. Coating repairs will be noted in terms of total area, the coating used in the repair, and the cost per unit area. This does not make it possible to track the effectiveness of coating repairs nor the basic durability characteristics of the original coatings. Similar statements apply to anodes.

Some operators have begun the development and implementation of computer based maintenance tracking systems. This study has made use of components of one such system identified as CAIRS (Computer Aided Inspection and Repair System) version 3.0. Given acquisition of the required data by ship owners and operators, and its input to this system, this system promises to revolutionize maintenance tracking. Perhaps, most importantly, the system will permit timely analyses of the effectiveness of repairs. Improvements in maintenance documentation is badly needed if ship maintenance is to be improved.

Repair Procedures. The inspection process prior to the vessel entering the shipyard varies depending upon the owner. Several months before the vessel is scheduled for the repair yard, an initial visual survey is conducted by the ships staff, the shoreside technical staff and an independent surveyor. A gaging survey may also be conducted to quantify the degree and extent of steel wastage.

Based on the results of the survey, a repair plan is written up and an estimate is made of the cost. The repair plan is then submitted to shipyards for bids. The contract is then awarded to the shipyard which makes the best offer. Once the ship enters the shipyard, visual and gaging surveys are again conducted. These secondary surveys usually reveal additional repair items since all the tanks are tree of cargo and ballast. Repairs are then made on items listed in the repair contract as well as any additional items discovered during the repair operations.

During the repair phase shipyard time and budgeting have a tremendous influence on the type of repairs made. If the work falls behind schedule or it budgeted funds are redirected for more critical needs, changes in the repairs approach will be made from the original repair specifications drawn at the office. For example, to re-weld a fracture and omit the installation of fabricated reinforcement brackets. After repairs are completed finalization of accounts usually occurs long after the ship has departed.

Steel and Coating Repair Observations. This study has provided the opportunity to survey a large number of ships that have been repaired or were being repaired. Repair observations are being documented in the TSCF [3] format. The following summarizes some of our initial observations concerning steel and coating repairs.

Not all repairs are sound from a naval architectural standpoint. Many operators make repairs using experienced based rules of thumb approaches. In many cases, cracks begin to reappear during the next inspection.

Often there are differences in the repairs proposed by the office technical department and what is actually done at the shipyard. This is due to either differences in opinion or budget and time constraints at the shipyard. Many of the repairs resulted in re-cracking.

Not all cracks are or can be repaired when they are found. Given present day inspection procedures and methods, it is highly unlikely that all significant cracks can be discovered. However, significant attention is given to the side shell and tank top structural elements. Cracks in the side shell and in the major structural members are repaired using temporary (e.g. end drilling cracks) or permanent methods (Figures 8 - 10). In many cases, it has been observed that cracking is initiated by corrosion (e.g. grooving corrosion in tank stiffener welds) or exacerbated by corrosion.

A common cracking problem in tankers is at the intersection of the side shell longitudinal at the web frames. In one class of ships, three ship operators tried three different approaches in bracket and detail design to solve such problems. One set of details were repaired three different times. Cracking started during the first few years of operations of these ships. Causes can be traced directly to improper design, ignored or unknown loadings and loading effects, and poor construction.

Corrosion protection philosophies vary greatly between tanker operators with regard to the use of tank coatings and anodes. Each operator has different histories of trial and error approaches that has evolved into their corrosion protection philosophies. Surface preparation of the coating areas during the initial coating of the newly built vessel seems to be the key ingredient in getting the maximum life for tank coatings. Coverage of anodes in ballast tanks with sediments accumulated in the tanks seems to be a key problem decreasing the effectiveness of anodes.

Repairs of cracks and coatings varies widely. Repairs of cracks can range from temporary cold patches to complete re-design of the detail and replacement of steel in the vicinity of the detail. Welding cracks is a popular repair that the data developed in this project indicates frequently must be repeated within a short period of time.

Drilling the ends of the cracks is a frequently used temporary repair measure that is used until the ship can be taken into the drydock. Repairs of these cracks can range from simple welding to addition of reinforcing elements. Again, the data developed during this project indicates that many of these repairs must be repeated in subsequent drydockings. In one case, a series of side-shell longitudinal cracks has been repaired four times, and each time a different repair procedure has been tried.

Many of the repairs identified by the TSCF [3] are not followed. We have seen repairs identified by the TSCF as being unsuccessful being used in current repairs. There is a wide variety of opinions on how repairs should be made, ranging from very high quality to very low quality. Our data indicates that high cost repairs do not necessarily translate to high durability repairs.

Also we have found that repairs accepted by one Classification Society surveyor or Coast Guard inspector for a given ship at given time and location will not be accepted by another for the same ship at a different time and location. We have also found that repairs specified by the owner - operator maintenance personnel frequently will be modified in the shipyard due to budget and time limitations. In many cases, very little engineering or structural analysis goes into the specification of repairs, even in the case of critical structural elements.

Study 5 - Durability Guidelines for New Ships

Two general observations concerning durability guidelines for new ships have developed during this project:

> **1) The primary problems with current ship structures does not seem to be focused in their capacity characteristics; rather it seems to be focused in their durability characteristics. Due to the large degrees of redundancy, ductility, and capacity, the structural system generally is very robust, i.e., it is very tolerant of localized damage or defects.**

> **2) The majority of the durability problems seem to be focused in the need for improvements in design of critical structural details and in improvements in corrosion protection and maintenance for these details.**

Experience developed during this study indicates empirically based, hand-book design, and in some cases analysis based design of critical structural details in mild and high tensile steel construction is not developing sufficiently durable structural systems. Conventional stress range - numbers of cycles to failure (SN) structural analysis procedures have been highly developed in the marine industry and these should be employed in design of critical structural details. Design of many of these details does not recognize the specific construction procedures that will be used to build the ship, and the problems of inspections and repairs (maintenance).

