

SSC-395

SHIP MAINTENANCE PROJECT

Phases II and III- Volume 1

*Program Summary and
Rational Basis for Corrosion Limits on Tankers*



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SHIP STRUCTURE COMMITTEE

1997

SHIP STRUCTURE COMMITTEE

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**SHIP MAINTENANCE PROJECT
 Phases II and III**

This report presents the results of the second and third phases of the subject project of which phase one was first presented in our four volume set -- SSC-386. These studies investigated the development of engineering technology that could lead improvements in structural maintenance for new and existing tankers. These projects built further upon the work started in phase I specifically focusing on critical structural details and corrosion limits.

The report has been divided into five volumes, each of which may stand alone. Volume one opens with a summary of all three phases by Professor Robert G. Bea, the coordinating investigator for the program and follows with a report on corrosion limits for tankers. The second and fifth volumes look into evaluation of cracked critical structural details in tankers. The third volume presents theory and user instructions for software to manage repair of critical structural details. The fourth volume applies to fatigue classification of critical structural details. The software developed in the project will be available on the next Ship Structure Committee CD Rom release, which is anticipated to be released in the next year. The industry is encouraged to contact Professor Bea at the University of California, Berkeley to discuss further possibilities in application of the work undertaken here in the industry.

J. C. CARD

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

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METRIC CONVERSION CARD

Approximate Conversions to Metric Measures

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

°F degrees Fahrenheit multiply by 5/9
°C degrees Celsius subtract 32, multiply by 5/9

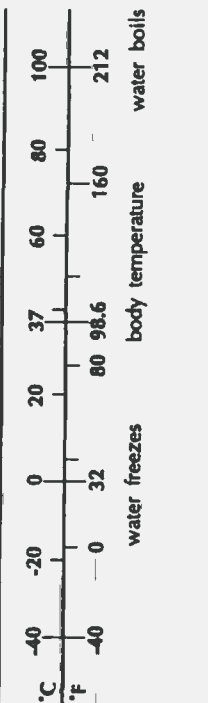
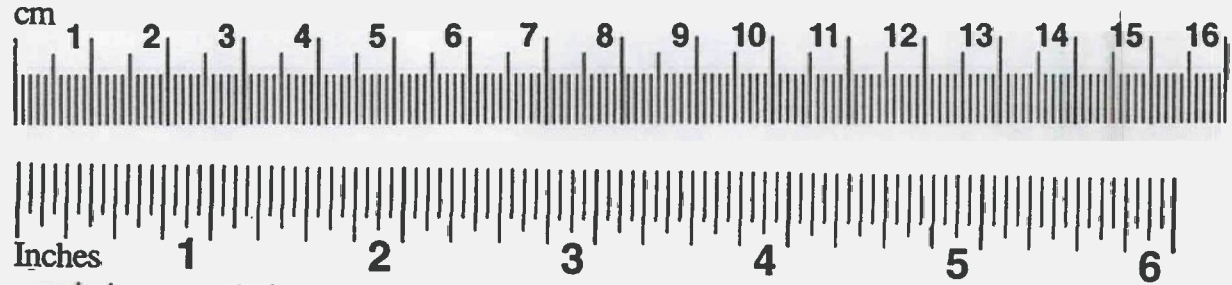
TEMPERATURE (exact)

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	metric ton (1,000 kg)	1.1	short tons	
VOLUME				
mL	milliliters	0.03	fluid ounces	fl oz
mL	milliliters	0.06	cubic inches	in ³
L	liters	2.1	pints	pt
L	liters	1.06	quarts	qt
L	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³

°C degrees Celsius multiply by 9/5, add 32
°F degrees Fahrenheit multiply by 5/9, add 32

TEMPERATURE (exact)



Ship Structural Maintenance Projects II and III

Cross Reference Listing

SSC Vol	SMP #	Title	Authors	Date	NTIS Number
	II				
2	-1	Fatigue Analysis of CSD in a 150K DWT Double-Hull Tanker	Xu, Bea	10/93	PB97-142830
2	-2	Fatigue Analysis of CSD in a 190K DWT Double-Hull Tanker	Xu, Bea	10/93	PB97-142830
2	-3	CSD Library and Finite Element Stress Contours	Xu, Bea	10/93	PB97-142830
1	-4	Development of a Rational Basis for Defining Corrosion Limits in Tankers	Mayoss, Bea	12/93	PB97-142822
3	-4a	RMS for CSD in Ships - User Manual	Ma, Bea	9/93	PB97-142848
3	-4b	RMS for CSD in Ships - Theory	Ma, Bea	9/93	PB97-142848
4		Fatigue Classification of CSD in Tankers	Schulte-Strathaus, Bea	1/94	PB97-142855
	III				
3	-1-1	RMS for Fatigue Cracks in Ship CSDs	Ma, Bea	10/94	PB97-142848
5	-2-1	Fitness for Purpose Analysis Procedure of Cracked CSDs in Tankers	Xu, Bea	1/95	PB97-142863
5	-2-2	A Load Shedding Model of Fracture Mechanics Analysis of Cracked SCDs in Tankers	Xu, Bea	1/95	PB97-142863
5	-2-3	FRACTURE- A Computer Code for Fracture Mechanics Analysis of Crack Growth of Cracked CSD in Tankers	Xu, Bea	1/95	PB97-142863
5	-5	Pro-IMR: A Computer Code for Probability-Based Inspection Planning	Xu, Bea	10/94	PB97-142863

The Ship Structural Maintenance Projects

1990 - 1995

By

Professor Robert Bea

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ABSTRACT

This paper summarizes the objectives, approach, organization, and results of a series of joint industry - government sponsored cooperative research projects that focused on development of engineering technology that could lead to improvements in structural maintenance for new and existing tankers.

The first phase of the Structural Maintenance for New and Existing Ships Project (SMP I) was conducted by the Department of Naval Architecture and Offshore Engineering at the University of California at Berkeley (UCB) during the 3-year period 1990 through 1992. The project was conducted in behalf of 22 sponsoring and participating organizations representing government regulatory bodies, classification societies, new-build and repair yards, and ship owners and operators.

The second and third phases of the SMP were conducted during the period 1993 through 1995. These phases of the research addressed high priority problems identified during SMP I.

INTRODUCTION

The *Structural Maintenance for New and Existing Ships Project* (SMP I) had two primary 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.

SMP I 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.

In addition to its technical objectives, SMP I had important organization objectives. The project was 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 provided significant benefits to the ship industry.

SMP I ORGANIZATION

There were four major organizational components in SMP I. The first component was the project sponsors and participants. There were 22 national and international organizations including ship owners and operators, ship construction and repair yards, classification societies and government agencies that comprised the first component (Table 1).

The second organization component was the Project Technical Committee (PTC). Each of the project sponsors and participants were represented on the PTC. The PTC was chaired by Mr. John Conlon of the American Bureau of Shipping (ABS). The purpose of the PTC was 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 was the Office of Research Services and Sponsored Projects Office at the University of California at Berkeley. This component was responsible for the project contracting, invoicing, and accounting.

The fourth organization component was the project researchers and consultants. Table 2 summarizes the names and responsibilities of the project researchers and consultants.

SMP I RESEARCH STUDIES

Six inter-related studies comprised SMP I. The fatigue and corrosion damage evaluations constituted the basic studies in the project (Studies 1 and 2). These evaluations, however, could not be completed without defining the boundary loading and fixity conditions of the local details where damage has occurred. Such boundary loads and conditions were developed in Study 3.

Based on results from Studies 1 - 3, repair strategies and guidelines were developed in Studies 4 and 5. Finally, software packages for personal computers with documentation were developed in Study 6. The following paragraphs describe in more detail the content of each of these studies. The reports developed during each of the studies are cited in the list of references.

Study 1 - Fatigue Damage Evaluations

The objective of this study was to develop and verify engineering approaches to assess fatigue effects on the performance characteristics of Critical Structural Details (CSD) in tanker hulls, including the effects of inspection, maintenance and repair. This study addressed both mild steel and HTS/LS steel hull structural elements and systems.

This study developed a database on fatigue cracking in tankers and developed simplified approaches for evaluating the fatigue durability of CSD, including a long-term hot-spot stress range - number of cycles (S-N) approach and a fracture mechanics based approach [4, 24-29]. Both deterministic and probabilistic fatigue analysis approaches were developed including software to perform the long-term stress range calculations [4,8,9,12,13]. The S-N approach was validated by comparing the computed and database based probabilities of fatigue failure in two types of CSD in a fleet of tankers [3, 28]. A reliability based evaluation was developed to provide insight into fatigue of groups of CSD [7]. A probability based inspection and repair analysis process that recognized realistic occurrences of weld flaws and probabilities of crack detection was developed and illustrated [7].

Study 2 - Corrosion Damage Evaluations

The objective of this study was 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.

The principal developments from this study were a database on general corrosion in tankers that could be interfaced with the fatigue cracking database [22], an evaluation of the statistical characteristics of the corrosion rates for various elements and locations in tankers [5], and the development of an approach to evaluate conditions in which plate renewals were implicated [22, 6].

Study 3 - Interaction of Details with Adjacent Structure

This study played a key role in that it provided input and support to the fatigue and corrosion damage effects parts of the project. The overall objective was to develop a reliable but simplified and practical analytical tool that could enable engineers to make the necessary structural system performance evaluations rapidly and with accuracy sufficient to make good 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, provided: (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 was organized into two principal tasks (Table 3). The first task was focused on structural analysis and the second task was focused on evaluation of loading characteristics.

The successful completion of Task 1 and Task 2 provided the foundation for 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 Personal Computer (PC) software necessary to implement the analysis [32,33, 34].

This study was focused on two general classes of tankers: a fleet of 165,000 dwt single-hull tankers and a fleet of 190,000 dwt double-bottom tankers [3,28]. The study resulted in development of global and local loading transfer functions that could be utilized in the long-term sea-state, heading, speed, and cargo or ballast condition dependent characterization of mid-ship hull loadings [32,9]. A global to local procedure based on linear beam theory was developed and studied using detailed finite element models [32]. Given the local primary loadings acting on the boundaries of a given CSD, detailed Finite Element Models (FEM) were developed to define the crack-opening hot-spot stresses at pre-defined locations on the CSD [33,34].

Study 4 - Fatigue and Corrosion Repair Assessments

The objective of this study was 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 work of the Tanker Structural Co-operative Forum (TSCF) provided a valuable starting point for this effort. As well, the special reports developed by

Committee V.3 (Service Experience - Ships), of the International Ship & Offshore Structures Congress (ISSC) provided important direction for this effort. In particular, the TSCF and ISSC have documented frequently occurring fatigue damage, and strategies to repair that damage. An objective of this study was to continue and extend the TSCF and ISSC developments. The study resulted in development of a simplified procedure and computer program that could be used to rapidly determine the comparative fatigue performance characteristics of alternative repairs to CSD [14].

Study 5 - Durability Guidelines for New Ships

The Ship Structures Committee (SSC) initiated a research project that was conducted in parallel with SMP I on the topic of development of Marine Structural Integrity Programs (*MSIP*) for ships [2]. The project addressed 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 could be used to develop life-cycle *MSIP* for new builds, the project was 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 reviewed 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 were incorporated into Study 5.

This study resulted in development of a handbook for naval architects and repair engineers that provides practical information on development of durable CSD in ships, repairs of these CSD, and software to guide repair engineers in the evaluation of alternative repairs [17].

Another parallel study was sponsored by the U. S. Coast Guard on the topic of inspections of CSD in tankers. Existing techniques and procedures were reviewed and recommendations developed to facilitate data gathering and analyses [15].

Study 6 - Development of Software and Applications Examples

This study, unlike the other technical studies, was focused at providing the background, standards and support so that the computer codes developed by the various researchers could be of uniform quality, would facilitate modification and be user friendly. As such, this study provided a uniform foundation and standard interfaces which served as a reference for all of the studies.

The software was intended to be of "Beta" grade, sufficiently "debugged" to allow initial applications. It was left to future industry efforts to develop the software to be of industrial grade and quality. The programs were written in the FORTRAN language for IBM PC and PC compatible equipment.

A major contribution of this study was the development of a front-end windows based input system that would provide information and data files for the integration of the other software components developed during the study [23]. This input system allows a user to define a wide variety of CSD in the classes of ships included in the loadings and structural analysis data files. Extensive 'help' screens were provided to assist the user in developing and validating the input.

SMP II RESEARCH STUDIES

The SMP II studies were conducted during the period 1992 - 1994. During SMP II, four additional research studies were conducted. These studies addressed high priority problems identified during SMP I. The studies were sponsored individually by various members of the SMP I project.

The SMP II studies were: 1) Fatigue Classifications of CSD in Tankers, 2) Study of the Fatigue of Proposed CSD in Double-Hull Tankers, 3) Development of a Rational Basis to Define Corrosion Limits in Tankers, and 4) Repair Management System (RMS) for CSD in Tankers.

Study 1 - Fatigue Classifications

The objective of this study was to develop methods that could assist naval architects in the performance of fatigue life evaluations for CSD in large oil tankers. This study focused on two topics: 1) fatigue classifications, and 2) development of a management system for selection of S-N curves.

This study resulted in development of a procedure to use the stresses at the hot spots (areas of high stress concentrations) of proposed CSD [30]. These hot spots are identified based on the results from detailed finite element analyses of a CSD and observations of fatigue cracking in ship CSD. This approach makes it necessary to define the way the hot spot stresses are obtained from the finite element analyses and to use S-N curves which are calibrated for this procedure.

The specific geometry and testing conditions associated with the details used to define S-N curves was obtained for 6 generic CSD. Different finite element analysis methods (e.g. plate and shell elements), mesh sizing procedures (e.g. equal to half the plate thickness), and hot spot "extrapolation" techniques were explored to define a method that would give consistent results for the variety of details.

Simple details for which there are well defined stress concentration factors also were studied (e.g. plates with holes, formed boundaries) to define a consistent procedure to define the hot spot stresses.

The results from this study indicated that one could 'collapse' the wide variety of S-N curves based on nominal stresses to two 'fundamental' S-N curves: one for welds, and one for plate edges [30]. The crack opening stress (normal to the direction of cracking) was identified as the fundamental stress for use with these 'fundamental' S-N curves.

The second part of this study resulted in the development of a computer based management system to assist naval architects in choosing appropriate S-N curves for given CSD. This management system and the hot spot extrapolation procedure developed in the first part of the study was used in a repetition of the fatigue calibration / verification study performed during SMP I. Unlike the experience in SMP I based on a traditional nominal stress S-N approach, it was found in SMP II that the revised procedure developed results that were not in good agreement with the observed fatigue behavior in the class of ships studied. The revised procedure under estimated the probabilities and frequencies of fatigue cracking in the CSD [30].

This study theorized that the observed under estimate of the fatigue cracking frequency was due to an under estimating of the cyclic stress ranges and due to unconservative damage accumulation developed by the linear damage accumulation model, S-N curves based on in-air testing, and ignoring mean stress effects. The under estimate of the cyclic stress ranges was attributed to the lack of recognition of 'second order' effects such as those due to green water on the decks, slamming and whipping.

Study 2 - Fatigue of Proposed CSD

The objective of this study was to conduct analytical studies of proposed CSD for new double hull tankers to assure that they have desirable durability and robustness (defect / damage tolerance) characteristics.

Fatigue analyses were performed on important CSD from two structural systems that were proposed for the next-generation of double-hull tankers [35,36, 37]. The objective of the analyses was to determine if the proposed CSD possess desirable degrees of durability. Alternative configurations of the CSD were studied to define effective means of increasing the durability characteristics.

The CSD that were studied were defined and provided by the study participants. Several innovative CSD that were proposed for the next-generation of tankers were analyzed [36]. One of these did not utilize cutouts in the side shell longitudinal - transverse webframe or bulkhead intersections.

Results from this study indicated that there is an extremely wide range in the expected durability characteristics of the proposed CSD. Modifications to the CSD designs were explored to determine how best to increase the fatigue lives. Comparisons of the results from this study with those performed by the ship designer have highlighted the importance of several parts of the analysis procedure and the needs for a consistent procedure to perform such analyses [3, 35]. In more than one case, the initial comparisons of predicted fatigue lives have differed by factors of 10 to over 50. Once the sources of the differences in the procedures were located and modifications introduced to make the procedures directly comparable, then the differences are much smaller.

Study 3 - Rational Corrosion Limits

The objective of this study was to evaluate the effects of internal corrosion on the strength of tanker structures and to provide a rational basis for determination of wastage limits. During SMP I, corrosion margins and allowable wastage as presently defined by the different classification societies were studied [6, 22]. This study documented the extremely large differences in design corrosion allowances and permissible wastage allowances for CSD in tankers. This study highlighted the need for a rational process to define corrosion margins and permissible wastage.

The structural capacity of a tanker is related to plating thickness which, in turn, is related to time through projected corrosion rates. An extensive corrosion rates database was developed during SMP I [5, 22]. Routines were written to statistically analyze the variability in the corrosion rates for various structural details, tank types, and locations [5]. This database was utilized to determine how corrosion might be distributed through the ship primary structure as a function of time, service, and protective measures [21]. The two classes of tankers studied during SMP I (165,000 dwt single hull and 190,000 dwt double bottom) were used as the study examples.

As corrosion progresses through the ship structure as a function of time, the time varying capacity (local and global) due to corrosion was determined. A series of parametric studies were performed to define how different rates and locations of corrosion affect the local leak integrity and global capacity of the ship hull structure. It is this inclusion of the time dimension that makes it possible to predict life cycle costs of steel maintenance and renewal and that can ultimately provide a rational basis for optimizing initial design and maintenance strategies [3,21].

Due to the multitude of uncertainties involved in this type of evaluation, reliability analysis methods were used evaluate the implications of the uncertainties. Reliability analysis also provided a convenient framework for the consideration of both ultimate and serviceability (e.g. leak integrity) limit states. Procedures were developed to evaluate the effects of general corrosion on the

strength characteristics (flexure, buckling, etc.) of components and these procedures linked with the corrosion database. Simplified procedures were developed to evaluate the limit state characteristics of the ship hull structure [21]. Verification of the process was demonstrated by application to a tanker that had experienced hull girder failure during an unloading process. Good agreement between the simplified method and the observed failure were achieved.

Study 4 - Repair Management System

The objective of this study was to further develop the computer based Repair Management System (RMS) developed during SMP I to assist tanker maintenance engineers in defining more efficient and effective steel repairs [1]. The RMS incorporated the guidelines on fracture and corrosion repairs and inspections developed during SMP I.

The approach taken in development of RMS was to provide intelligent front-end access to the information required to make repair decisions. The RMS approach combined the use of experience-based knowledge of fatigue of and repairs to CSD and simplified analytical procedures in order to rank repair alternatives according to the expected life and cost of the repair. The user must select the most appropriate alternative from knowledge of the economics of the ship. Depending on the economic goals of the owner, a different repair alternative can be selected [18].

The RMS study developed two primary contributions during SMP II. The first was a procedure to estimate the long-term cyclic stress range characteristics for a particular ship [19]. This procedure was based on the observed time to cracking of a particular CSD and a Weibull long-term stress range distribution. The two free parameters in the long-term stress range distribution were demonstrated to be relatively stable for the purposes of the simplified fatigue analysis [19].

The second contribution was development of stress reduction (or modification) factors that could be used to define how proposed modifications to CSD would change the stress concentration factors. These stress reduction factors were developed from an extensive finite element study of alternative CSD [18, 19, 20].

The RMS was incorporated into a highly interactive PC windows based program that made extensive use of graphical inputs and outputs. Extensive help windows were provided to guide repair engineers through the analyses and evaluations. Example applications were provided to illustrate how this system might be applied in repair yards [18].

SMP III RESEARCH STUDIES

SMP III was conducted during the period 1993 - 1995. During SMP III, four additional research studies were initiated. These studies addressed high priority problems identified during SMP II. The studies were sponsored individually by various members of the SMP I and II projects.

The SMP III studies were: 1) Fitness for Purpose of Cracked CSD in Tankers, 2) Development of a Ship Structural Integrity Information System - SSIIS, 3) Maintenance of Marine Structures: A State-of-the-Art Summary, and 4) Inspection of Marine Structures.

Study 1 - Fitness for Purpose of Cracked CSD

One of the most hotly debated topics that surfaced during SMP I was that of cracked CSD [3]. One community insisted that ships should not sail with cracks in their primary structure. Another community insisted that their ships did not sail with cracks in their primary structure. The MSIP study had clearly indicated that all structures could be expected to have cracks in their primary structure; it was a case of where, how big they were, and how they might affect the capacity and serviceability of the ship [2].

During SMP I, the possibility of developing S-N curves that reflected or incorporated different sizes of flaws was investigated [26]. Linear fracture mechanics formed the basis for such a development. Given the discovery of a crack in a CSD, these 'equivalent S-N' curves could be used with traditional fatigue methods to determine what the remaining life (time to reach critical crack size) might be. During SMP II, this concept was further explored and developed [39-46].

The first portion of the study resulted in development of S-N curves for welds that reflected the presence of different lengths of through-thickness cracks based on the results from linear fracture mechanics [39]. A computer program was written to facilitate performing the necessary fracture mechanics computations [40].

The second portion of the study explored the problems associated with 'load shedding' or load redistribution due to boundaries of the CSD or intersections of the propagating cracks with other structural elements. A first-generation analytical approach was developed to address load shedding effects [42, 43].

In the third portion of the study, the applications of the results from the previous two portions of the study were integrated into an example application that involved one of the classes of ships studied during SMP I. A probability based inspection and repair methodology was developed and programmed based on the earlier developments in SMP I [7] and the developments in SMP III [41].

Study 2 - Ship Structural Integrity Information System

The SSIIS project had two main objectives. The first objective was development and documentation of standards for development of a computerized ship structural integrity information system for tank ships with a focus on the inspection and fatigue durability characteristics of CSD. The second objective was demonstration of the application of these standards with a prototype PC based database and reporting system. This prototype database and reporting system was focused on the U. S. Coast Guard requirement for a Critical Area Inspection Plan (CAIP).

The background for the SSIIS was developed in the previous MSIP study [2]. The SSIIS was identified as one of several primary components in a comprehensive ship quality information system [31]. Other components addressed ship equipment and facilities, ship operations, and human and organization factors involved in ship operations and maintenance. SSIIS was one part of a comprehensive life-cycle, full-scope information and communications system intended to help improve the management and quality of commercial ships.

The project reviewed a variety of commercial, classification society, government agency, and owner / operator databases with the objective of identifying the advantages and disadvantages of these databases as they might be adopted into the framework of a comprehensive SSIIS. The study also reviewed a variety of CAIP reports that had been submitted to the U. S. Coast Guard with the objective of identifying the strong and weak points of these reports and defining how the generation of and formats for the reports might be improved in the SSIIS.

The study identified how advanced database technology and the availability of powerful and economic computer systems and storage capacity might be utilized to develop an integrated database system for ships [31]. A modular based system was defined that would allow components of SSIIS to be developed in an incremental fashion. An 'alpha' version of a SSIIS CAIP was developed.

In the second stage of this study, particular attention was given to how the process of ship surveys and inspections might be 're-engineered' so that the overall efficiency of the process of gathering , analyzing, reporting, and communicating information might be improved and made more efficient [11]. Such a process could provide positive incentives to develop and implement the SSIIS. Without this process, SSIIS was seen by most ship owners and operators as representing a 'cost' that could be avoided. Also, the advantages of interfacing the development of the SSIIS with the operations related components were explored for the same reasons: to provide positive incentives and to free available resources to develop and implement a comprehensive ship quality information system that could lead to safer and more efficient ship operations. A 'beta' version of a SSIIS CAIP was developed and its application illustrated [11].

Study 3 - Maintenance of Marine Structures

The objective of this study was to provide an overview of the current state of the art of maintaining marine structures as documented by Ship Structure Committee reports over the past four decades. The study documentation was intended to help provide a readily accessible and updatable database for development of future research planning [16]. Each part of the database and the associated report related to the strategic plan for SSC research developed by the Committee on Marine Structures of the National Academy of Engineering. The database was developed in Microsoft FoxPro for Windows.

The topics in the project report addressed included design for durability, maintenance, and repair; probability based design; steel structure assembly and welding; structural fastenings; vibration control; fatigue; structure fractures; corrosion protection and rates; corrosion surveys; inspections; non-destructive testing; in-service monitoring and instrumentation systems; database systems; and the SSC report database [16].

Study 4 - Inspection of Marine Structures

The objective of this study was to develop a better understanding of the probability of detection of fatigue cracks in tanker CSD [8, 15]. This factor exerts a major influence on the timing, effectiveness, and utility of probability based inspection and repair results [8, 41].

Based on a review of the literature and interviews with inspectors and ship surveyors, a model of the factors that influence the probability of detection of fatigue cracks was developed [10]. This study included a review of the treatment of the probability of detection of fatigue cracks in aviation, nuclear power, manufacturing equipment, and other marine structures (e.g. offshore platforms).

Four approaches to analyzing inspection performance were identified and evaluated for application to tanker inspections and surveys [10]. These included expert judgment, laboratory experiments, in situ experiments, and benchmarked inspection data. The results of the study suggested that in situ experiments, benchmarked inspection data, and a hybrid (in situ test on an out-of-service vessel) are potentially useful approaches to further develop inspection probability of detection characterizations [10].

An example of the use of benchmarked inspection data was developed during this study, demonstrating the feasibility of the approach. This exploratory study showed that inspection performance can vary greatly in different regions in the same vessel. Most importantly, this study revealed that the 'readily detected' crack is significantly larger than that estimated by most inspectors and analysts (e.g. a

90 % probability of detecting cracks with through thickness lengths in the range of 300 to 400 mm using traditional visual techniques [10].

CONCLUSIONS AND OBSERVATIONS

After six years of research, what was accomplished? The answer to this question depends on who is answering it. The following answers and observations are those of the author.

The original vision of developing practical tools and procedures for analyses of proposed ship structural repairs clearly were reached. In addition, the original vision of preparing guidelines for the cost-effective design and construction of lower maintenance ship structures which could also facilitate inspections and repairs clearly was realized. The products from this effort summarized in the list of references are an example of the results that can be developed from an intensive, coordinated and applied research program performed by a university for industry.

As a result of these efforts, it is contended that ship maintenance technology has been significantly advanced and made more practical for engineering use. The research studies have significantly advanced the technology of durability analysis, design, and repair (corrosion, fatigue cracking); inspections; and ship maintenance information and communication systems. In the author's opinion, one of the most important products of this research have been the students that have been educated and graduated to government and industry positions. These students represent the long-term potential of industrialization and application of the technology and understanding developed during the SMP.

Perhaps as important as any of the technology developments was the industry - classification society - owner / operator - builder / repairer - government technical forum that was developed and exercised. This forum repeatedly provided an open and neutral ground upon which debates of old and new ideas could be conducted. The organization acted to help disseminate the collective and impressive experience and wisdom of the participants. This forum acted to help develop important insights into what might be done in the future to improve the quality and efficiency of the durability and maintenance of commercial ships.

Were the tools and technology developed by the SMP perfect or complete? Were they without limitations? Did all of the studies reach all of their original objectives? The answer to these questions must be no. The products of this series of efforts represents the best that could be developed by a university, with the resources and objectives of a university, by dedicated students and faculty, within the available time, money, experience, and information provided to perform the studies. Perhaps, all those involved in this series of projects should appreciate what they were able to accomplish, not what they were not able to accomplish.

What was not accomplished? In the author's opinion, the primary shortfall was in the industrialization and application of the technology developed during the SMP. The potential for this shortfall was clearly recognized by the researchers and sponsors / participants during the SMP. However, the means for addressing this shortfall were not developed, and in most cases, have not been developed.

Many of the sponsors and participants and their engineering service contractors and consultants face very significant 'barriers' to being able to industrialize and apply this technology. Down-sizing, out-sourcing, cost-cutting, and 'early retirements' that have invaded all segments of this industry have exacerbated the situation. Unless and until these barriers are surmounted, the technology will not be applied and further developed. There must be equitable and long-term positive incentives and resources to further develop, industrialize, and utilize the technology. Wise industrialization and application of the SMP technology represents the next important challenge to enable the true long-term goals of this research to be reached.

