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SEA OPERATIONAL PROFILES FOR STRUCTURAL RELIABILITY ASSESSMENT

SHIP STRUCTURE COMMITTEE
1999

Ship
Structure
Committee

An Interagency Advisory Committee

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SEA OPERATIONAL PROFILES FOR STRUCTURAL RELIABILITY ASSESSMENTS

Recent efforts to improve the safety, cost-effectiveness, and integrity of marine structures have focused on developments in structural reliability assessment. A key factor in assessing structural reliability is a description of the loads experienced by the marine structure throughout its lifetime or the period of time under consideration. The definition of loads for a ship requires the knowledge of its sea-operational profile. The sea-operational profile can be expressed as a function of heading, sea state, and ship speed and in general is random in nature. These operational profiles are required for input to structural reliability methods that have been developed in previous SSC projects and could be used for reliability assessment of the fatigue resistance of structural components or the ultimate strength of either the hull girder or specific structural components on a more rational basis than the current rule-based system.

This project describes a methodology for establishing operational profiles of ships that are suitable for structural reliability techniques being developed under other SSC projects. The profiles developed are based on historical analyses of existing ship operations and are composed of combinations of ship heading, sea state, and ship speed, as well as descriptions of the uncertainties associated with each variable. The methodology developed is applicable to existing ship classes, including naval ships, and includes information for both lifetime and short-term (mission-oriented) reliability assessments of both fatigue and ultimate strength. Operational profiles were developed for four ship classes including a fast container ship, a tanker, a tramp steamer, and a small naval combatant. One of the resulting profiles was used to perform a sample reliability assessment of the fast container ship examining both short and long-term effects.

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16. Abstract

Sea Operational Profiles have been developed from log data for four ships of different type and function. Six profiles were developed for three commercially operated vessels, and four mission-specific profiles were developed for a US Coast Guard Cutter. Operational profiles were organized into joint probability distributions of speed vs. wave height (sea state), relative heading vs. wave height (sea state), listing of Marsden Zones traversed by the vessel and the relative time spent in each zone.

Three case study examples were completed in this project to demonstrate the reliability-based structural analysis approach using the developed sea operational profiles. Two case studies deal with the design wave approach (short-term analysis) and spectral approach (long-term analysis). The third case study deals with the application of the spectral approach for the mission oriented operational profile. Limitations and assumptions inherent in different approaches are documented and discussed.

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CONVERSION FACTORS
(Approximate conversions to metric measures)

To convert from	to	Function	Value
LENGTH			
inches	meters	divide	39.3701
inches	millimeters	multiply by	25.4000
feet	meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
$inches^2$ $feet^2$	$centimeters^2$ $meters^2$	multiply by	1.9665
$inches^2$ $feet^2$	$centimeters^3$	multiply by	196.6448
$inches^4$	$centimeters^3$	multiply by	16.3871
MOMENT OF INERTIA			
$inches^2$ $feet^2$	$centimeters^2$ meters	divide by	1.6684
$inches^2$ $feet^2$	$centimeters^4$	multiply by	5993.73
$inches^4$	$centimeters^4$	multiply by	41.623
FORCE OR MASS			
long tons	tonne	multiply by	1.0160
long tons	kilograms	multiply by	1016.047
pounds	tonnes	divide by	2204.62
pounds	kilograms	divide by	2.2046
pounds	Newtons	multiply by	4.4482
PRESSURE OR STRESS			
$pounds/inch^2$	$Newtons/meter^2$ (Pascals)	multiply by	6894.757
kilo $pounds/inch^2$	mega $Newtons/meter^2$ (mega Pascals)	multiply by	6.8947
BENDING OR TORQUE			
foot tons	meter tons	divide by	3.2291
foot pounds	kilogram meters	divide by	7.23285
foot pounds	Newton meters	multiply by	1.35582
ENERGY			
foot pounds	Joules	multiply by	1.355826
STRESS INTENSITY			
kilo $pound/inch^2$ $inch^{½}$(ksi√in)	mega Newton $MNm^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	$Joules/mm^2$	multiply by	0.1753
kilo pound/inch	kilo $Joules/m^2$	multiply by	175.3

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LIST OF ABBREVIATIONS

ARCO	Atlantic Richfield Co.
BIO	Bedford Institute of Oceanography
CDF	Cumulative Density Function
CODAG	Combined Diesel and Gas
COV	Coefficients of Variation
DREA	Defence Research Establishment (Atlantic)
FFT	Fast Fourier Transformation
FTL	Fleet Technology Limited
GPS	Global Positioning System
MEDS	Marine Environment Data Service
MVCS	Maneuvering with Variable Speed and Course
MVFOSM	Mean Value First Order Second Moment Method
MVS	Maneuvering with Variable Speed
NATO	North Atlantic Treaty Organization
NM	Nautical Miles
NOAA	National Oceanic and Atmospheric Administration
PDF	Probability Density Function
PWGSC	Public Works and Government Services Canada
RAO	Response Amplitude Operator
RMS	Route Mean Square
SNAME	Society of Naval Architects and Marine Engineers
SOP	Sea Operational Profile
SSC	Ship Structure Committee
STC	Science and Technology Corporation
TAPS	Trans-Alaskan Pipeline Service
USCG	United States Coast Guard
V/S	Variable Speed

LIST OF SYMBOLS

β	safety index
δ	correlation coefficient
μ_G	mean of the limit state function G
μ_i	relative time spent in each Marsden Zone
ϕ	heading
σ_d	nominal deck stress
σ_G	standard deviation of limit state function G
σ_v	total hull girder stress
σ_y	yield strength
D	fatigue damage
f_f	fraction of time spent at each heading
f_{ci}	still water stress probability density function for loading condition i
f(HS)	probability density function of significant wave height
f_i	heading angle
f_M	joint probability function (relative frequency) of H_s and T_z
f_{mc}	composite distribution of weight height probabilities
f_{mi}	joint probability of significant wave height and zero crossing period in Marsden zone i
$f_\phi(\phi \mid H_s)$	conditional probability of heading (ϕ) for given wave height H, or sea state
f_s	two-dimensional probability of speed and combined Marsden wave
fs_i	fraction of total time T spent at each condition
$f_v(V \mid H_s)$	conditional probability of speed V given a wave height H_s
f_{vmax}	maximum time fraction
f_{vmin}	minimum time fraction
$F_{hi}(H)$	cumulative distribution function of wave heights
F(HS)	time parameter cumulative Weibull distribution
F_{Ti}	long term total stress distribution
F_w	extreme wave cumulative probability distribution
F_{xj}	wave induced and slamming stress cumulative distribution function for sea state j
G	limit state function
H	design wave height
H_1	Weibull parameter
H_s	significant wave height
H_{s0}	slamming significant wave height
Hs_i	significant wave height
I_v	moment of inertia of the hull cross-section about the transverse neutral axis
j	Weibull parameter
$k_d k_w$	load combination factors
k	Weibull scale parameter
K	fatigue strength coefficient
K_G	global stress concentration factor

KG	height of centre of gravity above base line

LIST OF SYMBOLS (continued)

l	Weibull shape parameter
L_i	time spent in zone i in years
m	Weibull location parameter
m	inverse slope of S-N curve (fatigue strength exponent)
M_d	dynamic moment
M_{IY}	initial deck yield moment
M_p	peak loading observations
M_{sw}	still water bending moment
M_v	vertical bending moment amplitude
M_w	extreme wave moment
n_i	expected number of waves in zone i necessary to exceed wave height h
n_o	total number of wave data collected in zone i
$n(S_i)$	number of stress cycles at stress S_i
N	number of wave bending moments (or wave peaks); number of cycles to failure
$N(S_i)$	number of cycles to failure at stress S_i
p_f	probability of any heading
prob (H_s)	marginal probability of wave heights
prob(VandH$_s$)	joint probability of speed and wave height
	relative number of load applications in each loading scenario
P_{ci}	probability of loading condition i
P_{ei}	probability of encounter in zone i
P_{ssj}	probability of sea state j
R_i	return period in years of design wave height in zone i
S	constant amplitude stress range
SM_b	section modulus at bottom
SM_d	sectional modulus at back
t_i	average duration of a voyage in loading condition i
T_i	total time spent at loading condition I
T_s, T_z	wave period
T_{zi}	zero crossing period
v_{0I}	zero upcrossing rate
$v_I(z)$	upcrossing rate of level z
V_i	forward speed
w	bending moment
y_o	number of years of data collection in zone I
z	vertical distance from the neutral axis of the hull cross-section

1. INTRODUCTION

1.1 Administrative

This report is submitted to the Ship Structure Committee via the Defence Research Establishment Atlantic (DREA) as a result of the project entitled, “Sea Operational Profiles for Structural Reliability Assessment”, contracted to Fleet Technology Limited under Public Works & Government Services Canada (PWGSC) Contract No. W7707-6-4299/001/HAL. This report has been prepared by Fleet Technology Limited (FTL) of Kanata, Ontario, Canada, with input from Science & Technology Corporation (STC) of Columbia, Maryland, USA.

1.2 Background

Historically, ship structures have been designed to meet minimum scantling requirements for elastic strength. Until recently, fatigue cracking was not explicitly considered by ship designers because it was rarely detected in ships less than 10 years old and because the costs of repairing fatigue cracks in older ships was tolerated by owners. Since the late 1970’s, however, fatigue cracking has occurred more frequently in relatively new ships. This change has been attributed to the design and construction of more structurally optimized ships with thinner scantlings. This optimization, which has been motivated by commercial demands to reduce the fabrication costs and the weight of hull structures, has been achieved through greater use of high strength steels and the use of more sophisticated design tools. Increased exploitation of classification society rules which have permitted design stresses to increase with tensile strength up to a specified fraction of the tensile strength defined by the so-called material factor has also contributed to this unexpected increase in incidents of fatigue cracking.

Unfortunately, stress concentrations of structural details have not always been adequately reduced to compensate for the higher design stresses and higher local bending stresses associated with thinner scantlings. Furthermore, the fatigue strength of as-welded steel joints is essentially independent of tensile strength. Therefore, local cyclic stresses at structural details have sometimes been permitted to increase without a matching increase in fatigue strength of these details. In addition, corrosive environments have exacerbated this mismatch since the flexibility of thin structure promotes the flaking of rust that accelerates the wastage process and further increases the flexibility of thin structure.

In recent years, there has been a growing consensus that explicit procedures for predicting the fatigue strength and ultimate strength of ships structures are needed, at the design stage and in service, to fully exploit the cost-benefits of high strength steel fabrication and to optimize the inspection and repair of ship structures without compromising their safety and/or durability. It has also become apparent that such procedures must incorporate structural reliability methods to account for structural or model uncertainties and the random nature of wave loads.

To this end, the Ship Structure Committee has sponsored numerous projects aimed at the development and practical implementation of such procedures.

Some of these projects are:

- SR-1339 Effects of High Strength Steels on Strength Considerations of Design and Construction Details of Ships
- SR-1341 Residual Strength Assessment of Damaged Marine Structures
- SR-1344 Assessment of Reliability of Ship Structures (Phase II)
- SR-1345 Probability-based Design (Phase III): Implementation of Design Guidelines for Ships
- SR-1346 Improved Ship Structural Details relative to Fatigue
- SR-1374 A Guide to Damage Tolerance Analysis of Marine Structures
- SR-1379 Weld Detail Fatigue Life Improvement

An important prerequisite for structural reliability assessment of ship structures is the accurate determination of extreme loads and the distribution of cyclic loads in the short and long term. This, in turn, requires knowledge of a ship's operational profile over the life and missions of the ship, and the associated encounters with waves. This latter is known herein as the "sea-operational profile" or SOP.

1.3 Objective

The first objective of this project was to develop a methodology for determining sea-operational profiles that are: (i) applicable to existing classes of naval and commercial ships; and, (ii) suitable for either life-time or mission-oriented reliability assessments of fatigue and ultimate strength based on current and future SSC reliability-based analytical approaches.

A second objective of this project was to generate sea-operational profiles (including life-time and mission-oriented profiles) for four classes of ships. These profiles were to be based on historical analyses of existing ship operations and be presented in the form of histograms for different combinations of heading, sea state and ship speed.

A third objective was to review the trends and/or relationships of a vessel's operational profile factors and compare them against the assumptions employed in recent structural reliability studies.

2. PROBLEM DESCRIPTION

2.1 Structural Effects of Wave-Induced Loads

Primary components of wave-induced loads on ships are listed below:

- still water loads; static loading due the buoyant/weight distribution;
- low frequency steady-state: response largely rigid-body;
- high frequency steady-state (springing): response largely elastic
- high frequency transient (wave impact or slamming): response largely elastic;
- hydrostatic pressure loads;
- low frequency steady-state pressure loads;
- high frequency transient pressure loads (wave impact or slamming);
- inertia loads from cargo induced by ship motion;
- inertia loads from fluids induced by ship motion (sloshing).

Extreme values of wave-induced loads are required for ultimate strength assessment, whereas statistical distributions of the ranges of wave-induced loads are required for fatigue assessment. Long-range values are required for design purposes whereas short-range as well as long-range values are required for damage tolerance assessment. The degree to which each of the load types are significant depends upon, among other things, the ship type, the payload, structural configuration and location of structure. Tables 2.1 to 2.5 provide guidance in identifying the important loads for a selection of ship types.

Table 2.1: Highly Loaded Structural Elements - Tankers

STRUCTURE MEMBER	STRUCTURAL DETAIL	LOAD TYPE
Side-, bottom- and deck plating and longitudinals	Butt joints, deck openings and attachment to transverse webs, transverse bulkheads and intermediate longitudinal girders	Hull girder bending, stiffener lateral pressure load and support deformation
Transverse girder and stringer structures	Bracket toes, girder flange butt joints, curved girder flanges, panel knuckles including intersecting transverse girder webs, etc. Single lug slots for panel stiffeners, access and lightening holes	Sea pressure load combined with cargo or ballast pressure load
Longitudinal girders of deck and bottom structure	Bracket terminations of abutting transverse members (girders, stiffeners)	Hull girder bending, and bending/deformation of longitudinal girder and considered abutting member

Source: SSC SR-1374

Table 2.2: Highly Loaded Structural Elements - Bulk Carriers

STRUCTURE MEMBER	STRUCTURAL DETAIL	LOAD TYPE
Hatch corners	Hatch corner	Hull girder bending, hull girder torsional deformation
Hatch side coaming	Termination of end bracket	Hull girder bending
Main frames	End bracket terminations, weld main frame web to shell for un-symmetrical main frame profiles	External pressure load, ballast pressure load as applicable
Longitudinals of hopper tank and top wing tank	Connection to transverse webs and bulkheads	Hull girder bending, sea- and ballast pressure load
Double bottom longitudinals (1)	Connection to transverse webs and bulkheads	Hull girder bending stress, double bottom bending stress and sea, cargo, and ballast pressure load
Transverse webs of double bottom, hopper and top wing tank	Slots for panel stiffener including stiffener connection members, knuckle of inner bottom and sloped hopper side including intersection with girder webs (floors). Single lug slots for panel stiffeners, access and lightening holes	Girder shear force, and bending moment, support force from panel stiffener due to sea, cargo and ballast pressure load
(1) The fatigue life of bottom and inner bottom longitudinals of bulk carriers is related to the combined effect of axial stress due to hull girder- and double bottom bending, and due to lateral pressure load from sea or cargo.		

Source: SSC SR-1374

Table 2.3: Highly Loaded Structural Elements - Ore Carriers

HULL MEMBER	STRUCTURAL DETAIL	LOAD TYPE
Upper deck plating	Hatch corners and side coaming terminations	Hull girder bending
Side, bottom and deck longitudinals	Butt joints and attachment to transverse webs, transverse bulkheads, hatch openings corners and intermediate longitudinal girders	Hull girder bending, stiffener lateral pressure load and support deformation
Transverse girder and stringer structures	Bracket toes, girder flange butt joints, curved girder flanges, panel knuckles at intersection with transverse girder webs, etc. Single lug slots for panel stiffeners, access and lightening holes	Sea pressure load combined with cargo or ballast pressure
Transverse girders of wing tank (1)	Single lug slots for panel stiffeners	Sea pressure load (in particular in ore loading condition)
(1) The transverse deck-, side- and bottom girders of the wing tanks in the ore loading condition are generally subjected to considerable dynamic shear force- and bending moment loads due to large dynamic sea pressure (in rolling) and an increased vertical racking deflection of the transverse bulkheads of the wing tank. The rolling induced sea pressure loads in the ore loading condition will normally exceed the level in the ballast (and a possible oil cargo) condition due to the combined effect of a large GM-value and a small rolling period. The fatigue life evaluation must be considered with respect to the category of the wing tank considered (cargo oil tank, ballast tank or void). For ore-oil carriers, the cargo oil loading condition should be considered as for tankers.		

Source: SSC SR-1374

Table 2.4: Highly Loaded Structural Elements - Container Carriers

HULL MEMBER	STRUCTURAL DETAIL	LOAD TYPE
Side and bottom longitudinals	Butt joints and attachment to transverse webs, transverse bulkheads and intermediate longitudinal girders	Hull girder bending, torsion (1), stiffener lateral pressure load and support deformation
Upper deck	Plate and stiffener butt joints, hatch corner curvatures and support details welding on upper deck for container pedestals, etc.	Hull girder bending and torsional warping stress (2)

(1) Torsion induced warping stresses in the bilge region may be of significance from the forward machinery bulkhead to the forward quarter length.