Similarly, experience is indicating that well designed, applied, and maintained corrosion systems can provide the protection necessary for critical structural details. Improvements are needed in coatings and cathodic protection systems, and design of compatible structural - coating systems. The major problems are showing up in improperly designed, applied, and maintained corrosion systems, and incompatibilities between structural and corrosion protection systems (e.g. sediment covered anodes in ballast tanks, flexible bulkheads coated with stiff coatings, corrosion cells set up between the parent material and the weld heat-affected zone).

Experience developed during this project has suggested three key technical strategies in design for durability:

> **1) Damage Tolerant Design - design of a ship structure that is forgiving in its ability to be tolerant of defects, flaws, and damage and is able to maintain the critical aspects of capacity and redundancy.**

> **2) High Quality Production - design and manufacturing processes and procedures, and inspection methods that will assure a high quality ship structure.**

> **3) High Quality Maintenance - painstaking attention to inspection, maintenance, and repair/replacement of critical structure details throughout life to maintain the important aspects of capacity and redundancy.**

Design for Durability. Developments in design for durability include explicit requirements and procedures for design of critical structural details and systems for: a) **Repeated loadings,** b) **Constructability** c) **Inspectability,** d) **Repairability, and** e) **Corrosion protection (coatings, cathodic, maintenance).**

The primary objective of design for durability is to create an efficient ship structure devoid of unanticipated costly maintenance and out of service requirements. The extent of design for durability represents a trade-off between initial costs and long-term operating costs. The objective is to make a sufficient initial investment in durability quality to forestall escalation in future maintenance and out-of-service costs.

Information developed in Study 2 indicates that fatigue problems develop most frequently because of ignored or inaccurately characterized loadings, poorly designed connections (e.g. inappropriate or no analyses, high stress concentrations, bad load transfer mechanisms), poorly constructed systems, and poorly maintained systems (e.g. corrosion allowed to initiate or exacerbate fatigue).

Connections with low stress concentration factors, accurate determination of sustained and cyclic straining histories, use of ductile and fatigue resistant materials (including weldments), robust (damage tolerant) system designs, construction and maintenance quality assurance and control, and perceptive design methods are the key defenses against fatigue damage or low durability structure systems. Fatigue cracking data developed during this project indicates that much more care has to be taken in the design and construction of structural details to minimize stress concentrations when using high tensile steels.

Design for durability includes not only assessment of the effects of repeated loadings, but as well the associated aspects of design for constructability, corrosion protection, inspectability, and repairability. Design for constructability is intended to help assure that the ship structure system that is designed can be effectively (high likelihood of reaching quality objectives) and efficiently (lowest reasonable cost) constructed. This requires that the design and construction procedures and plans be thoroughly and properly integrated.

Design for inspectability is intended to help assure that the ship structure system can be adequately inspected and surveyed, during the construction phase and during the operations - maintenance phase. The reliability of inspectability is directly connected with the design for repeated loadings. Given that the degree of inspectability of the structural system is low, either during construction or operations - maintenance, then the requirements for defect tolerance (robustness) in the system are increased.

It is here that important questions should be raised concerning how ship structures are presently designed. Designs are focused on creation of minimum weight systems. These emphasize the use of thin plates (to contain cargo and ballast, and exclude sea water) reinforced by a multitude of frames and stiffeners (to provide stiffness and strength). Consideration of design for highly automated fabrication provides important additional constraints on the structural configurations and assemblages.

Primary attention needs to be directed to recognition of the very limited degrees of inspectability of the structural system, rather than assuming that inspections can or will be done with a high degree of detection and accuracy. This would tend to constrain the design of the system to use of thicker plates and fewer frames and stiffeners. Design for inspectability should also address provisions to facilitate human access and inspections. Adoption of greater spacings for members to facilitate access, avoiding blind spots in the structural arrangements, and providing access facilities (openings, ladders, walkways, removable staging systems) for entering important parts of the structure. Cleaning, degassing, and lighting systems also need to be provided. In addition, design for inspectability should address development of and provisions for remotely operated inspection systems and instrumentation systems.

Design for repairability should include explicit consideration of how the system can be repaired when there is damage or defects or when the system must be maintained. Too often, in the relative comfort of the design office, it is assumed that the critical structural details can be easily accessed, damaged or defective elements removed, and repairs made. Planning must be done at the design stage on how repairs and maintenance will be done. Again, this requires proper and thorough integration of the repair yard and maintenance objectives and capabilities with the other design objectives.

The information developed in Study 1 indicates that a key element in design for durability is corrosion protection, particularly for the critical internal structural elements associated with cargo and ballast tanks of VLCCs and ULCCs. Experience indicates that the most severe corrosion rates can be expected in ballast tanks. The corrosion effects may be the worst when the ballast tanks are empty or partially full. In this phase, cathodic protection can not protect the metal not covered by water. Cathodic protection efficiency can be reduced by sediment cover in the bottoms of the tanks. Corrosion can be exacerbated by adjacent heated cargo tanks.

Corrosion is also a problem in the cargo tanks. Generally, these tanks experience more of the pitting type of corrosion rather than general wastage. Tank washing and the area under loading line outlets can act to remove coatings and the protection provided by waxy crude cargos. Breakdown of coatings in the under-deck area of cargo tanks can be very severe. Coating breakdowns and partially coated areas can act to accelerate local corrosion.