ACKNOWLEDGMENTS

This series of research projects represents efforts and support provided by a large number of individuals and organizations. Faculty colleagues, graduate students, and staff labored hard and with care to make these efforts produce useful results. It was not easy. Their contributions are gratefully acknowledged.

Research sponsors, participants, and consultants have provided important guidance to the research. Of particular importance was the guidance provided by the Project Technical Committees and their chairmen. The continuing financial, technical, and political support provided by the Ship Structure Committee, the Maritime Administration National Maritime Enhancement Institute, the U. S. Coast Guard, the American Bureau of Shipping and other Classification Societies, the ship owners and operators, and the new build and repair yards have been of critical importance to this work. Without these resources, this work would not have been possible.

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Table 1- SMP I sponsoring and participating (*) organizations

Sector	Organization
Government	U.S. Coast Guard Military Sealift Command Maritime Administration Naval Sea Systems Command National Defense Headquarters (Canada)
Classification	American Bureau of Shipping Bureau Veritas Lloyd's Registry of Shipping* Germanischer Lloyd*
Shipyard	Lisnave Estaeiros Navais De Lisboa S.A. Jurong Shipyard Ltd. Ishikawajima-Harima Heavy Industries Co. Ltd. Mitsubishi Heavy Industries Ltd. Newport News Shipbuilding & Dry Dock Daewoo Shipbuilding & Heavy Machinery Ltd West States Inc.*
Owners	Amoco Transport Co. Arco Marine Inc. B.P. Marine Inc. Exxon Company International Chevron Shipping Co. Mobil Shipping and Transport Co.

Table 2 - SMP I Studies and Researchers

Project Responsibility	Name, Organization
Study 1 - Fatigue	Prof. Robert Bea, UCB Prof. Stig Berge, U. of Trondheim, Norway Y-k Chen, ABS Rolf Schulte-Strathaus, Research Assistant Espen Cramer, Research Assistant Peter Friis-Hansen, Research Assistant
Study 2 - Corrosion	Prof. Robert Bea, UCB Y-k Chen, ABS Rob Pollard, Research Assistant Roger Mayoss, Research Assistant
Study 3 - Interaction of Details with Adjacent Structure	Prof. Randolph Paulling, UCB Jim Stear, Research Assistant Tao Xu, Research Assistant
Study 4 - Repairs	Prof. Robert Bea, UCB Robert Baker, Research Assistant Martin Cepauskas, Research Assistant Keith Gallion, Research Assistant
Study 5 - New Build Guidelines & Inspections	Prof. Robert Bea, UCB Prof. Laura Demzetz, UCB Kai-tung Ma, Research Assistant Lt. Rob Holtzman, Research Assistant
Study 6 - Software Development	Prof. William Webster, UCB Scott Morris, Programming Assistant John Reed, Programming Assistant
Consulting to All Studies	Prof. Alaa Mansour, UCB Y. K. Chen, ABS J. Conlon, PTC Chairman, ABS

***Rational Basis for Corrosion Limits on
Tankers***

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1. INTRODUCTION

1.1. OVERVIEW

In the absence of a general analytical design tool for the purpose of judging the allowable extent of corrosion wastage in oil tankers, this particular area of ship structural analysis has been given to experience-based guidelines as the only feasible treatment. In the rule books of today's classification societies, the subject of "allowable wastage" is generally absorbed into simple equations that provide some indication of a minimum strength standard for newbuild designs and renewals. While safe ships have been built and are continuing to be built under the guidelines of these rule requirements, the provisions involve a startlingly simple set of variables when one considers the complexity and diversity of the structures, the environments, and the operation philosophies involved in today's tanker trade.

This report summarizes the work done under the sponsorship of Ishikawajima-Harima Heavy Industries (IHI) and Mitsubishi Heavy Industries (MHI) to develop a rational approach to defining corrosion limits in tankers. The objective of this project was to make advances in the area of setting allowable limits for the wastage of tanker structures based on a procedure involving rational analytical techniques as an adjunct to the traditional, experienced based approaches.

1.2. REVIEW OF CURRENT PRACTICE

The prediction of the actual loss in the structural capacity of the ship structure due to corrosion can only be dealt with on a case-by-case basis. The prediction must be based on the full facts of each specific design. The

methods by which these predictions are made are, by nature, unique to each design and no attempt will be made to review them. What is reviewed here are the criteria set out by the classification societies which define minimum requirements for hull strength and how appropriate forms of corrosion control can result in allowances for scantlings below the minimum values.

A unified hull girder longitudinal strength standard has been established by the International Association of Classification Societies (IACS) which all ships, new and existing, must satisfy. This standard, which comes in the form of a simple formula for the minimum midship section modulus, embodies the vast experience that has been accumulated by the members of the classification societies and has provided adequate safety for the world's fleet of ocean-going vessels. The standard was most recently revised in 1989 and is as follows:

S7 Minimum Longitudinal Strength Standards

S7.1 The minimum midship section modulus at deck and keel for ships $90\text{ m} \leq L \leq 500\text{ m}$ and made of hull structural steel is:

$$W_{\min} = cL^2B(C_b + 0.7)k \quad (\text{cm}^3)$$

where L = rule length (m)

B = rule breadth (m)

C_b = rule block coefficient (≥ 0.60)

$c = c_n$ for new ships

$c = c_s$ for ships in service = $0.9c_n$

$$\begin{aligned} c_n &= 10.75 - \left(\frac{300 - L}{100} \right)^{3/2} \quad \text{for } 90\text{m} \leq L \leq 300\text{m} \\ &= 10.75 \quad \text{for } 300\text{m} \leq L \leq 350\text{m} \\ &= 10.75 - \left(\frac{L - 300}{100} \right)^{3/2} \quad \text{for } 350\text{m} \leq L \leq 500\text{m} \end{aligned}$$

k = material factor

= 1.0 for ordinary hull steel

< 1.0 for higher tensile steel

S7.2 Scantlings of all continuous longitudinal members of hull girder based on the section modulus requirement in S7.1 are to be maintained within 0.4L amidships.

However, in special cases, based on consideration of type of ship, hull form and loading conditions, the scantlings may be gradually reduced towards the end of the 0.4L part, bearing in mind the desire not to inhibit the vessel's loading flexibility.

S7.3 In ships where part of the longitudinal strength material in the deck or bottom area are forming boundaries of tanks for oil cargoes or ballast water and such tanks are provided with an effective corrosion protection system, certain reductions in the scantlings of these boundaries are allowed. These reductions, however, should in no case reduce the minimum hull girder section modulus for a new ship by more than 5%.

By establishing this strength standard based on the acquired experience of successful designs, a safety margin to account for the inevitable wastage of hull steel structures has been built in to the formula. The individual classification societies then go on to provide exceptions to the rule to account for unusual design concepts and the use of corrosion protection systems [1]

1.3. PROBLEM DEFINITION

It is clear that much still needs to be done to study the *problem* that corrosion presents to tanker structures even before *solutions* can be obtained. There are many sources of uncertainties that are involved in this particular aspect of the aging of a vessel, and their effects, when combined, lead to a very complicated problem. The challenge, therefore, is two-fold. First, an overall approach must be developed to coordinate the vast amount of information, data, and general theoretical concepts involved. Secondly, each component, each module of the procedure must be generated using the most efficient and accurate analytical tools and theories available given the limitations of computational resources.

There is a vast difference between the structural analysis of a particular vessel under specific conditions and the general treatment of an entire tanker fleet. Highly sophisticated proven techniques are available to accurately predict the strength of ships' structures. For example, non-linear finite element analyses exist to compute the capacity of steel structures to resist failure in a variety of failure modes, and numerical techniques are

available to accurately describe the loading environment and load effects, but these techniques are only applicable to highly detailed case-specific studies, and they come at great cost in computer time and resources.

In contrast, as mentioned previously, the foundations of the classification society corrosion wastage criteria and structural guidelines consist of very broad general methods that can only be used as guidance. While these guidelines provide a quick evaluation of a newbuild's performance or an existing ship's condition, they have no rational analytical basis, and, as quantified by Shama [2] a large undue cost can be potentially developed as a consequence of an irrationally designed structure.

What follows is a description of the attempt made during this one-year project to bridge the gap between the specific and general methods of determining corrosion wastage limits. This implies the development of a rational analytical tool that is not too expensive to use, can be used interactively (as in the early stages of design or during a routine inspection), and can be applied to the general tanker fleet. It is with this goal in mind that the project was undertaken.

1.4. SOLUTION ALGORITHM

1.4.1. Life Assessment

The task of defining corrosion limits for a complicated structural system such as an oil tanker is, in fact, just one aspect of what can be generally termed the Life Assessment paradigm. A particular vessel can age in many ways over its lifetime, and the purpose of a life assessment is to develop some global index that describes the condition of the aging vessel in terms of safety or reliability or serviceability, etc. It follows naturally that the development of a life assessment procedure will provide a convenient framework from which to begin defining these corrosion limits.

The main result of a life assessment is a description of how the defined SI (inverse measure of the probability of "failure") behaves as the vessel ages, i.e. it determines $\beta(t)$, where β is the safety index and is a function of time. Once β falls theoretically below a predetermined minimum level, β_{\min} , the

time at which this occurs can be noted, and limits can be prescribed based on how β was defined and what caused it to drop below the allowable level. It is important to note that the initial limit (β_{\min}) is determined from considerations such as economic, political, and social issues. It is then the variables that constitute the definition of β in which the engineer is interested and to which limits will be assigned.

1.4.2. Time Variability and Corrosion Rates

The time dimension in this particular application of life assessment methods is constructed by the inverse of corrosion rates multiplied by steel thicknesses. For this reason, accurate corrosion rates are an essential part of this project. In the first year of the *Structural Maintenance for New and Existing Ships Project*, Pollard focused on the determination of corrosion rates in tanker internal structures. A large amount of wastage data was gathered from a wide range of gauging reports. Statistical analyses were performed to determine corrosion rate trends based on the type of tank, the type of structural detail, and the relative location of the detail within a tank. It is this type of information that facilitates a more realistic, rational view at monitoring the decline of a vessel's structure over the course of its design lifetime.

1.4.3. Reliability

Gauging corrosion rates and their effect on ships' structures is a very uncertain proposition, therefore, it is practically useless to approach this problem from a purely deterministic point of view. Any overall safety index that can be applied to this problem is itself a random variable in the extreme, and the uncertainties grow significantly the further into the future that β is projected. Much of the uncertainty is simply inherent in this very complex problem and can not be reduced. However, a large portion of the uncertainty will come from modeling errors which reflect the limitations of the available theories.

1.5. SHIP MAINTENANCE INFORMATION SYSTEM (SMIS)

1.5.1. Overview

The ever increasing availability of computer resources and the growing refinement of analytical techniques make it possible to take a more analytical angle at the problem of predicting that point in a vessel's life when the degree of corrosion wastage renders the structure *unreliable*. Naturally, the design of a computer application is an integral part of any attempt to develop a solution to a problem of such complexity as this one. Therefore, along with the engineering considerations involved in this project, the preliminary design of an information system, the Ship Maintenance Information System, is interwoven with the theory.

The goal implicit in the development of such a system is to develop a PC application based on the developed approach which has the following qualities:

- Efficiency - Intelligent use of available resources.
- Flexibility - Built in capability for customizing the system.
- Reliability - Robust system with error checking and input validation procedures.
- Maintainability - Clear and complete system documentation both of the system design and implementation.
- Usability - Can be applied by a wide range of users.
- Accuracy - Yields reasonable and useful results.

As a supplement to the theoretical effort aimed at achieving the stated objectives, the development of a model program was proposed to illustrate the point. This report, therefore, also documents the development of the Ship Maintenance Information System (SMIS), a PC based system that was modeled after the theoretical approach developed during this one year project. The SMIS is intended to be an illustration of how such an approach could be implemented.

1.5.2. Primary Programming Considerations

The lifetime structural characteristics of a vessel fleet constitutes an extremely complex physical situation which, to model, represents a formidable and sometimes overwhelming task. The amount of data required to represent even one year of a vessel's life could fill volumes. In order to treat the many aspects of this subject, it is necessary to break this large amount of data up into small pieces that can be handled one step at a time in

manageable portions. A relational database immediately suggests itself as a means by which to achieve this organization.

FOXPRO for WINDOWS is a Microsoft relational database management system. In addition to providing the tools by which to manage large amounts of related data, FOXPRO also provides a programming language which allows the development of a sophisticated user interface and the precise control of information flow. With these powerful capabilities provided, the entire application could be developed from within the FOXPRO environment.

However, while the underlying data structure is easily constructed and the management of the data can be framed in a "user friendly" interface, there are a number of aspects of the procedure that involve a significant amount of "number crunching," or the repeated manipulation of large data sets. These procedures are not suited to the data management environment, but rather to the speed and simplicity of FORTRAN programming.

1.5.3. Design Limitations

In an attempt to design this application, it is important to realize the limitations that are implicit in the scope of this one year project. Only the first of the two main challenges stated in the overview was addressed, i.e. only the general *approach* was modeled. The scope of the rigorous technical aspects was reduced to ensure that the design itself was completed. In view of this, the following general simplifications were made:

- It was not possible to address all of the failure modes that are the result of corrosion in hull structures. The strength (capacity) analyses were focused on failure due to buckling instability of the ships' structural components. Failure due to corrosion fatigue and cracking were not dealt with directly.
- The treatment of corrosion rates was limited to general *uniform* wastage. Pitting and grooving types of corrosion were not treated
- Simplified Reliability Methods were used to limit the complexity of the System Reliability problem to a manageable level.

1.5.4. Context Diagram

Shown in Figure 1.1 is the context layer diagram for the theoretical SMIS application. A context layer data flow diagram represents the general interface between the application and the external sources and sinks of information. This particular diagram shows that a combination of vessel specific data and fleet wide data are input into the system where they are used to describe the availability (a general description of reliability) of the vessel projected over time. The system then generates a report of corrosion limits based on the results of the life assessment. The components of this system will be developed over the next three chapters.

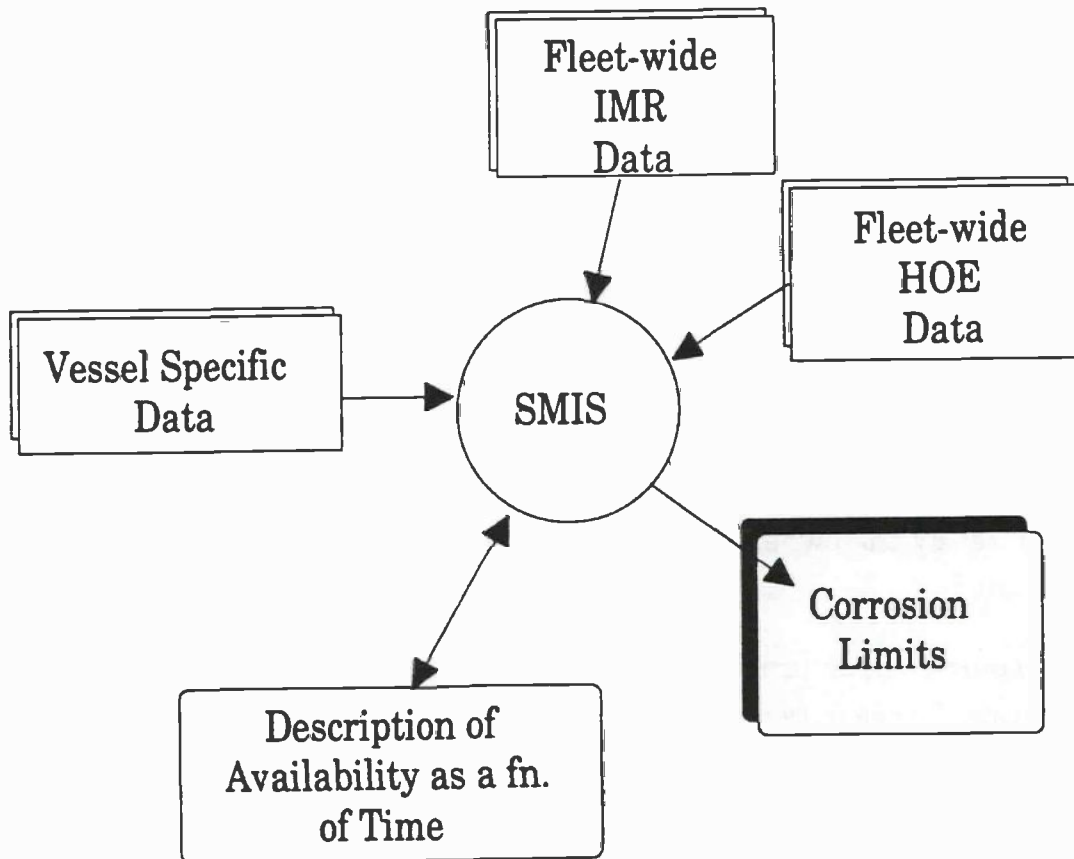


Figure 1.1: SMIS context layer diagram

2. LIFE ASSESSMENT

2.1. AVAILABILITY

A life assessment procedure provides a convenient framework from which to prescribe limiting conditions on any one of the many factors that affect the reliability of a vessel. Nippon Kaiji-Kyokai developed a model of a life assessment procedure for ships and offshore structures that could theoretically provide a comprehensive indication of the condition of a particular vessel at any one time during its operational lifetime. In this life assessment approach, the reliability is defined in terms of the **availability** of the vessel, a requirement set by the owners/operators that describes the percentage of time that the vessel *must* be in service.

During a ship's lifetime, it spends a certain amount of time being inspected or repaired. These "outages" can be attributed to three major categories of events:

1. Planned Inspection and Maintenance Routines (IMR) either required by law or set by the owners themselves (whichever is the more conservative practice).
2. The repair of structural failures that are due to a weakness in the ship's structure. These outages become more frequent as the ship ages.
3. The repair of structural failures following accidents that are caused by unforeseen extreme loading conditions and/or human and organizational error (HOE).

A numerical quantity called the *unavailability* can be defined as that fraction of time that the vessel is out of service (years-per-year) due to each of the above three categories. Respectively, these components of the total

unavailability, U , can be designated as U_{PL} , U_{SF} , U_{OT} . The availability, Av , is expressed as:

$$Av = 1 - U = 1 - (U_{PL} + U_{SF} + U_{OT})$$

If a design Av is given, and provided that the components of unavailability can be accurately calculated or predicted over the life of the vessel, judgments can be made concerning the acceptable or allowable deterioration of the vessel's structural strength. The figure below schematically shows this process in terms of the above quantities.

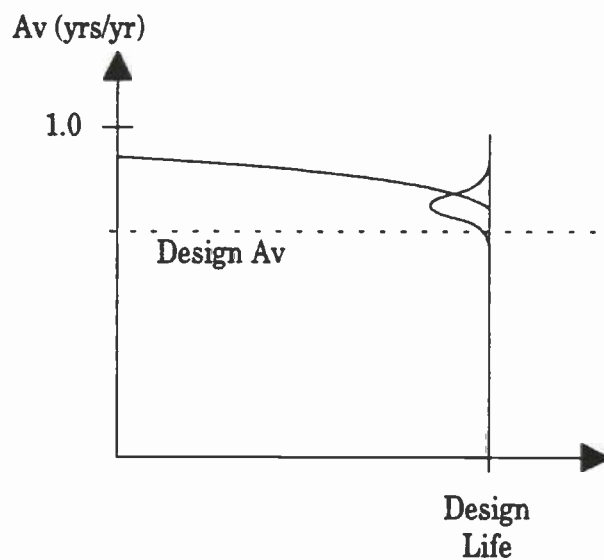


Figure 2.1 Availability as a Function of Time

In order to chart the values of unavailability over time, a combination of detailed structural analysis, experience, and a wealth of data are needed.

2.2. SUPPORT DATABASE

A database structure is needed to support the types of analyses involved in the assessment. The following three major database components serve as a starting point for the design of the required database structure:

- A preliminary survey database that would contain, among other things, information concerning the vessels particulars, its cargo, its route, its corrosion protection system, its inspection and maintenance routine, its intended service life, and its prescribed availability. (design A_V , U_{PL})
- A database of records and statistics of unforeseen accidents, instances of human error resulting in accidents, etc. (U_{OT})
- A database containing referential data such as gauging reports, crack inspections, the location and nature of structural failures, the time it took to repair them, etc. (U_{SF})

The nature of the analytical tool being proposed requires that a database management system be designed to maintain the data and control the flow of information. Without such a system, the tool would be difficult to employ, and then only by a small range users. Shown in fig. 2.2 is a data flow diagram (DFD) depicting the role of the database management system within the context of this project.

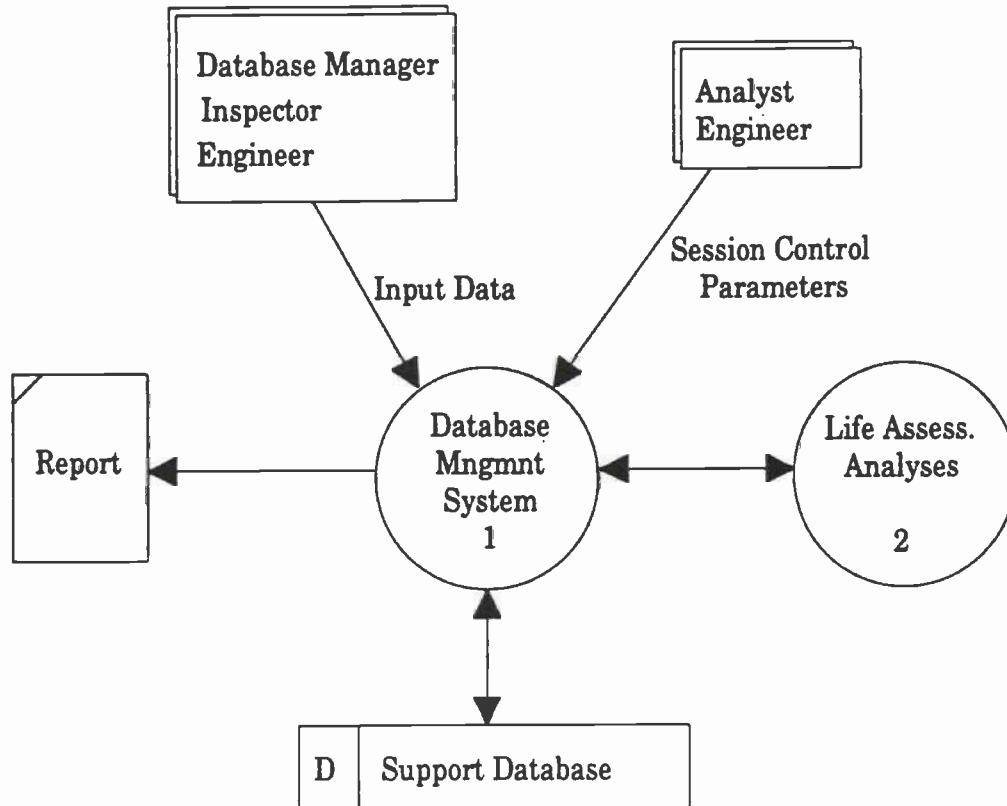


Figure 2.2: First layer DFD

As indicated in fig. 2.2, the SMIS database management system must be designed to accept input from a range of users, allow an engineer to control an analytical session, maintain and manage the data, act as a driver for the analytical routines, and produce reports to ease the interpretation of the results.

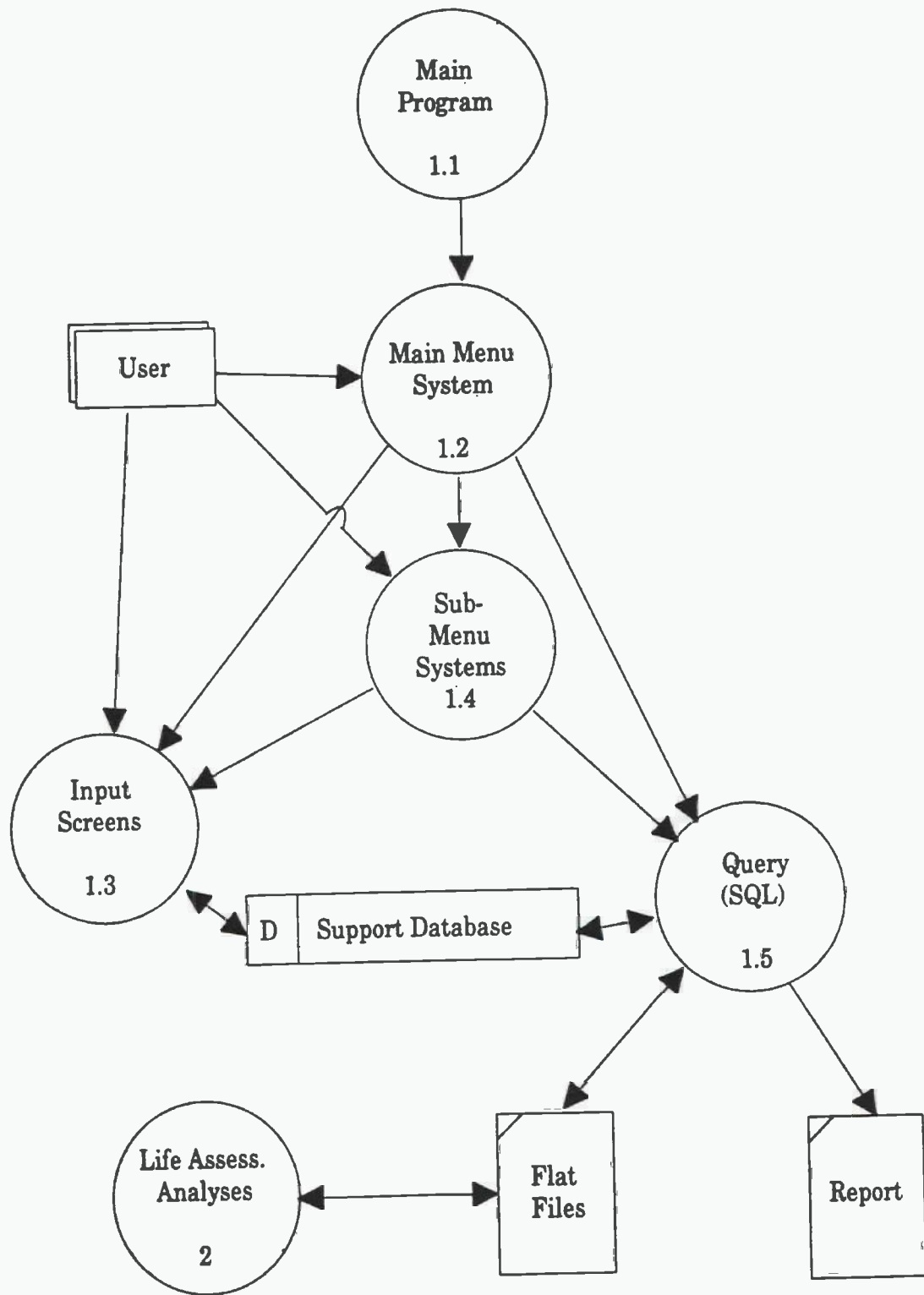


Figure 2.3: Second layer DFD - The Database Management System

Shown in fig. 2.3 is a more detailed view of the components of the database management system that are required to achieve its purpose. The exact structure of the support database, including the format of the data and how it will be used in the analysis will be discussed in the following chapters.

2.3. UN-AVAILABILITY

Figure 2.4 shows the relationship between the support database, the general analysis modules, and the three components of unavailability.