(2) The fatigue assessment of upper deck structures must include the combined effect of vertical and horizontal hull girder bending and the torsional warping response. For hatch covers, additional stresses introduced by the bending of transverse (and longitudinal) deck structures induced by the torsional hull girder deformation must be included in the fatigue assessment.

Source: SSC SR-1374

Table 2.5: Highly Loaded Structural Elements - Roll on/Roll off- and Car Carriers

HULL MEMBER	STRUCTURAL DETAIL	LOAD TYPE
Side and bottom longitudinals	Butt joints and attachment to transverse webs, transverse bulkheads and intermediate longitudinal girders	Hull girder bending, stiffener lateral pressure load and support deformation
Racking constraining girders, bulkheads, etc.	Stress concentration points at girder supports and at bulkhead openings	Transverse acceleration load (1)

(1) It should be noted that the racking constraining girders and bulkheads are in many cases largely unstressed when the ship is in the upright condition. Thus the racking induced stresses may be entirely dynamic, which implies that fatigue is likely to be the primary design criterion. For designs which incorporate "racking bulkheads", the racking deformations are normally reduced such that the fatigue assessment may be limited to stress concentration areas at openings of the racking bulkheads only. If sufficient racking bulkheads are not fitted, racking deformations will be greatly increased, and the fatigue assessment of racking induced stresses should be carried out for primary racking constraining members and vertical girder structures over the ship length as applicable.

Source: SSC SR-1374

2.2 Operational Profiles

Ideally, the basis for the design of ship structure is: "the loads generated by the ship's operational environment do not exceed the capacity of the ship's structural system". In order to accomplish this objective, the designer would size structural members based on assumed material properties and applied loads. In the design process neither the applied loads nor the material properties or construction tolerances are known with complete certainty. As a consequence, efforts have been directed toward the development of structural reliability analysis techniques that account for the variability in these design parameters.

The greatest uncertainty in the design or assessment of ship structures lies in the description of the loads experienced by the vessel or marine structure throughout its lifetime or a particular period of interest. The definition of loads for a ship requires the knowledge of its operational profile that may be expressed in terms of the vessel's mission, loading condition, heading, sea state and speed. These features of a ship's operational profile are random in nature but may be studied and characterized from ships operational logs.

Previous SSC research has developed reliability-based procedures which employ these probabilistic operational profile feature definitions and structural definitions to assess the integrity of ship structures. The focus of this project was to define through-life and mission-oriented ship operational profiles suitable for use in the reliability techniques developed or that are currently being developed under SSC projects.

While the concept and components of the operational profile are relatively easily defined, in practice, the characterization of a particular operational profile can be much more difficult due to a number of factors. Some of these are discussed in this report.

2.3 Load Estimation Methods

Two general approaches are outlined in previous SSC reports (References 1 and 2) for the design and analysis of ships or marine structures, to incorporate the statistical nature of the environment or loads:

- *short term* analysis
- *long term* analysis

The *short term* analysis approach identifies an extreme design condition which may be used to estimate the probability of an ultimate strength failure of a vessel, whereas the *long term* analysis approach may be used to predict the probability of structural failure due to either a progressive damage accumulation (a fatigue failure mode) or a one time overload event (ultimate strength failure).

While the emphasis of this project seems to be the development of the data required to employ the *long term* analysis approach, the *short term* analysis approach is discussed here to illustrate that the data required to perform this type of analysis is simply a subset of the data used in the *long term* analysis approach.

2.3.1 *Short term* Analysis

In a *short term* analysis a design wave height (or sea state characterized by a significant wave height) is identified such that its probability of encounter is less than or equal to a specified level. The response of the marine structure or vessel is assessed based on the design wave and the most unfavorable loading scenario (i.e., heading, loading condition, speed, etc.). The probability of failure may be calculated based on the design wave or sea state, but the probability of failure of the structural system in response to this load case is conditional upon the occurrence of an extreme wave load for each failure criterion. The *short term* or ultimate strength analysis approach is summarized in the five steps outlined in Table 2.6.

Table 2.6: Basic Steps of Short term Analysis

1) From a ship route, ocean wave statistics, and a specified encounter probability (or return period), determine the design storm condition.
2) Calculate the RMS value of the wave bending moment in the design sea condition using second order strip theory, towing tank experiments or 3-D code (non linear) if available. Also calculate the still water bending moment.
3) Estimate the strength parameters for each failure mode.
4) Calculate the conditional probability of failure or the safety index for each failure mode.
5) Estimate structural failure probability for each failure mode from calculated conditional failure probability and the wave encounter probability.

Source: Mansour et al [Ref. 2].

The key step in the *short term* analysis approach is relating the design wave height in a given area to the probability of encounter. The probability of encounter (P_{ei}), for a given wave height in a specific ocean zone is described by Mansour et al based on the following equations:

$$n_i = \frac{1}{1 - F_{h_i}(H)}$$

$$R_i = \frac{n_i}{n_o} y_o$$

$$P_{e_i} = 1 - \left(1 - \frac{1}{R_i}\right)^{L_i}$$

where:

n_i expected number of waves in zone i necessary to exceed wave height h

F_{hi} distribution function of individual wave heights generally assumed to follow a Weibulll probability distribution

design wave height

H return period in years of design wave height in zone i

R_i total number of wave data collected in zone i

n_o number of years of data collection in zone i

y_o time spent in zone i in years

L_i probability of encounter in zone i

P_{ei}

The design wave may be determined for the *short term* analysis approach using this formulation for a ship route that traverses multiple ocean zones based on a systems reliability approach. An upper (assuming statistical independence) and lower bound (assuming statistical dependence) or "exact" (assuming equal dependence) estimate of the probability of encounter may be calculated.

2.3.2 *Long Term* Analysis

The *long term* analysis approach determines the probability distribution of wave loads during the service life of a ship taking into account wave statistics along the route, loading conditions, speed, and heading. Since the resulting probability distribution(s) provide information on the entire load history, not just the extreme load events as in the *short term* analysis approach, these load distributions may be used to simulate a fatigue failure mode which is characterized as a damage accumulation process. The basic steps involved in a long term analysis approach are outlined in Table 2.7.

Table 2.7: Basic Steps of Long Term Analysis

1) Define the mission profile of the ship (ship route, expected service life, time at sea and in port, nominal and maximum speeds and fraction of service at each speed, distribution of headings, distribution of loading
2) From the ship route and available wave statistics, obtain the frequency of occurrence of different conditions the ship will encounter in each of the geographic areas.
3) From Step 2 and the mission profile of the ship, determine the frequency of encounters different sea conditions, loading conditions, speeds, and headings.
4) Determine the wave loads in each sea condition, loading condition, speed, and heading, using first or second order strip theory, or 3-D non-linear code, if available.
5) Use an extrapolation procedure to determine the distribution of maximum loads.

Source Mansour et al [Ref. 2].

The *long term* analysis approach requires considerably more effort and input data than the *short term* analysis. In particular, the statistical distribution of total stress (wave induced stresses and still water stresses) is a function of the sea-operational profile of a ship (relative duration of each vessel speed, heading, location and loading condition). Two approaches have been proposed by the Ship Structure Committee in SSC reports SR-1337 and SR-1344 for determining the wave induced load distribution for the *long term* approach.(described as Method A and B). Only Method B was used in the subsequent analysis.

Method A - Procedure Proposed by SSC (Ref. 1)

In this approach, it is assumed that there are i =1 to n_c loading conditions and j = 1 to n_{ss} sea states in a vessel's service life whose probabilities of occurrence may be considered mutually exclusive and collectively exhaustive (i.e. $\sum_{i=1}^{n_c} P_{c_i} = 1$ and $\sum_{j=1}^{n_{ss}} P_{ss_j} = 1$). In addition, it is assumed that the wave induced and slamming stress cumulative stress distribution function for sea state j is F_{xj} is independent of the still water stress distribution probability density function (PDF) f_{ci} for loading condition i.

A CDF (cumulative density function) which considers the contributions of all of the sea states to which a vessel is exposed is generated as the weighted average of the individual sea state wave induced total stress distributions (wave and slamming) as follows:

$$F_x'(r) = \sum_{j=1}^{n_{ss}} P_{ssj} F_{xj}(r)$$

For a particular loading condition, the *long term* total stress, including wave induced and still water effects is estimated by applying the convolution integral as follows:

$$F_{Ti}'(r) = \int_{-\infty}^{\infty} F_X'(r)\, f_{ci}(x)\, dx$$

With this *long term* total stress distribution expression for each loading condition a CDF for the average service life load levels of the vessel may be developed through a weighted average of the individual loading condition CDF's as follows:

$$F_T(r) = \sum_{i=1}^{n_c} P_{ci} F_{Ti}'(r)$$

This distribution may be used to simulate the cumulative damage effects involved in a fatigue limit state. In order to develop a more conservative or extreme load distribution which may be used to analyze either a fatigue or an ultimate limit state failure, the relative number of load applications (n_i) in each loading scenario is used in the weighted average as follows:

$$n_i = \frac{T_i}{t_i}$$

$$F_{TE}(r) = \sum_{i=1}^{n_c} P_{ci} \left[F_{Ti}'(r) \right]^{n_i}$$

where:

t_i average duration of a voyage in loading condition i

T_i is the total time spent at loading condition i

Method B - Procedure Proposed by SSC Ref. 2.

In this *long term* approach, the loading process is modeled as a series of stationary processes with independent peaks which may be characterized by i = 1 to p stationary conditions described by their:

- significant wave height, Hs_i,
- zero crossing period, T_{zi} ,
- forward speed, V_i,
- heading angle, f_i,
- and fraction of total time T spent at each condition, fs_i.

Based on this, the probability of individual peak load observations (M_p) exceeding a specified level (z) in a duration of time T is expressed as follows:

$$Q\left(M_p(T)\right) = P\left(\underset{T}{\mathrm{Max}}\, M_p > \zeta\right) = 1 - \exp\left(-T\sum_{i=1}^{p} v_{0i} fs_i\, e^{-1/2 v_i^2(\zeta)}\right)$$

where v_{0i} is the zero upcrossing rate and $v_i(z)$ is the upcrossing rate of level z.
The fraction of time spent is a specific stationary condition is taken as:
$fs = f_M(H_s,T_z)\, f_v(V|H_s)\, f_f(f)$

where f_M is the joint probability density function (relative frequency) of H_s and T_z calculated for n sea areas or zones (eg., Marsden zones) based on the fraction of the total time spent in each zone (P_j) as follows:

$$f_M(H_s, T_z) = \sum_{j=1}^{n} P_j f_{Mj}(H_s, T_s)$$

This procedure accounts for the fact that a ship's master usually reduces speed in order to avoid excessive slamming and green water on deck. Therefore the fraction of time spent at each forward speed (f_v) is made dependent on the significant wave height (H_s) as follows:

$$f_v(V = V_{max}|H_s) = \begin{cases} f_{v\,max} & \text{if } H_s \le H_{s0} \\ 1 - f_{v\,min} & \text{if } H_s > H_{s0} \end{cases}$$

$$f_v(V = V_{min}|H_s) = 1 - f_v(V = V_{max}|H_s)$$

where $f_{v\,min}$, $f_{v\,max}$ and H_{s0} are the minimum time fraction, maximum time fraction and reference slamming significant wave height, respectively, which are specified. The fraction of time spent at each heading (f_f) is calculated as simply the ratio of the total time versus the time spent at a specific heading. It is suggested in the SR-1344 that all of the possible headings be summarized in terms of five headings (0, 45, 90, 135, 180 degree angle between the vessel and the wave) and that either the probability of any heading (p_f) is considered equal ($p_0 = p_{45} = p_{90} = p_{135} = p_{180}$) or that the probability of trailing seas be reduced ($p_0 = p_{45} = p_{90} = 3p_{135} = 3p_{180}$).

These recommended relative heading probabilities need not be used. The relative probability may be collected from ship log data and may be a function of the mission profile (i.e., urgency or time sensitivity of the voyage).

2.3.3 Data Requirements for SSC Approaches to Load Analysis

The *short term* and two *long term* load analysis approaches, described in the previous sections, employ similar data in various levels of detail. The table below describes the data used by each approach and would need to be collected for their application.

Table 2.8: Data Requirements of SSC Load Analysis Approaches

Data	*Short Term*	*Long Term* SR-1337	*Long Term* SR-1344
Heading	• most unfavourable heading	• most unfavourable heading	• list of headings • relative time spent at each heading
Loading	• most unfavourable loading	• list of loading conditions • relative time spent in each loading condition • PDF of still water effects	• list of loading conditions
Speed	• most unfavourable speed	• most unfavourable speed	• list of ship velocity ranges • relative time spent at each velocity for given wave heights
Route	• list of Marsden zones • relative time spent in each zone	• list of Marsden zones or sea states • relative time spent in each zone or sea state	• list of Marsden zones • relative time spent in each zone
Wave Height	• statistical distribution of wave heights in each Marsden zone	• statistical distribution of wave heights in each sea state or Marsden zone • relative time spent in each sea state	• statistical distribution of wave heights in each Marsden zone • list of wave height ranges • Ref.erence wave height causing significant slamming (H_{s0})

In addition to the data that is strictly necessary for the analysis, it is useful to examine the correlations or relationships of the data describing vessel operational modes. The data collected as inputs for the SSC approaches may be used to calibrate other reliability-based design and analysis procedures as well.

3. VESSEL SELECTION

3.1 General

Six or seven different classes of ships were considered during the vessel selection phase of the project. The vessels being considered covered both government-operated vessels and those operated commercially and embraced vessels trading on a prescribed route and those operating on a lesser prescribed route, such as patrol vessels.

The vessels operated by the government which were examined included:

1. Canadian Navy
2. U.S. Coast Guard
3. Department of Fisheries and Oceans
4. NOAA/Woods Hole

Commercial vessels from the following fleets were examined, as well as the standard SL-7 fast container ship which has been the subject of earlier SSC research (15 SSC reports in all of which References 3 and 4 are examples) :

1. Marbulk Shipping Inc.
2. Marine Atlantic
3. Trans-Alaskan Pipeline Service (TAPS) Tankers

After researching the availability of logs and data, the four (4) vessels selected were:

1. ***SS SEALAND McLEAN***; (SL-7) Fast Container Ship
2. ***SS ARCO CALIFORNIA***; (TAPS Tanker)
3. ***Hamilton-Class*** US Coast Guard Cutter
4. ***M.V. THORNHILL*** *(Bulker on "tramp" routing).*

3.2 The Ships

The *SS SEALAND McLEAN*, was the first of a new high speed class of containership known as SL-7 and was constructed by the Rotterdam Dry Dock in 1972. The vessel was rated for a maximum speed of 33 knots and operated on a regular route in North Atlantic service between the ports of Portsmouth Virginia and Cherbourg. Table 3.1 lists particulars pertaining to the ship [Ref. 3].

The *SS ARCO CALIFORNIA* is a 190 000 dwt "San Diego Class" tanker from the Trans-Alaskan Pipeline Service (TAPS). A typical voyage of the *ARCO CALIFORNIA* consists of a round trip between Long Beach, CA and Valdez, AK. During the northbound voyages, the ship is in ballast or storm ballast condition travelling at roughly 15 knots for 150 hours. At

Valdez, it is usually docked for approximately 24 hours for loading of crude oil. The voyage to Long Beach is made at full-load and lasts about 150 hours.
The TAPS fleet must operate within a corridor in the Northwest Pacific. The vessel must not be more than 150 miles offshore and no closer than 50 miles to the U.S. coastline and 100 miles to the Canadian coastline. About 23 voyages a year are considered normal for the *ARCO CALIFORNIA* [Ref. 5].

The *MV THORNHILL* is a geared "handysize" bulk carrier. The ship entered service in 1987 and was purchased in 1993 by Marbulk Shipping Inc. The vessel operates on short term contracts, ("tramp" service) which take the vessel all over the world, as is evident from the data obtained for analysis. The vessel is rated at a service speed of 15 knots.

The *HAMILTON Class* of US Coast Guard High Endurance cutter is a class of 12 vessels built between 1967 and 1972 by Avondale Shipyards. These vessels are similar to many small frigates in other Navies, and were the first US military ships at sea with gas turbine propulsion (CODAG). They are of steel construction with largely aluminum superstructure and are distinguishable by their side-by-side funnels. Two data sets were acquired, one for the USCGC HAMILTON - which was analysed, and one for the USCGC CHASE, which data set was delivered but not analysed.

Table 3.1: Principal Characteristics of Selected Vessels

Particulars	*SS SEALAND McLEAN **	*SS ARCO CALIFORNIA*	*HAMILTON Class*	*M.V. THORNHILL***
Overall Length (m)	288.38	—	115.2	193.84
Length Between Perpendiculars (m)	268.38	290.17	107.0	183
Beam (molded), (m)	32.16	50.60	13.1	27.6
Draft, design (m)	9.144	—	6.1	10.24
Depth	—	23.77	—	14.8
Deadweight (tons)	27,752	191,716	—	37,938.7
Displacement (tons)	51,120	220,808	3,050	47,047

* This vessel was subsequently converted to a Sealift support ship *CAPELLA* (T-AKR 293) for the U.S. Military Sealift Command.

****** This vessel is being converted to a self-unloading bulk carrier

4. DATA SOURCES AND QUALITY

4.1 Ship Operational Profile Data

4.1.1 Summary of Ship Data

Data used in this project were taken from the ship's logs. Most of the data were manually entered in the vessel's operational profile database, with the exception of the *ARCO CALIFORNIA* and *HAMILTON Class* cutter where data were obtained in electronic form.