Coatings and cathodic protection are practical protective measures. Design that eliminates or minimizes traps for water and sediment, and provides scour or erosion protection must be encouraged. Coatings must be properly designed to match the projected expected service and maintenance, and flexibility of the components to be protected. They must be properly applied, cured, and maintained. Similar statements regard the design, installation, and maintenance of cathodic protection systems.

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Table 1
Sponsors and Participants in UCB SMP

Sector	Organization
Government	U.S. Coast Guard Military Sealift Command Maritime Administration Naval Sea Systems Command (Ship Structures Committee)
Classification	American Bureau of Shipping Bureau Veritas Lloyd's Registery of Shipping Germanischer Lloyd
Shipyard	Lisnave Jurong Shipyard Ltd. Ishikawajima-Harima Heavy Industries Co. Ltd. Mitsubishi Heavy Industries Ltd. Daewoo Shipbuilding & Heavy Machinery Ltd
Owner/Operator	Amoco Transport Co. Arco Marine Inc. B.P. Oil Company Exxon Company International Chevron Shipping Co. Mobil Shipping and Transport Co.

Table 2
Project Organization

Project Responsibility	Name, Organization
Consulting to All Studies	Prof. Alaa Mansour, UCB Y. K. Chen, ABS
Study 1 - Fatigue	Prof. Robert Bea, UCB Prof. Stig Berge, U. of Trondheim, Norway Rolf Schulte-Strathaus, Research Assistant Espen Cramer, Research Assistant
Study 2 - Corrosion	Prof. Robert Bea, UCB Rob Pollard, Research Assistant
Study 3 - Interaction of Details with Adjacent Structure	Prof. Randolph Paulling, UCB Jim Stear, Research Assistant
Study 4 - Repairs	Prof. Robert Bea, UCB Robert Baker, Research Assistant Martin Cepauskas, Research Assistant
Study 5 - New Build Guidelines	Prof. Robert Bea, UCB Research Assistant to be Appoin ted
Study 6 - Software Development	Prof. William Webster, UCB Scott Morris, Programming Assistant

Table 3
Summary of Tasks Comprising SMP Studies

Study	Tasks
1 **Fatigue**	Task 1 - Gather, archive (computer data bases), and assess (trends, statistics) data from participants and from the literature on fatigue and corrosion damage to ship hull structure elements, with particular emphasis given to damage developed in primary structural components of large tankers subjected to severe service conditions. Evaluate this data to determine important characteristics of fatigue crack initiation and propagation. Task 2 - Review, critique, and document existing approaches to evaluations of fatigue effects on the strength characteristics of welded details and hull components, with particular attention to defective / damaged components and higher strength steels; this will include evaluations of the fatigue damage causes and characteristics summarized in the data base study; Task 3 - Develop a general approach to evaluate the effects of fatigue on propagating known defects (existing cracks) in critical internal hull details, utilizing probabilistic stress-number of cycles (S-N) and fracture mechanics approaches; Task 4 - Based on a review of ship maintenance records, information which has been supplied by participants, and the technical literature on hull connection details, establish a fatigue classification system for the critical internal structural details, and establish fatigue strength limits considering both the structural analysis procedures and S-N classifications. Task 5 - Characterize the interactions between capacity of single components (similar to standard S-N curves) and hull service strength to define their criticality; Task 6 - Develop a PC-based program that will permit the practical evaluations of fatigue crack propagation, and effects on component strength and leak integrity.
2 **Corrosion**	Task 1 - Gather, archive (computer data bases), and assess (trends, statistics) data from participants and from the literature on corrosion damage to ship hull structure elements, with particular emphasis given to damage developed in critical internal structural components of large tankers subjected to normal service conditions. Evaluate this set of data to determine important characteristics of corrosion (local and general internal corrosion rates as function of time, tank contents, and ship routes), corrosion control systems and their performance, and effects of corrosion on component capacity. Evaluate this data to determine important correlations of corrosion and fatigue damage, and corrosion and hull-component flexibility. This task will be performed by the same personnel that perform the associated task in the fatigue study. Task 2 - Critically examine and report on allowable corrosion limits used by Classification Societies to assess the need for steel renewals. Task 3 - Evaluate the influence of flexure of a component on its corrosion rate based on analysis of data from in-service vessels; Task 4 - Study the feasibility of an experimental program which examines the effect of flexure on corrosion rates, including the design of an experiment, necessary equipment, and budget; Task 5 - Develop guidelines and recommended limits on local flexibility of components for new constructions; Task 6 - Develop guidelines for existing vessels to mitigate flexure-related corrosion of an area by increasing its local stiffness; Task 7 - Develop theoretically and empirically based guidelines for the evaluation of the effects of corrosion on the strength and leak integrity of critical internal structural details and define appropriate wastage allowance limits; Task 8 - Develop PC-based software to analyze specific corrosion problems based on the guidelines developed in Tasks 5 - 7, showing corrosion rates versus time, member flexibility and location and type of protection. The software will give the evaluator insights into where, when, and with what rates corrosion damage can be expected in the critical internal components comprising tanker hulls. Task 9 - Verify the analytical methods and software with several corrosion/hull flexure case studies.