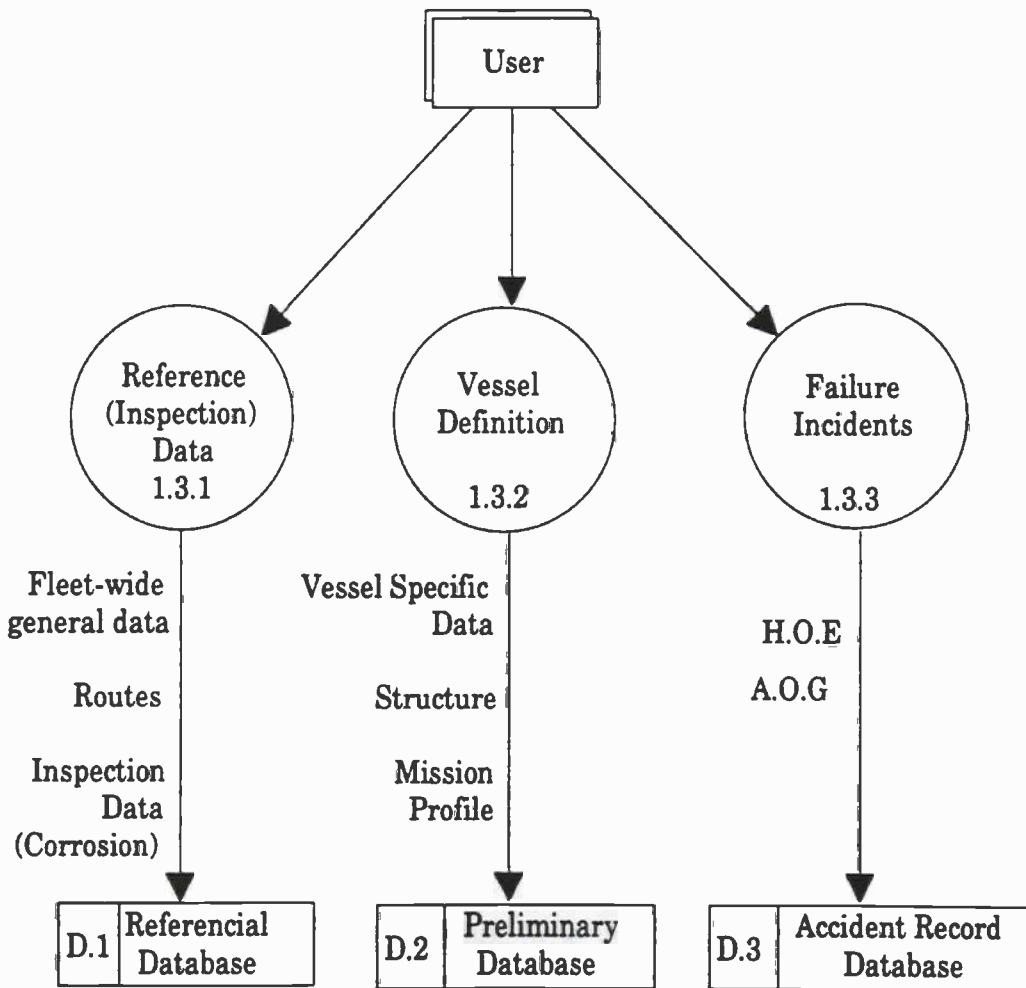


Figure 2.4: Second layer DFD - Life Assessment Analyses

2.3.1. **U_{PL}: Planned Outages**

The unavailability due to planned outages and the vessel's IMR can be derived from the information that is contained in the Preliminary Survey database. This quantity which may vary with time (the owner might think it necessary to decrease the amount of time between inspections as the ship gets older) must be supplied to the database.

2.3.2. **U_{OT}: Human Error and Other Causes**

The unavailability due to accidents and human error can be evaluated based on past experience. This is the reason for the database containing records and statistics of such events.

2.3.3. **U_{SF} : Unavailability due to Structural Failure**

The majority of the analytical effort undertaken in this project surrounded the calculation of the unavailability due to structural failure. This effort involves: collecting and categorizing the incidents of failure, providing a statistical interpretation of the corrosion wastage data, developing a statistical model of the prescribed loading condition, developing a best estimate of the structural capacity, and finally, through reliability methods, obtaining the annual probability of failure for each mode of failure and for each year of the service life.

U_{SF} , as defined by NK, is as follows:

$$U_{SF}(t) = \sum_{n=1}^I \frac{MTTR_n}{MTTR_n + MTBF_n(t)}$$

where there are I failure modes, and MTTR and MTBF are defined by the following:

MTTR_{*i*}: Mean time to repair failure *i*. (obtained from the structural failure incident database)

MTBF_{*i*} : Mean time between failures in the *i*th mode.

The mean time between failure for a particular mode (in years) is simply the inverse of the annual probability of failure for that mode. The calculation of the probability of failure in a particular mode is a subject of reliability analysis that is well known throughout the industry. For a given loading condition (Demand) and a predicted structural strength (Capacity) there are several levels of complexity that may be employed to obtain the probability of failure. There is a great deal of analysis, judgment, and experience that is required before meaningful results can be realized.

2.4. FAILURE MODES

For the purpose of estimating USF , it is necessary to collect structural failure incidences into general categories from which information can be drawn that will be applicable to any vessel in the fleet. In reality, no two structural failure incidences are exactly alike. However, these incidences can be classed, and it is these classes or modes of failure upon which the analytical tool will operate. According to Daidola et. al. [3] in terms of the longitudinal strength of a hull girder, there are five general categories of failure:

- Yield failure due to bending of the ship considered as a beam
- Compression instability buckling
- Brittle fracture
- Fatigue fracture
- Ultimate plastic collapse

These five general modes can be further separated into categories based primarily on the type of structural sub-elements that are affected. Only compression instability buckling and ultimate collapse are treated in this study; although, given the appropriate support data and analytical techniques, the overall procedure could be extended to treat the other three general categories of failure.

It is necessary to calculate the Mean Time Between Failure (MTBF) and the Mean Time To Repair (MTTR) for each failure mode that can be identified as being a likely to occur during the design lifetime of the vessel. The development of MTBF for a particular mode is an analytical matter that will be discussed in the next chapter. MTTR, on the other hand, must be obtained from fleet-wide data and experience in a manner similar to that for obtaining corrosion rate information. Therefore, under the heading of Referential Data, the support database must contain information in a form that will yield appropriately categorized repair information

This categorization process requires a great deal of shipyard experience and data and could potentially be carried out to a high level of detail. Unfortunately, this type of data is generally held as confidential and was not available during this study. However, some additional general categorization can be made which can serve as an illustration and a starting point for further work on this topic.

In the case of compressive instability buckling, repair information can be separated into the following five general categories:

Class I - failure leading to the replacement of longitudinal stiffeners (tripping, stiffener induced buckling, plate induced buckling)

Class II - failure leading to the replacement of internal plating between stiffeners (buckling of plating between stiffeners)

Class III - failure leading to the replacement of shell (external) plating between stiffeners (buckling of plating between stiffeners)

Class IV - failure leading to the replacement of an internal stiffened panel (overall grillage buckling)

Class V - failure leading to the replacement of an external stiffened panel (overall grillage buckling)

While these five classes cover nearly all of the types of compressive instability buckling failures, some additional information must be supplied in order to get accurate information regarding how much time a particular

vessel will be out of service because of them. For example, there is a high degree of correlation between failure modes and in the case of an entire stiffened panel being replaced, including the time it takes to repair each stiffener on the buckled panel would result in an overestimation of the repair time. These difficulties can be dealt with but only if the required information is provided.

3. STRUCTURAL FAILURE, U_{SF}

3.1. OVERVIEW

The determination of the unavailability due to year-to-year type structural failures, U_{SF} , comprises the major analytical effort of this Life Assessment routine. A large amount of data analysis as well as theoretical concepts are required to model a particular vessel's service lifetime.

As mentioned in the previous chapter, U_{SF} has been defined by NK as a function of the mean time between failure incidences and the mean time that the vessel is unavailable while the failure is being repaired.

Since specific types of failure tend to occur more often as a vessel ages, U_{SF} is a function of time and the particular failure modes that are associated with the vessel. $MTTR_n$ (Mean Time To Repair failure mode 'n') is a quantity that is obtained for each failure mode through the analysis of Inspection and Maintenance Routine (IMR) data collected and stored in the support database and will be assumed to be constant over the life of the vessel being examined. $MTBF_n$ (Mean Time Between Failure mode 'n') is cast in terms of years, and is defined as the inverse of the annual probability of failure for the n^{th} failure mode. These probabilities will increase in time due to wastage of the internal structure. Since the above summation is over all possible failure modes, there will be a marked increase in U_{SF} over the lifetime of the ship.

3.2. GENERAL PROCEDURE

The task of developing an estimate of the annual probability of failure for any given failure mode can be divided into a number of modules or

subroutines each of which constitute a major component of the calculation. These modules are listed below:

- Vessel Definition Module
- Failure Definition Module
- Capacity Module
- Demand Module
- Reliability Module
- Corrosion Module

The general procedure involves defining a section of a particular vessel's hull and the failure modes associated with it. For example, many incidences of buckling occur around the midship section where the primary bending moment is generally at its peak. These incidences might range from very localized buckling of plating between stiffeners to overall collapse of the primary structure.

Next, the loading effects are determined based on a particular vessel's geometry and loading environment. The capacity of the structure and its elements are then calculated and compared with the demands of the seaway loads. This involves the use of reliability methods that treat both individual structural elements and systems of elements. Combining knowledge of the resulting probability of failure and knowledge of the consequences (repair time) of failure for each mode results in a calculation of USF for one given time step.

Using the corrosion data contained in the referential database, corrosion rates can be calculated and applied to each element of the defined section. The designated time step defines the extent of the wastage of these elements and their capacities are then recalculated. Applying the same loads as before, the procedure for determining USF is repeated. The next time step is made, the section is corroded further, and the entire process is repeated until USF is defined over the entire Design Life of the vessel.

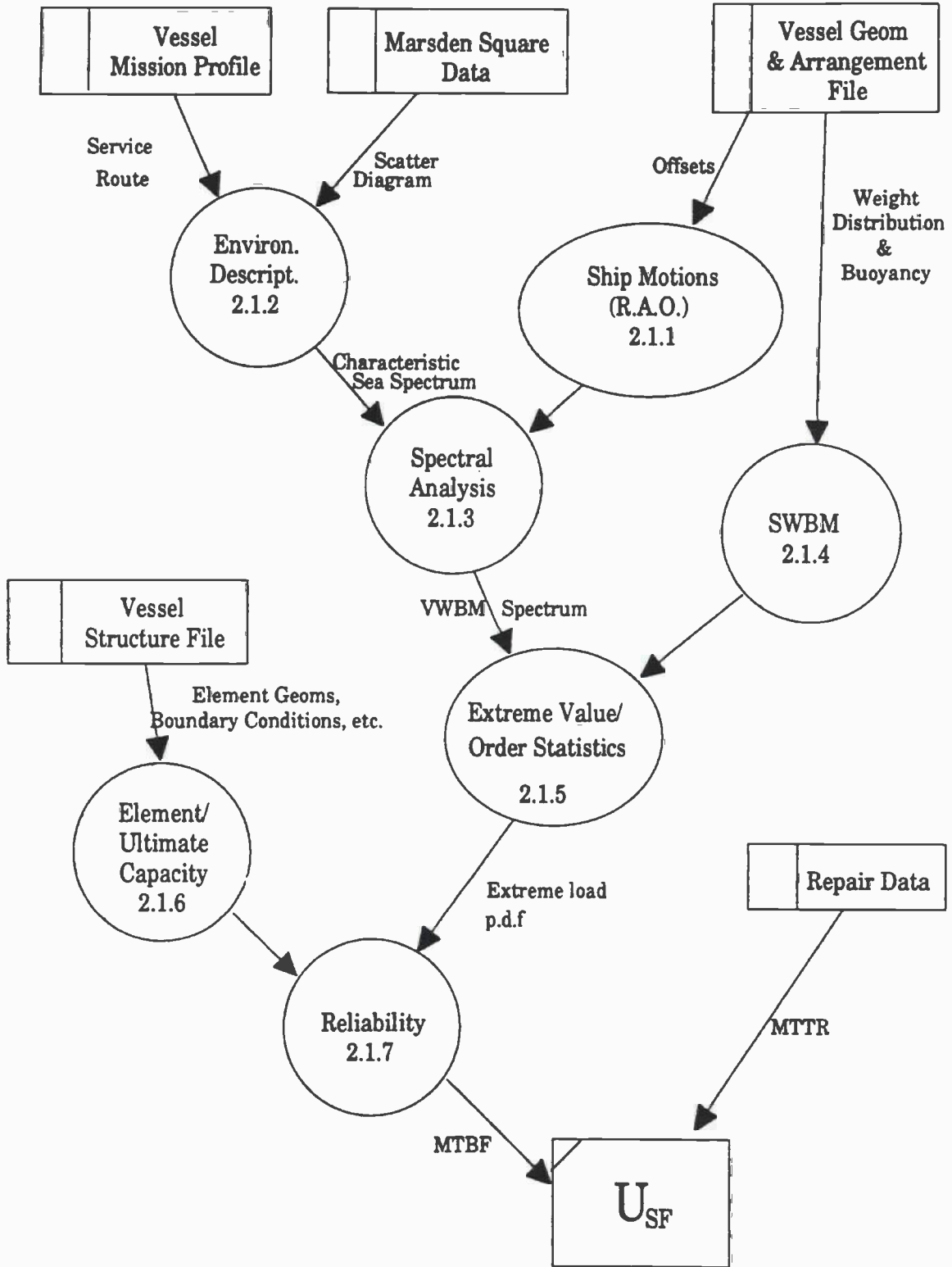


Figure 3.1: Overview of the U_{SF} Calculation

Figure 3.1 contains a data flow diagram for the calculation of U_{SF} . Components of each module in the procedure and their relationship of the support database components are depicted.

With the general procedure outlined above, what follows is a description of each module and how it fits in to the calculation of $U_{SF}(t)$.

3.3. VESSEL DESCRIPTION MODULE

Purpose: To provide all of the vessel specific information that will be needed as input to the analyses that follow in subsequent modules.

In order to complete the analyses outlined in the preceding section for a specific vessel, the preparation of a large amount of preliminary data is required. Specifically, extensive information must be provided on the physical structure of the vessel as well as its intended operational performance or *mission profile*.

The Physical Vessel

There are two main aspects involved in the physical description of a vessel. One aspect involves the description of the hull geometry and weight distribution for the purpose of calculating stillwater and vertical wave bending moments, and the other involves a description of the internal longitudinal structural components for the purpose of calculating the capacity of the hull to resist these moments.

With the obvious exception of the outside hull form, an oil tanker is generally made up of rectangular cells. It is divided internally by decks, transverse bulkheads, and longitudinal bulkheads, which constitute planar divisions parallel to the base plane, section plane, and centerline plane, respectively. Therefore, a logical point to begin the vessel description is with the designation of these major internal divisions. The configuration of the cell spaces is naturally a complicated one, and therefore, simply stating the number of each type of division will generally not lead to an accurate description of the internal spaces. In order to make this description possible, it is necessary to assume that a hierarchy exists, i.e., one type of structure represents the primary division, another type constitutes the secondary, etc.

Shown in Fig. 3.2 is one possible model for this hierarchy depicted as "one-to-many" relationships. In words it states that for every vessel there are many sections separated by transverse bulkheads, and for every section there are a number of deck levels separated by decks and inner bottoms, and, finally, for every deck level there are a number of transverse compartments separated by longitudinal bulkheads. There will naturally be configurations that can not be described by this model, however, it is simple enough to facilitate a quick and fairly realistic description of the internal arrangement of a vessel.

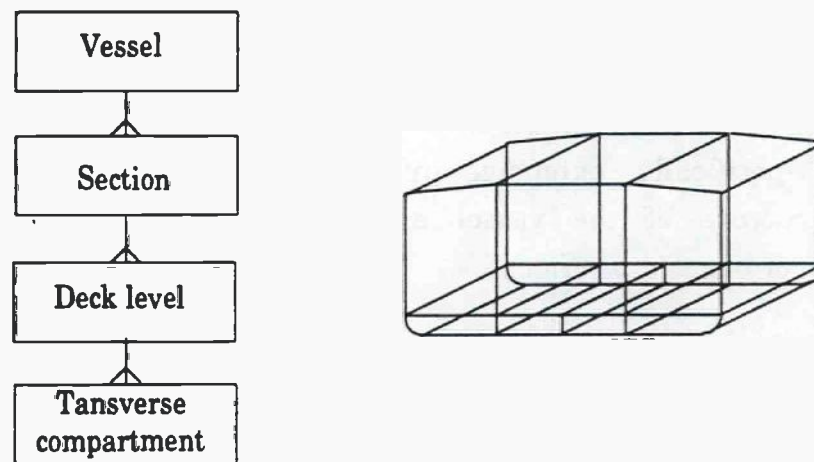


Figure 3.2: Description of the Internal Arrangement

3.3.1. Description of Vessel for Load Calculation

The loading conditions that will be experienced by a vessel during its lifetime are based on the superposition of the stillwater loads and the loads that are a result of the vessel's response to its wave environment. For the wave loads in this study, only the vertical wave bending moment will be examined as this is the primary component of the axial stresses that cause buckling in a vessel's longitudinal members. Other loads such as transverse moments and slamming will not be treated, although there is room for such analysis within the overall procedure.

As mentioned, the hull is subdivided longitudinally into stations. Typically, there are around 20 stations defined between perpendiculars and the result is a longitudinally "discretized" vessel as shown in fig. 3.3:

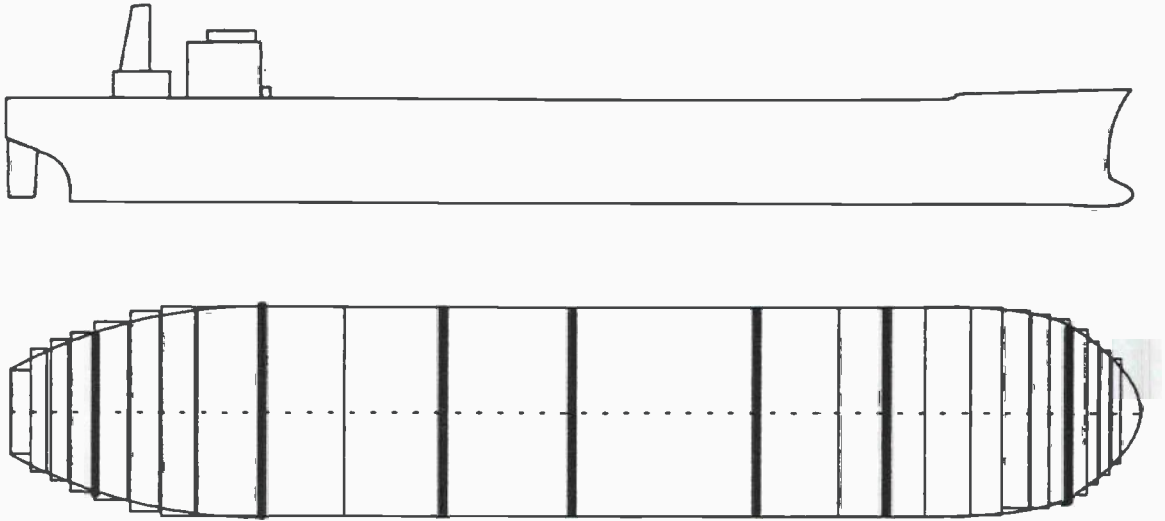


Figure 3.3: Division of a vessel into transverse sections

For the calculation of both the stillwater and vertical wave bending moment, the weight and hull form are needed at each station.

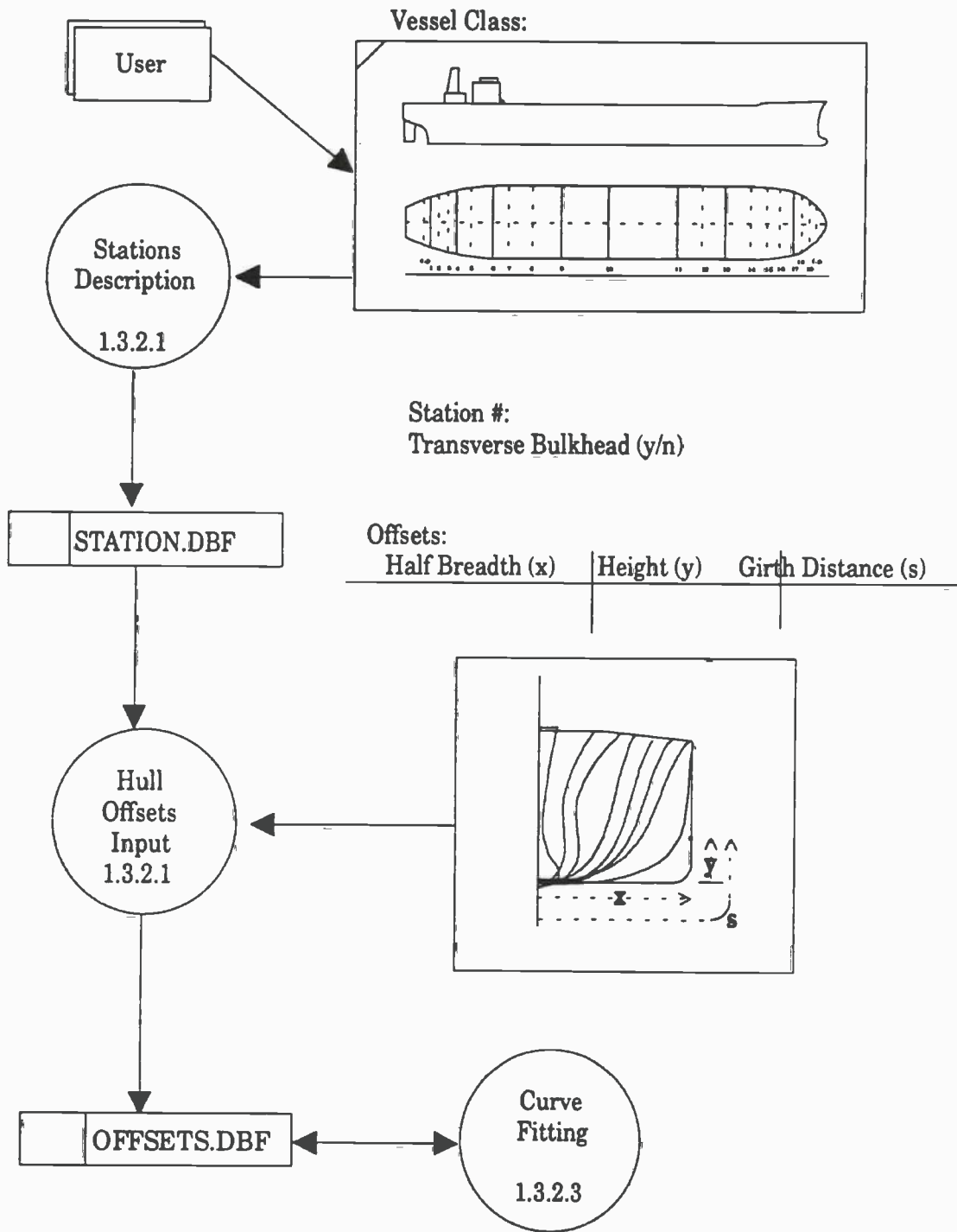


Figure 3.4: Station description for the purpose of load calculations

The computation of the stillwater loads is simply an element of the basic hydrostatic calculations that are performed in every design process. It requires a knowledge of the longitudinal weight distribution in a variety of operating conditions (most importantly: full load and ballast conditions) and also the outside form of the "wetted" hull in each operating condition for the purpose of calculating the bouyancy distribution.

3.3.2. Description of Vessel for Capacity Calculation

A mathematical idealization of a ship's structure can be acheived in many ways and to many degrees of complexity. For the purpose of this study, analyses are performed on a single transverse cross-section of the vessel hull at a time. This two-dimensional structural model is extended to three dimensions by assuming a parallel prismatic form between a specified transverse web-frame spacing.

An idealized transverse section can be subdivided into elements and groups of elements whose structural response can be estimated using established theories and structural analysis techniques. Combining system reliability methods with these element response analyses will lead to a fairly comprehensive treatment of a parallel section of the hull from individual panel buckling up to the collapse of the primary structure. What follows is a description of a method that can be implemented in such an application.

Section Idealization

Keeping in mind the assumptions and limitations of the structural analysis techniques to be used, subdiving one of a vessel's transverse sections requires some judgement in order to ensure that the the structural response (buckling) of the resulting elements are accurately described by the theories. The basic building blocks of a longitudinally framed parallel section of a vessel consist of a panel of shell plating along with an attached longitudinal stiffening structure. The term "element" used in the context of this study applies to these building blocks and examples are shown in the figures below. Fig. 3.5 & 3.6 shows a cut out panel section that could, for example, have been taken from the side shell. The shaded portion constitutes an "element" as described above and, in this particular figure, is representative of an

element that has an 'L' shaped longitudinal. Figure 3.6 shows the four cross-sectional configurations that will be considered in this study.

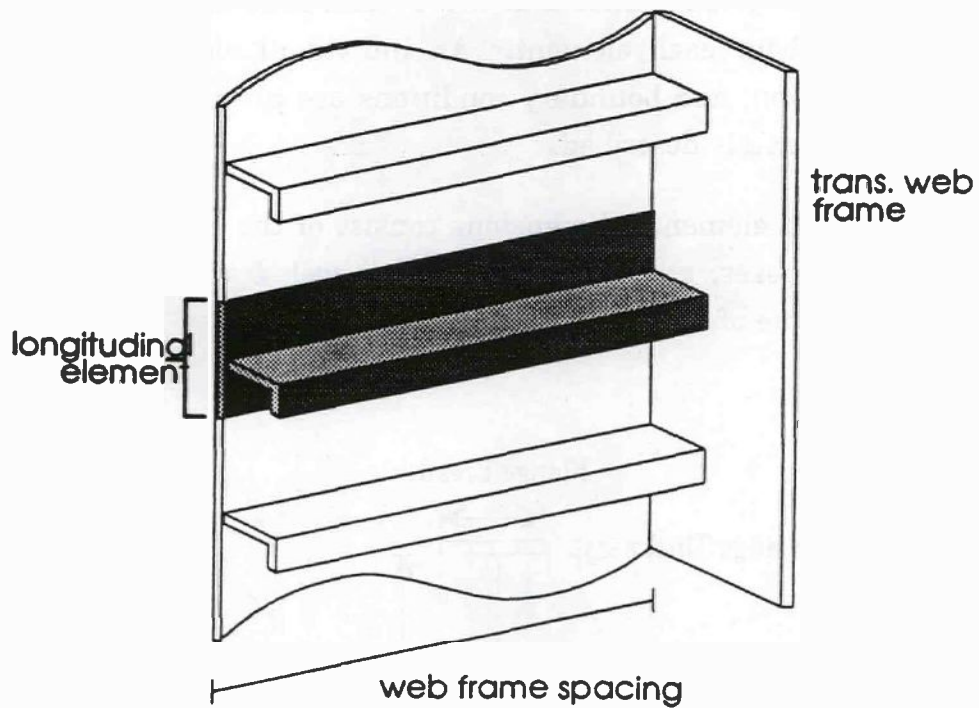


Figure 3.5: Schematic representation of an example "element"

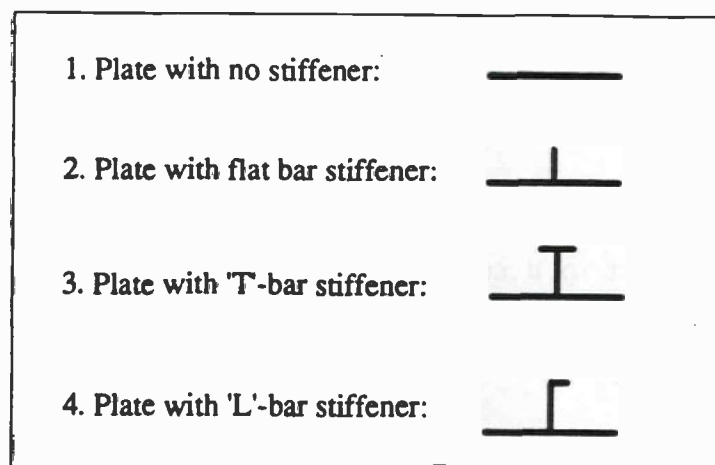


Figure 3.6: Possible configurations for element cross section.