The ship log data recording frequency varied from ship to ship. For example, data for the *SS SEALAND McLEAN* were reported in four-hour intervals whereas, the logs for the *MV THORNHILL* are presented as daily summaries. Time intervals for data collected for the *ARCO CALIFORNIA* and *HAMILTON Class* varied between 1 minute and 1 hour. Typically reported information includes voyage ID, date and time, latitude, longitude, ship course, wind direction, ship speed, and Beaufort Number or wind speed. The ship log for the *USCG HAMILTON Class* also included wave height, swell height, and swell length. A summary of the data collected in this project is presented in Table 4.1.

Table 4.1: Operational Profile Data Collection Summary

Vessel/Type	Profiles	Hrs. of Data at Sea	# of Entries	Location of Operation	Data set Span	Days in port/year
SS SEALAND McLEAN SL-7 Container ship	Eastbound Westbound	2330.5 2063.6	620 600	North Atlantic	3 years	172
ARCO CALIFORNIA TAPS Tanker	Northbound Southbound	2161 2183	945 967	North Pacific	20 months	128
MV THORNHILL Tramper Bulk Carrier	Loaded Ballast	3624.4 1563.4	151 66	World shipping routes	1 year	148
USCG HAMILTON Class Cutter	Short Training Long Training Patrol Enforcement/ Rescue	471 951 617 4207	1343 2114 1796 11703	East Coast East Coast East Coast/ Caribbean East Coast/ Caribbean	2.25 years	220
USCG CHASE Class	Not developed	~	3557	~	7 months	~

An index of ship log data files is provided in Appendix A, and the electronic files are delivered separately, with this report.

4.1.2 Review of SL-7 Data

The SL-7 was a vessel selected by the SSC over 20 years ago for studies of ship loading and response in a seaway. Consequently, voyages were better documented than might be expected for a commercial ship. Data used in this report covered three operating seasons, from October 1972 to March 1975. Each leg of the voyage (where voyage is defined as consisting of two legs, one eastbound and one westbound) was analyzed separately, and was named as either an Eastbound or Westbound Operational Profile. A total of 620 and 600 log entries for eastbound and westbound operation, respectively, were collected. This data corresponds to 2330.5 hours of eastbound and 2063.6 hours of westbound operational information.

4.1.3 Review of Data for *ARCO CALIFORNIA* (TAPS Fleet)

The second vessel analyzed was the *SS ARCO CALIFORNIA*. The voyages recorded for this vessel took place between November 1992 and July 1994. The vessel operated on the Trans-Alaskan Pipeline Service (TAPS) on a year-round basis between Long Beach, California and Valdez, Alaska. This vessel was also the subject of load and seaway measurements and the data, which was made available courtesy of ARCO and SeaRiver for the *ARCO CALIFORNIA*, was in an electronic form, 10-minute observations for every recorded voyage. Those voyages not covered by the electronic data were taken from the ship's logs.

Operational profiles were developed for two loading conditions: ballast and fully-loaded conditions. The ballasted condition corresponds to the northbound voyage and the loaded condition to the southbound voyage. The collected data covers 2161 hours northbound (945 entries) and 2183 hours (967 entries) southbound.

4.1.4 Review of Data for *MV THORNHILL*

The *MV THORNHILL* operates on short term contracts (tramp service) which takes the vessel all over the world as evidenced from the data set. The data obtained for this vessel covered a time period between August 1996 and August 1997 and was reported in daily summaries. The data covers 3624.4 hours in a loaded condition (151 data entries) and 1563.4 hours in a ballast condition (66 entries).

4.1.5 Review of Data for *HAMILTON Class*

The largest amount of data was collected for the *HAMILTON Class* USCG Cutter. The staff of Science and Technology Corporation reviewed logs and records and developed an electronic file. A total of 40 spreadsheet files with approximately 17,000 entries was analyzed covering approximately 6250 hours of operation. Every file contained a number of spreadsheets, each being one trip or one mission. The data analyzed includes 295 days at sea in the period from December 1988 to February 1991.

This data was sorted into four composite operational profiles which summarize and describe the vessel's mission:

- OP #1: 1-6 days at sea, 100 NM radius. Activities include training, gun exercise, man overboard drill, machinery testing, patrol.
- OP# 2: 3-8 days at sea, 500 NM radius. Activities include training, gun exercise, sonar work, machinery testing, patrol, and transit.
- OP#3 1-6 days at sea, 1300 NM radius. Activities include transit, patrol, and exercise.
- OP#4 2-30 days at sea, 2500 NM radius. Activities include law enforcement, hurricane relief, transit and training.

The number of hours for OP# 1, 2, 3 and 4 were 470.8, 950.7, 616.9 and 4207.1 hours, respectively.

As expected, the logical grouping of this data set was the most challenging part of the data collection exercise.

4.1.6 Review of Data for CHASE CLASS

Operational profiles for this vessel were not developed. Data includes 3557 data log entries organized into 10 spreadsheets, where each sheet represents one mission. Data covers the period from January to August 1998.

4.2 Ship Speed and Heading

As noted earlier, there are extraneous factors that can affect the operational profile of the vessel. An example is the use of advanced electronic weather forecasting and routing information that permits a master to take pre-emptive action to avoid bad weather, thus skewing the operational profile.

Voluntary speed reduction or changing course are factors that were thought to be important and were investigated based on the log data.

It was thought that a pattern would exist between the speed of the ship and the sea state or wind force it encountered, at least at higher speeds. Ship speed and/or engine rpm or throttle position (full ahead, etc.,) are typical log entries and these entries are made only periodically, at the time of log entry. The speed recorded in a commercial ship is more likely to be the speed made good by calculation or from the GPS rather than the actual local speed of the vessel, since in a commercial sense this is all that is required. While it is expected that any change of engine speed would be logged, it is probable that small changes made for short periods of time are not recorded.

Trends and relationships in the data were examined using the Hamilton Class Cutter data. Figure 4.1(a) shows a three-dimensional plot of speed, relative heading and wave height (sea state) for the data in Operational Profile #2. Figures 4.1(b), (c), and (d) are the projections of the same plot onto three principal planes. Figure 4.1(b) shows the relationship between speed and heading, Figure 4.1(c) the relationship between wave height and speed, and Figure 4.1(d) the relationship between wave height and heading. Units of the plotted parameters are knots, degrees, and feet for speed, relative heading and wave height, respectively.

The correlation coefficient, which expresses the relative strength of the association between parameters, was calculated for each pair of the three operational profile parameters. The following expression was used to calculate the correlation coefficient δ:

$$\delta_{XY} = \text{Covariance }(X, Y) / [\text{Variance }(X) \text{ Variance }(Y)]^{0.5}$$

The value for δ will always fall between –1 and 1. The closer the absolute value of δ falls to 1 the stronger the linear relationship between X and Y. The correlation coefficient will be 0 if X and Y are independent.

Results of the calculations are presented in Table 4.2. As can be seen, the relationship between speed and wave height is very weak. The correlation between speed and wave height is negative. This reflects the tendency for larger speeds to occur with the smaller wave heights. Speed and relative heading are positively correlated, but the relationship is very weak as indicated by the correlation coefficient. A relatively weak 12% correlation exists between relative heading and wave height. This may show an indication of preferred headings during severe weather conditions.

Table 4.2: Correlation Coefficients for Three Principal Planes, Operational Profile #2

I	X = Speed Y = Relative Heading	δ = 0.0083	Weak Correlation
II	X = Speed Y = Wave Height	δ = -0.0073	Weak Correlation
III	X = Relative Heading Y = Wave Height	δ = 0.1165	12% Correlation

These correlation coefficients are two-dimensional, and do not reflect any three-dimensional correlation that may exist between the parameters. However, they do indicate that statistical correlation among the parameters (in two dimensions) is very weak.

To examine the statistical correlation in three dimensions, plotting of data was performed using the MAPLE V software package, which allows viewing the plotted data from any angle in 3D space (see Figure 4.1(a)). From this qualitative analysis based on visual inspection, no evidence of a three-dimensional correlation among the speed, relative heading and wave height data was observed.

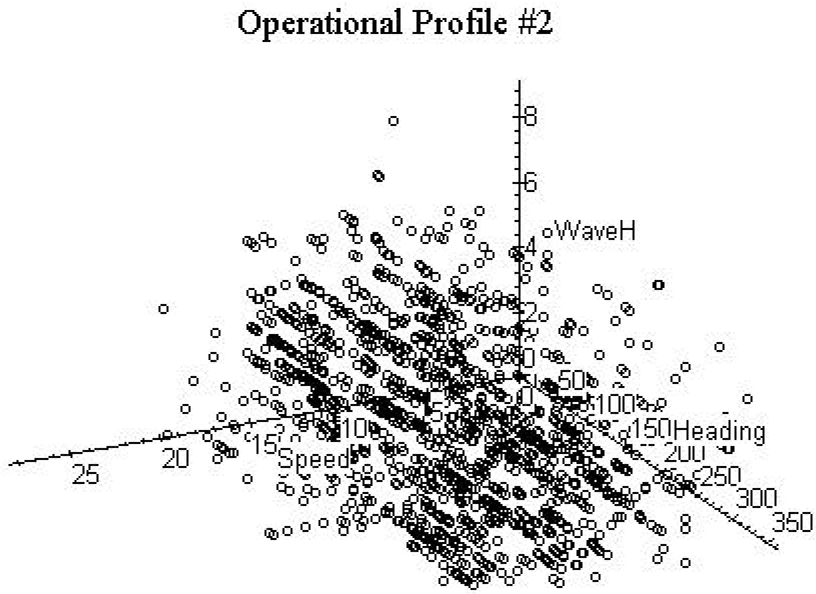

Figure 4.1(a): 3D Relationship Among Speed, Heading and Wave Height

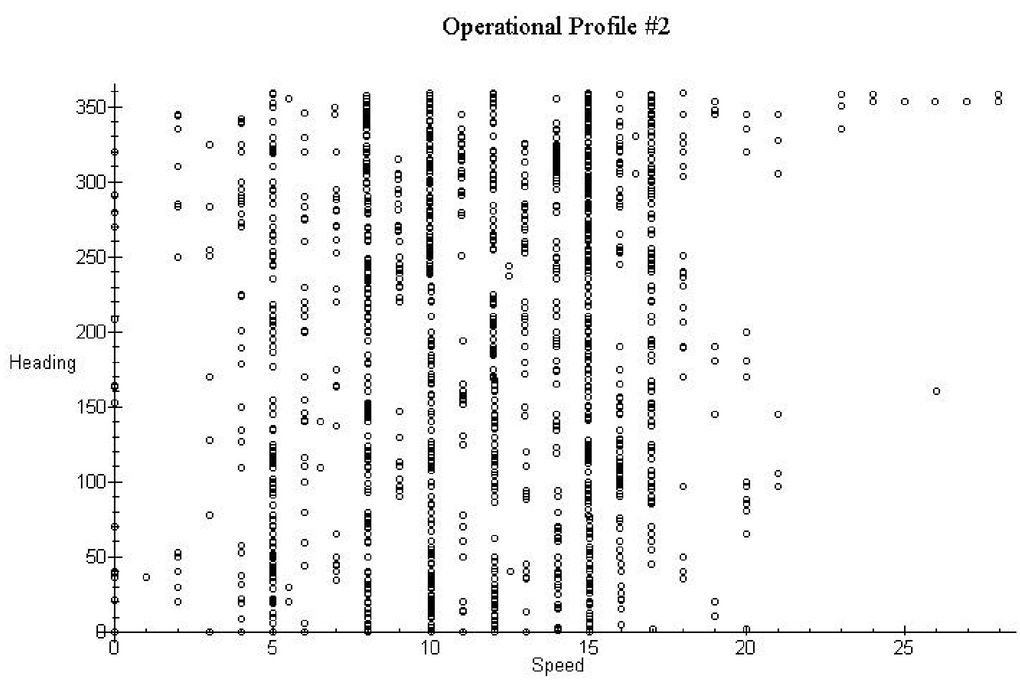

Figure 4.1(b): Heading vs. Speed, Operational Profile #2

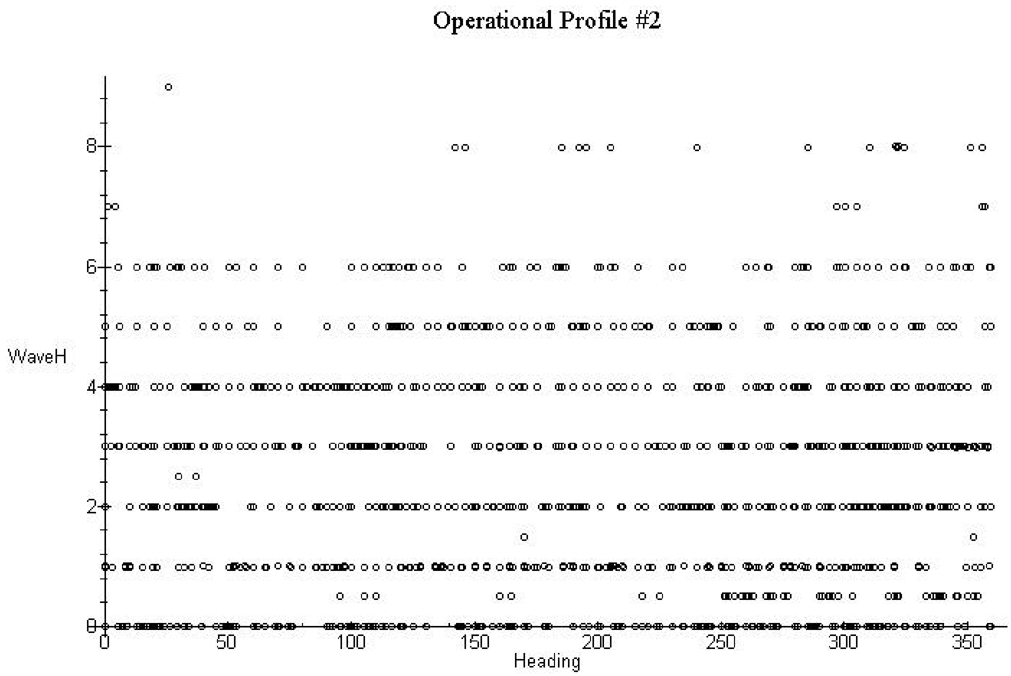

Figure 4.1(c): Wave Height (Sea State) vs. Heading, Operational Profile #2

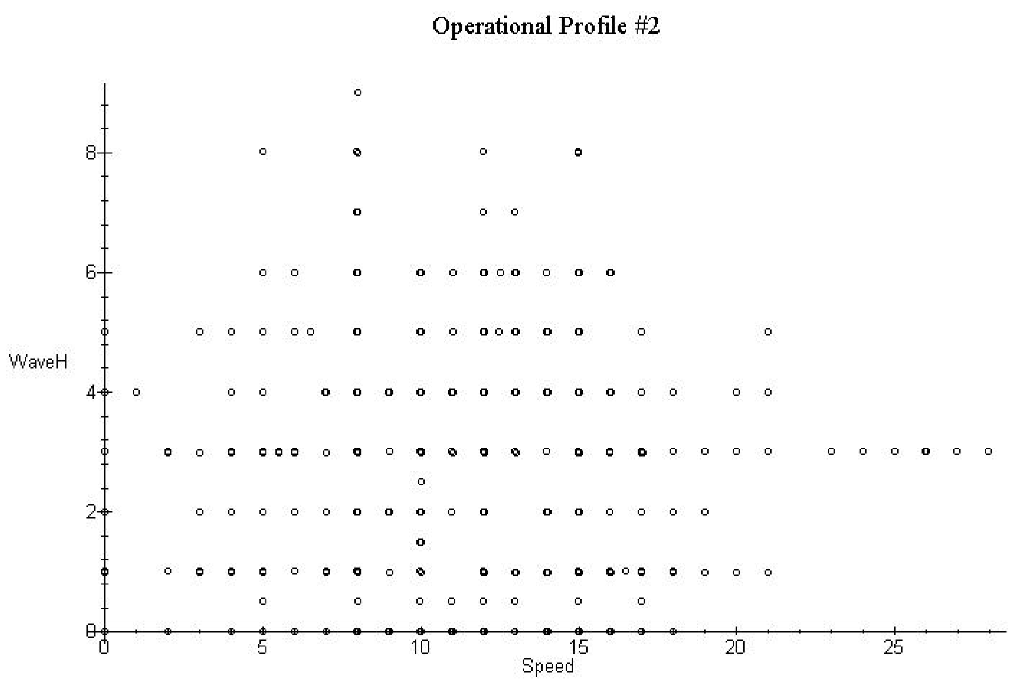

Figure 4.1(d): Wave Height (Sea State) vs. Heading, Operational Profile #2

Calculations of two-dimensional coefficients were performed for the data from Operational Profile #2 only. Three-dimensional plots similar to the one in Figure 4.1(a) were produced and examined for the remaining three operational profiles of the Hamilton Class. The shape and scatter of the data were very similar to that shown here. Hence the same conclusions may be drawn.

From this we conclude that the assumption of independence of speed and heading is not unreasonable.

There were some observations of changes in speed as a result of high seas and these are discussed in some detail in Appendix B. However, such action was neither consistent nor did it follow a pattern associated with specific headings or sea states.