Table 3
Summary of Tasks Comprising SMP Studies

Study	Tasks
3 **Interaction of Details with Adjacent Structure**	<u>Task 1</u> - Determine the extent of structure (module size) necessary to accurately model the local element-global structure interaction. Classification society practices usually require that a module consisting of three or four tank spaces on one side of the center line be modelled for the proper three dimensional analysis of transverse strength of tanker structures. Such a large and detailed model is probably unnecessary for the local response analysis of concern in this project. A major initial part of the work will be concerned with defining the module of adjacent structure of minimum extent necessary to accurately depict the boundary conditions and loading of the detail under consideration. While this module is expected to be much smaller than the four tank lengths mentioned above, in the early part of the project, it will be necessary to carry out one or more large scale computations embracing the entire ship, followed by several smaller scale computations focussed on progressively smaller modules in order to identify the minimum module extent and to verify and calibrate the conclusions. The structural components and their response will, in general, be modelled by standard elastic finite element methods. The module structural model will be designed around a system of substructures representing the hull components adjacent to the detail. These components will in most cases, consist of panels of plating and associated stiffeners. The structural detail, e.g., a bracket, will then be modelled by a fine finite element mesh in order to focus on the local structural response. The load input to the analysis will be the aforementioned substructure body and boundary loads. <u>Task 2</u> - In parallel with the determination of appropriate module size, which affects the boundary conditions of the structural detail under consideration, it will be necessary to develop a procedure for generating appropriate boundary loads on the detail. Such loads will accurately reflect the local internal reactions due to the ship's weight and buoyancy distribution and the seaway effects. The module sizing study of Task 1 will be conducted in such a manner that it will be possible to track the behavior of boundary loads on the succession of module sizes as we focus in on the local detail. The loading system will reflect the weight, load and ballast distributions, the distribution of buoyancy and seaway effects drawn from the rule loads specified by classification societies as well as current ship motions and loads computational procedures.

Table 3
Summary of Tasks Comprising SMP Studies

Study	Tasks
4 **Repairs**	Task 1 - Gather, archive (PC and main-frame computer data bases), and assess (trends, statistics) data from participants and from the literature on corrosion and fatigue damage repairs to ship hull structure elements; Task 2 - Review, evaluate, organize, summarize, and document existing approaches to repair of fatigue damages to critical internal hull structural details (mild and HTS steel); and develop critical detail fatigue design guidelines to help minimize maintenance costs associated with new builds; Task 3 - Review, evaluate, organize, summarize and document existing approaches to repair of corrosion damages to critical internal hull structural details; and develop corrosion design and protection guidelines to help minimize maintenance costs associated with new builds; Task 4 - Based on given unit costs (repair, out-of-service), repair time and tonnage estimates, and the likelihoods of repair effectiveness, develop economics based procedures for evaluation of alternative repair programs (Figures 2, 3); Task 5 - Develop a PC-based program that will assist analyses of the effectiveness of proposed fatigue and corrosion damage repairs (these analyses will address the local effectiveness of proposed repairs contrasted with the global effectiveness addressed by the global structural analyses).
5 **New-Build Guidelines**	Task 1 - Define information that should be provided for durability design including the life-cycle structural integrity plan, design criteria, damage tolerance plan, durability development approach, materials selection and fabrication, and operations - maintenance plans. Task 2 - Define improvements in structural analyses methods that can lead to acceptable durability characteristics of the ship's critical elements including analyses explicitly addressing damage tolerance and durability. Task 3 - Define requirements for testing of critical structural components to demonstrate adequate capacity, durability, and damage tolerance, and in-service monitoring of critical elements in VLCCs and ULCCs aimed at improving understandings of loadings and operations procedures effects on loadings. Task 4 - Define the characteristics of an industry-wide computer data base system for archiving design and construction information, operations structural tracking and maintenance tracking of the performance characteristics of the critical internal structural elements.
6 **Software**	Task 1 - development of standards for the coding of the programs, the writing of documentation, and the selection of appropriate data base software Task 2 - development of an appropriate user interfaces for the codes developed in the various studies.

Table 4
Descriptive Fields for Fatigue Data Base

Field Name	Input
Vessel ID	Number
Tank ID	Number and Location (S,C,P)
Member cracked	Character field
Survey ID	Date of survey
Drawing no.	Number
Zones	Location and Height
Side	P,S or blank
Frame no.	Number
Distance from Frame	Decimal Number
Crack Type	Set of Keywords (Option to edit or modify new keywords when needed
Crack Length	Length in units
Crack Class	Number, Year
Date of Survey	Month, Year
Date of Repair	Month, Year
Sort of Repair	Character Field
Cause for Damage	Set of Keywords
Comments	Character Field

Table 5
Summary of Tankers Included in the Data Base

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

Table 6
Corosion Factors Included in Corrosion Data Base

Ship Size Delivery Date Cargo Type Double Bottom(Y/N) Double Side (Y/N) Class Society Trade Route[1] Tank Location	Tank Type Time in Cargo Time in Ballast Corrosion Protection System Ballast Type Tank Temperature[2] Tank Humidity[2]	Cargo Sulphur (%) Cargo Water (%) Wax in Cargo (Y/N) Heated Cargos (%) Tank Washing IGS (Y/N) Corrosion Type Corroded Detail Detail Location

1- Seldom well defined
2- For Ballast tanks, often an estimate

Table 7
List of Critical Internal Structural Details Included in Corrosion Data Base

DETAIL	CODE
Deck Plating	DP
Deck Long. Web	DLW
Deck Long. Flange	DLF
Side Plating	SP
Side Long. Web	SLW
Side Long. Flange	SLF
Bottom Plating	BP
Bottom Long. Web	BLW
Bottom Long. Flange	BLF
Long. BHD Plating	LBP
Long. BHD Long.	WEBLBLW
Long. BHD Long. Flange	LBLF
T-BHD Plating	TBP
T-BHD Stiffener Web	TBSW
T-BHD Stiffener Flange	TBSF
Horizontal Girder Web	HGW
Horizontal Girder Flange	HGF
Vertical Girder Web	VGW
Vertical Girder Flange	VGF
T-Web Plating	TWP
T-Web Flange	TWF
Swash BHD Plating	SBP