The structural analysis routines that will be described require a fair amount of information about each element. An individual element's dimensions, location, orientation, and boundary conditions are all necessary ingredients and must be accurately described.

Dimensions: An element's dimensions consist of the cross sectional shape and plate thicknesses, and the (longitudinal) web frame spacing. Shown below is an example of the conventions used in this study:

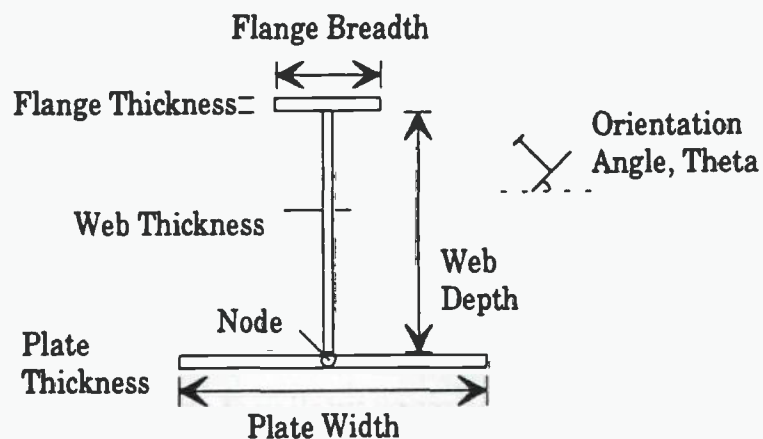


Figure 3.7: Element dimension conventions

Location: An element's location is defined as the location of the element node with respect to a coordinate system whose origin is defined as the intersection of the centerline and baseline of the section. An element's node is taken as the center of the element's plate component (see figure above).

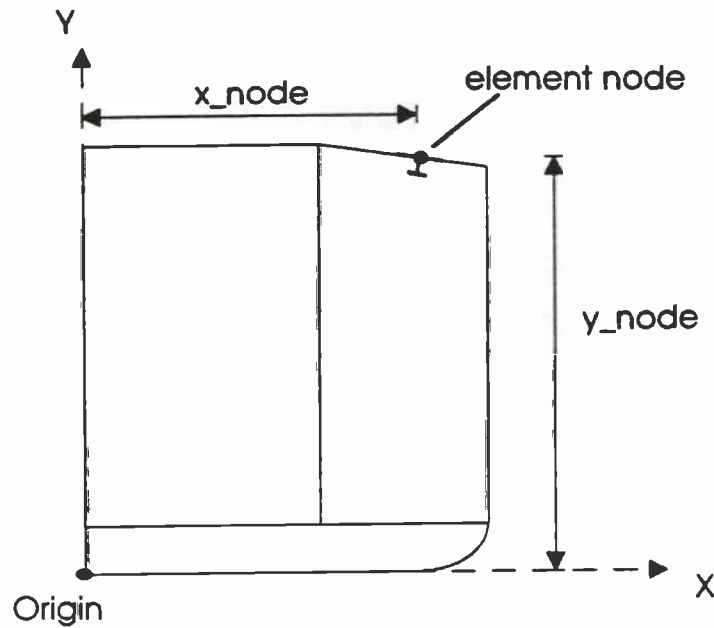


Figure 3.8: Element location.

Boundary Conditions: An element's structural response is strongly influenced by the conditions that exist at its boundaries. Through careful definition of these element boundary conditions, it is possible to model element-to-element interactions as well as the presence of lateral loads arising from hydrostatic and internal cargo pressure.

3.3.3. Mission Profile

The mission profile of a vessel outlines various information regarding the vessel's operation requirements, limitations, and expectations. For the purpose of this study, the following information is required:

- Design Lifetime (years)
- % of time in Ballast voyages
% of time in Full Load voyages
- Ballast Route (Marsden Squares and associated time factor)
Full Load Route (Marsden Squares and associated time factor)

- Operating Policy: Speed vs. Significant Wave Height for both Ballast and Full Load Conditions
- Inspection and Maintenance Routine

Shown below is a schematic example of how the *planned* unavailability can be prescribed. It reflects the possibility that planned inspection and maintenance might step up over time.

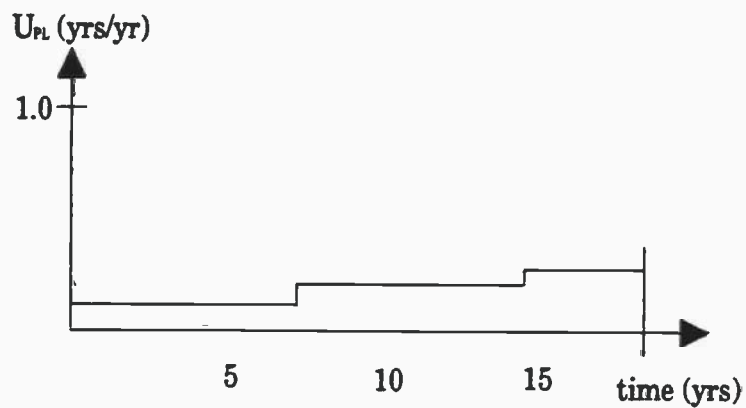


Figure 3.9: Planned unavailability

3.4. DEMAND MODULE

Purpose: To develop a probabilistic model of the extreme vertical bending moment for a specific vessel.

3.4.1. Overview

The "demand" that is imposed on a tanker vessel is made up of many different loading effects. Slamming loads, stillwater bending moments, wave loads, and inertial forces all contribute to the typical global loading conditions experienced by a vessel. In view of longitudinal strength, which is the focus of this study, only vertical bending moment will be considered since it constitutes nearly all of the demand that is placed on the longitudinal structural components.

The two principal components of this vertical bending moment are the StillWater Bending Moment (SWBM) and the Vertical Wave Bending Moment (VWBM). In deterministic terms, the Total Vertical Bending Moment (TVBM) can be expressed as:

$$TVBM = SWBM \pm VWMB$$

The Convention used here is that a negative value indicates a "sagging" moment, while a positive value indicates a "hogging" moment. In addition, a particular vessel is assumed to experience the VWBM symmetrically in the hogging and sagging mode (hence, the \pm in the equation).

In reality, there is a great deal of uncertainty associated with the above equation. Among the many factors contributing to this uncertainty, those associated with the inherent randomness of the ocean environment are dominant along with the modeling errors that are introduced as a result of the assumption that a ship responds linearly to its environment. In any case, the only rational approach to modelling the total vertical bending moment is to represent all of the factors contributing to TVBM in a probabilistic sense rather than an exact mathematic (deterministic) sense.

More specifically, both SWBM and VWBM are random variables and therefore, so is TVBM. The purpose of this module therefore is to develop an

expression for the probability distribution of TVBM for a specific vessel, given its route and response characteristics. This probabilistic representation of TVBM (demand) will then be compared to a similar representation of the Capacity of the structure to determine the failure probability.

Due to conservative design philosophies, instability of tanker structures in the buckling mode is generally brought about only by extreme environmental (wave) conditions. While the stillwater loads can be controlled and minimized to a certain extent, the extreme sea conditions make the vertical wave bending moment the dominant load effect and therefore drives the analysis of the longitudinal structure. Much work has been done to develop probabilistic models of extreme sea conditions and their effect on a vessel, and the approach taken in this study is based on that developed by Mansour [4]

3.4.2. Environment

The first step in this process involves determining what sea conditions a tanker is likely to face based on available sea data. A vessel's trade route can be separated into areas over which the sea conditions, typically characterized by significant wave height, are relatively constant. There have been a number of attempts to gather comprehensive ocean data, but there has yet to be produced an adequate set of consistent, complete measurements from which directional wave energy spectra can be derived. The most comprehensive collection of measurements to date is that compiled by Hogben and Lumb during a period of seven years from 1953 to 1961. Data involving wave height and periods were collected for areas that were grouped into Marsden square zones (shown below). An example of their data is presented below for the case of the Norwegian Sea area (Marsden square #1). In effect, the table represents a scatter diagram (observed percentage frequency of occurrence) of a combination of wave height and period.

Table 1.: Scatter Diagram for Northern North Atlantic Trade Zone (Marsden Squares 1,2,6,7, & 8)

Wave Period (seconds)

Wave Ht.	2.5	6.5	8.5	10.5	12.5	14.5	16.5	18.5	20.5	21+	Total
0-1m	13.7	3.5									
1-2	11.5	15.5									
2-3	1.6	7.9									
3-4	0.3	2.2									
4-5	0.1	0.8									
5-6	0.03	0.15									
6-7	0.03	0.15									
7-8	0.008	0.07									
8-9	0.004	0.03									
9-10	0.003	0.02									
10-11		.0005									
11+		.0005									

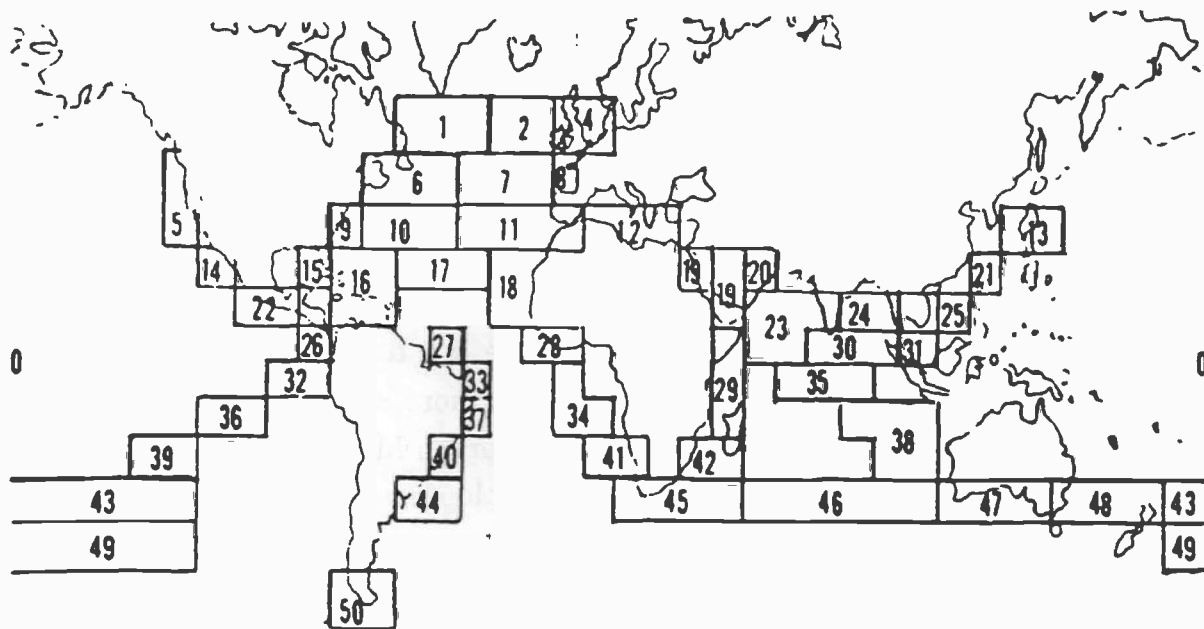


Figure 3.10: Marsden Square Zones

With a vessel's mission profile outlined in the Vessel Description Module, it is then possible to calculate the total relative frequency of occurrence for each combination of significant wave height and zero up-crossing period based on the designated Marsden Squares and the relative time spent in each one in either the ballast and full load conditions. That is:

$$p(H_s, T_z) = \sum p_i(H_s, T_z) \cdot f(i)$$

where: p_i = observed frequency of occurrence of the combination of H_S and T_Z in Marsden Square, i .

$f(i)$ = the time factor (percentage of time) that the vessel spends in Square i

The summation is taken over all Marsden Squares along the vessel's route

A separate $p(H_S, T_Z)$ matrix is formed for each of the two load conditions.

In order to calculate the response of a particular vessel, each sea state on the vessel's trade route must first be described in terms of a characteristic wave energy spectrum. While the set of wave records presented by Hogben and Lumb does not provide enough information to develop fully directional sea spectra for each Marsden square, there are other idealized point spectra that can be calculated from the data and that can provide valuable input to the ship response "black box" that will be discussed in the next section.

Of the various point spectra that are well known to the field, the Bretschneider Spectrum is chosen for use in this study since its two parameters (wave height and period) allow a more accurate description of a seaway than a one parameter spectrum (Pierson-Moskowitz) while the sea data available is insufficient for the development of, say, the Ochi 6-parameter spectrum.

The Bretschneider Spectrum has the form :

$$S_{\zeta}(\omega) = \frac{A}{\omega^5} \exp\left[\frac{-B}{\omega^4}\right]$$

where the parameters A and B are in fact dependent on the parameters of wave height and period. A and B have several forms depending on what characteristic values for height and period are used. For example, if Hogben and Lumb's data is presented in terms of Significant wave height (H_S) and Zero Up-crossing period (T_Z), then it is convenient to express A and B in terms of H_S and T_Z as follows:

$$A = 243 \frac{H_x^2}{T_x^4}; \quad \text{and} \quad B = \frac{965}{T_x^4}$$

The implication of using an idealized *point spectrum* is that the wave field in the open ocean consists of two dimensional long crested waves. This is obviously a misrepresentation of the real situation especially in storm (extreme) conditions and use of this model could potentially lead to a significant overestimation of the environment to which a vessel is subjected. The sea is generally "softened" by its directionality, and this effect may be partially accounted for by the use of a *spreading function* in conjunction with a point spectrum. At the 15th International Towing Tank Conference (ITTC 1978), it was proposed that the Bretschneider spectrum be combined with a spreading function of the form: $\frac{2}{\pi} \cos^2 \mu$ (where $-\pi/2 \leq \mu \leq \pi/2$) to model average conditions. The final form of the characteristic wave energy spectrum for a particular Marsden Square is:

$$S_{\zeta}(\omega, \mu) = \frac{2}{\pi} S_{\zeta}(\omega) \cos^2 \mu$$

where $S(\omega)$ is as defined previously.

3.4.3. Environmental Effects (Load)

With a spectral representation of any given seaway established according to the preceding section, it is possible to calculate a variety of ship response spectra for a specific vessel provided that a Transfer Function or Response Amplitude Operator (R.A.O.) can be developed for the responses of the particular vessel. For this study of course, it is the vertical wave bending moment at a transverse section that is of interest.

The calculation of the vertical wave bending moment response of a vessel at a particular section involves (first) the solution of the equations of motion for a ship in regular seas, (second) the evaluation of incremental vertical forces (excluding stillwater buoyant forces) based on these motions, and (third) the integration of these forces over the length of the vessel.

The vertical wave bending moment at a particular section is equal to the difference between the inertial force and the sum of the external forces: exciting force (E), restoring force, (R) and body motion force (D) [7].

$$VWBM(x) = I_s - (E_s + R_s + D_s)$$

Employing linear ship motion theory (along with strip theory) leads to the computation of the response amplitude operator as a function of relative wave incident angle, frequency, and ship speed. Then, under the assumption that the theory of linear superposition over the frequency domain holds true, this function can then be used as the "black box" by which the output spectrum is obtained from the input (wave energy) spectrum.

$$S_{VWBM}(\omega_e) = |RAO_{VWBM}(\omega_e, \mu_0, U_0)|^2 \cdot S_{\zeta}(\omega_e, \mu_0, U_0);$$

where: μ = the relative angle between the ship's forward motion and the dominant incident wave direction;

U_0 = the vessel's forward speed;

$$\omega_e = \text{the wave encounter frequency} = \left| \omega - \left(\frac{\omega^2 U_0}{g} \right) \cdot \cos \mu_0 \right|;$$

$$S_{\zeta}(\omega_e; \mu_0, U_0) = \frac{S_{\zeta}(\omega)}{|1 - (2\omega U_0/g) \cdot \cos \mu_0|}$$

In this study, information on relative heading angle is not available; therefore, it will be assumed that the "worst case" relative heading in view of vertical wave bending moment corresponds to either direct head or following seas ($\mu_0 = 0^\circ, 180^\circ$).

The calculation of extreme values of VWBM which will be discussed in section 3.5.5 requires that the value of the average (or expected) vertical wave bending moment for a specific sea condition be known. From spectral analysis, the area under $S_{VWBM}(\omega)$ or the zeroth moment of $S_{VWBM}(\omega)$, m_0 is equal to the mean square value of the response (E_{VWBM}):

$$E_{VWBM} = m_{0,VWBM} = \int_0^{\infty} S_{VWBM}(\omega) d\omega$$

And the average value, \overline{VWBM} , is related to the mean square value by the expression:

$$\overline{VWBM}(H_s, T_z) = 0.866 \sqrt{E_{VWBM}}$$

Thus, for a particular vessel, a table similar table can be developed, detailing the average vertical wave bending moment response to a given combination of H_s and T_z . This table would represent, for a specific vessel, a complete set of input data for the purpose of calculating the extreme values of vertical wave bending moments that the vessel might encounter during its lifetime.

3.4.4. Stillwater Bending Moment

It should be remembered that a tanker typically divides a significant amount of its "at sea" time between at least two different loading conditions. In this study, both full load and ballast conditions will be treated for each vessel. This distinctions affects not only the stillwater moment, but also the response of the vessel to wave action due to perhaps a different draft line or more significantly, different inertia effects resulting from a redistribution of weight from one loading condition to the other.

The calculation of SWBM is a simple matter of hydrostatics and involves the difference between the Weight and Buoyancy distributions along the length of the vessel. Although the stillwater bending moment can be controlled to a certain extent and calculated fairly accurately, there still remains a significant element of uncertainty in its representation for analytical purposes. Nikolaidis and Kaplan [5] analyzed data presented by Guedes Soares and Moan (1988) and predicted that the standard deviation of stillwater bending moments for a particular tanker is about 0.21 multiplied by the rule based value. Treating the ballast and full load conditions separately would do much to reduce this estimation of uncertainty.

Due to the fact that the tanker operators have a fair amount of control and information about the stillwater bending moment, the description for SWBM for both loading conditions will be left up to the user to supply at the beginning of the life assessment rather than derived from fleetwide data as done by Nikolaidis and Kaplan. It will be assumed that SWBM follows a normal (Gaussian) probability law given by:

$$\phi_S(s) = \frac{1}{\sigma_S \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{s-m}{\sigma_S} \right)^2}$$

where S is a random variable representing SWBM, m is equal to the mean value, $\overline{\text{SWBM}}$, and σ_S is the standard deviation. Thus, the two values, m and σ_S , need only be supplied in order to describe SWBM for a particular vessel.

3.4.5. Extreme Total Vertical Bending Moment Distribution

With a description of a vessel's environment, response to the environment in terms of vertical moment, and stillwater bending moment characteristics established as in the preceding, the extreme value distribution of the Total Vertical Bending Moment can be developed for both full load and ballast loading conditions.

The basic time increment involved in this study is a one-year period. This constitutes a "long-term" situation in view of ocean statistics. While this fact does not affect the stillwater component of the total vertical bending moment, it carries strong implications for the interpretation of the wave statics and vessel response. "Long-term" implies that the vertical wave bending response of a vessel during this time period can not be described by a stationary statistical model. However, empirical studies have shown that the amplitude of the vertical wave bending response over the long term follows (approximately) an exponential probability law with the average (expected) value of the wave bending moment as a parameter:

$$f_x(x) = \left(\frac{1}{\lambda}\right) \cdot e^{-\left(\frac{x}{\lambda}\right)} \quad x \geq 0$$

$$F_x(x) = 1 - e^{-\left(\frac{x}{\lambda}\right)} \quad x \geq 0$$

where \mathbf{X} is a random variable representing VWBM, and $\lambda = \overline{\text{VWBM}} =$ average value of VWBM.

Defining the random variable, \mathbf{Y}_n as the extreme value of wave bending moment, \mathbf{X} , in n records of \mathbf{X} , the use of *order statistics* permits the probability law which governs \mathbf{Y}_n to be expressed as follows [Mansour, JSR '72]:

$$\phi_{Y_n}(y) = \frac{n}{\lambda} \cdot e^{-\left(\frac{y}{\lambda}\right)} \cdot \left[1 - e^{-\left(\frac{y}{\lambda}\right)}\right]^{n-1} \quad y \geq 0$$

$$\Phi_{Y_n}(y) = \left[1 - e^{-\left(\frac{y}{\lambda}\right)}\right]^n \quad y \geq 0$$

As stated before, Hogben and Lumb's data were collected over a period of about seven years and therefore constitutes a *seven year record*. The parameter n in the above equation can be estimated for a particular vessel as the nearest integer to the value of the vessel's design life (in years) divided by seven. For example, most vessels have a design life of approximately twenty years and consequently, they span roughly three record periods of Hogben and Lumb's sea data; i.e. $n \approx 3$.

Therefore, in order to completely know the distribution of the extreme value of vertical wave bending moment, the value of the average wave bending moment over the seven year record period is the only remaining item to be calculated. Given that the average response to each sea state has been calculated along with the probability that the vessel will experience that sea state, the total average wave bending moment is then simply:

$$\lambda_j = \sum_{H_s} \sum_{T_s} \lambda_j(H_s, T_s) \cdot p_j(H_s, T_s)$$

where j corresponds to either Ballast (1) or Full Load (2) conditions

Letting T be a random variable representing the *total vertical bending moment*, the equation for TVBM can now be expressed as:

$$T_n = S \pm Y_n$$

Combining the two probability laws governing S and Y_n , leads to the following expression for T (see Mansour, 1972 for derivation):

$$\Phi_{T_n}(t) = \frac{n}{\lambda} \cdot \frac{1}{\sigma_s \sqrt{2\pi}} \int_0^{\infty} e^{-\frac{y}{\lambda} - 0.5 \left(\frac{t-y-m}{\sigma_s} \right)^2} \cdot \left[1 - e^{-\frac{y}{\lambda}} \right]^{n-1} dt$$

$$\Phi_{T_n}(t) = \frac{n}{\lambda} \cdot \frac{1}{\sigma_s \sqrt{2\pi}} \int_0^{\infty} e^{-\frac{y}{\lambda}} \cdot \left[1 - e^{-\frac{y}{\lambda}} \right]^{n-1} \cdot \int_{-\infty}^{\infty} e^{-0.5 \left(\frac{t-y-m}{\sigma_s} \right)^2} dt dy$$

Theoretically, this process would be repeated for each section of the vessel in both loading conditions which, for the case of a vessel with twenty designated stations, would result in forty repetitions of a process that is already computationally demanding. In order to reduce this demand, it is possible to develop the above expression for just the midship section in each of the loading conditions and then make assumptions as to how TVBM varies along the length of the vessel. For example, both the mean of TVBM and the variance could be assumed to vary along a vessel's length according to a distribution factor illustrated in Fig. 3.12:

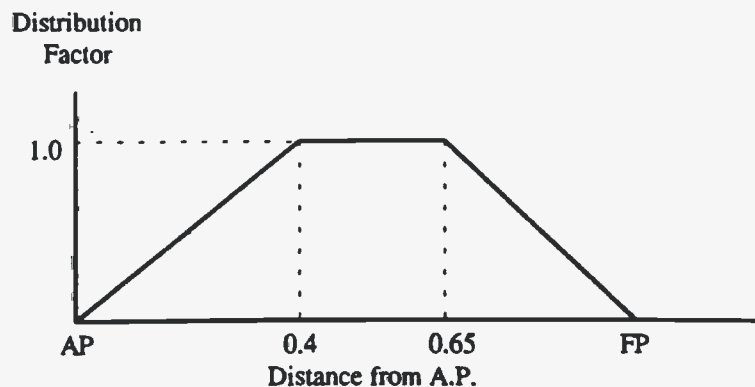


Figure 3.12: Distribution factor of TVBM along the vessel length

While this may be a bold assumption, it reduces the necessary repetitions from forty to two (one for each load case).

3.4.6. Local Loads

The calculation of local loads (i.e. axial stresses on each element as defined for a section's structure) can be achieved by employing beam theory. The axial stress σ_e , on an element at station x , and at a distance y_{na} from the instantaneous neutral axis is given by:

$$\sigma_e(x, y_e) = \frac{TVBM(x) \cdot y_{na}}{I(x)}$$

where $I(x)$ is equal to the area moment of inertia of the section about the neutral axis.

3.5. CAPACITY MODULE

Purpose: To produce, for a specified vessel, probability distribution functions of the capacity of the vessel's structure to resist the failure modes defined in the Failure Definition Module.

3.5.1. Overview

As the second aspect to the reliability problem, the Capacity module generates a probabilistic description of a vessel's structure to resist the seaway loading in both the hogging and sagging modes. The capacity of the structures defined in the Vessel Description module can be generally described in terms of their load/displacement curves. This applies to both local and ultimate failure modes.

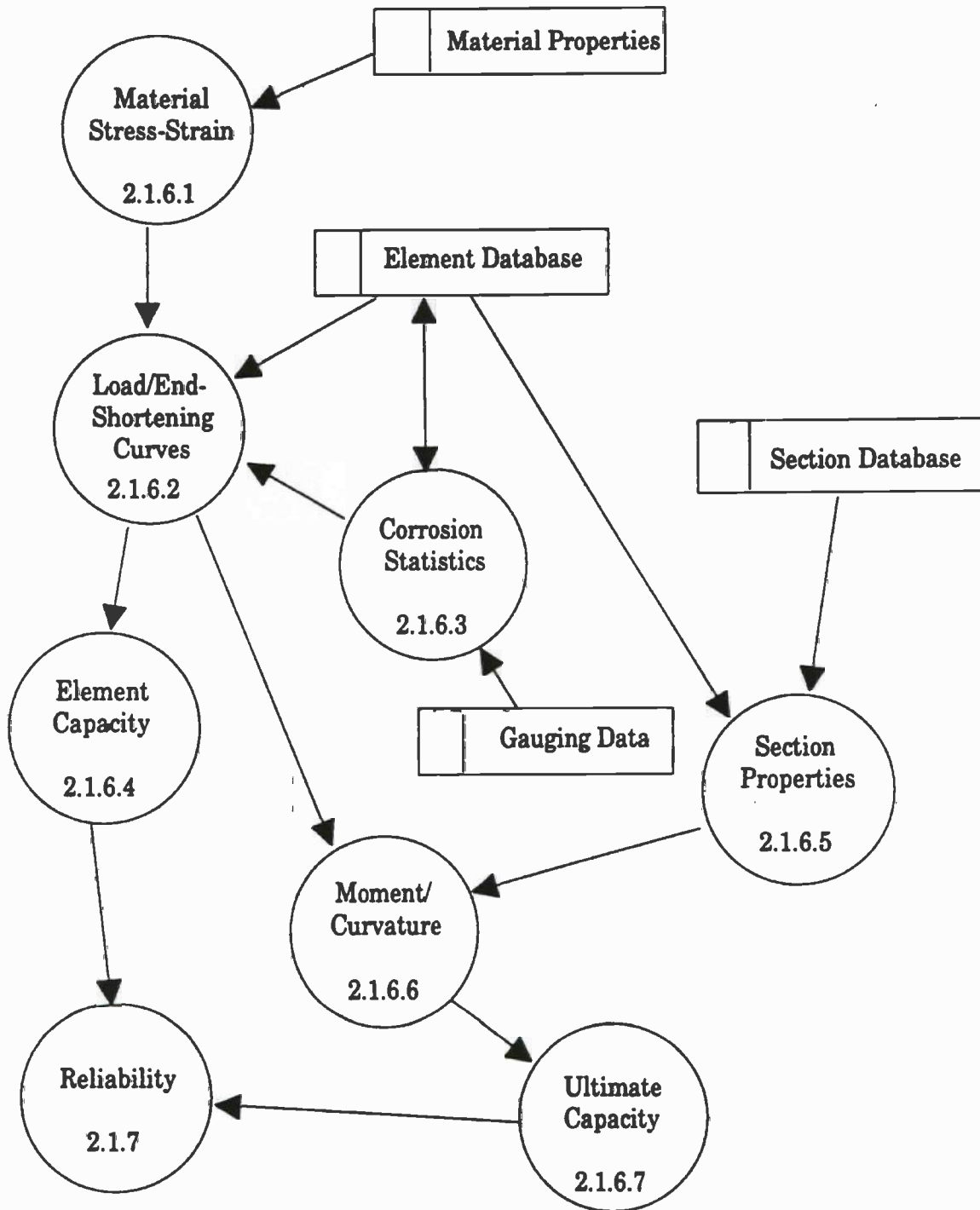


Figure 3.14: Element and Ultimate Capacity.