Ship's heading data is also recorded in logs often in terms of the sixteen points of the compass (N, NNE, NE, ENE, E, etc.). It was agreed at the outset that the heading data would be grouped in eight 45' sectors - such that North would in fact encompass all headings from -22.5' to + 22.5' each side of North. Thus small changes in heading to avoid weather would not be recorded.

Discussion of these and the resulting statistical distributions are provided in Appendix B.

4.3 Wave Data

4.3.1 Sources of Data

While the procedures specified herein rely on site-specific wave statistics based on geographical location (in this case the Marsden Zones [Ref. 6]), it was also advantageous to investigate any wave data which was recorded onboard. Such data would provide the wave environment being experienced by the vessel and may allow assessment of voluntary speed reduction, heading changes, etc.

There were two different sources of wave data that accompanied the original data obtained for this project. These were log reports and color-coded weather maps (TAPS data only). Data from wave buoys was retrieved from the Internet once vessel routes were defined.

All ships logs report wind data, generally using the Beaufort Scale. Only the *SS SEALAND McLEAN* (SL-7) and the *HAMILTON Class* reported wave data in the log books.

The SL-7 data (for the third season only) [Ref. 3] was reported in four hour intervals and consisted of wind speed, wave heights, swell heights and swell length. The wave heights recorded by the SL-7 were derived from the Tucker Wave Meter [Ref. 4]. This latter comprises pressure sensors and accelerometers mounted on both sides of the vessel forward.

Graphical color-coded weather maps were received with the *ARCO CALIFORNIA* data. [Ref. 7]. The maps contain noon-hour (GMT) forecast wave heights and directions for the particular day of the voyage. They cover the winter voyages of 92/93 and 93/94 and a very large area as shown in the example in Figure 4.2.

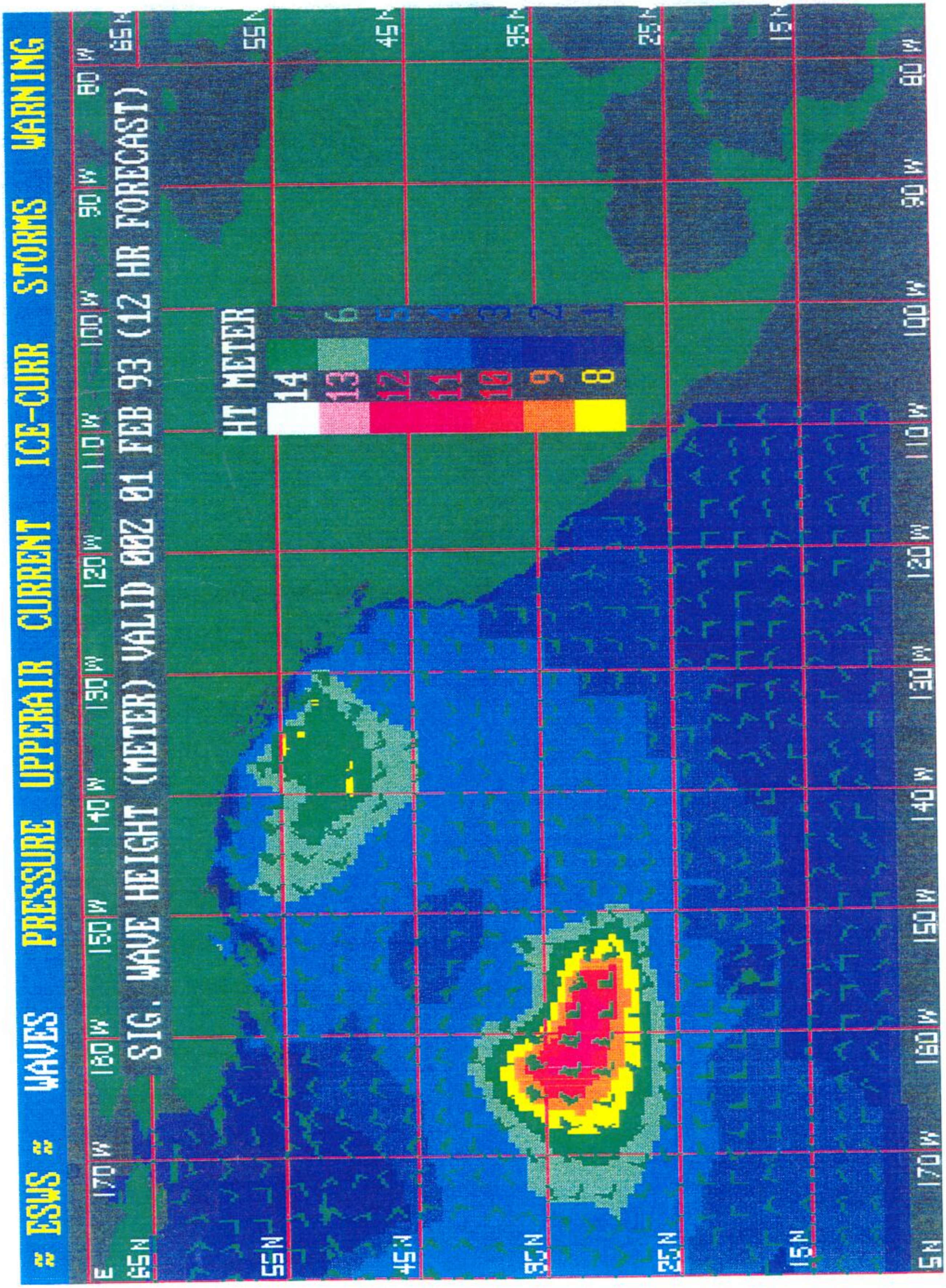

Figure 4.2: Example of Weather Data used in *ARCO CALIFORNIA* Work

Figure 4.2: Example of Weather Data used in *ARCO CALIFORNIA* Work

Once the routes of the vessels were defined, wave buoy data were sought along each of the described courses. A search was conducted on the Internet by browsing various sites that have ties with wave data collection. Three major sites focused on were the National Oceanic and Atmospheric Administration, [NOAA], the Bedford Institute of Oceanography [BIO] and the Marine Environment Data Service [MEDS]. Wave data sites available on the Internet are: www.nodc.noaa.gov maintained by NOAA, and www.meds.dfo.ca maintained by MEDS.

Wave data information could not be located for either the *SS SEALAND McLEAN* or the *M.V. THORNHILL* routes; however wave buoys were located along the route of the *ARCO CALIFORNIA*. These buoys were available on both the NOAA and MEDS sites, but the NOAA site was chosen due to the fact it contained direct links to the data on the Internet.

4.3.2 Problems with Wave Data

Two problems were experienced with the observed wave data.

The SL-7 used a Tucker Wave Meter, as mentioned, to record wave height measurements. There were problems associated with using the wave data because of certain characteristics of the *McLEAN*. Firstly, the vessel often rolls in quartering seas and heels in strong winds off the bow that can displace the position of the pressure sensors by several feet above or below its nominal depth. Also, there are questions concerning whether the water pressure at the sensor, which is measured through a half-inch (1/2) hole in the side of the ship, represents the instantaneous wave height at that location, during top speed of 33 knots. Because of these factors, the data produced by the Tucker Wave Meter would have to be calibrated for direct use. A set of correction curves is given in [Ref. 3] as a function of depth and encounter frequency. Corrections were applied to a few data points and were compared to observed wave heights onboard the ship. No correlation was found and subsequent to further research in [Ref. 4] and other related documents, the wave meter readings recorded in the SL-7 data were not used.

As discussed earlier, the colour-coded weather maps supplied with the *ARCO CALIFORNIA* data show both wave height and direction for the area of interest over a large area. The predicted (forecasted) wave heights were compared with observed significant wave heights [Ref. 7]. The observed values were taken directly from the logs and were shown to have a correlation of 0.69. Because of this low correlation factor, the forecast data was not used in any of the analyses.

The only weather data recorded by all ships was the wind speed, in Beaufort Number. It was, therefore, of value to correlate the Beaufort wind scale with corresponding NATO sea state, the latter being the scale of choice agreed by the Steering Committee. Table 4.3 shows the relationship between the Beaufort Number and the NATO sea state.

Table 4.3: Beaufort Wind Scale and NATO Sea State

Beaufort Number	Wind Speed Range (knots)	NATO Sea State	Wind Speed Range (knots)	Wave Heights Range (m)
1	0-3	1	0-6	0-0.1
2	4-6			
3	7-10	2	7-10	0.1-0.5
4	11-16	3	11-16	0.5-1.25
5	16-21	4	16-21	1.25-2.5
6	22-27	5	22-27	2.5-4.0
7	28-33	6	28-47	4.0-6.0
8	34-40			
9	41-47			
10	48-55	7	48-55	6.0-9.0
11	56-63	8	56-63	9.0-14.0
12	>63	>8	>63	>14

Once the data had been placed into the correct sea state, the next step was to determine a method of correlating the recorded sea state with a range of wave heights. This method was tested on the data from the *ARCO CALIFORNIA* voyages. Two different approaches were considered to correlate the ship's recorded weather (wind speed) and the exact weather (wave height) at particular time periods. The first approach was to directly associate the recorded Beaufort Number, from the ship's logs, with the wave height ranges affiliated with the particular NATO sea state. It was quickly noted that this was not very effective. When a certain wind speed, Beaufort Force, is recorded, the probable associated wave height may not be experienced for a long time, due mainly to two factors. When wind blows, it must continue for a certain length of time before it can reach its associated wave height, for example, if a force of Beaufort 5 recorded, its maximum wave height being 2.4 meters (unlimited duration and fetch). It would take eight hours to reach 75% of that height and twelve hours to reach 90%. Coincident with this aspect, the direction of the wind force must be consistent over a certain period of time. If a wind is blowing long enough to establish an increasing wave height and suddenly changes direction, it will cause the wave height to decrease because of the opposing direction. If the original wind force remained during this change, then a recording of this Beaufort Number would be misleading with regard to correlating the existing wave height. Because of the two important factors listed above regarding wave height estimations, this approach was not considered for use in the analysis due to its inconsistency.

The second approach to correlate the Beaufort Number and wave heights, and likely the last one to be examined, is to obtain historical records of wave height measurements along the vessel's given route. The first step in this process was to search the Internet for available data that was discussed earlier. Once the vessel's route had been defined and buoys located, the next step was to download this data and begin comparing it to the recorded data in the logs. The wave measurements recorded by these buoys are not directly measured by sensors on the buoys. Rather, the accelerometers or inclinators on board the buoys measure the heave acceleration or the vertical displacement of the buoy hull during acquisition time. The data is transformed into a frequency domain aboard the buoy by a processor using a Fast Fourier Transformation (FFT). To account for hull and electronic noise, response amplitude operator (RAO) processing is performed on the data. It is from this transformation that non-directional wave measurements are derived. The buoys contain hourly data for every day they were in use. Once the data was retrieved, it was compared to the recorded Beaufort Number for correlation. The first comparison used 26 different data points. From this first attempt, it was clearly shown that there was no correlation between the buoy data and recorded wind data. The second attempt to develop a relationship used 68 data points. Like this first result, no correlation was achieved.

The method currently employed is to take the recorded wave height from the moored buoys and use it directly in the analysis, without trying to correlate it with the Beaufort Number. The final method is the most accurate and seems to be the only one available at this time.

There are, however, problems associated with this procedure and should be closely examined. The main problem deals with the amount of data that is available. Historical data was located for the *ARCO CALIFORNIA*, but it does not cover all of the route, in fact it covers less than 20%. No historical data was obtained at all for the *SS SEALAND McLEAN* and the *M.V. THORNHILL*.

A more detailed search is necessary to find data for the times and areas where none could be found. Because of this lack of data, it may be necessary to continue to attempt some kind of relationship between the recorded Beaufort Number and wave heights recorded by the moored buoys.

The basic objectives of attempting to correlate the observed environmental data with measured at the buoy site were:

a) To attempt to correlate variations with speed and wave climate. The ships' logs indicated minimal variation in speed, and thus no sensitivity to wave climate.
b) To determine a variation in heading with weather. Again, the log data indicates no large variations in heading (~45^{o}), although additional minor changes may have occurred.
c) To determine the influence of weather routing, i.e., avoidance of major weather systems. If a basic correlation between reported and measured wave data could be made, it might be determined that the measured buoy data spectra should be "skewed" towards a milder environment to reflect the influence of weather routing. However, failure to demonstrate a basic correlation precludes this type of adjustment.

4.3.3 Wave Height Distributions in Marsden Zone Areas

The calculation of the statistical distribution of wave heights for particular Marsden zone areas was done using a cumulative probability function and Weibull parameters. The three parameters probability density function was

$$f(H_s) = [\, j/(H_1 - H_o)] * \{[(H_s - H_o)/(H_1 - H_o)]^{j-1}\} * (\exp - [(H_s - H_o)/(H_1 - H_o)]^{j})$$

By substituting $H_o = 0$, and integrating the density function, a Weibull cumulative distribution function is obtained

$$F(H_s) = 1 - \exp [(H_s/H_1)^{j}] , \quad H_s > 0$$

H_1 = Weibull parameter
H_s = Significant wave height
j = Weibull parameter

By using the above equation along with the two Weibull parameters j and H_1, for long term probability distribution of the significant wave height, a statistical distribution of the significant wave height expected to occur in a particular zone can be found. For example, if a vessel was designed for operation in Marsden zone 21, then by using the above equation and the corresponding Weibull parameters for that area, the distribution of sea states it expects to encounter is calculated.

For this project, the values used for H_s correspond to the extreme value of wave height range for each NATO sea state. From the above example, it is shown that 43.66% of the waves experienced are below 2.5 meters and 73.57% below 4 meters.

5. DEVELOPMENT OF OPERATIONAL PROFILES

5.1 Methodology for Development of Operational Profiles

Operational profiles were developed from the raw log data following the approach set out in Figure 5.1.

In the case of the commercial vessels, the quantity of data was such that this development was carried out manually. While ship and wave heading data were transcribed to relative wave heading, and data expressed as points of the compass (NNE etc.)were converted to degrees and then into the five relative heading categories, the principal data reduction was in establishing the times spent at various speeds, relative headings and locations.

In general for the commercial vessels, the route was well established and there were only two loading conditions as described earlier. For the *HAMILTON Class* however, the data was much more extensive and required a more automated process, and, in addition, it was necessary to examine the activity of the vessel in order to classify the missions.

Step 1

Data were organized into 40 spreadsheets, each sheet representing a separate mission or task. In the first stage of the analysis, the course of the vessel for each sheet was calculated and plotted. This form of analysis provided information on the distance (in nautical miles) the vessel travelled, duration of the mission in days, and a rough indication as to what the ship was doing during each mission. For example, if the plot of relative course was erratic, then it was concluded the ship was performing some kind of a task. On the other hand, if the plot of relative course was a smooth curve, the conclusion was the ship was transiting from one point to another. It should be noted here that this analysis of relative course was carried out at a “global scale”, meaning the relative course was plotted for the entire data set in a sheet.

Step 2

A mission description was provided by Science and Technology Corporation for each spreadsheet. It described exactly what the mission of the ship was for each sheet, the location, and for the transit missions, places of departure and arrival. As a check it was found that sheets with mission description “transit” correlated well with the smooth plots of relative course of the respective sheets.

Data from the spreadsheets were organized in four bins (operational profiles) on the basis of mission, distance traveled and time spent at sea. The number of operational profiles was a trade-off, as a larger number of profiles would have resulted in fewer data points in each, thus reducing the statistical significance of the data. From a total of 40 spreadsheets, two were discarded as they did not fit any of the four defined operational profiles.