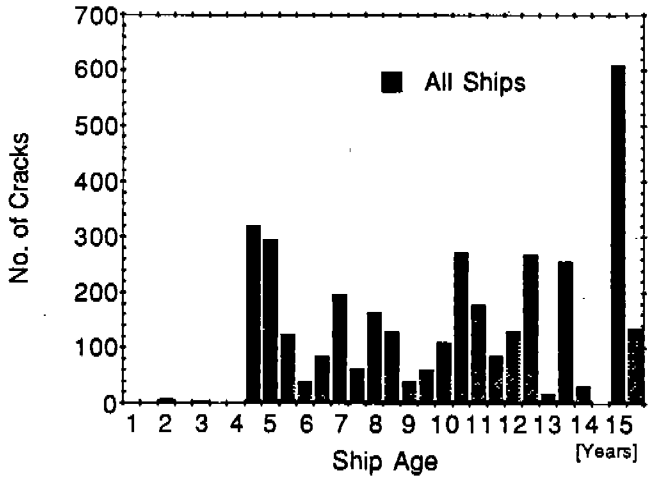


Figure 1 Number of Cracks vs. Time until Detection

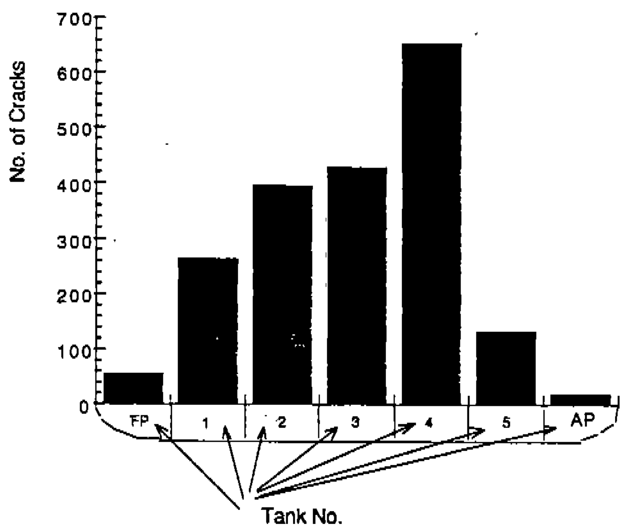


Figure 2 No of Cracks per Tank (4 Ships same Class)

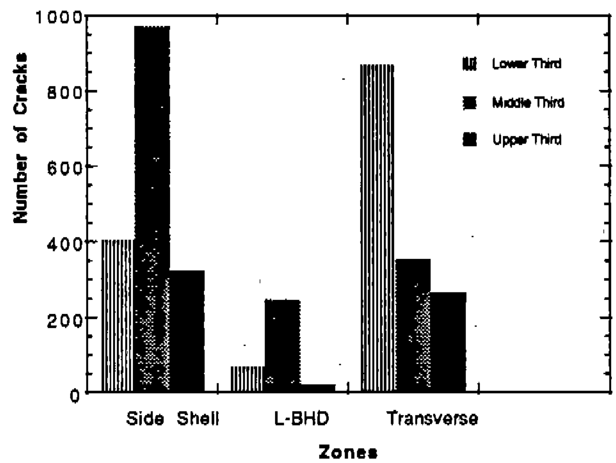


Figure 3 No. of Cracks per Zone (All Ships)

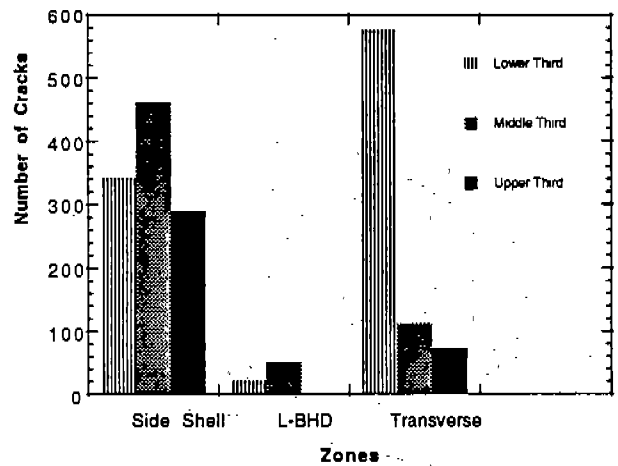


Figure 4 No. of Cracks per Zone (4 Ships of the same Class)