The event of an element surpassing its elastic limit due to extreme loading does not necessarily constitute failure as there is generally some residual strength left in the plastic regime. In order to maintain generality in this study, structural capacity will be defined as that level of load at which the slope of the load/displacement curve reaches zero. This, in effect, defines the ultimate limit state for each element and group of elements. While some elements may need to be replaced or repaired at lower limit states such as the elastic limit or some limiting value on displacement, this information is too detailed for the general treatment presented here.

What follows is the development of these load/displacement curves for the structures defined in the Vessel Description Module.

3.5.2. Element Load/End-Shortening Curves

Specifically, the load/displacement curve for a particular element is cast in terms of axial load vs. the shortening at the ends of the element. In view of buckling, there is a high degree of geometric non-linearity involved in the computation of this relationship. While there are many design equations and theories available to predict these curves and the buckling capacity of stiffened panels, these generally have as their basis a linear formulation with some correction factor to account for non-linearities.

The most rational approach is to deal with the non-linearities directly in a non-linear finite element formulation. With the proper load and boundary information supplied by the Vessel Description module, the structural response of each element can be determined.

Shown below are some possible finite element models that can be used to describe the types of structural arrangements and response behavior.

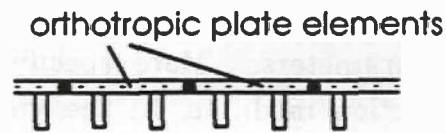
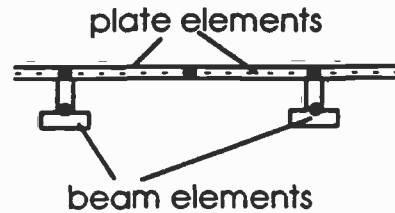
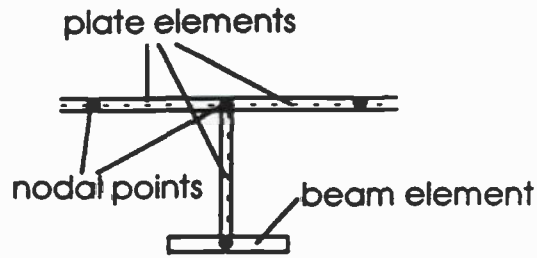


Figure 3.15: Possible Finite Element Models

There are four types of general responses that need to be modeled. They are:

- buckling of plating between stiffeners
- column buckling (stiffener or plate induced)
- stiffener tripping (or torsional buckling)
- overall panel buckling

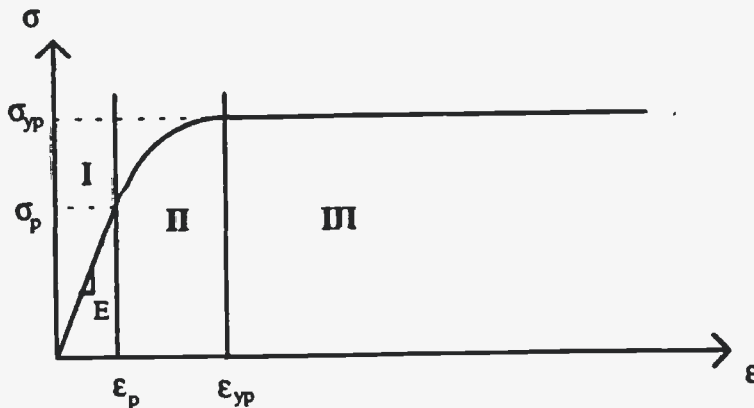
For a given element geometry, each response mode might require a distinct finite element model in order to accurately reproduce the intended structural behavior. This could potentially result in a large computational effort, especially if the number of different types of elements for the section under consideration is large.

As an alternative, the design equations mentioned previously can be used, combining both analytical theory and empirical data to predict the critical stresses at which a stiffened panel might buckle and, further, to develop approximate load/end-shortening curves for a given element cross section. What follows is an illustrative procedure for determining these curves based on design equations.

It can be assumed that the load/end-shortening curve for a particular element can be based on the stress-strain curve of the material (steel) of which it is made. The element stress-strain curve will follow the material stress-strain curve up until a critical point at which the element becomes unstable in compression and buckles. It is necessary, therefore to first develop material stress-strain curves.

Generalized material stress-strain curves can be developed based on a relatively small number of parameters. More specifically, given (for a particular steel) the elastic section modulus, E , the yield stress, σ_{yp} , the proportional limit stress σ_p , and Poisson's ratio ν , it is possible to estimate the stress vs. strain characteristics of that steel in a complete yet approximate sense.

This is achieved by dividing the stress-strain curves into three regions signifying: (I) the linearly elastic range, (II) the nonlinear elastic range, and (III) the perfectly plastic (yield) range as shown in the figure below.



Steel Type	
E	Elastic Modulus
σ_{yp}	Yield stress
σ_p	Proportional limit
ν	Poisson's ratio

Figure 3.16: Material Properties

Region I $\epsilon \leq \epsilon_p$

The stress-strain relationship in this region is simply linear with the Elastic modulus as the constant of proportionality, i.e.

$$\sigma = E\epsilon$$

Region II $\epsilon_p < \epsilon \leq \epsilon_{yp}$

This region generally signifies a nonlinear "softening" of the material which is represented by a gradual change in the slope of the stress-strain curve. An expression for the curve in this region is as follows:

$$\sigma = \frac{\sigma_{yp}^2}{k_2} \frac{e^{(\epsilon - \epsilon_p/k_1)}}{\left[1 + \frac{\sigma_{yp}}{k_2} e^{(\epsilon - \epsilon_p/k_1)} \right]}; \quad k_1 = \frac{(\sigma_{yp} - \sigma_p)\sigma_p}{E\sigma_{yp}}, \quad k_2 = \frac{\sigma_{yp}^2 - \sigma_{yp}\sigma_p}{\sigma_p}$$

Region III $\epsilon_{yp} < \epsilon \leq \epsilon_{fp}$

Perfect plasticity is assumed in this region which is to say that the material can no longer continue to support increasing load and deforms plastically

With the material behavior defined as above, it remains to determine the critical stress at which an element becomes unstable and buckles. This critical stress can be assumed to divide the load end shortening curve into two regions, one region in which the element behaves according to the stable material behavior, and the other in which the element rapidly "sheds" its load indicated by a negative slope in the load/end-shortening curve. In general, different elements will exhibit load shedding characteristics to varying degrees, but this phenomenon is very difficult to formulate mathematically.

Buckling of the plate between stiffeners does not necessarily result in the failure of the stiffened panel. However, the buckling strength of the

stiffener/attached plating combination is strongly affected by the stiffness of the plate between stiffeners, and buckling in this region can lead to a significant reduction in the stability of the column type stiffener/plating combination. This effect can be modeled in terms of the "effective width" concept.

Shown in Fig. 3.17 is a flow chart describing the calculation of the critical buckling stress of an element. This model includes the effect of buckling of the plate between stiffeners by considering that if the critical stress of the plate between stiffeners is less than that of the stiffener and attached plate as a column, then only an "effective" width of the plate should be considered in the computation of the column strength. The effective width is calculated using the computed critical column stress. The column stress is then recalculated using the new width of the attached plating and an iterative process is begun.

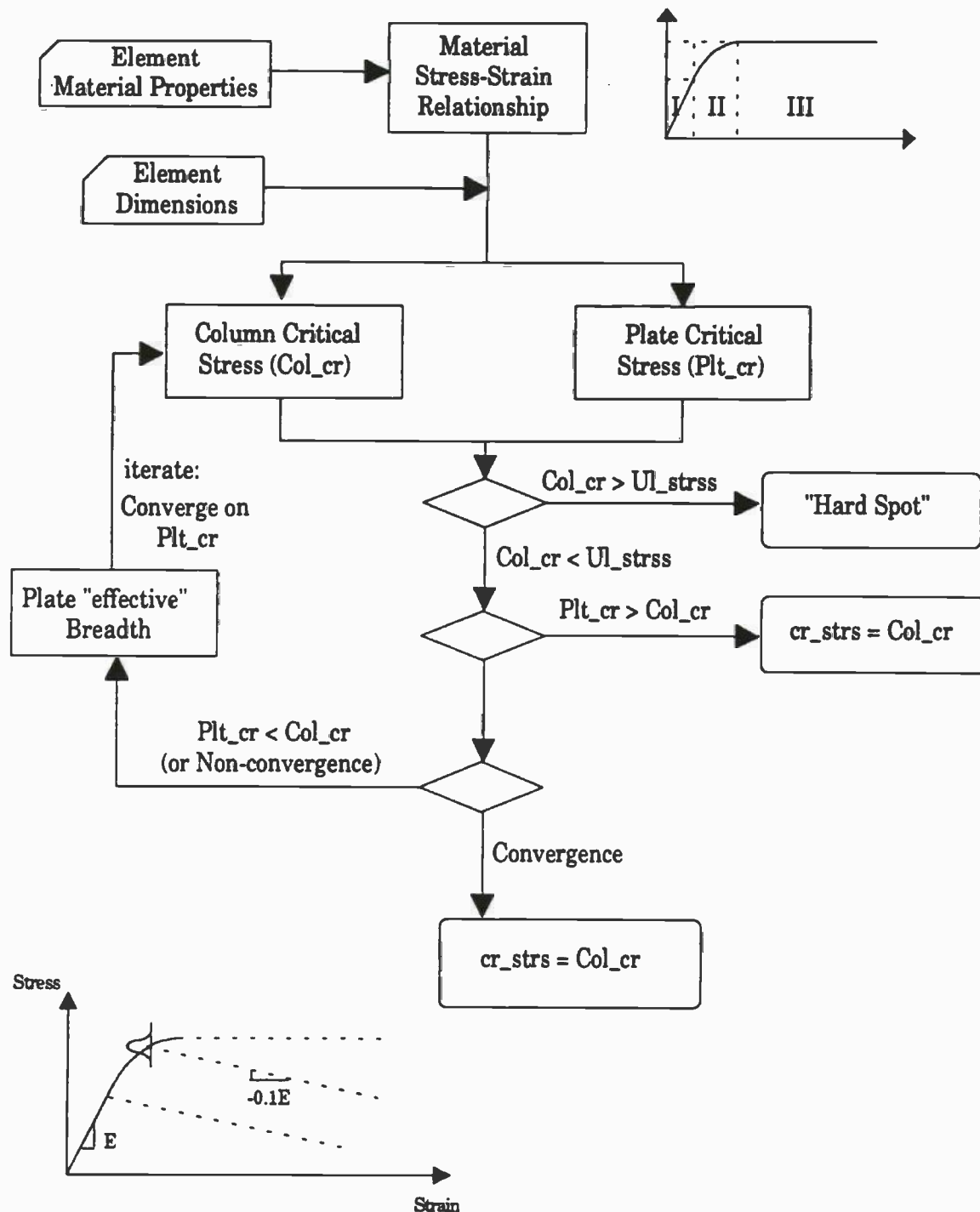


Figure 3.17: Flow Chart for Element Capacity Calculation

Another case might arise in which the critical stress of the element considered as a column is greater than the ultimate stress of the material of which it is composed. The element may then be considered as a "hard spot"

meaning that the behavior of the element in compression follows that of the material.

3.5.3. Ultimate Capacity

While the finite element treatment of individual elements and specific element groups provide accurate predictions of their load/end-shortening curves, it is not feasible to apply these same methods to the entire section's structural system. The computational complexity of such a problem precludes the development of an interactive PC-based computer application.

Instead, the ultimate capacity of a given section can be determined by a method that was outlined by Smith [6]. This general procedure, outlined below, determines a Resisting Moment vs. Curvature relation for a prismatic box girder section based on the individual load/end-shortening curves of its constitutive structural elements.

Step 1: determine the properties of the section (as built or corroded). This includes calculating the second moment of area, I , and the position of the neutral axis.

Step 2: determine the elastic limit of the section, i.e. the moment and corresponding curvature at which the first element in the cross section reaches its elastic limit defined by its individual load/end-shortening curve. Theoretically, the moment curvature relation of the entire section is linear to this point.

Step 3: from the elastic limit point, apply an incremental curvature to the section the magnitude of which can be arbitrarily defined as a small percentage of the elastic limit curvature.

Step 4: with the assumption that plane sections remain plain, the strain on each element can be calculated as:

$$\epsilon_e = y_e \cdot C ; \quad y_e = \text{distance of element above neutral axis}$$
$$C = \text{section curvature}$$

Step 5: from each element's load/end-shortening curve, the element forces can be calculated corresponding to the strain calculated in step 4.

Step 6: Since, at this point, at least one element has passed its linear elastic point, a "softer" more flexible local structure will result in an imbalance in horizontal forces and a shift in the neutral axis is required to ensure that only a pure bending moment is acting on the section. This generally would require an iterative procedure where the neutral axis is shifted away from the plastic region, the strains and forces are recalculated, and the process is repeated until there is a zero net horizontal force. However, if the section curvature increment is small enough, one incremental shift of the neutral axis can be assumed to be accurate enough, and is given by:

$$SHIFT = \frac{\sum (A_e \cdot \sigma_e)}{C \cdot \sum (E_e \cdot A_e)}$$

Step 7: determine the bending moment that corresponds to the current state of curvature. This moment is simply calculated as:

$$M = \sum \sigma_e \cdot A_e \cdot y_e$$

Step 8: apply the next increment in section curvature.

From this point steps 4 through 8 are repeated until the complete moment/curvature relation is obtained. The flow chart in Fig. 3.18 graphically illustrates the procedure.

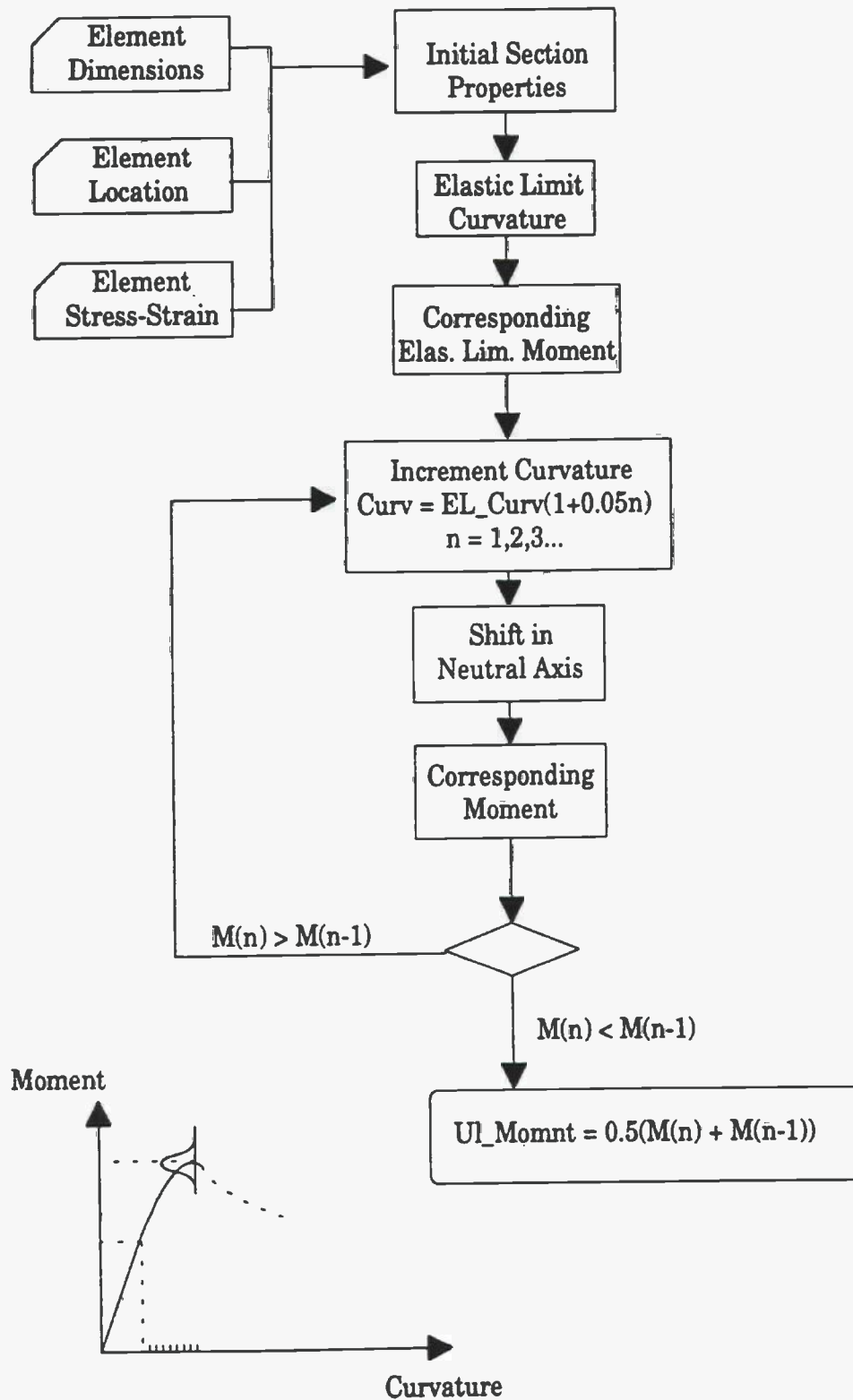


Figure 3.18 : Flow chart for Ultimate Capacity Calculation

3.6. CORROSION MODULE (TIME VARIABILITY OF CAPACITY)

Purpose: To provide a means by which to calculate corrosion rates from general wastage data drawn from the entire fleet, to assign these corrosion rates to the elements and sub-elements of the specific vessel in question, and then to control the time step procedure in the life assessment.

Although the inclusion of corrosion rates and the effect of corrosion in the life assessment procedure is a fairly straightforward matter, it is of extreme importance in that it constitutes the time variability component without which there would be no life assessment. The corrosion module consists of three parts:

- The collection of corrosion data,
- The statistical analysis of corrosion data, and
- The integration of the results into the life assessment procedure.

3.6.1. Corrosion Data Collection and Modelling

There is an abundance of gauging reports from which data can be drawn, collected during regular inspections of the entire tanker fleet over many years. The challenge involved in this part of the Corrosion Module is how to model the data in such a way that trends can be identified that will be useful to the analysis. It is not sufficient or rational to provide just one number as a representation of the corrosion rate situation for an entire vessel. There are many factors that influence the wastage of tanker structures and the values for mean rate can vary substantially throughout the body of a vessel. Pollard [8] compiled the following list of important factors effecting corrosion rates:

Ship size	Tank type	Cargo sulphur content
Delivery date	Time in cargo	Cargo water
Cargo type	Time in ballast	Wax in cargo
Double bottom	Corrosion protection	Heated cargo
Double side	system	Tank washing
Class society	Ballast type	Corrosion type
Trade route	Tank temperature	Corroded detail
Tank location	Tank humidity	Location
	Inert gas	

The corrosion rates to be used in the life assessment procedure are determined through a statistical analysis of the corrosion gauging data stored in the referencial database. During the first year of the Structural Maintenance for New and Existing Ships Project conducted at the University of California at Berkeley, these data were collected and analyzed []. Corrosion rates were categorized by a combination of tank type and detail type and also by a combination of tank type and general location within the tank. The tank types that are considered in the study fall into the following four descriptions:

- 1) Cargo only
- 2) Ballast only
- 3) Cargo/clean ballast
- 4) Cargo/dirty ballast

The second category which involves trends in corrosion wastage as they are affected by general location within the tank (upper third, middle third, lower third, etc.) provides qualitative information only, and therefore can not easily be used as input in the analysis. While location within the tank has a significant influence on the corrosion rate of the structural components, the data is not detailed enough to provide a quantification of these trends.

A further deficiency in this data model arises when one considers that the tank-type/detail-type category only gives information regarding the tank-type on one side of the plating, generally the side on which the longitudinal stiffeners are located. An area of longitudinal bulkhead plating, for example can have heated cargo on one side and cold water ballast in the adjacent wing tank, while another area of longitudinal bulkhead plating of the same cargo tank can have more heated cargo in the wing tank on the other side. This situation could result in a significantly different corrosion rate for what would be considered an identical tank-type/detail-type combination by the database.

In developing this module, efficient use can be made of the way in which the Vessel Definition Module handled the input of each structural element. A "key" identifier can be assigned to a particular sub-element plating at the time that gauging data (thicknesses) are entered into the database. For example, when a vessel undegoes inspection and a measurement is taken of

the thickness of a particular sub-element, knowledge of the element to which the plating belongs in conjunction with the section number corresponding to that element will give access to the following information from the element database:

- type of element (side shell, longitudinal bulkhead, etc.)
- the contents of the tanks to either side of the plate sub-element (cargo only, ballast only, etc.)
- the region within the tank where the element is located (ullage, middle, lower, etc.)
- the original thicknesses of the sub-elements.

This information, plus the identification of the sub-element type (plate, web, flange) at the time the measurement is input, can lead to a fairly comprehensive description of the major factors that are involved in the identification of corrosion rate trends.

3.7. RELIABILITY MODULE (PROBABILITY OF FAILURE)

Purpose: To calculate the probability of failure in each failure mode defined in the Failure Definition Module based on the demand and capacity determined for the vessel in question.

Three major sources of uncertainty in the failure probability calculations come from the Capacity, Demand, and Corrosion modules. In this study there are two levels of structural failure to be examined; the element (local) failure level and the ultimate (global) failure level. With the probability density function for load approximated by the normal distribution, and with the corrosion and capacity information similarly described, the entire reliability problem reduces to the fundamental level.

For a particular failure mode i , a "safety margin", M can be defined as:

$$M_i(t) = C_i(t) - D_i$$

The probability, then, that $M < 0$ is equal to the probability that the capacity of the structure to resist failure mode i is less than the demand that is placed on the structure, which in turn is simply the probability of failure in mode i .

M constitutes a random variable, also normally distributed, whose mean value, μ , and standard deviation, σ , can be easily calculated for any time instant and any failure mode. Assuming independence between the capacity and the demand:

$$\begin{aligned}\mu_M &= \mu_C - \mu_D \\ \sigma_M &= \sqrt{\sigma_C^2 + \sigma_D^2}\end{aligned}$$

The probability of failure is therefore:

$$p_{f,i} = p[M < 0] = \Phi\left(\frac{0 - \mu_M}{\sigma_M}\right) = \Phi(-\beta)$$

where $\beta = \frac{\mu_M}{\sigma_M}$ is defined as the "safety index" and can be thought of as the number of standard deviations by which μ_M exceeds zero.

3.8. AVAILABILITY

With the various global variables defined as they have been in the preceding, there are a number of ways in which the reliability of a particular vessel can be formulated within the context of its life span. For example, the reliability can be cast in terms of the mean and standard deviation of the *time* that it takes for the calculated availability to drop below the design value, or, alternatively, the mean and standard deviation of the *availability* can be presented at the end of the vessel's design life. These two alternative formulations are presented in figure 3.20. The subtle difference between the two is that in the first formulation, the uncertainty in the time dimension is treated while the limiting availability is taken as deterministic (design A_v), whereas in the second formulation, the weight of uncertainty rests on the availability dimension while the design life determines the limiting time.

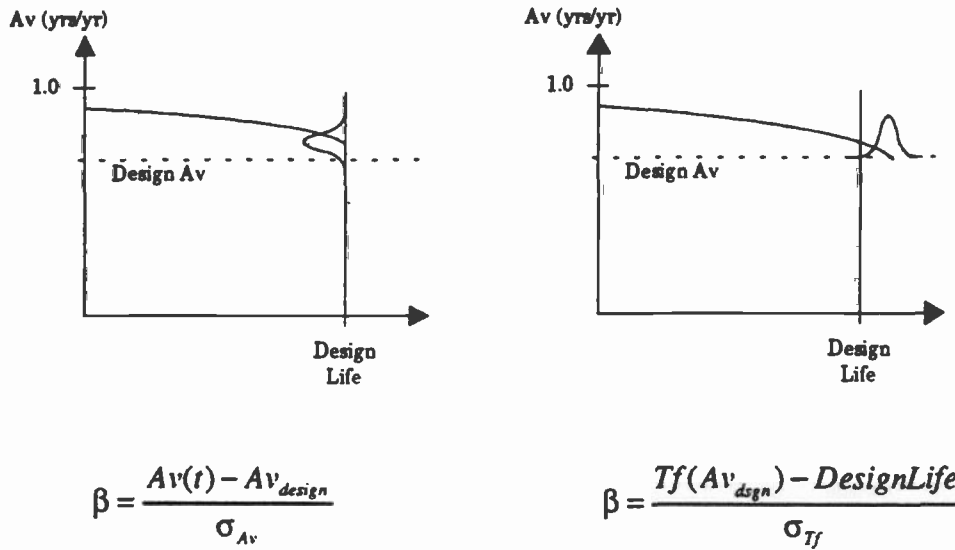


Figure 3.20: Alternative Reliability Formulations

For the purpose of defining corrosion limits, it is more important that the uncertainty in time is treated since the time dimension is directly involved in the determination of corrosion rates.

4. SYNTHESIS OF THE MODEL APPLICATION

4.1. OVERVIEW

Presented in this chapter is the initial development of a computer application which is modelled after the approach detailed in the preceding chapters. The following simplifications were made to facilitate the development of the model:

- 1) The load definition module was eliminated, using in its place a rule based definition of the extreme bending moment amidship.
- 2) The 'time until failure' was based solely on the ultimate capacity of a section to withstand the imposed bending moment. While this is only a component *of a component* of the overall availability of a vessel, it clearly and adequately represents a limiting condition, and further, the additional data and routines needed to complete the entire availability calculation was beyond the scope of this project.
- 3) The database files are accessed directly through FOXPRO, eliminating the need for the development of input screens.
- 4) Corrosion rates were 'hard-wired' or manually input to the system due to the fact that the data did not exist in the designed format. Corrosion rates were based on Pollard's findings.

Shown in Figure 4.1 is the context layer diagram for the model SMIS application. When compared with Figure 1.1 this diagram expresses the above simplifications in graphic form. By employing a rule based definition of the loads and by eliminating the need for all that is required for the calculation of the three components of Unavailability, the external inputs become simply the midship section idealization and the general parameters

used in the calculation of the extreme midship bending moment. The system then bases its definition of wastage limits on the prediction of the time that it takes for the wastage of the scantlings to decrease the ultimate capacity of the section to the point at which it no longer can satisfactorily withstand the rule based load.

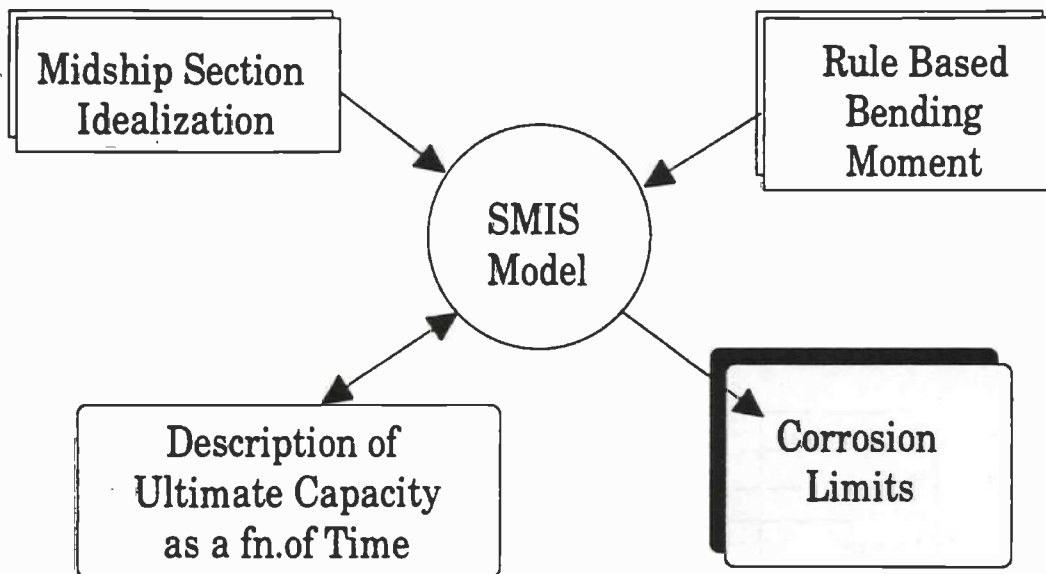


Figure 4.1: Context layer diagram for the model SMIS application

4.2. DATABASE MANAGEMENT

Without the need to support the entire unavailability calculation, the structuring and management of the database becomes considerably simpler. Direct input of data to the database files further reduces the complexity of the database management issue by eliminating the need for input screens. The principal components of the database are simply the CLASS and SECTION idealization databases. Shown in Figure 4.2 is the next layer DFD followed by the structure of the developed database (Fig. 4.3).