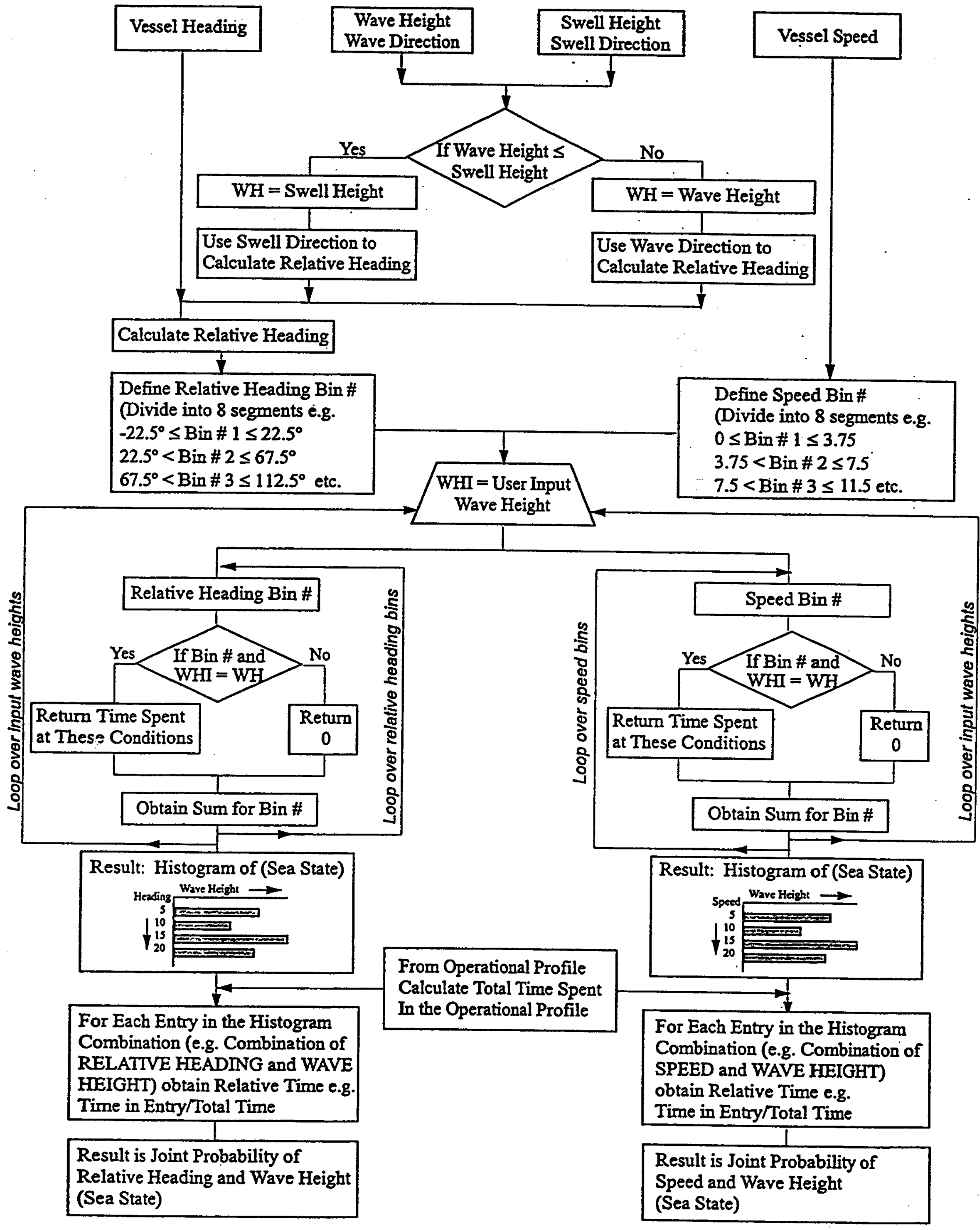

Figure 5.1: Approach to Developing Operational Profiles

Step 3

The resulting data bins (operational profiles) were organized into histograms of speed vs. time at speed for each wave height (Sea State), and heading vs. time at heading for each wave height (Sea State).

The information generated for each vessel operational profile includes the following:

- Joint probability (two-dimensional probability) of speed and wave height or sea state;
- Joint probability (two-dimensional probability) of heading (relative to wave) and wave height or Sea State;
- A listing of Marsden Zones [Ref. 6] as shown in Figure 5.2, traversed by the vessel and the relative time spent in each zone.

The vessel heading and sea state probability distribution tables are discretized in terms of five headings. This heading discretization scheme was selected for two reasons:

(1) Headings relative to wave direction more precise than 45 degrees are difficult to discern and thus are not generally recorded.
(2) By assuming port/starboard symmetry of vessel reaction to incident waves pair-wise groupings of relative headings are possible as follows:

- Head Seas
- Strbd. Bow same as Port Bow
- Strbd. Beam same as Port Beam
- Strbd Quartering same as Port Quartering
- Following Seas

All of the probability tables presented in Section 5 indicate the relative amount of vessel time at sea spent in each operational state (e.g., heading/sea state, or speed/sea state or transiting a Marsden Zone). Time spent along side or in port is noted in each operational profile summary (Table 4.1) and is incorporated in the long and short term probabilistic design calculations.

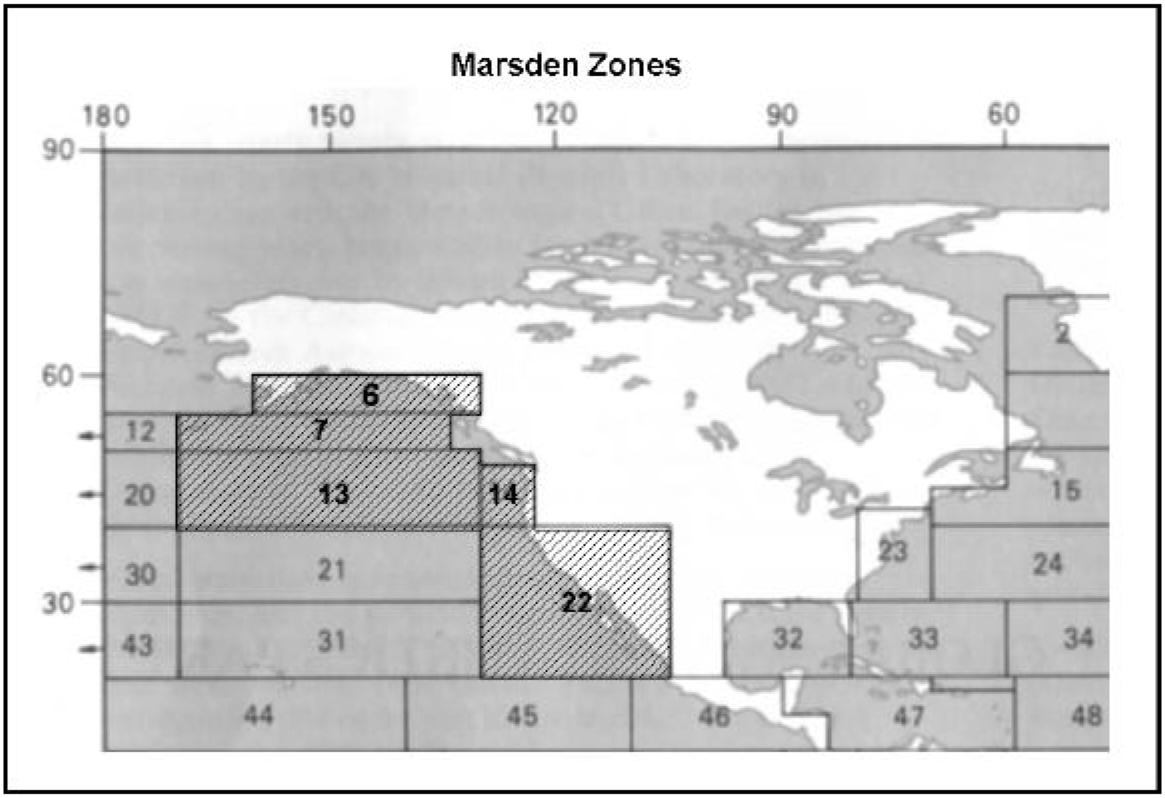

Figure 5.2: Marsden Zones. (Adopted from [Ref. 6])

The normalized speed, wave height and heading joint probability distributions, for each operational profile, are tabulated in the sections that follow. Any peculiarities or discrepancies noted in the collected data are discussed with each operational profile.

5.2 *SS SEALAND McLEAN* (SL-7) - Operational Profiles

Table 5.2.1: Eastbound Voyage - *SS SEALAND McLEAN*

	NATO Sea State							
Speed (kn.)	1	2	3	4	5	6	7	SUM
0-6	0.0000	0.0000	0.0092	0.0061	0.0061	0.0000	0.0000	**0.0214**
6-10	0.0000	0.0000	0.0031	0.0000	0.0000	0.0000	0.0000	**0.0031**
10-14	0.0000	0.0061	0.0092	0.0153	0.0245	0.0245	0.0000	**0.0795**
14-18	0.0183	0.0398	0.0092	0.0153	0.0031	0.0031	0.0000	**0.0887**
18-22	0.0245	0.0367	0.0336	0.0306	0.0275	0.0000	0.0000	**0.1529**
22-26	0.0031	0.0245	0.0398	0.0367	0.0183	0.0520	0.0000	**0.1743**
26-30	0.0092	0.0183	0.0856	0.0520	0.0459	0.0428	0.0000	**0.2538**
30-34	0.0000	0.0092	0.0398	0.0405	0.0612	0.0757	0.0000	**0.2263**
SUM	**0.0550**	**0.1346**	**0.2294**	**0.1965**	**0.1865**	**0.1980**	**0.0000**	**1.0000**

	NATO Sea State							
Heading	1	2	3	4	5	6	7	SUM
Head Seas	0.0000	0.0022	0.0097	0.0099	0.0149	0.0184	0.0000	**0.0551**
Strbd. Bow	0.0022	0.0094	0.0270	0.0270	0.0384	0.0456	0.0000	**0.1496**
Strbd.Beam	0.0025	0.0127	0.0375	0.0376	0.0535	0.0648	0.0000	**0.2087**
Strbd.Quart	0.0064	0.0229	0.0699	0.0607	0.0822	0.0965	0.0000	**0.3386**
Following	0.0036	0.0147	0.0466	0.0453	0.0636	0.0743	0.0000	**0.2480**
SUM	**0.0148**	**0.0620**	**0.1906**	**0.1804**	**0.2526**	**0.2996**	**0.0000**	**1.0000**

Marsden Zone	Total East %
15	5.1
16	29.6
17	11.0
23	9.3
24	28.8
25	16.2
SUM	100

Table 5.2.2: Westbound Voyage - *SS SEALAND McLEAN*

	NATO Sea State							
Speed (kn.)	1	2	3	4	5	6	7	SUM
0-6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**
6-10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**
10-14	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**
14-18	0.0205	0.0102	0.0000	0.0137	0.0102	0.0171	0.0000	**0.0717**
18-22	0.0068	0.0102	0.0068	0.0068	0.0000	0.0137	0.0068	**0.0512**
22-26	0.0137	0.0102	0.0512	0.0580	0.0512	0.0563	0.0017	**0.2423**
26-30	0.0171	0.0375	0.0341	0.0717	0.0307	0.1075	0.0068	**0.3055**
30-34	0.0375	0.0410	0.0683	0.0520	0.0708	0.0597	0.0000	**0.3294**
SUM	**0.0956**	**0.1092**	**0.1604**	**0.2022**	**0.1630**	**0.2543**	**0.0154**	**1.0000**

	NATO Sea State							
Heading	1	2	3	4	5	6	7	SUM
Head Seas	0.0277	0.0315	0.0456	0.0425	0.1099	0.0531	0.0038	**0.3142**
Strbd. Bow	0.0411	0.0462	0.0749	0.0607	0.0767	0.0717	0.0011	**0.3724**
Strbd.Beam	0.0206	0.0231	0.0390	0.0329	0.0401	0.0385	0.0004	**0.1946**
Strbd.Quar.	0.0080	0.0087	0.0151	0.0118	0.0247	0.0134	0.0000	**0.0818**
Following	0.0030	0.0033	0.0057	0.0046	0.0153	0.0051	0.0000	**0.0370**
SUM	**0.1005**	**0.1128**	**0.1803**	**0.1525**	**0.2667**	**0.1818**	**0.0054**	**1.0000**

Marsden Zone	Total West %
15	0.0
16	17.8
17	16.8
23	5.9
24	41.6
25	17.8
SUM	**100**

5.3 *ARCO CALIFORNIA* (TAPS FLEET) – Operational Profiles

Table 5.3.1: Northbound Profile Data - *ARCO CALIFORNIA*

	NATO Sea State							
Speed(kn.)	1	2	3	4	5	6	7	SUM
0-6	0.0000	0.0020	0.0000	0.0000	0.0049	0.0120	0.0000	**0.0189**
6-10	0.0021	0.0009	0.0025	0.0040	0.0102	0.0435	0.0000	**0.0633**
10-14	0.0122	0.0265	0.0517	0.0445	0.0696	0.1001	0.0013	**0.3061**
14-18	0.0340	0.0979	0.1416	0.1181	0.1155	0.1045	0.0000	**0.6117**
SUM	**0.0484**	**0.1273**	**0.1959**	**0.1667**	**0.2002**	**0.2601**	**0.0013**	**1.0000**

	NATO Sea State							
Heading	1	2	3	4	5	6	7	SUM
Head Seas	0.0064	0.0164	0.0251	0.0216	0.0252	0.0353	0.0001	**0.1301**
Strbd. Bow	0.0163	0.0416	0.0648	0.0555	0.0686	0.0953	0.0005	**0.3427**
Strbd.Beam	0.0162	0.0420	0.0652	0.0557	0.0695	0.0945	0.0005	**0.3437**
Strbd.Quar.	0.0056	0.0152	0.0229	0.0193	0.0209	0.0230	0.0001	**0.1068**
Following	0.0035	0.0106	0.0147	0.0124	0.0157	0.0198	0.0001	**0.0767**
SUM	**0.0480**	**0.1258**	**0.1928**	**0.1644**	**0.1999**	**0.2679**	**0.0013**	**1.0000**

Table 5.3.2: Southbound Profile Data - *ARCO CALIFORNIA*

Speed (kn.)	NATO Sea State							
	1	2	3	4	5	6	7	SUM
0-6	0.0028	0.0000	0.0009	0.0000	0.0000	0.0010	0.0007	**0.0054**
6-10	0.0056	0.0031	0.0033	0.0082	0.0086	0.0261	0.0010	**0.0559**
10-14	0.0129	0.0219	0.0503	0.0378	0.0449	0.0896	0.0019	**0.2593**
14-18	0.0900	0.1253	0.1322	0.1007	0.1338	0.0968	0.0005	**0.6793**
SUM	**0.1113**	**0.1503**	**0.1866**	**0.1467**	**0.1873**	**0.2135**	**0.0041**	**1.0000**

Heading	NATO Sea State							
	1	2	3	4	5	6	7	SUM
Head Seas	0.0084	0.0114	0.0167	0.0128	0.0160	0.0221	0.0005	**0.0879**
Strbd. Bow	0.0234	0.0326	0.0380	0.0295	0.0383	0.0375	0.0005	**0.1998**
Strbd. Beam	0.0283	0.0375	0.0439	0.0355	0.0454	0.0497	0.0009	**0.2413**
Strbd.Quart.	0.0421	0.0586	0.0729	0.0565	0.0724	0.0800	0.0013	**0.3840**
Following	0.0098	0.0136	0.0164	0.0129	0.0165	0.0176	0.0003	**0.0871**
SUM	**0.1120**	**0.1537**	**0.1880**	**0.1472**	**0.1886**	**0.2070**	**0.0035**	**1.0000**

Marsden Zone	Time % Northbound.	Time % Southbound
6	20.0	26.0
7	18.0	18.0
13	9.0	11.0
14	30.0	20.0
22	23.0	25.0
SUM	**100**	**100**

5.4 *MV THORNHILL* – Operational Profiles

Table 5.4.1: Loaded Condition - *MV THORNHILL*

	Sea State							
Speed (kn.)	1	2	3	4	5	6	7	SUM
10-12	0.0079	0.0000	0.0000	0.0073	0.0132	0.0331	0.0000	**0.0616**
12-14	0.0310	0.0320	0.2172	0.2144	0.1986	0.1532	0.0000	**0.8464**
14-16	0.0000	0.0199	0.0265	0.0290	0.0068	0.0098	0.0000	**0.0920**
SUM	**0.0389**	**0.0519**	**0.2437**	**0.2507**	**0.2187**	**0.1961**	**0.0000**	**1.0000**

	Sea State							
Heading	1	2	3	4	5	6	7	SUM
Head Seas	0.0067	0.0065	0.0321	0.0343	0.0317	0.0324	0.0000	**0.1437**
Strbd. Bow	0.0216	0.0190	0.1172	0.1209	0.1141	0.1037	0.0000	**0.4964**
Strbd.Beam	0.0038	0.0116	0.0370	0.0376	0.0272	0.0227	0.0000	**0.1400**
Strbd.Quar.	0.0028	0.0072	0.0253	0.0256	0.0194	0.0159	0.0000	**0.0963**
Following	0.0034	0.0100	0.0327	0.0332	0.0242	0.0202	0.0000	**0.1236**
SUM	**0.0383**	**0.0542**	**0.2443**	**0.2516**	**0.2166**	**0.1950**	**0.0000**	**1.0000**

Marsden Zone	Total Time %	**Marsden Zone**	Total Time %	**Marsden Zone**	Total Time %
5	1.4	**28**	2.9	**59**	1.4
11	1.4	**29**	3.0	**60**	3.4
13	2.8	**30**	6.9	**61**	3.4
16	1.5	**32**	0.7	**62**	2.8
17	0.7	**33**	1.4	**66**	1.4
18	1.4	**36**	2.7	**67**	3.4
19	0.7	**37**	3.5	**68**	3.5
20	4.8	**39**	0.5	**69**	0.7
21	6.2	**40**	5.0	**75**	3.6
22	2.0	**47**	2.1	**84**	3.4
25	0.7	**50**	3.5	**85**	2.8
26	3.4	**56**	2.8	**90**	2.8
27	3.4	**58**	2.1	**Other**	33
				SUM	**100**

Table 5.4.2: Ballast Condition - *MV THORNHILL*

Speed(kn.)	Sea State							SUM
	1	2	3	4	5	6	7	
<10	0.0000	0.0000	0.0000	0.0000	0.0158	0.0000	0.0158	**0.0317**
10-12	0.0163	0.0000	0.0148	0.0158	0.0076	0.0000	0.0000	**0.0546**
12-14	0.1436	0.1415	0.0603	0.1401	0.0608	0.1210	0.0000	**0.6675**
14-16	0.0000	0.0632	0.0953	0.0000	0.0445	0.0433	0.0000	**0.2464**
SUM	**0.1599**	**0.2048**	**0.1705**	**0.1560**	**0.1287**	**0.1644**	**0.0158**	**1.0000**

Heading	Sea State							SUM
	1	2	3	4	5	6	7	
Head Seas	0.0262	0.0153	0.0162	0.0255	0.0115	0.0131	0.0000	**0.1078**
Strbd. Bow	0.0275	0.0201	0.0151	0.0269	0.0120	0.0172	0.0000	**0.1187**
Strbd.Beam	0.0673	0.1095	0.0934	0.0657	0.0709	0.0863	0.0120	**0.5052**
Strbd.Quar.	0.0267	0.0448	0.0391	0.0260	0.0243	0.0352	0.0000	**0.1962**
Following	0.0104	0.0164	0.0137	0.0101	0.0087	0.0130	0.0000	**0.0722**
SUM	**0.1580**	**0.2061**	**0.1775**	**0.1541**	**0.1275**	**0.1647**	**0.0120**	**1.0000**

Marsden Zone	Total Time %	**Marsden Zone**	Total Time %
5	3.3	27	1.6
11	4.9	**28**	5.0
13	16.2	**29**	6.6
16	3.2	**30**	6.5
18	3.1	**39**	1.6
19	1.6	**50**	3.3
20	11.4	**59**	1.6
21	3.2	**60**	3.3
22	4.9	**69**	3.3
26	6.5	**75**	8.9
		SUM	**100**

5.5 USCG *HAMILTON Class* Cutter – Operational Profiles

In the data files, there were a number of entries where the ship was underway or with variable speed (V/S), or maneuvering with variable speed and course (MVCS), or maneuvering with variable speed (MVS). These entries were not used in the development of the joint probabilities of the operational profiles, but are characteristics of each. Time spent at each of these entries is given in the profile description.