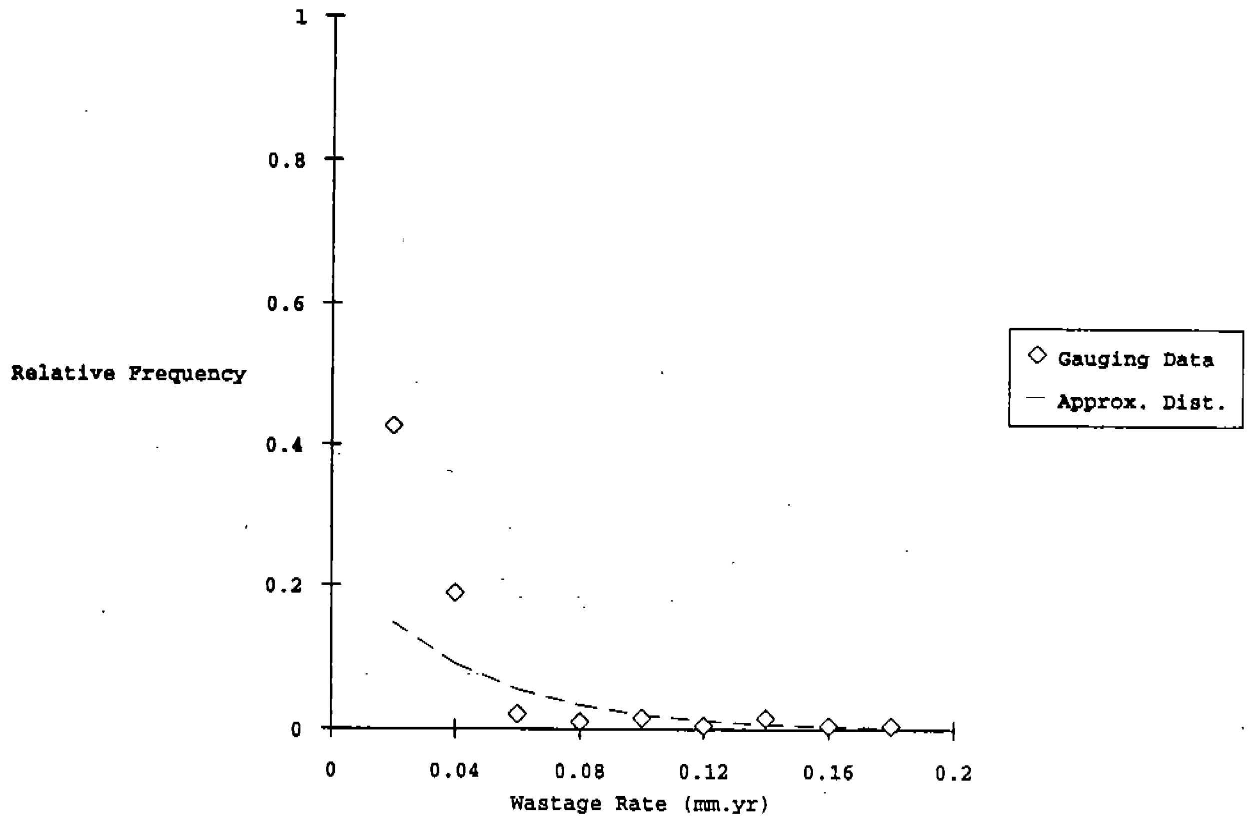


Fig. 5 PDF for KEYI: Ballast Only - LBLW

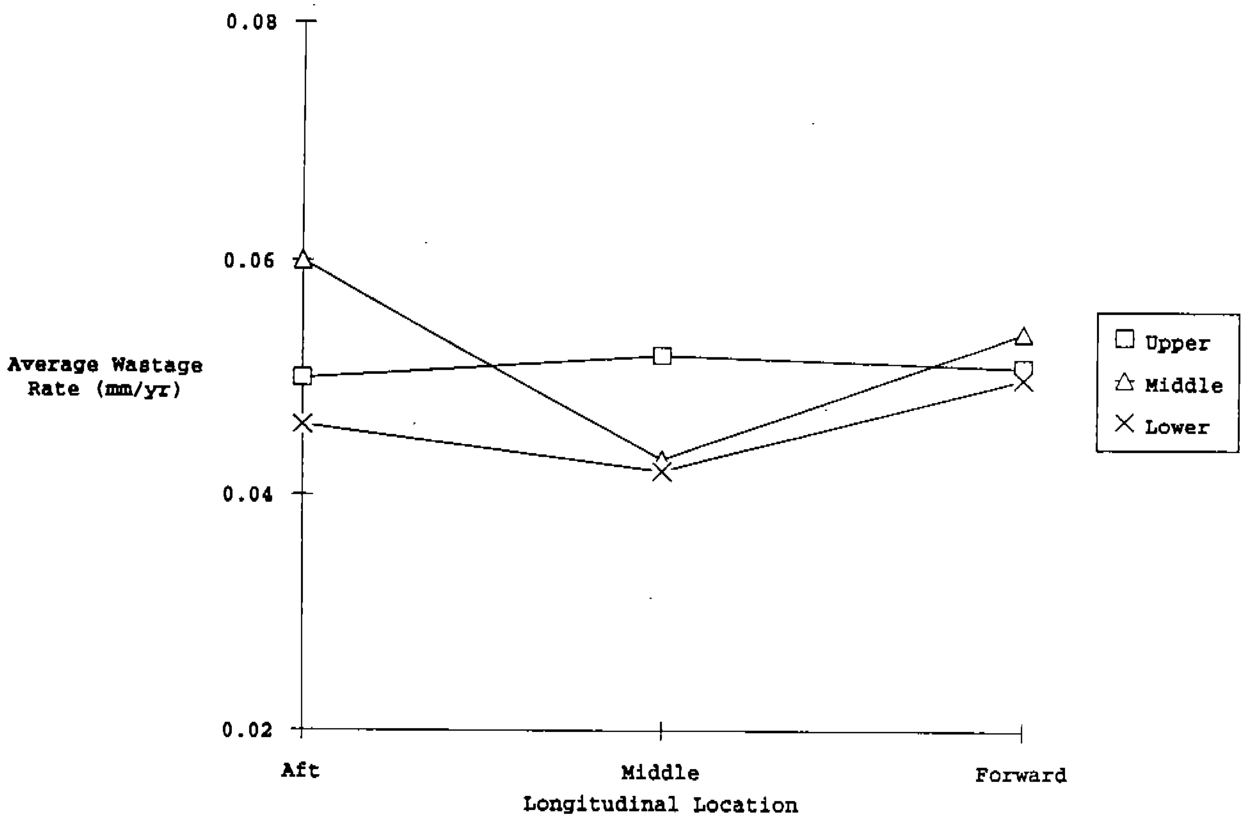


Fig. 6 Wastage Rate for KEYII: Ballast Only - Location Pairs