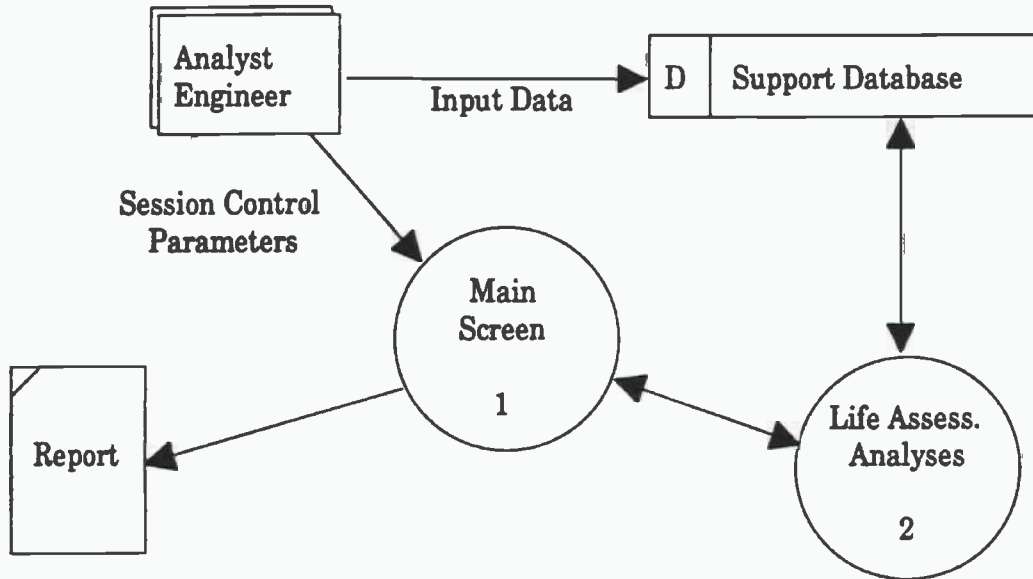


Fig 4.2: Second Layer DFD

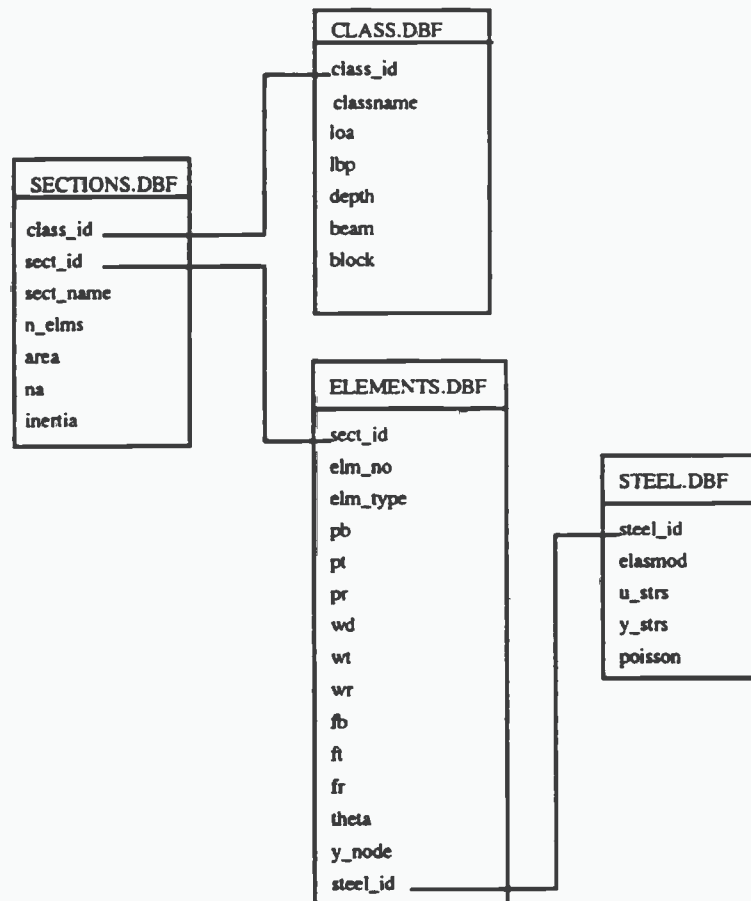


Fig 4.3: Structure of the support database for model SMIS application

The definition of a vessel is simply a matter of filling the data structure defined above.

4.3. THE ANALYTICAL SESSION

4.3.1. Setting up an Analytical (Life Assessment) Session

Setting up an analytical session involves little more than identifying which section of which vessel is to be considered and any biases that are applied to customize the loading condition. In addition, the time increment in years needs to be designated along with a minimum value for the safety index, β upon which the "life assessment" is based. A single main screen was developed to accept the input of these session parameters, do some elementary calculations and prompt the user to begin the analysis once the session parameters have been defined. Shown in Fig. 4.4 is this Main Screen as it appears on the monitor.

SECTION IDENTIFICATION		SESSION PARAMETERS	
Vessel Class:	216 DWT VLCC	Minimum Beta level:	0.05
Section:	Midship	Time Step (in years):	

Design LOADS:				
	<input checked="" type="checkbox"/> Hog		<input type="checkbox"/> Sag	
	SWBM	VWBM	SWBM	VWBM
Mean:	25550823	278011051	246318256	84243420
Bias:	0.0	0.0	0.0	0.0
Coef of Var:	0.0	0.0	0.0	0.0

Figure 4.4: SMIS Main Screen

Values for the stillwater and vertical wave bending moments in both the hogging and sagging condition are automatically computed once a particular vessel class is chosen from the popup. At the same time, the "sections" popup is filled with section names for the chosen vessel and the input fields for biases and coefficients of variation are enabled and default values are displayed (1.0 for biases, and 0.0 for COV's). A field also exists for a user input "session id code" which is stored in the support database and can be used to distinguish the results of a particular analytical session for later study.

Once all of this information has been input, including the time step (typical values should be around five to seven years for this increment) and minimum β level, a button labeled "Begin" starts the analysis.

4.3.2. Analysis

The main analysis routines lie beneath the setup screen and automatically control the flow of the analysis, the links to the support database, and the generation of results. The program calculates the safety index at a particular time step based on the computation of the designated section's ultimate capacity in both hogging and sagging modes and the combination of the defined stillwater and vertical wave bending moments. If the calculated safety index is greater than the defined minimum, then the "age" of the vessel is increased by one time increment, the section's scantlings are reduced according to the appropriate corrosion rates, and the process is repeated until the safety index drops below the set minimum. In addition to calculating the safety index at each time step, the program builds moment curvature diagrams according to the procedure outlined in chapter three.

The following is a list of the principle modules that comprise the analysis routine and a brief description of each.

Module: MAIN

Purpose: This is the main module that performs the remaining preliminary computations regarding loads, coordinates the subroutines, and generally controls the flow.

Input: Session control parameters from main screen

Output: Global information regarding the section at each time step which is stored in the LIFE.DBF database (i.e. safety index, hog capacity, sag capacity, initial neutral axis, etc)

Called by: Main Screen

Calls: CORRODER, CAPACITY

Module: CORRODER

Purpose: This module develops the important "elms" array which contains the element specific information such as dimensions and material properties and includes the correct plate thicknesses according to current age of the vessel and the appropriate corrosion rates.

Input: "Temp" array which is downloaded from the ELEMENTS.DBF database and contains the element-by element description of the chosen section.

Output: "Elms" array which is similar to the Temp array but has updated the element dimensions to reflect wastage of an aged vessel.

Called by: MAIN

Calls: none

Module: CAPACITY

Purpose: This module follows the procedure for calculating ultimate capacity of a section based on the load/end-shortening curves of its constituent elements. Program is executed for a particular time step.

Input: "Elms" array described above

Output: *caphog* and *capsag* (ultimate capacity in hogging and sagging conditions) both of which are returned to the MAIN. Additionally, the moment curvature relationship is uploaded to MOMCURV.DBF.

Called by: MAIN

Calls: ELMPROPS, STRSSTRN

Module: ELMPROPS

Purpose: This module calculates three element properties which are added to the elms array.

Input: The information contained in one record (row) from the elms array

Output: *cr_strs* (critical buckling stress), *area* (cross sectional area), and *inertia* (moment of inertia about the centroid) particular to an element, and stored in columns 14,15, and 16 of the elms array

Called by: CAPACITY

Calls: none

Module: STRSSTRN

Purpose: This module returns the stress corresponding to an input strain level for a particular element based on its material properties and critical buckling stress.

Input: *cr_strs, elasmod, u_strs, y_strs, poisson, strain*

Output: *stress*

Called by: CAPACITY

Shown in Fig. 4.5 is a schematic view of the modules involved in the initial application.

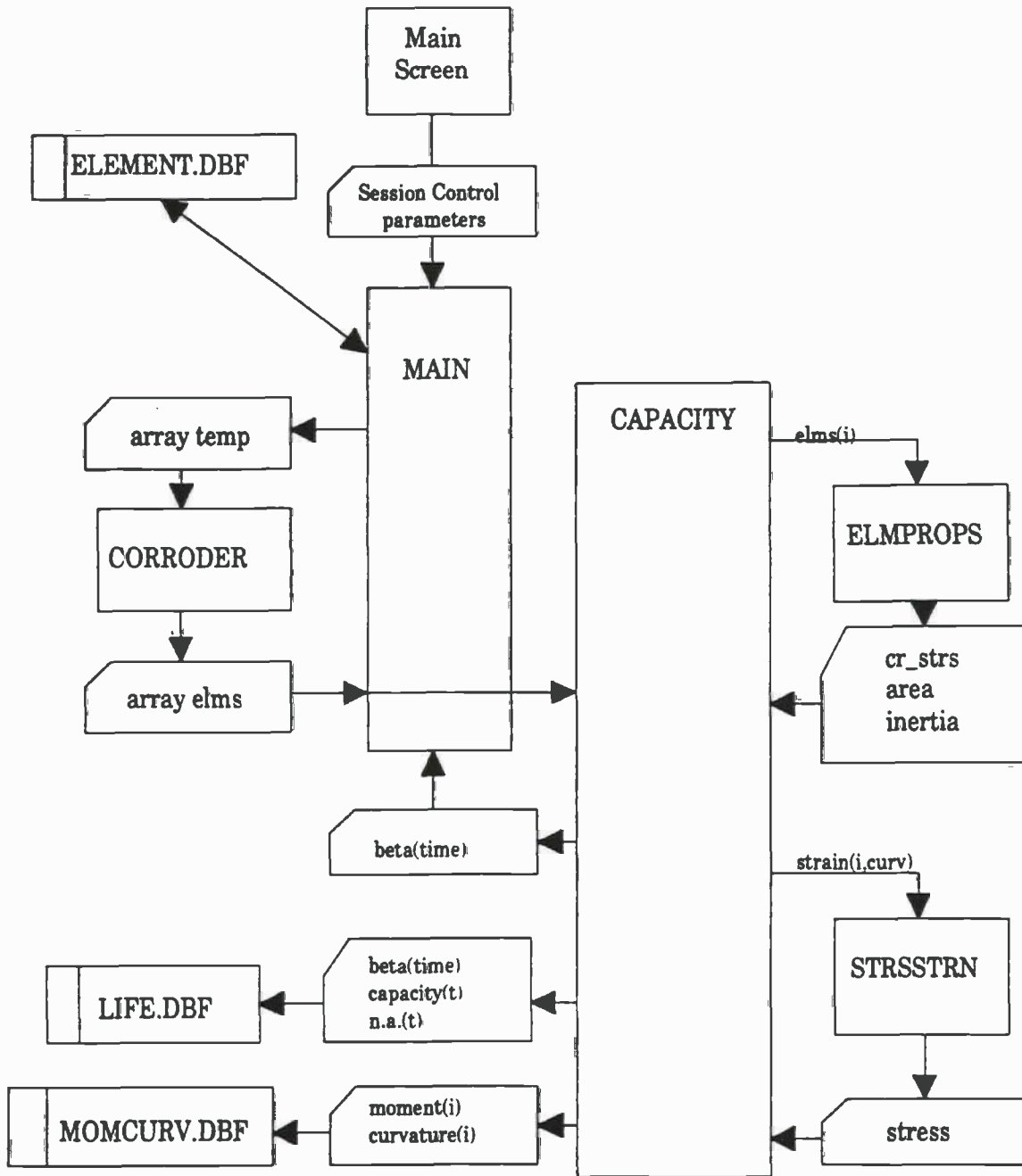


Figure 4.5: General Flow Chart for the Analysis

While the CAPACITY module is fairly robust and genuine in its approach, the ELMPROPS module which calculates the capacity of an element is scarcely more than symbolic and the development of a sophisticated load/endshortening module would add significantly to the value of this program.

5. EXAMPLE APPLICATION

5.1. EXAMPLE VESSEL

The vessel that was chosen for the example application is a 216,000 DWT single bottom VLCC named the *Energy Concentration*. In July of 1980, the *Energy Concentration* suffered a "broken back" while discharging oil at the Mobil Terminal in Rotterdam. While there were many factors that lead up to the ultimate collapse, the fact that the VLCC was ten years old at the time suggests that wastage of the structure, particularly the bottom plating and longitudinals, must have played an important role. In addition to presenting an interesting corrosion study, this event was extensively studied by Rutherford and Caldwell [Ultimate Longitudinal Strength of Ships: a Case Study] the results of which can be used as a comparison.

A brief description of the physical characteristics of the *Energy Concentration* is given in the following tables and figures.

General Particulars

L.O.A.	326.75 m
L.B.P.	313.0 m
Breadth (mld)	48.19 m
Depth (mld)	25.2 m
Gross tonnage	98,894 tons
Deadweight	216,269 tons
Block Coef.	0.809

The overall design and layout of the *Concentration* was typical of VLCC's built around 1970. The cargo section of the hull was divided by two

longitudinal and seven transverse bulkheads, making a total of five center tanks and twelve wing tanks (Fig. 5.1).

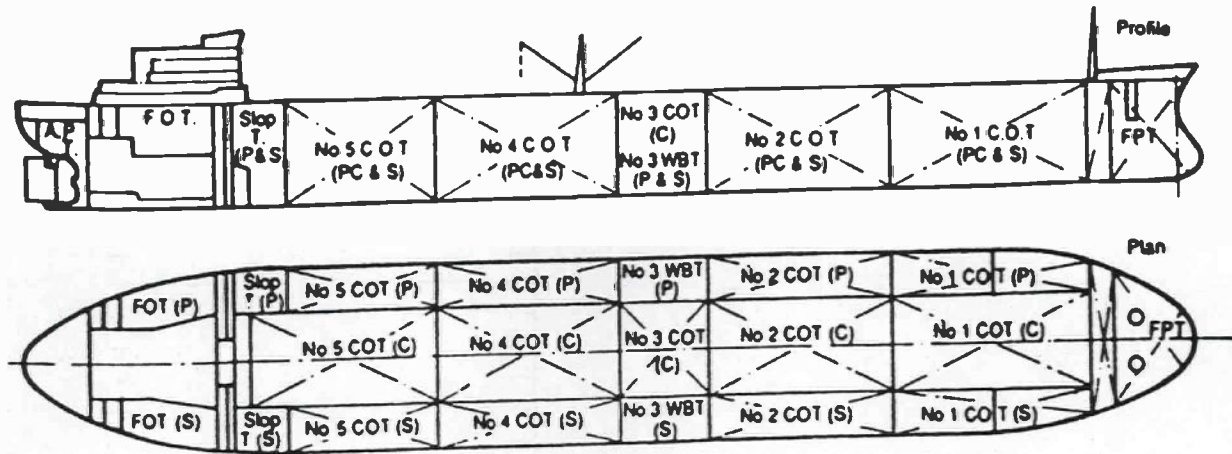


Figure 5.1: General Arrangement (Profile and Plan)

The catastrophic collapse of the *Concentration* occurred around frame 76 where the stillwater bending moment was at its maximum value of roughly 17,940 MNm. Shown in Fig. 5.2 is a section view of the longitudinal structure of this mid body portion of the hull. The bottom, side, deck and longitudinal bulkhead plating are reinforced by closely spaced longitudinal stiffeners. The longitudinal structure is then supported by transverse web frames spaced 5.1 meters apart.

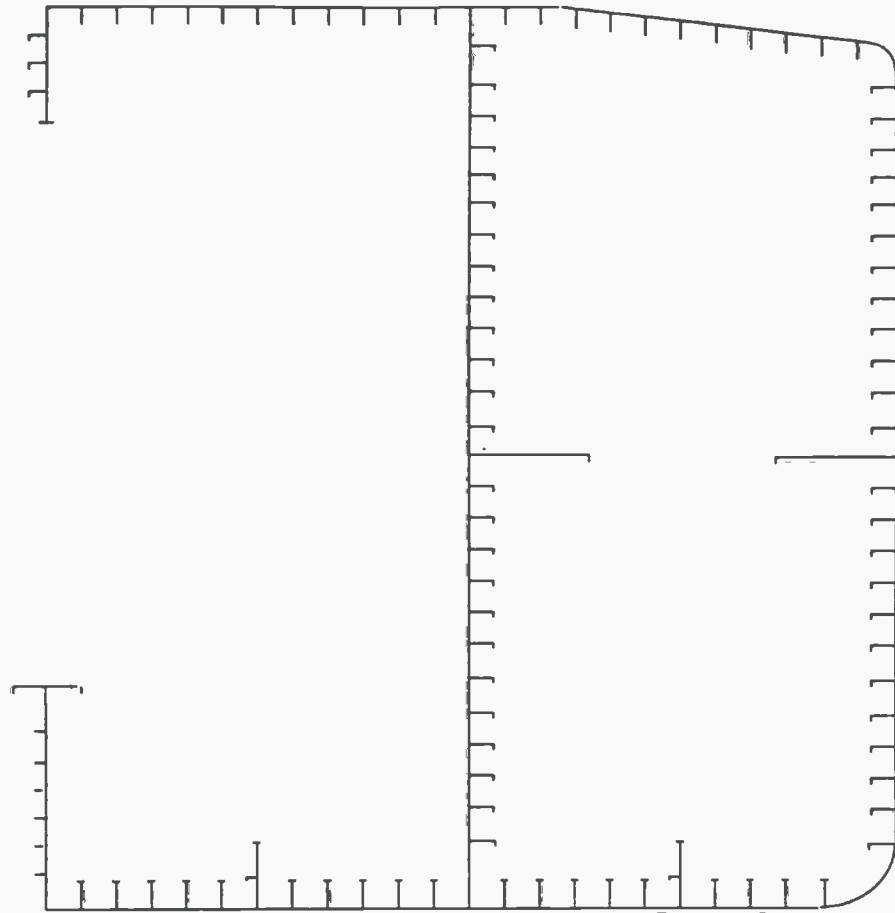


Figure 5.2: Midship Section of the Energy Concentration

For this study, the hull was idealized as a combination of over two hundred plate stiffener element combinations. A full list of the elements that constitute this section is given in the appendix to this report. In the table below are a few examples of the input required to define an element of the cross section.

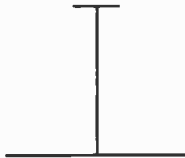
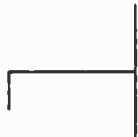

Element id:	B01S	S17S	D05S
Configuration:			

Plate	plate breadth (mm) plate thickness (mm) corrosion rate(mm/yr)	1000 25 0.197	925 23.5 0.051	1000 25.0 0.11
Web	web depth (mm) web thickness (mm) corrosion rate(mm/yr)	797 15 0.063	747 12.7 0.035	480 32 0.063
Flange	flange width (mm) flange thickness (mm) corrosion rate(mm/yr)	200 33 0.053	180 25 0.050	- - -

Material	Type	HTS	MS	HTS
	elastic mod (N/mm ²)	4233	4233	4233
	yield stress (N/mm ²)	350	315	350
	ultimate strs(N/mm ²)	555	525	555

5.2. LOAD CONDITION

The Concentration failed while in port and in the hogging condition. The demand placed on the vessel consisted solely of a hogging still water bending moment. In order to simulate this demand situation for the SMIS calculation, the sagging loads can be left as they were calculated since these represent non-extreme loads, and are unlikely to drive the overall safety index. The hogging vertical wave bending moment can be eliminated by setting its bias factor equal to zero. Finally, the extreme stillwater hog moment of 17,940 MNm can be derived from the "rule based" by assigning an appropriate bias factor. The stillwater hog moment calculated by the SMIS was 5,851 MNm implying a required bias factor of around 3.0.

6. RESULTS AND CONCLUSIONS

6.1. RESULTS OF THE EXAMPLE APPLICATION

The ultimate capacity of the Concentration in the hogging mode is shown in Fig. 6.1. The capacity was calculated for each of six time steps ranging from the zero year (as-built) section up until the ten year mark which corresponds to the age of the vessel when it sailed into port for the last time. The horizontal line in each graph represents the extreme stillwater load applied to the reliability calculation.

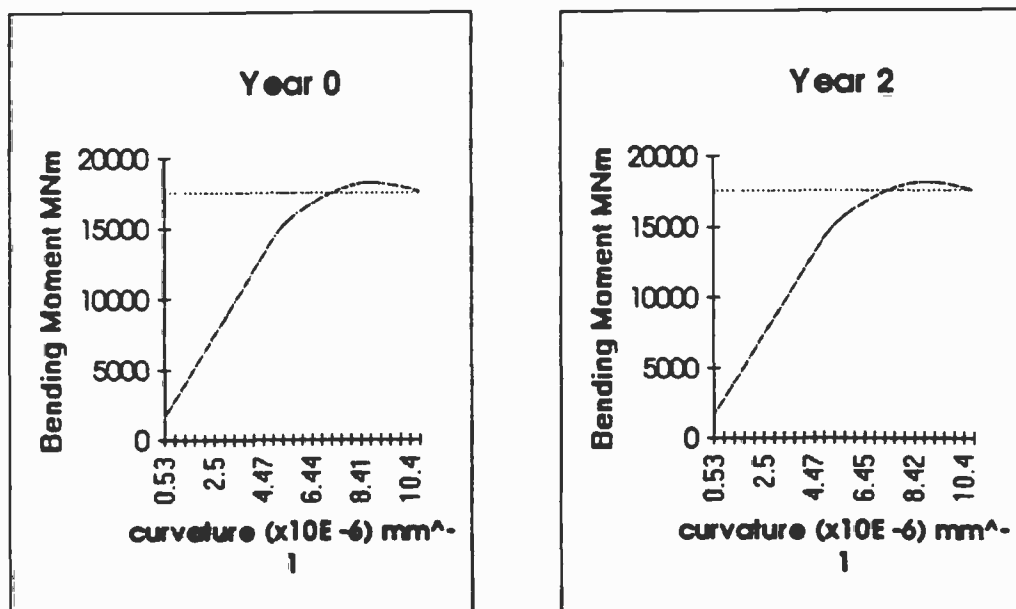


Figure 6.1a: Hogging Moment/Curvature Relations as a Function of Time

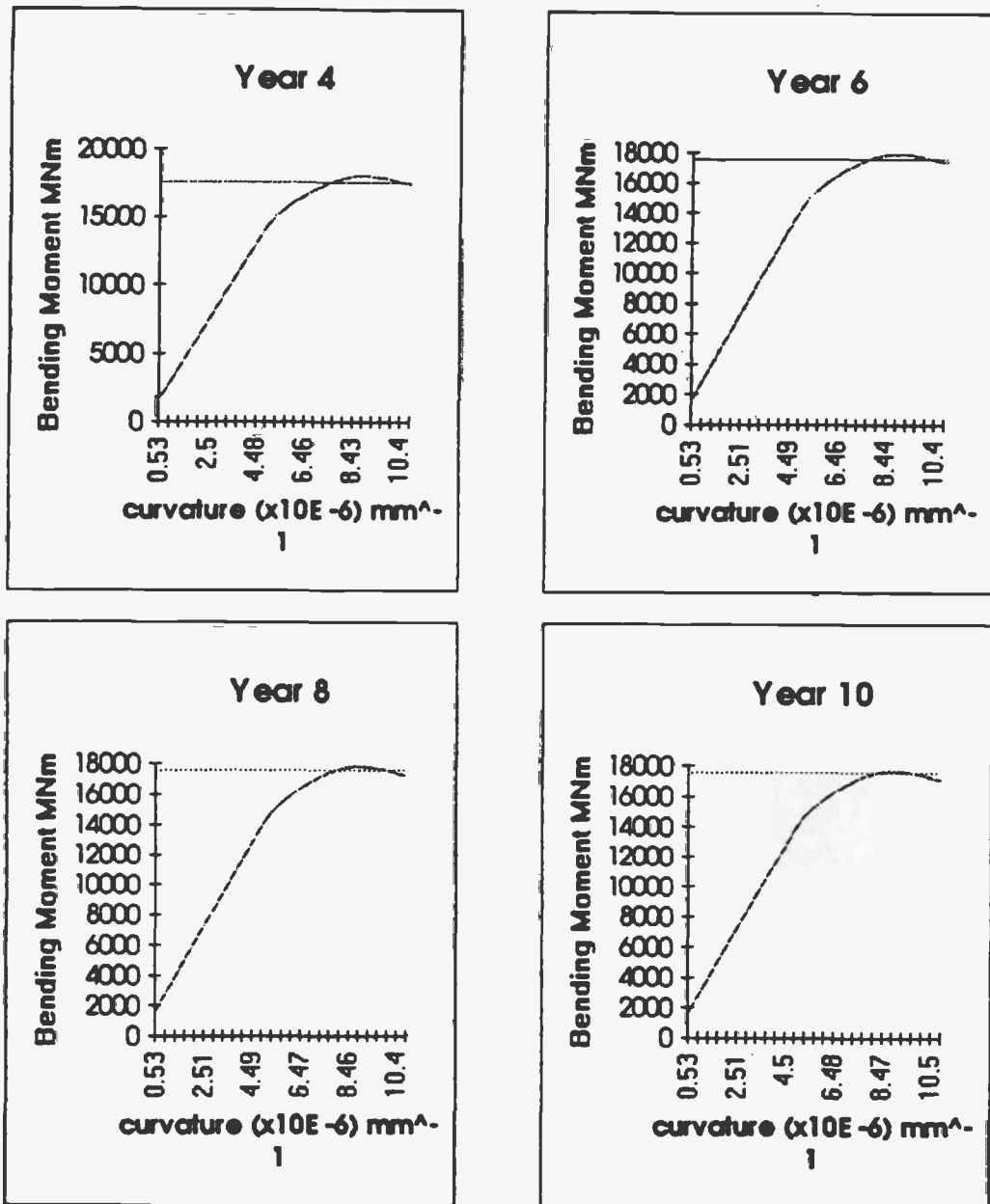


Figure 6.1b: Hogging Moment/Curvature Relations as a Function of Time

The capacity of the midship section structure in the hogging mode was found to decline almost linearly with time at a rate of roughly 1,500 MNm/year. This trend is displayed graphically in Fig. 6.2

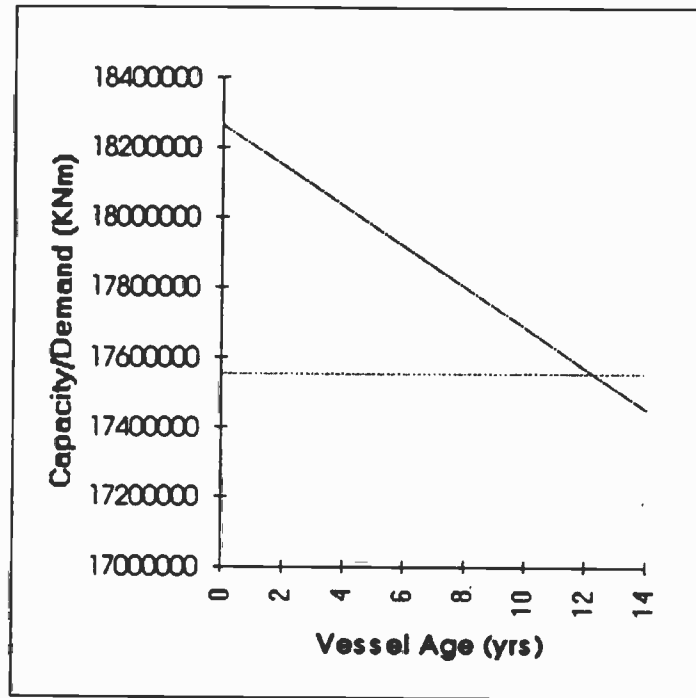


Figure 6.2: The Decline in Ultimate Capacity of the Midship Section

6.2. RELIABILITY OF SAMPLE VESSEL AND CORROSION LIMITS

Presented below is the decline in "beta" over the lifespan of the *Energy Concentration* as calculated by in the example application. The trend that the numbers display illustrates what would be expected. The graph represents a slightly accelerated (i.e. non-linear) decrease in the safety index. This is the result of a higher percentage of elements entering the non-linear regions of their load/end-shortening curves. The non-linearity would be more pronounced if the uncertainty in corrosion rates were included in the model

resulting in a "spreading out" of the probability density function for the ultimate capacity.