5.5.1 Operational Profile #1 Short Training Activity

Description: 1-6 days at sea, 100 NM radius.	
Activities include: training, gun exercise, man overboard drill, machinery testing, patrol.	
Number of files used in the OP#1:	10
Number of Entries:	1343

Table 5.5.1: Operational Profile #1 - USCG *HAMILTON Class*

Total number of hours at sea	Total number of hours Underway	Total number of hours V/S	Total number of hours DIW	Total number of hours MVCS	Total number of hours MVS	Total number of hours START	Total number of hours MOORED	Total number of hours STOP
471	3.9	3.3	6.7	4.1	2.0	1.0	10.7	155.6

Operational Profile #1

Speed (kn.)	Wave Height (m)						SUM
	0-0.305	0.305-0.61	0.61-0.915	0.915-1.22	1.22-1.525	1.525-1.83	
0-3.75	0.1985	0.1582	0.0504	0.0003	0.0000	0.0000	**0.4074**
3.75-7.50	0.0688	0.0426	0.0101	0.0031	0.0000	0.0000	**0.1246**
7.50-11.25	0.0453	0.0872	0.0339	0.0072	0.0048	0.0000	**0.1785**
11.25-15.0	0.1306	0.0561	0.0441	0.0166	0.0044	0.0003	**0.2522**
15.0-18.75	0.0098	0.0143	0.0008	0.0100	0.0000	0.0012	**0.0360**
18.75-22.5	0.0013	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0013**
22.5-26.25	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**
26.25-30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**
SUM	**0.4543**	**0.3585**	**0.1393**	**0.0372**	**0.0092**	**0.0015**	**1.0000**

Heading	Wave Height (m)						SUM
	0-0.305	0.305-0.61	0.61-0.915	0.915-1.22	1.22-1.525	1.525-1.83	
Head Seas	0.0943	0.0359	0.0250	0.0249	0.0010	0.0000	**0.1811**
Strbd. Bow	0.0735	0.0621	0.0224	0.0130	0.0019	0.0000	**0.1728**
Strbd. Beam	0.1580	0.1581	0.0639	0.0116	0.0041	0.0000	**0.3957**
Strbd.Quart.	0.0786	0.0520	0.0190	0.0087	0.0021	0.0014	**0.1618**
Following	0.0432	0.0305	0.0147	0.0002	0.0000	0.0000	**0.0886**

SUM	**0.4475**	**0.3386**	**0.1450**	**0.0584**	**0.0090**	**0.0014**	**1.0000**

5.5.2 Operational Profile #2 Long Training Activity

Description: 3-8 days at sea, 500 NM radius. Activities include training, gun exercise, sonar work, machinery testing, patrol, and transit. Number of files used in the OP#2: 9 Number of Entries: 2114

Table 5.5.2: Operational Profile #2 - USCG *HAMILTON Class*

Total number of hours at sea	Total number of hours Underway	Total number of hours V/S	Total number of hours DIW	Total number of hours MVCS	Total number of hours MVS	Total number of hours START	Total number of hours MOORED	Total number of hours STOP
951	7.0	9.6	1.9	34.2	3.5	0.2	152.3	55.7

Total number of hours at sea	Total number of hours MVC	Total number of hours ANCHORE D
951	2.1	10.7

Operational Profile #2

Speed (kn.)	Wave Height (m)									SUM
	0-0.305	0.305-0.61	0.61-0.915	0.915-1.22	1.22-1.525	1.525-1.83	1.83-2.135	2.135-2.44	2.44-2.745	
0-3.75	0.0366	0.0047	0.0046	0.0217	0.0256	0.0000	0.0000	0.0000	0.0000	**0.0932**
3.75-7.50	0.0214	0.0165	0.0207	0.0128	0.0063	0.0196	0.0000	0.0019	0.0000	**0.0992**
7.50-11.25	0.0802	0.0639	0.0771	0.0556	0.0327	0.0246	0.0020	0.0028	0.0013	**0.3400**
11.25-15.0	0.0664	0.0266	0.0581	0.0613	0.0303	0.0491	0.0055	0.0083	0.0000	**0.3056**
15.0-18.75	0.0402	0.0217	0.0385	0.0366	0.0081	0.0013	0.0000	0.0000	0.0000	**0.1463**
18.75-22.50	0.0055	0.0001	0.0022	0.0046	0.0001	0.0000	0.0000	0.0000	0.0000	**0.0125**
22.50-26.25	0.0000	0.0000	0.0026	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0026**
26.25-30	0.0000	0.0000	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0005**
SUM	**0.2503**	**0.1334**	**0.2042**	**0.1926**	**0.1032**	**0.0946**	**0.0075**	**0.0130**	**0.0013**	**1.0000**

Heading	Wave Height (m)									SUM
	0-0.305	0.305-0.61	0.61-0.915	0.915-1.22	1.22-1.525	1.525-1.83	1.83-2.135	2.135-2.44	2.44-2.745	
Head Seas	0.0671	0.0206	0.0425	0.0188	0.0090	0.0114	0.0023	0.0005	0.0000	**0.1721**
Strbd. Bow	0.0564	0.0309	0.0449	0.1124	0.0355	0.0200	0.0034	0.0030	0.0010	**0.3074**
Strbd. Beam	0.0668	0.0202	0.0369	0.0352	0.0149	0.0148	0.0000	0.0025	0.0000	**0.1914**
Strbd.Quart.	0.1464	0.0181	0.0334	0.0241	0.0125	0.0181	0.0000	0.0022	0.0000	**0.2547**
Following	0.0229	0.0147	0.0106	0.0084	0.0088	0.0096	0.0000	0.0017	0.0000	**0.0765**

SUM	**0.3596**	**0.1044**	**0.1682**	**0.1990**	**0.0806**	**0.0739**	**0.0057**	**0.0099**	**0.0010**	**1.0000**

5.5.3 Operational Profile #3 Patrol

Description: 1-6 days at sea, 1300 NM radius. Activities include transit, patrol, and exercise. Number of files used in the OP: 10 Number of Entries: 1796

Table 5.5.3: Operational Profile #3 - USCG *HAMILTON Class*

Total number of hours at sea	Total number of hours Underway	Total number of hours V/S	Total number of hours DIW	Total number of hours MVCS	Total number of hours MVS	Total number of hours START	Total number of hours MOORED	Total number of hours STOP
617	1.8	0.0	0.9	40.5	0.9	0.3	26.6	0.0

Operational Profile #3

Speed (kn.)	Wave Height (m)									SUM
	0-0.305	0.305-0.61	0.61-0.915	0.915-1.22	1.22-1.525	1.525-1.83	1.83-2.135	2.135-2.44	2.44-2.745	
0-3.75	0.0011	0.0023	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0037**
3.75-7.50	0.0095	0.0121	0.0075	0.0016	0.0026	0.0000	0.0000	0.0000	0.0000	**0.0332**
7.50-11.25	0.0353	0.0153	0.0377	0.0307	0.0140	0.0000	0.0000	0.0000	0.0000	**0.1330**
11.25-15.0	0.0603	0.0544	0.0360	0.0422	0.0123	0.0217	0.0077	0.0055	0.0024	**0.2425**
15.0-18.75	0.1032	0.1120	0.1325	0.1017	0.0358	0.0161	0.0049	0.0000	0.0000	**0.5062**
18.75-22.50	0.0104	0.0133	0.0306	0.0121	0.0141	0.0000	0.0000	0.0000	0.0000	**0.0805**
22.50-26.25	0.0004	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0006**
26.25-30	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0003**
SUM	**0.2206**	**0.2094**	**0.2443**	**0.1888**	**0.0787**	**0.0378**	**0.0125**	**0.0055**	**0.0024**	**1.0000**

Heading	Wave Height (m)									SUM
	0-0.305	0.305-0.61	0.61-0.915	0.915-1.22	1.22-1.525	1.525-1.83	1.83-2.135	2.135-2.44	2.44-2.745	
Head Seas	0.0820	0.0317	0.0134	0.0132	0.0058	0.0107	0.0067	0.0000	0.0000	**0.1634**
Strbd. Bow	0.0327	0.0711	0.0527	0.0447	0.0089	0.0000	0.0012	0.0016	0.0021	**0.2149**
Strbd. Beam	0.0499	0.0558	0.0684	0.0592	0.0089	0.0111	0.0000	0.0000	0.0000	**0.2534**
Strbd.Quart.	0.0674	0.0297	0.0535	0.0482	0.0407	0.0117	0.0028	0.0032	0.0000	**0.2572**
Following	0.0422	0.0150	0.0352	0.0060	0.0123	0.0000	0.0004	0.0000	0.0000	**0.1112**
SUM	**0.2742**	**0.2033**	**0.2233**	**0.1713**	**0.0765**	**0.0334**	**0.0111**	**0.0048**	**0.0021**	**1.0000**

5.5.4 Operational Profile #4 - Enforcement/Rescue

Description: 2-30 days at sea, 2500 NM radius.	
Activities include law enforcement, hurricane relief, transit and training	
Number of files used in the OP#4:	11
Number of Entries:	11703

Table 5.5.4: Operational Profile #4 - USCG *HAMILTON Class*

Total number of hours at sea	Total number of hours Underway	Total number of hours V/S	Total number of hours DIW	Total number of hours MVCS	Total number of hours MVS	Total number of hours START	Total number of hours MOORED	Total number of hours STOP
4207.1	13.6	0.0	9.2	92.3	0.8	2.4	120.7	83.7

Operational Profile #4

Speed (kn.)	Wave Height (m) 0-0.305	0.305-0.61	0.61-0.915	0.915-1.22	1.22-1.525	1.525-1.83	1.83-2.135	2.135-2.44	2.44-2.745	2.745-3.05	3.05-3.66	SUM
0-3.75	0.0339	0.0138	0.0135	0.0031	0.0019	0.0012	0.0011	0.0003	0.0000	0.0000	0.0000	**0.0689**
3.75-7.50	0.0443	0.0420	0.0357	0.0339	0.0146	0.0099	0.0057	0.0011	0.0039	0.0011	0.0007	**0.1929**
7.50-11.25	0.0458	0.0411	0.0832	0.0555	0.0233	0.0132	0.0071	0.0026	0.0013	0.0008	0.0004	**0.2743**
11.25-15.0	0.0489	0.0352	0.0547	0.0658	0.0356	0.0169	0.0071	0.0025	0.0004	0.0000	0.0000	**0.2671**
15.0-18.75	0.0366	0.0394	0.0237	0.0231	0.0273	0.0182	0.0056	0.0029	0.0000	0.0008	0.0000	**0.1777**
18.75-22.50	0.0021	0.0034	0.0040	0.0034	0.0032	0.0004	0.0000	0.0007	0.0004	0.0000	0.0000	**0.0177**
22.50-26.25	0.0000	0.0003	0.0006	0.0002	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0015**
26.25-30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**
SUM	**0.2117**	**0.1751**	**0.2155**	**0.1850**	**0.1064**	**0.0599**	**0.0265**	**0.0103**	**0.0060**	**0.0026**	**0.0011**	**1.0000**

Heading	Wave Height (m) 0-0.305	0.305-0.61	0.61-0.915	0.915-1.22	1.22-1.525	1.525-1.83	1.83-2.135	2.135-2.44	2.44-2.745	2.745-3.05	3.05-3.66	SUM
Head Seas	0.0652	0.0295	0.0370	0.0366	0.0198	0.0214	0.0063	0.0036	0.0027	0.0009	0.0006	**0.2147**
Strbd. Bow	0.0583	0.0546	0.0573	0.0457	0.0395	0.0169	0.0093	0.0028	0.0019	0.0002	0.0001	**0.286**

											7
Strbd.Beam	0.0556	0.0459	0.0535	0.0453	0.0155	0.0075	0.0036	0.0015	0.0000	0.0005	0.0000	**0.2289**
Strbd.Quart.	0.0342	0.0237	0.0434	0.0376	0.0191	0.0073	0.0027	0.0009	0.0002	0.0000	0.0000	**0.1690**
Following	0.0265	0.0140	0.0242	0.0154	0.0087	0.0054	0.0031	0.0009	0.0008	0.0008	0.0004	**0.1002**
SUM	**0.2308**	**0.1677**	**0.2154**	**0.1806**	**0.1027**	**0.0585**	**0.0251**	**0.0097**	**0.0056**	**0.0024**	**0.0010**	**1.0000**

6. APPLICATION OF METHODOLOGY

Sample applications of the short and long term analysis procedure outlined in [Ref. 2] have been completed to demonstrate the adequacy of the collected data as well as to illustrate any inconsistencies in the procedures. The vessel route selected for these case studies is the TAPS tanker in the North Pacific Ocean covering Marsden Zones 6, 7, 13, 14 and 22. Information on vessel time spent in each Zone and operating condition was obtained from the sea operational profile developed for TAPS tankers given in Section 5.2.

6.1 Case Study #1 (Short Term Analysis)

6.1.1 Description of Procedure

This study presents a procedure for calculating ship/storm encounter probabilities that can be used for establishing extreme design environmental conditions. The encounter probabilities provide meaningful criteria for design since they involve the design life of the ship, as well as wave statistics in the expected region of operation. The procedure involves a number of steps, each comprising several tasks and requiring several sets of data. Steps 1 and 2 identify the single most severe sea condition based on some small probability of encounter. The extreme design condition is characterized by the extreme wave height that will be encountered during the period of interest, which, for this analysis, is taken to be 20 years. In Step 3, this wave height is used to compute extreme wave loading. The implicit assumption is that the highest wave height yields the highest load effect. The wave period, required to fully describe the extreme design condition, was obtained from the encounter period at which transfer function (or response amplitude operator RAO) was at maximum. With extreme wave loading calculated, Step 4 covers calculations of structural probability of failure.

It should be noted here that short term analysis approach is, in fact, a ***design wave*** approach and may be more reasonably referred to as such. The time parameter L_i , in the analysis is defined as a time spent (in years) in the Marsden Zone (see Section 2.3.1), and may take any value. The name "short term" stems from the assumption that sea conditions characterized by wave height and wave period to which the vessel is subjected are constant over one to three hours. In literature this is usually referred to as a "stationarity" assumption in the statistical description of the sea.

<u>Step 1: Short Term Analysis (Design Wave Approach)(Case #1)</u>

From wave data [Ref. 6], similar to that shown in Table 6.1.1, cumulative probability distribution functions of significant wave heights are determined for each Marsden Zone in which the vessel operates. In the analysis, it is assumed that significant wave height follows a three-parameter Weibull distribution given by:

$$F(H_s) = 1 - \exp\{-[(H_s - m)/k]^{l}\}$$

Where m is the location parameter, k is the scale parameter, and l is the shape parameter of the Weibull distribution. The parameters of Weibull distributions are calculated (Mansour et. al., 1997) for each Marsden Zone, as shown in Table 6.1.2.

Table 6.1.1: Sample Non-Directional Wave Data for Marsden Zone 6. (Adopted from Hogben et al, 1986).

Total	**1**	**24**	**125**	**266**	**283**	**182**	**81**	**28**	**8**	**2**	**1**	**1000**
H_s												
>14	~	~	~	~	~	~	~	~	~	~	~	~
13-14	~	~	~	~	~	~	~	~	~	~	~	~
12-13	~	~	~	~	~	~	~	~	~	~	~	~
11-12	~	~	~	~	~	~	~	~	~	~	~	**1**
10-11	~	~	~	~	~	~	~	~	~	~	~	**1**
9-10	~	~	~	~	1	1	1	~	~	~	~	**3**
8-9	~	~	~	~	1	2	1	1	~	~	~	**5**
7-8	~	~	~	1	2	3	2	1	1	~	~	**11**
6-7	~	~	~	2	5	7	5	2	1	~	~	**22**
5-6	~	~	1	5	12	13	8	4	1	~	~	**45**
4-5	~	~	2	13	26	25	14	5	2	~	~	**87**
3-4	~	~	7	32	51	40	19	6	2	~	~	**158**
2-3	~	2	21	68	83	51	20	5	1	~	~	**251**
1-2	~	6	50	103	84	36	10	2	~	~	~	**292**
0-1	1	16	44	41	18	4	1	~	~	~	~	**125**
	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	Total
	T_z											

Table 6.1.2: Significant Wave Height Weibull Probability Distribution Parameters

Marsden Zone	Scale Parameter k	Shape parameter l	Location Parameter m
6	2.26032	1.25714	0.55011
7	2.81349	1.49968	0.62740
13	2.60645	1.41403	0.62772
14	2.13950	1.28599	0.54784
22	1.56905	1.25626	0.61804

Step 2: Short Term Analysis (Case #1)

With the cumulative probability distribution function calibrated for each Marsden Zone, relevant statistics including an estimate of return period and probability of encounter in each Zone are calculated for the design wave heights.