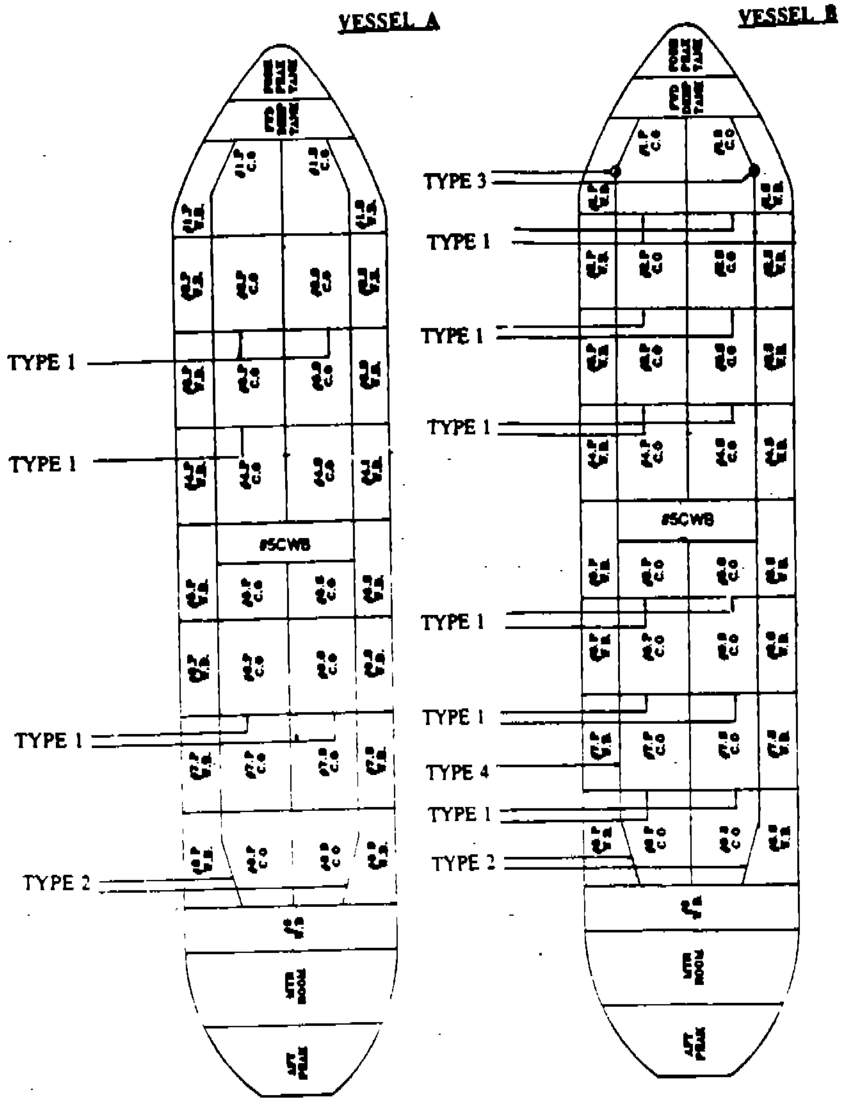
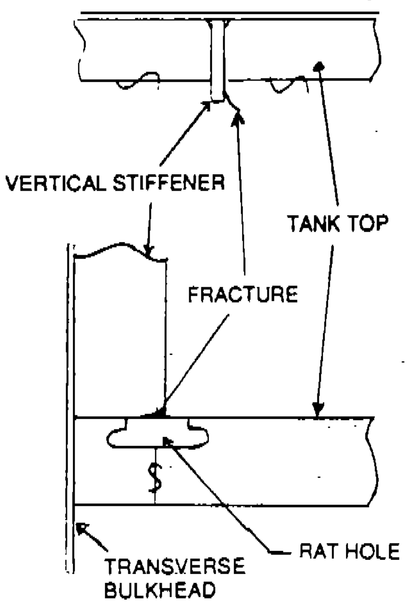


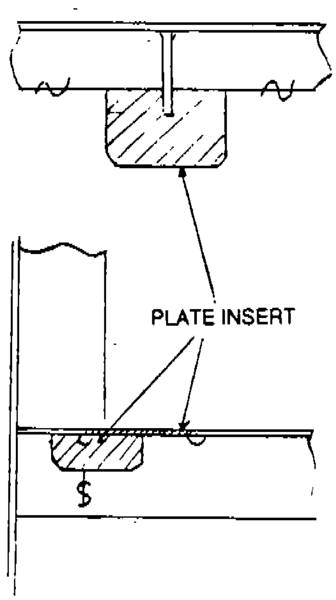
Figure 7 Comparison of Crack Locations of two Class Vessels