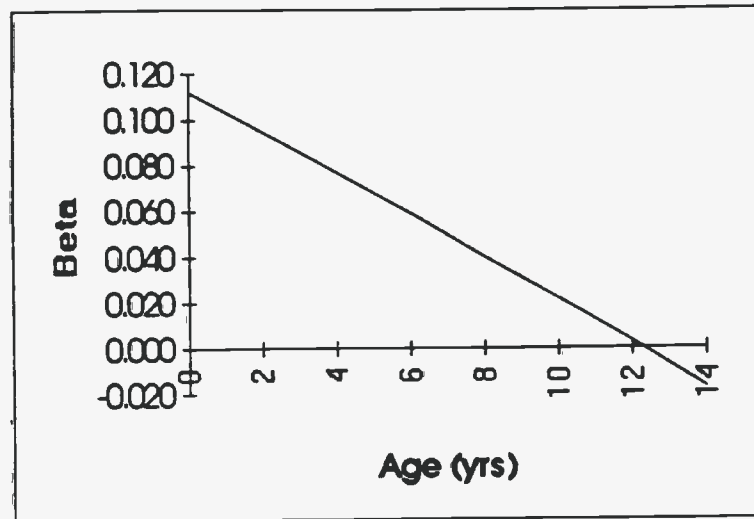


Figure 5.4: Decline in Reliability over Time

6.3. CORROSION LIMITS

While there were many factors involved in the failure of the *Energy Concentration*, clearly the wastage of the internal structure was one of them. The wealth of information surrounding this particular event provided the insight in this case that otherwise would have to come from a very thorough treatment as per the approach outlined in this study. Only a comprehensive treatment of all the major factors involved will lead to accurate predictions of the allowable wastage limits.

In the mean time, with the benefit of hindsight and a historically based estimate of corrosion rates, wastage limits can be assigned to each sub-element of the failed section. Applying a ten year time-until-failure, and assuming that corrosion rates remain constant over the long term, the allowable wastage can be calculated. The results for the bottom shell element presented earlier are as follows:

Subelement	corrosion rate (mm/yr)		time-until failure (yrs)	=	allowable wastage (mm)
Plate	0.197	x	10	=	1.97
Web	0.063	x	10	=	0.63
Flange	0.053	x	10	=	0.53

6.4. RECOMMENDATIONS FOR FUTURE WORK

The goal of this project was to develop a rational approach to the definition of corrosion limits in tankers. The basic framework for an analytical tool that can be used to solve this problem has been laid out in the preceding sections along with an example application to illustrate the procedure. There remains much work to be done in order to implement the ideas presented in this study and create an application that can be used by the industry.

A endeavor such as this one actually involves two disciplines: Naval Architecture and Computer Systems Analysis. In order to develop a working application based on this study, the expertise of both fields are required. Listed below are recommendations for future work in both areas:

6.4.1. Naval Architecture Topics

- **Element Behavior**: Among the many uncertainties involved in the modeling of this problem, the prediction of the individual element behavior plays a very significant role. This uncertainty alone, if not treated properly, could potentially invalidate the results of the reliability calculation. Topics to be considered are: lateral hydrostatic pressure, initial imperfections, and residual stresses.
- **Boundary Conditions and Interaction Between Elements**: The effect that adjacent elements have on each other plays a significant role in the calculation of buckling strength.
- **Loading Module**: A loading module based on ship motion theory needs to be incorporated into the application.

- **Uncertainty and Correlation:** A comprehensive treatment, module by module, of all the uncertainties involved is crucial to the success and usefulness of the system. This includes modelling correlation between failure modes and correlation between repair times.
- **HOE:** Some recent work being done in the area of Human and Organizational Errors could be incorporated into the approach.

6.4.2. Computer Systems Topics

- **Data Gathering:** In order to support all of the aspects of the life assessment procedure, the database must have sufficient and accurate data.
- **Data Modeling:** This task involves taking the raw data and setting it in a format that can be used by the analytical routines while at the same time providing for the ease of input.
- **User Interface:** A consistent user interface needs to be designed that will allow a range of users to operate. This includes providing help screens, menu bars, error checking, input (data entry) screens, and output (reporting) screens.

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APPENDIX A: SOURCE CODE FOR SMIS


```

* .....
*
* * 11/30/93      ANALYSIS.SPR      22:35:45
*
* .....
*
* * Author's Name
*
* * Copyright (c) 1993 Company Name
* * Address
* * City, Zip
*
* * Description:
* * This program was automatically generated by GENSCRN.
*
* .....

```

```

#REGION 0
REGIONAL m.currearea, m.talkstat, m.compstat

```

```

IF SET("TALK") = "ON"
    SET TALK OFF
    m.talkstat = "ON"

```

```

ELSE
    m.talkstat = "OFF"

```

```

ENDIF
m.compstat = SET("COMPATIBLE")
SET COMPATIBLE FOXPLUS

```

```

m.rborder = SET("READBORDER")
SET READBORDER ON

```

```

m.currearea = SELECT()

```

```

* .....
*
* * ANALYSIS/Windows Databases, Indexes, Relations
*
* .....
*

```

```

IF USED("class")
    SELECT class
    SET ORDER TO TAG "class_id"

```

```

ELSE
    SELECT 0
    USE (LOCFILE("\smis\dbfs\class.dbf", "DBF", "Where is class?"));
    AGAIN ALIAS class ;
    ORDER TAG "class_id"

```

```

ENDIF

```

```

IF USED("section")

```

```

        SELECT section
        SET ORDER TO TAG "sect_id"
ELSE
    SELECT 0
    USE (LOCFILE("\smis\dbfs\section.dbf","DBF","Where is section?"));
        AGAIN ALIAS section ;
        ORDER TAG "sect_id"
ENDIF

IF USED("element")
    SELECT element
    SET ORDER TO TAG "elm_id"
ELSE
    SELECT 0
    USE (LOCFILE("\smis\dbfs\element.dbf","DBF","Where is element?"));
        AGAIN ALIAS element ;
        ORDER TAG "elm_id"
ENDIF

IF USED("steel")
    SELECT steel
    SET ORDER TO TAG "steel_id"
ELSE
    SELECT 0
    USE (LOCFILE("\smis\dbfs\steel.dbf","DBF","Where is steel?"));
        AGAIN ALIAS steel ;
        ORDER TAG "steel_id"
ENDIF

IF USED("life")
    SELECT life
    SET ORDER TO 0
ELSE
    SELECT 0
    USE (LOCFILE("\smis\dbfs\life.dbf","DBF","Where is life?"));
        AGAIN ALIAS life ;
        ORDER 0
ENDIF

IF USED("momcurv")
    SELECT momcurv
    SET ORDER TO 0
ELSE
    SELECT 0
    USE (LOCFILE("\smis\dbfs\momcurv.dbf","DBF","Where is momcurv?"));
        AGAIN ALIAS momcurv ;
        ORDER 0
ENDIF

SELECT class

```

```

* .....
* *

```

```

* *      Windows Window definitions
* *
* .....
*

```

```

IF NOT WEXIST("smis");
  OR UPPER(WTITLE("SMIS")) == "SMIS.PJX" ;
  OR UPPER(WTITLE("SMIS")) == "SMIS.SCX" ;
  OR UPPER(WTITLE("SMIS")) == "SMIS.MNX" ;
  OR UPPER(WTITLE("SMIS")) == "SMIS.PRG" ;
  OR UPPER(WTITLE("SMIS")) == "SMIS.FRX" ;
  OR UPPER(WTITLE("SMIS")) == "SMIS.QPR"
  DEFINE WINDOW smis ;
    AT 3.083, 8.750 ;
    SIZE 24.538,100.200 ;
    TITLE "Section Analysis" ;
    FONT "MS Sans Serif", 8 ;
    FLOAT ;
    NOCLOSE ;
    MINIMIZE ;
    SYSTEM
ENDIF

```

```

* .....
* *
* *      ANALYSIS/Windows Setup Code - SECTION 2
* *
* .....
*

```

```

#REGION 1
PUBLIC m.class_id, m.sect_id, m.ds_life,m.ntimes,m.ds_load,;
      m.loadbias,m.loadcov
DIMENSION sections(40,2)

SET UDFPARMS TO REFERENCE

STORE '' TO sections

SELECT DISTINCT ALLTRIM(UPPER(class.classname)), class.class_id;
FROM CLASS;
ORDER BY class.classname;
INTO ARRAY classes

m.beta_min = 0.0
m.ntimes = 0.0

m.swhog = 0.0
m.b_swhog = 1.0
m.cov_swhog = 0.2
m.vwhog = 0.0
m.b_vwhog = 1.0
m.cov_vwhog = 0.2

```

m.swsag = 0.0
m.b_swsag = 1.0
m.cov_swsag = 0.2
m.vwsag = 0.0
m.b_vwsag = 1.0
m.cov_vwsag = 0.2

m.session = ''

```
• .....  
• •  
• • ANALYSIS/Windows Screen Layout  
• •  
• .....  
•
```

#REGION 1

IF WVISIBLE("smis")

ACTIVATE WINDOW smis SAME

ELSE

ACTIVATE WINDOW smis NOSHOWN

ENDIF

@ 3.769,57.600 SAY "Minimum Beta level:" + CHR(13) + ;

"" + CHR(13) + ;

"Time Step (in years):" ;

SIZE 3.000,19.800, 0.000 ;

FONT "MS Sans Serif", 8 ;

STYLE "T"

@ 1.923,57.600 SAY "SESSION PARAMETERS" ;

FONT "MS Sans Serif", 8 ;

STYLE "BT"

@ 3.769,4.200 SAY "Vessel Class:" ;

FONT "MS Sans Serif", 8 ;

STYLE "T"

@ 5.615,4.200 SAY "Section:" ;

FONT "MS Sans Serif", 8 ;

STYLE "T"

@ 1.923,4.800 SAY "SECTION IDENTIFICATION" ;

FONT "MS Sans Serif", 8 ;

STYLE "BT"

@ 13.923,4.800 SAY "Mean:" ;

FONT "MS Sans Serif", 8 ;

STYLE "T"

@ 15.769,4.800 SAY "Bias:" + CHR(13) + ;

"" + CHR(13) + ;

"Coef. of Var.:" ;

SIZE 3.000,13.000, 0.000 ;

FONT "MS Sans Serif", 8 ;

STYLE "T"

@ 9.308,45.600 SAY "Design LOADS:" ;

FONT "MS Sans Serif", 8 ;

STYLE "BT"

```

@ 8.308,2.600 TO 8.308,98.200 ;
    PEN 1, 8 ;
    STYLE "1"
@ 12.000,55.200 TO 19.462,55.200 ;
    PEN 1, 8
@ 1.000,52.800 TO 8.385,52.800 ;
    PEN 1, 8
@ 19.385,3.000 TO 19.385,98.600 ;
    PEN 1, 8 ;
    STYLE "1"
@ 12.615,23.600 SAY "SWBM"           VWBM" ;
    FONT "MS Sans Serif", 8 ;
    STYLE "T"
@ 12.615,64.800 SAY "SWBM"           VWBM" ;
    FONT "MS Sans Serif", 8 ;
    STYLE "T"
@ 3.692,21.600 GET m.which_class ;
    PICTURE "@^" ;
    FROM classes ;
    SIZE 1.538,22.167 ;
    DEFAULT 1 ;
    FONT "MS Sans Serif", 8 ;
    STYLE "B" ;
    WHEN _qld1cflsi() ;
    VALID _qld1cfmvc()
@ 5.538,21.600 GET m.which_sect ;
    PICTURE "@^" ;
    FROM sections ;
    SIZE 1.538,22.167 ;
    DEFAULT 1 ;
    FONT "MS Sans Serif", 8 ;
    STYLE "B" ;
    WHEN _qld1cfni6() ;
    VALID _qld1cfnm1() ;
    DISABLE
@ 3.769,79.600 GET m.betamin ;
    SIZE 1.000,8.800 ;
    DEFAULT 0 ;
    FONT "MS Sans Serif", 8 ;
    PICTURE "@K 99.999"
@ 5.615,82.000 GET m.timestep ;
    SIZE 1.000,6.400 ;
    DEFAULT 0 ;
    FONT "MS Sans Serif", 8 ;
    PICTURE "@K"
@ 13.923,22.000 GET m.swhog ;
    SIZE 1.000,13.600 ;
    DEFAULT 0 ;
    FONT "MS Sans Serif", 8 ;
    PICTURE "@KZ 999999999.9" ;
    DISABLE
@ 15.769,24.400 GET m.b_swhog ;
    SIZE 1.000,6.400 ;
    DEFAULT " " ;

```

FONT "MS Sans Serif", 8 ;
PICTURE "@K" ;
DISABLE
@ 17.615,24.400 GET m.cov_swhog ;
SIZE 1.000,6.400 ;
DEFAULT " " ;
FONT "MS Sans Serif", 8 ;
PICTURE "@K" ;
DISABLE
@ 13.923,38.800 GET m.vwhog ;
SIZE 1.000,13.600 ;
DEFAULT 0 ;
FONT "MS Sans Serif", 8 ;
PICTURE "@KZ 99999999.9" ;
DISABLE
@ 15.769,41.200 GET m.b_vwhog ;
SIZE 1.000,6.400 ;
DEFAULT " " ;
FONT "MS Sans Serif", 8 ;
PICTURE "@K" ;
DISABLE
@ 17.615,41.200 GET m.cov_vwhog ;
SIZE 1.000,6.400 ;
DEFAULT " " ;
FONT "MS Sans Serif", 8 ;
PICTURE "@K" ;
DISABLE
@ 13.923,62.800 GET m.swsag ;
SIZE 1.000,13.600 ;
DEFAULT 0 ;
FONT "MS Sans Serif", 8 ;
PICTURE "@KZ 99999999.9" ;
DISABLE
@ 15.769,65.200 GET m.b_swsag ;
SIZE 1.000,6.400 ;
DEFAULT " " ;
FONT "MS Sans Serif", 8 ;
PICTURE "@K" ;
DISABLE
@ 17.615,65.200 GET m.cov_swsag ;
SIZE 1.000,6.400 ;
DEFAULT " " ;
FONT "MS Sans Serif", 8 ;
PICTURE "@K" ;
DISABLE
@ 13.923,79.600 GET m.vwsag ;
SIZE 1.000,13.600 ;
DEFAULT 0 ;
FONT "MS Sans Serif", 8 ;
PICTURE "@KZ 99999999.9" ;
DISABLE
@ 15.769,82.000 GET m.b_vwsag ;
SIZE 1.000,6.400 ;
DEFAULT " " ;

```

FONT "MS Sans Serif", 8 ;
PICTURE "@K" ;
DISABLE
@ 17.615,82.000 GET m.cov_vwsag ;
SIZE 1.000,6.400 ;
DEFAULT " " ;
FONT "MS Sans Serif", 8 ;
PICTURE "@K" ;
DISABLE
@ 11.154,31.200 GET m.hog ;
PICTURE "@*C Hog" ;
SIZE 1.308,8.333 ;
DEFAULT 0 ;
FONT "MS Sans Serif", 8 ;
STYLE "BT"
@ 11.154,72.000 GET m.sag ;
PICTURE "@*C Sag" ;
SIZE 1.308,8.167 ;
DEFAULT 0 ;
FONT "MS Sans Serif", 8 ;
STYLE "BT"
@ 21.231,35.400 GET m.begin ;
PICTURE "@*HN \<Begin" ;
SIZE 1.769,10.333,1.333 ;
DEFAULT 1 ;
FONT "MS Sans Serif", 8 ;
STYLE "B" ;
VALID _qld1cfoom()
@ 21.231,52.200 GET m.quit ;
PICTURE "@*HN \<Quit" ;
SIZE 1.769,10.167,0.667 ;
DEFAULT 1 ;
FONT "MS Sans Serif", 8 ;
STYLE "B" ;
VALID _qld1cfotw()
@ 1.923,89.200 GET m.session ;
SIZE 1.000,6.400 ;
DEFAULT " " ;
FONT "MS Sans Serif", 8

```

```

IF NOT WVISIBLE("smis")
    ACTIVATE WINDOW smis
ENDIF

```

READ CYCLE

RELEASE WINDOW smis

```

* *****
* *
* *           Windows Closing Databases
* *
* *****
*

```

```
IF USED("class")
  SELECT class
  USE
ENDIF

IF USED("section")
  SELECT section
  USE
ENDIF

IF USED("element")
  SELECT element
  USE
ENDIF
```

```
IF USED("steel")
  SELECT steel
  USE
ENDIF
```

```
IF USED("life")
  SELECT life
  USE
ENDIF
```

```
IF USED("momcurv")
  SELECT momcurv
  USE
ENDIF
```

```
SELECT (m.currarea)
```

```
#REGION 0
```

```
SET READBORDER &rborder
```

```
IF m.talkstat = "ON"
  SET TALK ON
ENDIF
```

```
IF m.compstat = "ON"
  SET COMPATIBLE ON
ENDIF
```

```

* .....
* *
* * ANALYSIS/Windows Cleanup Code
* *
* .....
*
```

```
#REGION 1
```



```
*****
*
*      PROCEDURE startprg
*
*-----*
```

```
* Input:
```

```
Global variables: Sect_id, TimeStep, Ds_Load, LoadBias, LoadCov
```

```
* Output:
```

```
Report
```

```
* Called by: Main Screen
```

```
* Calls: CORRODER
          MOM_CURV
```

```
*****
*
*      DIMENSION curvtr(60), moment(60)
```

```
curvtr = 0.0          && initial value for curvature
moment = 0.0          && initial value for moment
```

```
*      initialize the demand and capacity in the hogging condition
```

```
m.dmdhog = m.vvhog * m.b_vvhog + m.svhog*m.b_svhog
m.vdmdhog = sqrt((m.cov_vvhog*m.vvhog)^2 + (m.cov_svhog*m.svhog)^2)
m.caphog = 0.0
m.cov_caphog = 0.33
```

```
*      initialize the demand and capacity in the sagging condition
```

```
m.dmdsag = m.vwsag * m.b_vwsag + m.swsag*m.b_swsag
m.vdmdsag = sqrt((m.cov_vwsag*m.vwsag)^2 + (m.cov_swsag*m.swsag)^2)
m.capsag = 0.0
m.cov_capsag = 0.33
```

```
*****
*      begin
```

```
m.beta = 100    && impossibly high
```

```
n_elms = 0
```

```
SELECT Section.space, Element.pb, Element.pt, Element.pr, Element.wd,;
       Element.wt, Element.wr, Element.fb, Element.ft, Element.fr, Element.theta,;
       Element.y_node, Steel.elasmod, Steel.u_stress, Steel.y_stress,;
       Steel.poisson;
FROM Section, Element, Steel;
WHERE Element.sect_id = Section.sect_id;
```

```

        AND Steel.steel_id = Element.steel_id;
        AND Section.sect_id = m.sect_id;
    INTO ARRAY temp

```

```

m.count = ALEN(temp)
n_elms = INT(m.count/16)

```

```

m.step = 1

```

```

DO WHILE m.beta > m.Betamin

```

```

    dimension elms(n_elms,16)

```

```

    lastbeta = m.beta

```

```

    m.year = (m.step-1)*m.timestep

```

```

    DO CORRODER

```

```

    DO CAPACITY

```

```

    m.caphog = m.caphog/1000000
    m.capsag = m.capsag/1000000

```

```

    m.betahog = (m.caphog - m.dmdhog);
               /sqrt((cov_caphog*m.caphog)^2 + vdmdhog^2)

```

```

    m.betasag = (m.capsag - m.dmdsag);
               /sqrt((cov_capsag*m.capsag)^2 + vdmdsag^2)

```

```

    m.beta = betahog

```

```

    SELECT life

```

```

    APPEND BLANK
    GATHER MEMVAR

```

```

    m.step = m.step + 1

```

```

ENDDO

```

```

m.step = m.step - 1

```

```

TTF = (m.step-1)*m.timestep + (m.Betamin-lastbeta) *;
      m.timestep/(m.beta-lastbeta)

```

```

? TTF
WAIT WINDOW 'YOU WON'
*   Set up wastage limit report

```

```

*****
*

```

PROCEDURE CORRODER

.....

Input:

Sect_id - Section identification
m.time - The "age" of the vessel for a particular timestep

Output:

elms(n,16) - Array containing the following info for each of n section elements:
frame spacing
plate width
plate thickness (corroded)
web depth
web thickness (corroded)
flange width
flange thickness (corroded)
theta
elasmod
u_strs
Y_strs
poisson

Called by: ANALYSIS

Calls: ELMPROPS
STRSSTRN

j = 1
j = 1
done = .F.

DO WHILE .NOT. done

elms(j,1) = temp(i)

elms(j,2) = temp(i+1)
elms(j,3) = temp(i+2) - m.year*temp(i+3)

elms(j,4) = temp(i+4)
elms(j,5) = temp(i+5) - m.year*temp(i+6)

elms(j,6) = temp(i+7)
elms(j,7) = temp(i+8) - m.year*temp(i+9)

elms(j,8) = temp(i+10)
elms(j,9) = temp(i+11)

```
elms(j,10) = temp(i+12)
elms(j,11) = temp(i+13)
elms(j,12) = temp(i+14)
elms(j,13) = temp(i+15)
```

```
i = i + 16
j = j + 1
```

```
IF i > m.count
  done = .T.
ENDIF
```

```
ENDDO
```

```
RETURN
```

***** END *****

PROCEDURE CAPACITY

* Input:
* elms array - contains the element specific info for the section
* m.count - length of elms array

* Output:
* Mnt_crv - Moment vs Curvature array

* Called by: ANALYSIS

* Calls: ELMPROPS
* STRSSTRN

* DIMENSION el_curv(n_elms), strss(n_elms)
* Initialize...

```
m.sect_area = 0.0
y_times_a = 0.0
I_nodes = 0.0
cr_strs = 0.0
I_node = 0.0
area = 0.0
```

```

* Calculate initial section properties:      sect_area (section area)
*
* (neutral axis location)                  na
*
* (section mom. inertia)                   inertia

```

```

FOR i = 1 TO n_elms
  m.space = elms(i,1)
  m.pb    = elms(i,2)
  m.pt    = elms(i,3)
  m.wd    = elms(i,4)
  m.wt    = elms(i,5)
  m.fb    = elms(i,6)
  m.ft    = elms(i,7)
  m.theta = elms(i,8)
  m.y     = elms(i,9)
  m.elasmod = elms(i,10)
  m.u_strs = elms(i,11)
  m.y_strs = elms(i,12)
  m.poisson = elms(i,13)

  DO elmprops WITH m.space,m.pb,m.pt,m.wd,m.wt,m.fb,m.ft,m.theta,m.y,;
                 m.elasmod,m.u_strs, m.y_strs,m.poisson

  elms(i,14) = cr_strs
  elms(i,15) = area
  elms(i,16) = I_node

  m.sect_area = m.sect_area + area
  y_times_a = y_times_a + y*area
  I_nodes = I_nodes + I_node
ENDFOR

m.na = y_times_a/m.sect_area
orig_na = m.na

i_prllel = 0

FOR i = 1 TO n_elms
  I_prllel = I_prllel + elms(i,15)*(elms(i,9) - m.na)^2
ENDFOR

m.inertia = I_nodes + I_prllel

SELECT momcurv

```

```

.....
*
* SAG
*
.....

```

- * Find elastic limit curvature, curvature at which first element reaches its elastic limit, stress y_strs

```

elaslim = 10.                && impossibly high
y_strm = 0.000000000000
el_curv = 0.000000000000

```

- * calculate elastic limit curvature in the hogging condition

```

FOR i = 1 TO n_elms

  y_na = elms(i,9) - m.na
  y_strm = elms(i,12)/elms(i,10)
  IF elms(i,14) < elms(i,12)
    IF y_na < 0
      el_curv = elms(i,14)/(elms(i,10)*y_na)
    ELSE
      el_curv = y_strm/y_na
    ENDIF
  ELSE
    el_curv = y_strm/y_na
  ENDIF

  elaslim = MIN(ABS(el_curv),elaslim)
ENDFOR

done = .F.
j=2
curvtr(j) = elaslim
stress = 0.0

postj = 5

DO WHILE .NOT. done

  k = j-1
  forcesum = 0.0                && reset values
  ea_sum = 0.0
  moment(j) = 0.0

  FOR i = 1 TO n_elms
    strain = curvtr(j)*(elms(i,9) - m.na)
    DO strstr WITH elms(i,10),elms(i,11),elms(i,12);
      ,elms(i,14),strain

    strss(i) = stress
    forcesum = forcesum + stress*elms(i,15)
    ea_sum = ea_sum + elms(i,10)*elms(i,15)
  ENDFOR

  IF j > 2
    shift = forcesum/(ea_sum*curvtr(j))
  ELSE
    shift = 0.0

```

```

ENDIF

m.na = m.na + sbift

FOR i = 1 TO n_elms
    moment(j) = moment(j) +;
                                strss(i)*elms(i,15)*(elms(i,9)-m.na)
ENDFOR

m.momnt = moment(j)
m.curvatr = curvtr(j)

APPEND BLANK

GATHER MEMVAR

IF moment(j) <= moment(k)
    if postj = 5
        jcap = k
    endif
    postj = postj - 1
    if postj = 0
        done = .T.
        loop
    endif
    j = j+1
    curvtr(j) = curvtr(j-1) + (0.75*elaslim)
ELSE
    j = j+1
    curvtr(j) = curvtr(j-1) + (0.75*elaslim)
ENDIF
ENDDO

m.capsag = moment(jcap)

```

```

.....
*
*   HOG
*
.....