Table 6.1.3 summarizes the encounter probabilities and associated significant wave heights for each Marsden Zone. In addition, an upper and lower bound estimate of the overall probability of encounter is calculated for each Marsden Zones.

Table 6.1.3: Calculated Twenty-Year Encounter Probabilities for Significant Wave Heights for Each Marsden Zone

Sig. Wave Height (m)	Marsden Zone					Probability	
	6	7	13	14	22	Lower Bound	Upper Bound
14	0.3243	0.1097	0.0807	0.1144	0.0018	0.3243	0.5111
15	0.1455	0.0346	0.0277	0.0422	0.0005	0.1455	0.2321
16	0.0611	0.0103	0.0091	0.0150	0.0001	0.0611	0.0931
17	0.0247	0.0029	0.0029	0.0052	0.0000	0.0247	0.0354
18	0.0098	0.0008	0.0009	0.0017	0.0000	0.0098	**0.0132**

Encounter probabilities range from a 1.32% chance of encountering an 18 m wave height to 51.1% chance of encountering a 14m wave height in 20 years of operation in the North Pacific, specifically in Marsden Zones 6, 7, 13, 14 and 22. In the analysis, it was assumed that the ship spends 18.3 years at sea, and 1.7 years in port. This was based on the assumption of 23 days/year for loading/unloading and 7 days/year for maintenance.

At the beginning of this section it was mentioned that the design sea condition is selected based on some small probability of encounter. In this example the design level of wave encounter probability is taken as 1.5%. Thus, (from Table 6.1.3) a wave height of 18 m was taken as the design significant wave height.

From the table, it can be seen that highest encounter probabilities occur in Marsden Zone 6 for all wave heights considered. Thus the lower bound of the system equates to the encounter probabilities in Zone 6, as the lower bound assumes complete independence between the probabilities of encounter in each Zone. The encounter probability in each Zone is considered to be part of the overall probability of a series system, and if individual encounter probabilities are perfectly correlated, then the lower bound estimate is simply the maximum of the individual probabilities. In this case, the maximum of the individual probabilities for each wave height happens to occur in Zone 6. This is an indication that most severe weather conditions exist in Zone 6.

Step 3: Short Term Analysis (Case #1)

At this stage, the RMS value of the wave bending moment for the identified design significant wave height is calculated. In this exercise, the RMS values were calculated for a Product Tanker whose characteristics are shown in Table 6.1.4.

Table 6.1.4: Principal Data - Example Tanker

Ship length (Lpp)	187.15 m
Ship Beam	28.96 m
Draft	12.4 m
Displacement	58,800 tonnes
KG	12.2 m
SM (deck)	15.94 m^3
SM (bottom)	23.08 m^3
Full Load SWBM	0.43 x 10^6 kNm (sag)
Ballast Cond. SWBM	1.00 x 10^6 kNm (hog)

A linear ship motion program SHIPMO 7 [Ref. 8] was used to develop response spectra and the associated RMS value for the vertical bending moment. Since Step 2 does not provide the period of the design storm wave, the ship was analyzed (full load condition) in a number of short term extreme sea states at seven headings (from 0 to 180 degrees) to identify the period (encounter frequency) and heading at which bending moment is the most severe. The maximum wave bending moment occurred amidships at 180 deg. heading angle (head seas) with an amplitude of 3.38 x 10^6 kNm and corresponding RMS of 0.97 x 10^6 kNm in the fully loaded condition. The wave period of 11.42 seconds was obtained from the encounter frequency at which the maximum value of the RAO occurred in the ship motion analysis. Wave bending moment at this heading and period for the ballast condition were 2.65 x 10^6 kNm and RMS of 0.91 x 10^6 kNm. Using the dispersion relation for waves in deep water, wave length was calculated to be 203.76 m. Resulting wavelength to ship length ratio (8/L) is 1.09, which is very close to the familiar value of 1 used in the classical "wave static balance" calculations of maximum bending moment. Complete lists of parameters associated with the design short term wave loading condition are given in Table 6.1.5.

Table 6.1.5: Calculated Design Wave Parameters - from Parametric Analysis

Significant Wave Height:	18.00 m (from Step 2)
Peak Period:	11.42 s
Wavelength:	203.76 m
Wave Steepness:	0.088
Ship Speed:	12.0 knots

Step 4: Short Term Analysis (Case #1)

In this example, the only mode of failure considered is yielding due to hull girder bending. The strength parameter used in the calculations is the initial deck yield moment M_{IY}. This is defined as the global hull girder bending moment that, if applied to the ship, would cause the stress in the partial-section of the ship in tension to just reach the yield strength of the material [Ref.2].

The goal is to evaluate the probability of initial yield in a storm condition specified by a significant wave height of 18 m and peak period of 11.42 seconds. The storm is assumed to be stationary under these conditions for a period of one hour.

Loads

In Table 6.1.6a, M_{sw} actual is the calculated still water bending moment. For the probabilistic analysis, the mean M_{sw} is taken as 60 percent of the actual value, and a coefficient of variation (COV) of 0.25 is assumed [Ref. 2]. There are two distinct stillwater bending moments: one for each loading condition. When in the fully loaded condition, the ship has a sagging stillwater bending moment, whereas, the ballast condition induces a hogging stillwater bending moment.

The mean of the extreme wave-induced bending moment M_w is calculated for the design short term loading condition by using RMS data for both the ballast and loaded conditions with an extreme value cumulative probability distribution F_w [1] of the form:

$$F_w=\exp\{-N \exp[-w^2/(2 \times RMS^{1/2})]\} \quad (6.1)$$

where w is the bending moment, N is the number of moment peaks in one hour (60x60/11.42 ≈315 peaks), and RMS is the vertical moment root-mean square as obtained from SHIPMO7. Figure 6.1.1 shows this distribution. The 50 percent probability of excedence value is taken as the mean M_w for the reliability analysis.

In order to model the effects of slamming, a dynamic moment M_d is introduced into the analysis. The dynamic moment is taken to be a fraction of the extreme wave moment. For the fuller formed commercial ships (tanker in this example), a value of 20 percent of M_w was used.

Coefficients of variation (COV) are taken as follows: 0.25 for still water bending moment (M_{sw},) 0.1 for extreme wave moment (M_w,) and the largest value of 0.3 for dynamic moment (M_d).

Strength

Table 6.1.6b presents the statistical parameters for the initial yield moment. These values were calculated by multiplying the appropriate section modulus (SM_I) by the yield strength (σ_y) of the material.

$$M_{IY}= \alpha \; SM_I * \sigma_y \quad (6.2)$$

Where subscript I denotes deck or bottom. Yield strength is based on a material with a nominal yield strength of 259 MPa. For reliability analysis α=1.15, or mean strength M_{IY} is taken to be 15 percent larger than the calculated value in order to correct for inherent conservatism in the calculated strength.

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[1] Cumulative distribution of the largest peak based on the upcrossing analysis (Mansour, 1990)

Load combination factors were used in the limit state equation to account for the correlation between loads. Two combinations factors namely k_d and k_w were used: k_d to combine the wave induced and dynamic bending moment, and k_w to combine the wave moment with the stillwater moment. Mean values of the coefficients were 0.7 and 1.0 for k_d and k_w. The selected coefficients of variation for k_w and k_d were 0.05 and 0.15, respectively (Mansour et al., 1997).

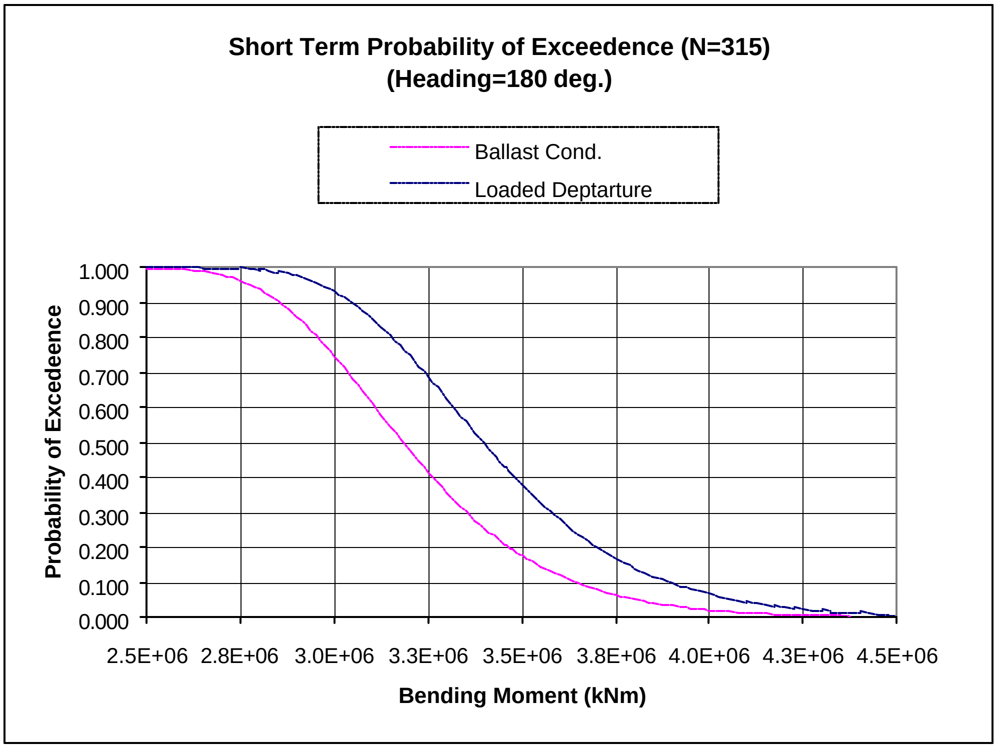


Figure 6.1.1: Extreme Value Cumulative Distribution

Limit State Equation

Now that all of the variables have been quantified, the next step in the analysis is the formulation of the limit state equation. Since we are dealing with only one failure mode we will have one limit state equation for two cases: loaded and ballast condition.

$$G = M_{IY} – [\ M_{sw} + k_w\ (M_w + k_d\ M_d)] \tag{6.3}$$

Where:

$$\mu_G = \mu_G – [\ \mu_{Msw} + k_w\ (\mu_{Mw} + k_d\ \mu_{Md})] \tag{6.3.1}$$

and

$$\sigma_G = [\sigma_{MIY}^2 + \sigma_{Msw}^2 + M_w^{\ 2}\ \sigma_{kw}^2 + k_w^{\ 2}\ M_d^{\ 2}\ \sigma_{kd}^2 + k_w^{\ 2}\ \sigma_{Mw}^2 + k_w^{\ 2}\ k_d^{\ 2}\ \sigma_{Md}^2]^{1/2} \tag{6.3.2}$$

The safety index β according to the Mean Value First Order Second Moment Method (MVFOSM) is defined as the mean of the limit state function μ_G divided by its standard deviation σ_G.

$$\beta = \mu_G/\sigma_G \tag{6.4}$$

Table 6.1.6c presents the values of the mean, standard deviation of the limit state equation, and evaluates the safety index (β) for loaded and ballast condition.

Table 6.1.6a: Short Term Analysis Probabilistic Load Data (Case #1)

	Actual	Mean	COV	Distribution	Comment
M_{sw} [kNm]	0.430E+06	2.580E+05	0.25	Normal	Ballast Cond
	1.000E+06	6.000E+05	0.25	Normal	Loaded Dept.
M_w [kNm]		3.175E+06	0.10	Extreme	Ballast Cond.
		3.400E+06	0.10	Extreme	Loaded Dept.
M_d [kNm]		6.350E+05	0.30	Extreme	Ballast Cond.
		6.800E+05	0.30	Extreme	Loaded Dept.
k_w		1.00	0.05	Normal	
k_d		0.70	0.15	Normal	

Table 6.1.6b: Short Term Analysis Probabilistic Strength Data (Case #1)

		Mean	COV	Distribution	Comment
M_{IY} [kN*m]		4.748E+06	0.10	Lognormal	deck* (Ballast Con.)
		6.874E+06			bottom* (Load Dep.)
SM_d [m^3]		15.94	0.10	Normal	
SM_b [m^3]		23.08	0.10	Normal	
					*Nominal Yield Stress σ_y =259 MPa

Table 6.1.6c: Short Term Analysis Probabilistic Results

Limit Function:				
Mean:	2.398E+06	**Safety Index:**	**2.94**	**Loaded Departure**
Standard Dev.	8.155E+05	**P_f =0.0016**		

Limit Function:				
Mean:	8.705E+05	**Safety Index:**	**1.42**	**Ballast Cond.**
Standard Dev.	6.147E+05	**P_f =0.0778**		

The results of the reliability analysis for the example ship and operational profile indicate that the “level of safety” quantified by safety index β are 2.94 for the loaded condition and 1.42 for the ballast condition. These safety indices, 2.94 and 1.42, correspond to probabilities of failure of 0.0016 and

0.0778, respectively. It should be noted that computed probabilities given in this example are conditional probabilities given that the ship encounters a specific storm for a specified length of time.

6.1.2 Discussion of Case Study #1 (Short Term Analysis)

Sensitivity to Operational Parameters

Encounter probabilities are highly dependent on the time spent in Marsden Zones as well as the route of a ship. The issue is complicated by the uncertainty that is associated with the ship's operational profile, as it may change during the lifetime of the ship. For example, the *SS SEALAND McLEAN* was designed for a speed of 33 knots. However, between mechanical problems and operational decisions based on fuel prices, the ship never operated at that design speed again. Circumstances such as reduced operating speeds will increase sailing time and consequently change the time spend in the individual Marsden Zones and thus exposure time to extreme conditions. Another obvious reason for change in a vessel's operational profile would be a complete change of route (e.g., due to a change in contract). Changes in operational profile invalidate initial design calculations and require updating to ensure continued vessel safety.

To demonstrate the sensitivity of the short term analysis to design storm encounter probability, existing data on time spent in Marsden Zones 6, 7, 13, 14 and 22 given in Section 5.1 were modified to reflect a change in routing. Table 6.1.7 contains original data (defined as Case 1) and modified data (Case 2):

Table 6.1.7: Change in Exposure Time - Example Case

Marsden Zone	Case 1: Time(years)	Case 2: Time (years)
6	4.76	7.80
7	3.29	5.40
13	2.00	2.90
14	3.66	2.20
22	4.58	0.00

The length of time spent in Zones 6, 7 and 13 is increased between 31 to 39 percent. Time in Zone 14 was reduced by approximately 39 percent while Zone 22 was completely excluded from the ship route.

Figure 6.1.2 presents the upper bound of the probability of encounter of the system of Marsden Zones for the original (Case 1) and modified (Case 2) data, for the range of significant wave heights. This figure is complemented by Table 6.1.8 where plotted data are shown in numerical form together with associated vertical wave bending moment data. It should be noted that wave bending moments were calculated from the maximum value of the RAO evaluated in the ship motion analysis for the wave with period of 11.42 seconds.

As it can be seen from the figure, the change in exposure time had noticeable influence on the probabilities of encounter. For all significant wave heights examined values for Case 2 are higher than corresponding values for Case 1. The upper bound increased from 24% at 14m wave height to approximately 49% at 18m wave height.

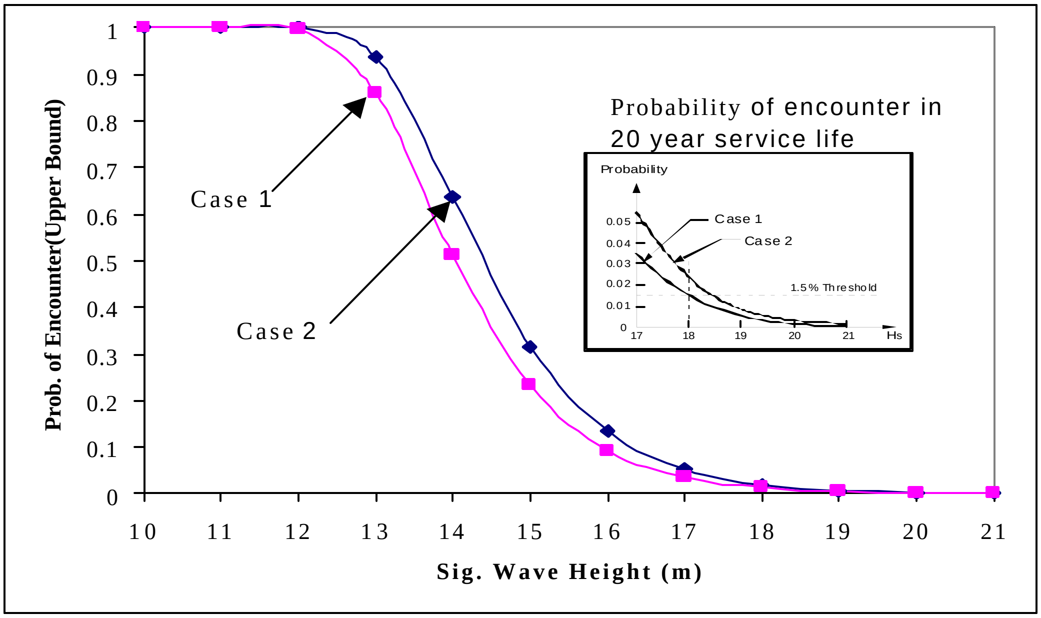


Figure 6.1.2: Distribution of Probabilities of Encounter – Sensitivity Analysis

Since in our example, the design level of encounter probability was rather small (1.5%), the tail portion of the distribution is sketched in the window of Figure 6.1.2. For Case 1, the design wave height of 18m. has probability of encounter of 1.3% and was selected as a design wave height. For Case 2, a design wave height based on 1.5% probability lies between 18 and 19 m. Thus, the change in operational profile from Case 1 to Case 2 has changed the design wave height. This indicates the necessity to perform sensitivity analysis to investigate any possible changes in the parameters of a design storm if short term analysis is used as design criteria and there is any uncertainty in the expected vessel operation profile.