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

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

TYPICAL DAMAGE	REPAIR





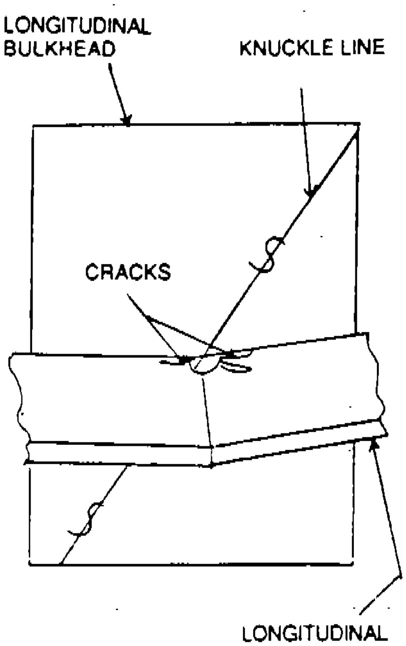
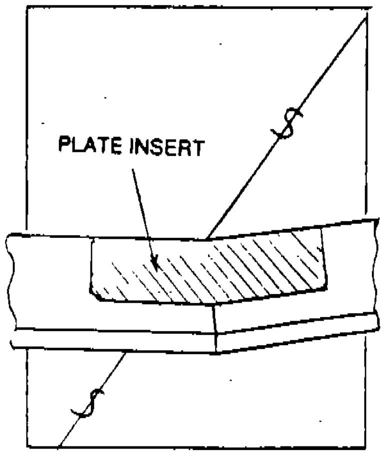
FACTORS CONTRIBUTING TO DAMAGE

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

Figure 8 Repair Case Study 3

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

EXAMPLE No. 3: Cracks and wastage at longitudinal stiffener

TYPICAL DAMAGE	REPAIR
	

FACTORS CONTRIBUTING TO DAMAGE

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

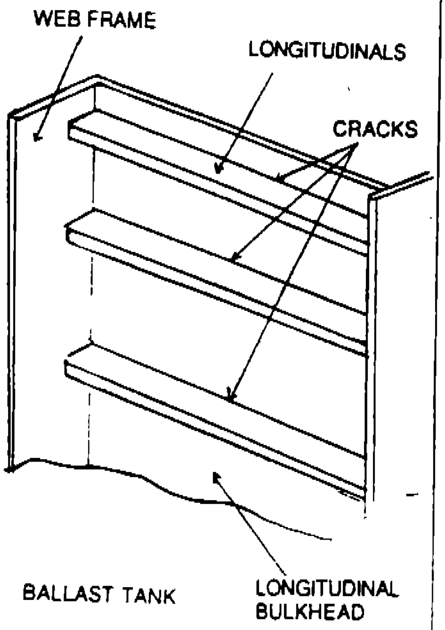
Figure 9 Repair Case Study 4

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

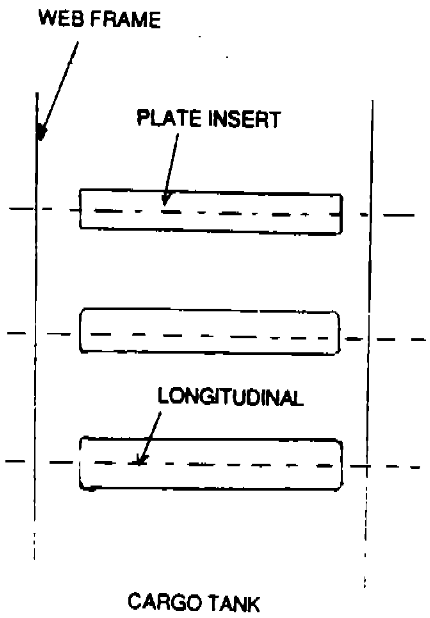
EXAMPLE No. 4: Cracks in longitudinal bulkhead along topside of longitudinals

TYPICAL DAMAGE	REPAIR

TYPICAL DAMAGE



REPAIR



FACTORS CONTRIBUTING TO DAMAGE

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

Figure 10 Repair Case Study 6

Greg White

First, I'd like to say that I was impressed with the thoroughness with which you've attacked this immense problem. It is going to be extremely helpful in the long term. I'm interested in your discussion on corrosion. Approximately ten years ago, when I was working for Exxon, we were doing a similar internal survey of ships. What we found was that the surveyors would go in there and because the structure is so large, we were getting corrosion measurements out which were almost useless. There was no real way of knowing, with the few corrosion measurements they had taken on this huge area, what the real values were. What I want to ask is how are you addressing that problem? Are you preplanning an area to cover and a number of sites, or leaving it up to the inspectors to look for the worst corrosion spots? Is there some means to take the information you're getting and come up with some sort of confidence interval on the wastage experienced and expected?

Robert Bea

First, on the data for these 1970 to early 1980s ships we were, of course, having to work with the data the operators gave us so there's not much of a chance to, I'll call it, restructure history. One of the principal things the project had to go through initially was looking at repetitive surveys within the ship that were of high enough quality to enter into the database. We encountered the very same problem you addressed, much of the data quality was not sufficient to resolve the questions that we were trying to answer. So that data was called, "thank you, but no thank you." The data that was selected has been repeated, it is high quality, it's been done in a number of identical locations across a number of surveys. So we have some information to help us with data confidence. I think that we have noted in that development that are a bit, I'll call it disarming, is that whenever an area is heavily corroded, whether or not it's fracturing very seldom shows up in the surveyor reports. That steel is identified for renewal. The cracking information is very generally deficient because of that.

On the other point that you addressed, as we go forward in the inspection process improving when, where and how we inspect, I think it is important to define how we archive that massive data. Rob Pollard has spent many Saturdays and Sundays inputting almost a million data points into the database. There's got to be an easier way. I think it's time for computers, perhaps digital voice systems, they're being used in many other industries. We're looking at that within a component of this project.