```

- * Find elastic limit curvature, curvature at which first element ceases to behave elastically

```

elaslim = - 10.                && impossibly low
y_strn = 0.000000000000
el_curv = 0.000000000000

```

- * reset neutral axis to original position

```
m.na = orig_na
```

- * calculate elastic limit curvature in the sagging condition

```
FOR i = 1 TO n_elms
```

```
  y_na = elms(i,9) - m.na  
  y_strn = elms(i,12)/elms(i,10)  
  IF elms(i,14) < elms(i,12)  
    IF y_na > 0  
      el_curv = elms(i,14)/(elms(i,10)*y_na)  
    ELSE  
      el_curv = y_strn/y_na  
    ENDIF  
  ELSE  
    el_curv = y_strn/y_na  
  ENDIF  
  
  elaslim = -MIN(ABS(el_curv),ABS(elaslim))
```

```
ENDFOR
```

```
done = .F.  
j=2  
curvtr(j) = elaslim  
stress = 0.0
```

```
forcesum = 0.0  
ea_sum = 0.0  
postj = 5
```

```
DO WHILE .NOT. done
```

```
  k = j-1  
  forcesum = 0.0  
  ea_sum = 0.0  
  moment(j) = 0.0
```

```
&& reset values
```

```
  FOR i = 1 TO n_elms  
    strain = curvtr(j)*(elms(i,9) - m.na)  
    DO strstrn WITH elms(i,10),elms(i,11),elms(i,12);  
      ,elms(i,14),strain  
    strss(i) = stress  
    forcesum = forcesum + stress*elms(i,15)  
    ea_sum = ea_sum + elms(i,10)*elms(i,15)
```

```
  ENDFOR
```

```
  shift = forcesum/(ea_sum*curvtr(j))
```

```
  m.na = m.na + shift  
  moment(j) = 0.0
```

```
  FOR i = 1 TO n_elms  
    moment(j) = moment(j) +;  
      strss(i)*elms(i,15)*(elms(i,9)-m.na)
```

```
  ENDFOR
```

```
  m.momnt = moment(j)  
  m.curvatr = curvtr(j)
```


APPEND BLANK

GATHER MEMVAR

```
IF ABS(moment(j)) <= ABS(moment(k))
  if postj = 5
    jcap = k
  endif
  postj = postj - 1
  if postj = 0
    done = .T.
  endif
  j = j+1
  curvtr(j) = curvtr(j-1) + (0.75*elaslim)
ELSE
  j = j+1
  curvtr(j) = curvtr(j-1) + (0.75*elaslim)
ENDIF
```

ENDDO

m.caphog = -moment(jcap)

RELEASE elms

RETURN

..... END

.....

PROCEDURE ELMPROPS

.....

• Input:
• elms array - Contains element dimensions and material properties
• Output:
• Cr_strs - critical buckling stress for element i
• Area - Cross sectional are of element
• I_node - Area moment of inertia for the element about a
horizontal axis passing throught he elements node

• Called by: CAPACITY

• Calls: none

PARAMETER m.space,m.pb,m.pt,m.wd,m.wt,m.fb,m.ft,m.theta,m.y,m.elasmod,;

```

      m.u_strs,m.y_strs,m.poisson
*
      last = 0.0
*
      Calculate critical stress for plate between stiffeners

      kD = 4*m.elasmod*m.pt^3/(12*(1-m.poisson^2))
      plt_cr = kD*PI()^2/(m.pt*m.pb^2)
*
      done = .F.
      kbeta = (pb/pt)*sqrt(u_strs/elasmod)
      pbc = m.pb

      area = m.pb*m.pt + m.wd*m.wt + m.fb*m.ft
*
      Calculate column (Euler) buckling stress

      e_area = m.pb*m.pt + m.wd*m.wt + m.fb*m.ft

      centroid = (0.5*m.wd^2*m.wt + m.fb*m.ft*m.wd)/e_area

      I_cent = (m.pb*m.pt^3 + m.wt*m.wd^3 + m.fb*m.ft^3)/12 + ;
               m.pb*m.pt*centroid^2 + m.wd*m.wt*(0.5*m.wd - centroid)^2;
               + m.fb*m.ft*(m.wd - centroid)^2

      gyradius = SQRT(I_cent/e_area)

      col_cr = elasmod*(PI()*gyradius/m.space)^2
*
      Calculate I_node

      cr_strs = 1.8*col_cr

      I_plate = (m.pt*m.pb^3/12)*SIN(m.theta)^2
      I_web = m.wt*m.wd^3*COS(m.theta)^2/3
      I_flg = (m.ft*m.fb^3/12)*SIN(m.theta)^2

      I_node = I_plate + (I_web + m.wd*m.wt*(0.5*m.wd*COS(m.theta))^2);
               + (I_flg + m.ft*m.fb*(m.wd*COS(m.theta))^2)

      RETURN
*
      ***** END *****
*
      *****
*
      Procedure STRSSTRN
*
      *****

```

```

*
* Input:
*   ElasMod - Yeung's Modulus
*   U_Strs  - Ultimate Stress
*   Y_Strs  - Proportional Limit (Yield) Stress
*   CR_Strs - Critical Buckling strength calculated from Procedure
*             "CRITICAL"
*   Strain  - Input strain level
*
* Output:
*   Stress  - Element Stress corresponding to the imposed Strain

```

```

-----
*
* Called by: MOM_CURV
* Calls:   none
*
-----

```

```

Parameters m.ELASMOD,m.U_STRS,m.Y_STRS,CR_STRS,STRAIN

```

```

stress = 0.0
HARDSPOT = .F.
PLASTIC = .F.
ELASTIC = .F.

```

```

* Compute the yield and ultimate strains in order to define the regions
* in which the input strain might fall

```

```

Y_STRN = m.Y_STRS/m.ELASMOD

```

```

K1 = ((m.U_STRS-m.Y_STRS)*m.Y_STRS/(m.ELASMOD*m.U_STRS))
K2 = (m.U_STRS**2-m.Y_STRS*m.U_STRS)/(m.U_STRS*m.Y_STRS)
U_STRN = K1*LOG(K2*0.99*m.U_STRS/(0.01*m.U_STRS))

```

```

* Calculate the strain corresponding to the critical buckling stress

```

```

DO CASE
  CASE CR_STRS <= m.Y_STRS
    CR_STRN = CR_STRS/m.ELASMOD
    ELASTIC = .T.
  CASE (CR_STRS > m.Y_STRS .AND. CR_STRS < m.U_STRS)
    CR_STRN = Y_STRN + K1*LOG(K2*CR_STRS/(m.U_STRS-CR_STRS))
    PLASTIC = .T.
  OTHERWISE
    CR_STRN = U_STRN
    HARDSPOT = .T.
ENDCASE

```

```

* Compute the Stress

```

```

IF strain < 0.0                                && element is in tension
  HARDSPOT = .T.
  TENSION = .T.

```

```

        CR_STRN = U_STRN
        STRAIN = -STRAIN          && one-sided material stress-strain crv
ELSE
    TENSION = .F.
ENDIF

IF (STRAIN > CR_STRN)
    IF (HARDSPOT)
        STRESS = m.U_STRS
    ELSE
        STRESS = CR_STRS + (CR_STRN - STRAIN)*0.1*m.ELASMOD
    ENDIF
ELSE
    IF (STRAIN <= Y_STRN)
        STRESS = STRAIN*m.ELASMOD
    ELSE
        IF (STRAIN > Y_STRN and. STRAIN < U_STRN)
            EXPON1 = EXP((STRAIN - Y_STRN)/K1)
            STRESS = (m.U_STRS/K2)*EXPON1/(1+EXPON1/k2)
        ELSE
            STRESS = m.U_STRS
        ENDIF
    ENDIF
ENDIF

IF TENSION
    STRESS = -STRESS
ENDIF

```

RETURN

```

* .....
* *
* * _QLD1CFLSI      m.which_class WHEN
* *
* * Function Origin:
* *
* * From Platform:   Windows
* * From Screen:    ANALYSIS, Record Number: 22
* * Variable:       m.which_class
* * Called By:      WHEN Clause
* * Snippet Number: 1
* *
* .....

```

```

FUNCTION _qld1cflsi && m.which_class WHEN
#REGION 1
m.which_class = 1

```

```

* .....
* *
* * _QLD1CFMVC      m.which_class VALID
* *
* * Function Origin:

```

```

*
*
* * From Platform:   Windows
* * From Screen:    ANALYSIS, Record Number: 22
* * Variable:       m.which_class
* * Called By:      VALID Clause
* * Snippet Number: 2
*
*
* .....
*

```

```

FUNCTION _qld1cfmvc  && m.which_class VALID
#REGION 1
m.class_id = classes(which_class,2)

```

```

SELECT class

```

```

SEEK m.class_id
m.recnum = RECNO()
GOTO m.recnum
SCATTER MEMVAR

```

```

* Calculate Load

```

```

IF m.lbp >= 90.0 .AND. m.lbp <= 300.0
  C = 10.75 - ((300-m.lbp)/100) * SQRT((300-m.lbp)/100)
ELSE
  IF m.lbp >= 300.0 .AND. m.lbp <= 350.0
    C = 10.75
  ELSE
    C = 10.75 - ((m.lbp-350)/150) * SQRT((m.lbp-350)/150)
  ENDIF
ENDIF

```

```

m.vwhog = 190.0*C*m.lbp^2*m.breadth*m.block/1000
m.vwsag = 110.0*C*m.lbp^2*m.breadth*(m.block+0.7)/1000

```

```

m.swhog = 0.75*m.vwhog
m.swsag = 0.75*m.vwsag

```

```

SHOW GET m.vwhog ENABLE
SHOW GET m.vwsag ENABLE
SHOW GET m.swhog ENABLE
SHOW GET m.swsag ENABLE
SHOW GET m.b_vwhog ENABLE
SHOW GET m.b_vwsag ENABLE
SHOW GET m.b_swhog ENABLE
SHOW GET m.b_swsag ENABLE
SHOW GET m.cov_vwhog ENABLE
SHOW GET m.cov_vwsag ENABLE
SHOW GET m.cov_swhog ENABLE
SHOW GET m.cov_swsag ENABLE

```

```

* set up the 'sections' array
SELECT DISTINCT section.sect_name,section.sect_id;
FROM section;

```

```
WHERE section.class_id = m.class_id;
ORDER BY sect_id;
INTO ARRAY sections
```

```
SHOW GET m.which_sect ENABLE
_CUROBJ = OBJNUM(which_sect)
```

* find the correct class record and point to it

```

* .....
*
* * _QLD1CFNI6      m.which_sect WHEN
*
* * Function Origin:
*
* * From Platform:   Windows
* * From Screen:    ANALYSIS, Record Number: 23
* * Variable:       m.which_sect
* * Called By:      WHEN Clause
* * Snippet Number: 3
*
* .....
*

```

```

FUNCTION _qld1cfni6  && m.which_sect WHEN
#REGION 1
m.which_sect = 1

```

```

* .....
*
* * _QLD1CFNMT      m.which_sect VALID
*
* * Function Origin:
*
* * From Platform:   Windows
* * From Screen:    ANALYSIS, Record Number: 23
* * Variable:       m.which_sect
* * Called By:      VALID Clause
* * Snippet Number: 4
*
* .....
*

```

```

FUNCTION _qld1cfnmt  && m.which_sect VALID
#REGION 1
m.sect_id = sections(m.which_sect,2)

```

```

* .....
*
* * _QLD1CFOOM      m.begin VALID
*
* * Function Origin:
*

```

```

* * From Platform:   Windows
* * From Screen:    ANALYSIS,   Record Number: 40
* * Variable:      m.begin
* * Called By:     VALID Clause
* * Snippet Number: 5
* *
* .....
*

```

```

FUNCTION _qld1cfoom  && m.begin VALID
#REGION 1
do startprg

```

```

* .....
* *
* * _QLD1CFOTW      m.quit VALID
* *
* * Function Origin:
* *
* * From Platform:   Windows
* * From Screen:    ANALYSIS,   Record Number: 41
* * Variable:      m.quit
* * Called By:     VALID Clause
* * Snippet Number: 6
* *
* .....
*

```

```

FUNCTION _qld1cfotw  && m.quit VALID
#REGION 1
clear read
rele wind

```


APPENDIX B: SECTION IDEALIZATION TABLE

ELM ID	PB	PT	PR	WD	WT	WR	FB	FT	FR	Y NODE	THETA	STEEL ID
B01P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B02P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B03P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B04P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B05P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B05S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B06P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B06S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B07P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B07S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B08P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B08S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B09P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B09S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B10P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B10S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B11P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B11S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B12P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B12S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B13P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B13S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B14P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B14S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B15P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B15S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B16P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B16S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B17P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B17S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B18P	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B18S	1000.0	25.0	0.197	797.0	15.0	0.063	200.0	33.0	0.053	0.125	0.00	2222
B19P	950.0	18.0	0.051	297.0	11.5	0.035	100.0	16.0	0.050	950.000	1.07	2222
B19S	950.0	18.0	0.051	297.0	11.5	0.035	100.0	16.0	0.050	950.000	1.07	2222
B20P	425.0	25.0	0.035	475.0	18.0	0.051	0.0	0.0	0.000	1900.000	3.14	2222
B20S	425.0	25.0	0.035	475.0	18.0	0.051	0.0	0.0	0.000	1900.000	3.14	2222
B21P	950.0	18.0	0.051	297.0	11.5	0.035	100.0	16.0	0.050	950.000	1.07	2222
B21S	950.0	18.0	0.051	297.0	11.5	0.035	100.0	16.0	0.050	950.000	1.07	2222
B22P	370.0	16.0	0.035	475.0	18.0	0.051	0.0	0.0	0.000	1900.000	3.14	2222
B22S	370.0	16.0	0.035	475.0	18.0	0.051	0.0	0.0	0.000	1900.000	3.14	2222
D01P	1000.0	25.0	0.110	480.0	32.0	0.063	0.0	0.0	0.000	25800.000	3.14	2222
D01S	1000.0	25.0	0.110	480.0	32.0	0.063	0.0	0.0	0.000	25800.000	3.14	2222
D02P	1000.0	25.0	0.110	480.0	32.0	0.063	0.0	0.0	0.000	25800.000	3.14	2222

ELM ID	PB	PT	PR	WD	WT	WR	FB	FT	FR	Y NODE	THETA	STEEL ID
G05C	925.0	22.0	0.066	230.0	12.7	0.045	0.0	0.0	0.000	4600.000	1.57	2222
G06C	925.0	22.0	0.066	230.0	12.7	0.045	0.0	0.0	0.000	5525.000	1.57	2222
G07C	925.0	18.0	0.066	297.0	11.5	0.045	100.0	16.0	0.047	22085.000	1.57	2222
G08C	925.0	18.0	0.066	297.0	11.5	0.045	100.0	16.0	0.047	23010.000	1.57	2222
G09C	925.0	18.0	0.066	297.0	11.5	0.045	100.0	16.0	0.047	23935.000	1.57	2222
G10C	925.0	18.0	0.066	297.0	11.5	0.045	100.0	16.0	0.047	24860.000	1.57	2222
L01P	925.0	22.0	0.066	347.0	11.5	0.045	125.0	22.0	0.047	900.000	1.57	2222
L01S	925.0	22.0	0.066	347.0	11.5	0.045	125.0	22.0	0.047	900.000	1.57	2222
L02P	925.0	22.0	0.066	797.0	15.0	0.045	180.0	25.0	0.047	1800.000	1.57	2222
L02S	925.0	22.0	0.066	797.0	15.0	0.045	180.0	25.0	0.047	1800.000	1.57	2222
L03P	925.0	22.0	0.066	897.0	15.0	0.045	200.0	25.0	0.047	2725.000	1.57	2222
L03S	925.0	22.0	0.066	897.0	15.0	0.045	200.0	25.0	0.047	2725.000	1.57	2222
L04P	925.0	20.0	0.066	945.0	16.0	0.045	200.0	25.0	0.047	3650.000	1.57	1111
L04S	925.0	20.0	0.066	945.0	16.0	0.045	200.0	25.0	0.047	3650.000	1.57	1111
L05P	925.0	20.0	0.066	897.0	15.0	0.045	200.0	25.0	0.047	4575.000	1.57	1111
L05S	925.0	20.0	0.066	897.0	15.0	0.045	200.0	25.0	0.047	4575.000	1.57	1111
L06P	925.0	19.0	0.066	897.0	15.0	0.045	200.0	25.0	0.047	5500.000	1.57	1111
L06S	925.0	19.0	0.066	897.0	15.0	0.045	200.0	25.0	0.047	5500.000	1.57	1111
L07P	925.0	19.0	0.066	847.0	14.0	0.045	180.0	25.0	0.047	6425.000	1.57	1111
L07S	925.0	19.0	0.066	847.0	14.0	0.045	180.0	25.0	0.047	6425.000	1.57	1111
L08P	925.0	19.0	0.066	797.0	14.0	0.045	180.0	25.0	0.047	7350.000	1.57	1111
L08S	925.0	19.0	0.066	797.0	14.0	0.045	180.0	25.0	0.047	7350.000	1.57	1111
L09P	925.0	18.0	0.066	747.0	12.7	0.045	180.0	25.0	0.047	8275.000	1.57	1111
L09S	925.0	18.0	0.066	747.0	12.7	0.045	180.0	25.0	0.047	8275.000	1.57	1111
L10P	925.0	18.0	0.066	747.0	12.7	0.045	150.0	25.0	0.047	9200.000	1.57	1111
L10S	925.0	18.0	0.066	747.0	12.7	0.045	150.0	25.0	0.047	9200.000	1.57	1111
L11P	925.0	17.0	0.066	697.0	12.7	0.045	150.0	25.0	0.047	10125.000	1.57	1111
L11S	925.0	17.0	0.066	697.0	12.7	0.045	150.0	25.0	0.047	10125.000	1.57	1111
L12P	925.0	17.0	0.066	697.0	12.7	0.045	150.0	25.0	0.047	11050.000	1.57	1111
L12S	925.0	17.0	0.066	697.0	12.7	0.045	150.0	25.0	0.047	11050.000	1.57	1111
L13P	925.0	17.0	0.066	647.0	12.7	0.045	150.0	25.0	0.047	11975.000	1.57	1111
L13S	925.0	17.0	0.066	647.0	12.7	0.045	150.0	25.0	0.047	11975.000	1.57	1111
L14P	925.0	17.0	0.066	647.0	12.7	0.045	0.0	0.0	0.000	12900.000	1.57	1111
L14S	925.0	17.0	0.066	647.0	12.7	0.045	0.0	0.0	0.000	12900.000	1.57	1111
L15P	925.0	16.0	0.066	647.0	11.5	0.045	125.0	25.0	0.047	13825.000	1.57	1111
L15S	925.0	16.0	0.066	647.0	11.5	0.045	125.0	25.0	0.047	13825.000	1.57	1111
L16P	925.0	16.0	0.066	647.0	11.5	0.045	125.0	25.0	0.047	14750.000	1.57	1111
L16S	925.0	16.0	0.066	647.0	11.5	0.045	125.0	25.0	0.047	14750.000	1.57	1111
L17P	925.0	16.0	0.066	647.0	11.5	0.045	125.0	25.0	0.047	15675.000	1.57	1111
L17S	925.0	16.0	0.066	647.0	11.5	0.045	125.0	25.0	0.047	15675.000	1.57	1111
L18P	925.0	14.0	0.066	647.0	11.5	0.045	125.0	25.0	0.047	16600.000	1.57	1111
L18S	925.0	14.0	0.066	647.0	11.5	0.045	125.0	25.0	0.047	16600.000	1.57	1111
L19P	925.0	14.0	0.066	597.0	11.5	0.045	125.0	25.0	0.047	17525.000	1.57	1111
L19S	925.0	14.0	0.066	597.0	11.5	0.045	125.0	25.0	0.047	17525.000	1.57	1111
L20P	925.0	14.0	0.066	597.0	11.5	0.045	125.0	25.0	0.047	18450.000	1.57	1111
L20S	925.0	14.0	0.066	597.0	11.5	0.045	125.0	25.0	0.047	18450.000	1.57	1111
L21P	925.0	16.0	0.066	597.0	11.5	0.045	125.0	22.0	0.047	19375.000	1.57	1111

ELM ID	PB	PT	PR	WD	WT	WR	FB	FT	FR	Y NODE	THETA	STEEL ID
L21S	925.0	16.0	0.066	597.0	11.5	0.045	125.0	22.0	0.047	19375.000	1.57	1111
L22P	925.0	16.0	0.066	597.0	11.5	0.045	125.0	22.0	0.047	20300.000	1.57	1111
L22S	925.0	16.0	0.066	597.0	11.5	0.045	125.0	22.0	0.047	20300.000	1.57	1111
L23P	925.0	16.0	0.066	549.0	11.5	0.045	125.0	22.0	0.047	21225.000	1.57	1111
L23S	925.0	16.0	0.066	549.0	11.5	0.045	125.0	22.0	0.047	21225.000	1.57	1111
L24P	925.0	18.0	0.066	447.0	11.5	0.045	125.0	22.0	0.047	22175.000	1.57	2222
L24S	925.0	18.0	0.066	447.0	11.5	0.045	125.0	22.0	0.047	22175.000	1.57	2222
L25P	925.0	18.0	0.066	447.0	11.5	0.045	125.0	22.0	0.047	23100.000	1.57	2222
L25S	925.0	18.0	0.066	447.0	11.5	0.045	125.0	22.0	0.047	23100.000	1.57	2222
L26P	925.0	18.0	0.066	447.0	11.5	0.045	125.0	22.0	0.047	24025.000	1.57	2222
L26S	925.0	18.0	0.066	447.0	11.5	0.045	125.0	22.0	0.047	24025.000	1.57	2222
L27P	925.0	18.0	0.066	447.0	11.5	0.045	125.0	22.0	0.047	24950.000	1.57	2222
L27S	925.0	18.0	0.066	447.0	11.5	0.045	125.0	22.0	0.047	24950.000	1.57	2222
S01P	900.0	25.0	0.051	847.0	15.0	0.035	180.0	32.0	0.050	1800.000	1.57	2222
S01S	900.0	25.0	0.051	847.0	15.0	0.035	180.0	32.0	0.050	1800.000	1.57	2222
S02P	925.0	23.5	0.051	847.0	15.0	0.035	180.0	25.0	0.050	2725.000	1.57	2222
S02S	925.0	23.5	0.051	847.0	15.0	0.035	180.0	25.0	0.050	2725.000	1.57	2222
S03P	925.6	23.5	0.051	847.0	14.0	0.035	180.0	32.0	0.050	3650.000	1.57	1111
S03S	925.6	23.5	0.051	847.0	14.0	0.035	180.0	32.0	0.050	3650.000	1.57	1111
S04P	925.0	23.5	0.051	847.0	14.0	0.035	180.0	25.0	0.050	4575.000	1.57	1111
S04S	925.0	23.5	0.051	847.0	14.0	0.035	180.0	25.0	0.050	4575.000	1.57	1111
S05P	925.5	23.5	0.051	797.0	14.0	0.035	180.0	25.0	0.050	5500.000	1.57	1111
S05S	925.5	23.5	0.051	797.0	14.0	0.035	180.0	25.0	0.050	5500.000	1.57	1111
S06P	925.5	23.5	0.051	797.0	14.0	0.035	180.0	25.0	0.050	6425.000	1.57	1111
S06S	925.5	23.5	0.051	797.0	14.0	0.035	180.0	25.0	0.050	6425.000	1.57	1111
S07P	925.5	23.5	0.051	747.0	12.7	0.035	180.0	25.0	0.050	7350.000	1.57	1111
S07S	925.5	23.5	0.051	747.0	12.7	0.035	180.0	25.0	0.050	7350.000	1.57	1111
S08P	925.0	23.5	0.051	747.0	12.7	0.035	180.0	25.0	0.050	8275.000	1.57	1111
S08S	925.0	23.5	0.051	747.0	12.7	0.035	180.0	25.0	0.050	8275.000	1.57	1111
S09P	925.0	23.5	0.051	747.0	12.7	0.035	150.0	25.0	0.050	9200.000	1.57	1111
S09S	925.0	23.5	0.051	747.0	12.7	0.035	150.0	25.0	0.050	9200.000	1.57	1111
S10P	925.0	23.5	0.051	697.0	12.7	0.035	150.0	25.0	0.050	10125.000	1.57	1111
S10S	925.0	23.5	0.051	697.0	12.7	0.035	150.0	25.0	0.050	10125.000	1.57	1111
S11P	925.0	23.5	0.051	697.0	12.7	0.035	150.0	25.0	0.050	11050.000	1.57	1111
S11S	925.0	23.5	0.051	697.0	12.7	0.035	150.0	25.0	0.050	11050.000	1.57	1111
S12P	925.5	23.5	0.051	647.0	12.7	0.035	150.0	25.0	0.050	11975.000	1.57	1111
S12S	925.5	23.5	0.051	647.0	12.7	0.035	150.0	25.0	0.050	11975.000	1.57	1111
S13P	925.0	23.5	0.051	647.0	12.7	0.035	125.0	22.0	0.050	12900.000	1.57	1111
S13S	925.0	23.5	0.051	647.0	12.7	0.035	125.0	22.0	0.050	12900.000	1.57	1111
S14P	925.0	23.5	0.051	647.0	11.5	0.035	125.0	25.0	0.050	13825.000	1.57	1111
S14S	925.0	23.5	0.051	647.0	11.5	0.035	125.0	25.0	0.050	13825.000	1.57	1111
S15P	925.0	23.5	0.051	647.0	11.5	0.035	125.0	25.0	0.050	14750.000	1.57	1111
S15S	925.0	23.5	0.051	647.0	11.5	0.035	125.0	25.0	0.050	14750.000	1.57	1111
S16P	925.0	23.5	0.051	647.0	11.5	0.035	125.0	25.0	0.050	15675.000	1.57	1111
S16S	925.0	23.5	0.051	647.0	11.5	0.035	125.0	25.0	0.050	15675.000	1.57	1111
S17P	925.0	23.5	0.051	597.0	11.5	0.035	125.0	25.0	0.050	16600.000	1.57	1111
S17S	925.0	23.5	0.051	597.0	11.5	0.035	125.0	25.0	0.050	16600.000	1.57	1111

S18P ELM ID	925.0 PB	23.5 PT	0.051 PR	597.0 WD	11.5 WT	0.035 WR	125.0 FB	25.0 FT	0.050 FR	17525.000 Y NODE	1.57 THETA	1111 STEEL ID
S18S	925.0	23.5	0.051	597.0	11.5	0.035	125.0	25.0	0.050	17525.000	1.57	1111
S19P	925.0	23.5	0.051	597.0	11.5	0.035	125.0	22.0	0.050	18450.000	1.57	1111
S19S	925.0	23.5	0.051	597.0	11.5	0.035	125.0	22.0	0.050	18450.000	1.57	1111
S20P	925.0	23.5	0.051	597.0	11.5	0.035	125.0	22.0	0.050	19375.000	1.57	1111
S20S	925.0	23.5	0.051	597.0	11.5	0.035	125.0	22.0	0.050	19375.000	1.57	1111
S21P	925.0	23.5	0.051	549.0	11.5	0.035	125.0	22.0	0.050	20300.000	1.57	1111
S21S	925.0	23.5	0.051	549.0	11.5	0.035	125.0	22.0	0.050	20300.000	1.57	1111
S22P	925.0	23.5	0.051	549.0	11.5	0.035	125.0	22.0	0.050	21225.000	1.57	1111
S22S	925.0	23.5	0.051	549.0	11.5	0.035	125.0	22.0	0.050	21225.000	1.57	1111
S23P	925.0	23.5	0.051	447.0	11.5	0.035	125.0	22.0	0.050	22150.000	1.57	2222
S23S	925.0	23.5	0.051	447.0	11.5	0.035	125.0	22.0	0.050	22150.000	1.57	2222
S24P	925.0	23.5	0.051	447.0	11.5	0.035	125.0	22.0	0.050	23075.000	1.57	2222
S24S	925.0	23.5	0.051	447.0	11.5	0.035	125.0	22.0	0.050	23075.000	1.57	2222
S25P	925.0	23.5	0.051	447.0	11.5	0.035	125.0	22.0	0.050	24000.000	1.57	2222
S25S	925.0	23.5	0.051	447.0	11.5	0.035	125.0	22.0	0.050	24000.000	1.57	2222

PROJECT TECHNICAL COMMITTEE MEMBERS

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

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Members

LT Robert Holzman U. S. Coast Guard

Fred Seibold Maritime Administration

Dr. Walter MacLean U. S. Merchant Marine Academy

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William Siekierka Naval Sea Systems Command,
Contracting Officer's
Technical Representative

Dr. Robert Sielski National Academy of Science,
Marine Board Liaison

CDR Steve Sharpe U.S. Coast Guard, Executive Director
Ship Structure Committee