Table 6.1.8: Upper Bound on Probabilities of Encounter - Sensitivity Analysis

Sig. Wave Height (m)	Upper Bound Case 1	Upper Bound Case 2	Vertical Bending Moment (kNm)
10	1.0000	1.0000	1.88E+06
11	1.0000	1.0000	2.07E+06
12	0.9972	0.9997	2.25E+06
13	0.8609	0.9374	2.44E+06
14	0.5111	0.6374	2.63E+06
15	0.2321	0.3156	2.82E+06
16	0.0931	0.1326	3.00E+06
17	0.0354	0.0519	3.19E+06
18	0.0132	0.0197	3.38E+06
19	0.0048	0.0074	3.57E+06
20	0.0018	0.0027	3.76E+06

21	0.0006	0.0010	3.94E+06

Vertical wave bending moments shown in Table 6.1.8 are related to the wave heights through the linear relationship due to assumptions inherent in the strip method used in the ship motion calculations.

The probability of encounter P_{ei} is defined as:

$$P_{ei} = \text{Probability [excedence of } H_s \text{ in life } L_i]$$

where L_i is the time spent in zone i in years, and H_s is the significant wave. This indicates that encounter probability of certain significant wave height is essentially a probability of exceeding that significant wave height. This interpretation can be extended to the bending moment, where for the example of an 18m wave height in Table 6.1.8, probability of excedence of 3.38×10^6 bending moment is 1.32% for the Case 1, and 1.97% for the Case 2.

Wave Period and Directionality

The short term analysis provides information on the encounter probability of the design storm conditions described by the wave height. However, to completely describe a short term sea condition the wave period is needed. In the example above, the marginal probabilities of wave heights in Marsden Zones, as given in [Ref. 6], were used. That is, all of the wave information in the region was combined in a single wave height distribution regardless of wave period. For a comprehensive application, it would be prudent to repeat the same analysis for every wave period given in the scatter diagrams of the operational zones (Marsden Zones). Obviously, this represents a significant increase in the time required to complete the analysis; an alternative may be to review the variability in wave period and direction in the operating zones, and make an assessment concerning the suitability of creating a combined wave height distribution.

Another factor to consider is the limiting wave steepness; not all combinations of wave height and period are physically possible, i.e., the wave will “break”. Thus it may be possible to eliminate some combinations of design wave height and period.

Linearity

Finally, in the short term analysis, an extreme wave loading was evaluated using a linear strip theory program (SHIPMO 7). However, in the case of the extreme design wave, the response of the ship may be significantly non-linear. If non-linear effects are expected to be important, which will apply to many design cases, then an alternative to directly employing the strip theory results should be found. The simplest approach is to augment the linear response using dynamic response factors (multipliers) to account for non-linear effects. These factors may be available for a particular type of hull form from empirical (model or full scale) data.

Another alternative is to restrict the input wave conditions to the linear range, and extrapolate the linear predictions using extreme value theory. This approach will involve modifying the process outlined previously, as both a “design wave condition” (i.e., the 1.5% threshold in the example) and the linear wave condition (at some higher probability of encounter) would be used in the analysis. Also, one could generate the extreme wave loads using a more sophisticated code than linear strip theory; however, validation of the code may be an issue.

It should be noted that non-linear effects are not expected to be significant in a long term analysis, due to the relatively low occurrence probability of the wave conditions generating those effects.

6.2 Case Study #2 (Long Term Analysis)

6.2.1 Description of Procedure

In this study, we will use the same ship as in the previous example, (i.e., a product tanker) operating in the North Pacific Marsden Zones 6, 7, 13, 14, and 22. The aim of the long term analysis approach is to determine the probability distribution of wave loads during the service life of a ship and thus assess the fatigue strength of the vessel structure. Figure 6.2.1 schematically depicts the long term procedure. As can be seen from the figure, there are three levels of load range spectrum that need to be developed. The first level of load range spectrum is developed for all possible combinations of speed, heading and wave height (sea state) for a **single** wave period. The same procedure is repeated for all wave periods occurring in the zones where the ship operates. This yields a load range spectrum specific for an operational profile. If more than one operational profile exists for a vessel, the procedure just described has to be repeated as many times as there are numbers of profiles. Finally, lifetime load range spectrum is obtained as a sum of the product of each ordinate of operational profile spectrum and the weighting factor reflecting the time spent in particular operational profile. For the sake of clarity, in the example developed in this section, only a first level load range spectrum was calculated. The wave period selected was 7.5 seconds which approximately corresponds to the mean wave period in the North and Central Pacific Ocean [Ref. 9].

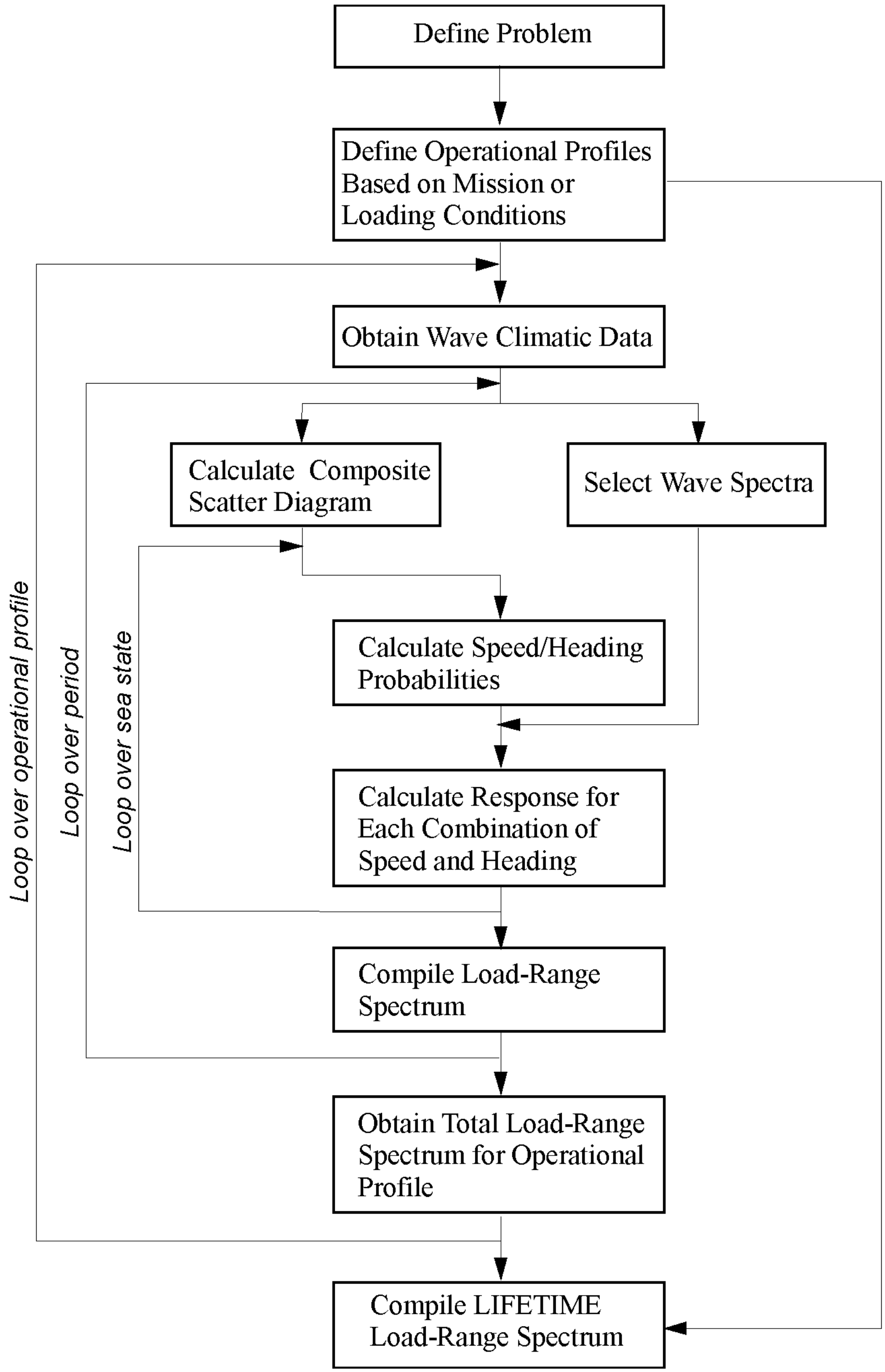


Figure 6.2.1: Schematic of Long Term Procedure

Step 1: Long Term Analysis (Case #2)

Table 6.2.1 presents the distribution of wave heights for the Marsden Zones of interest. Table 6.2.2 is taken from Section 5.2, and contains percent time spent in the Marsden Zones for the Southbound voyage.

Table 6.2.1: Distribution of Wave Height Probabilities (f_{mi}) for Marsden Zones

Hs [m]	Marsden Zone				
	6	**7**	**13**	**14**	**22**
0-1	0.1250	0.0480	0.0630	0.1280	0.1580
1-2	0.2920	0.2130	0.2380	0.3080	0.3800
2-3	0.2510	0.2730	0.2760	0.2590	0.2780
3-4	0.1580	0.2130	0.2010	0.1560	0.1230
4-5	0.0870	0.1280	0.1140	0.0800	0.0430
5-6	0.0449	0.0660	0.0571	0.0380	0.0129
6-7	0.0219	0.0320	0.0271	0.0170	0.0039
7-8	0.0109	0.0150	0.0121	0.0080	0.0010
8-9	0.0049	0.0070	0.0061	0.0030	0.0010
9-10	0.0029	0.0030	0.0030	0.0020	0.0000
10-11	0.0010	0.0010	0.0010	0.0010	0.0000
11-12	0.0010	0.0010	0.0010	0.0000	0.0000
SUM:	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**

Table 6.2.2: Data From Operational Profile (*ARCO CALIFORNIA*)

Marsden Zone	% of time at sea (μ_i)
6	26.0
7	18.0
13	11.0
14	20.0
22	25.0

The composite distribution of wave heights $f_{mc}\ (H_s;T_s)_{composite}$ is shown in Table 6.2.3, and was developed from:

$$f_{mc}\ (H_s;T_s)_{composite} = \sum \mu_i\ f_{mi}\ (H_s;T_s)_i \qquad (6.5)$$

where H_s and T_s are significant wave height and wave period respectively, and μ_i is the relative time spent in each Marsden Zone. The summation is taken over the (i) number of zones in which the ship operates. As in Case Study #1, for simplicity, the probabilities given are wave height marginal probabilities, that is, all wave period information in each Zone was combined in a single wave height distribution. This assumption will be discussed further later.

Table 6.2.3: Composite Distribution of Wave Height Probabilities (f_{mc})

Hs [m]	Marsden Combined
0-1	0.1131
1-2	0.2970
2-3	0.2660
3-4	0.1634
4-5	0.0849
5-6	0.0407
6-7	0.0188
7-8	0.0087
8-9	0.0041
9-10	0.0020
10-11	0.0008
11-12	0.0006

Step 2: Long Term Analysis (Case #2)

In this step, we combine the composite wave height probability distribution (Table 6.2.3) with the joint probability of vessel speed and sea state (Table 6.2.4) according to the expression:

$$f_s = f_{mc} (H_s;T_s)_{composite}\, f_V (V \mid H_s) \qquad (6.6)$$

The term $f_V (V \mid H_s)$ is the conditional probability of speed V given a wave height H_s (or sea state). This term is calculated from Table 6.2.4 as follows:

$$f_V (V \mid H_s) = prob (V \mid H_s) = prob(V \text{ and } H_s) / prob (H_s) \qquad (6.7)$$

where: prob(V and H_s) is the joint probability of speed and wave height (entries in Table 6.2.4), and prob (H_s) is the marginal probability of wave heights, shown in the bottom row of Table 6.2.4 as bolded numbers.

Table 6.2.4: Joint Probability of Speed and Sea State (Operational Profile, *ARCO CALIFORNIA*)

SPEED	NATO Sea State							
(kn.)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	SUM
0-6	0.0028	0.0000	0.0009	0.0000	0.0000	0.0010	0.0007	**0.0054**
6-10	0.0056	0.0031	0.0033	0.0082	0.0086	0.0261	0.0010	**0.0559**
10-14	0.0129	0.0219	0.0503	0.0378	0.0449	0.0896	0.0019	**0.2593**
14-18	0.0900	0.1253	0.1322	0.1007	0.1338	0.0968	0.0005	**0.6793**
SUM	**0.1113**	**0.1503**	**0.1866**	**0.1467**	**0.1873**	**0.2135**	**0.0041**	**1.0000**

Table 6.2.5 presents the results of the calculation of f_s:

Table 6.2.5: Results - Two-Dimensional Probability Distribution (f_s)

SPEED	NATO Sea State							
(kn.)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	SUM
0-6	0.0014	0.0000	0.0014	0.0000	0.0000	0.0006	0.0062	**0.0096**
6-10	0.0028	0.0012	0.0053	0.0148	0.0075	0.0154	0.0082	**0.0552**
10-14	0.0065	0.0082	0.0800	0.0686	0.0392	0.0527	0.0164	**0.2717**
14-18	0.0457	0.0472	0.2103	0.1826	0.1167	0.0570	0.0041	**0.6636**
SUM	**0.0564**	**0.0566**	**0.2970**	**0.2660**	**0.1634**	**0.1256**	**0.0349**	**1.0000**

Step 3: Long Term Analysis (Case #2)

Up to this stage, the probabilities calculated were two-dimensional probabilities of speed V, and combined Marsden Zone. Now a third parameter, heading, will be incorporated in the analysis. Table 6.2.6 presents the joint probability of heading and sea state for the *ARCO CALIFORNIA* (see Section 5.2).

Table 6.2.6: Joint Probability of Heading and Sea State (for *ARCO CALIFORNIA*)

	NATO Sea State							
Heading	1	2	3	4	5	6	7	SUM
Head Seas	0.0084	0.0114	0.0167	0.0128	0.0160	0.0221	0.0005	**0.0879**
Strbd. Bow	0.0234	0.0326	0.0380	0.0295	0.0383	0.0375	0.0005	**0.1998**
Strbd. Beam	0.0283	0.0375	0.0439	0.0355	0.0454	0.0497	0.0009	**0.2413**
Strbd.Quart.	0.0421	0.0586	0.0729	0.0565	0.0724	0.0800	0.0013	**0.3840**
Following	0.0098	0.0136	0.0164	0.0129	0.0165	0.0176	0.0003	**0.0871**
SUM	**0.1120**	**0.1537**	**0.1880**	**0.1472**	**0.1886**	**0.2070**	**0.0035**	**1.0000**

Total probability (three-dimensional probability) or percent of time for each operational condition is calculated from

$$f_{stotal} = f_S \, f_\phi \, (\phi \mid H_s) \qquad (6.8)$$

where $f_\phi \, (\phi \mid H_s)$ is the conditional probability of heading (ϕ) for given wave height H_s or sea state. This term is calculated from Table 6.2.6 as follows:

$$f_\phi \, (\phi \mid H_s) = \text{prob} \, (\phi \mid H_s) = \text{prob}(\phi \text{ and } H_s) \, / \, \text{prob} \, (H_s) \qquad (6.9)$$

The values of f_ϕ calculated for every entry from the Table 6.2.6 are multiplied by each entry in the Table 6.2.5. There are four ranges of speeds x five headings = 20 results. This must be repeated for each of seven sea states. Thus, a matrix of three-dimensional probability of simultaneous occurrence of speed

(V), heading (ϕ) for the given wave height or sea state (H_s) in the combined Marsden Zone has 5 x 4 x 7 = 140 entries. Table 6.2.7 gives the results of the calculations.

The values shown in Table 6.2.7 are probabilities standardized by multiplying by 1000. Thus the probability of occurrence of Sea State 2 in head seas, with a vessel speed between 14-18 knots is 3.504/1000 = 0.003504. Some of the probabilities are small, and some are zero as it can be seen for the cases at Sea State 7.

Table 6.2.7: Joint Probabilities - Speed, Heading, Sea State

SPEED (kn.)	Sea State 1					Sea State 2				
	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following	Head Seas	Stb .Bow	Stb. Beam	Stb. Quart.	Following
0-6	0.109	0.301	0.364	0.542	0.126	0.000	0.000	0.000	0.000	0.000
6-10	0.214	0.594	0.717	1.067	0.248	0.086	0.246	0.283	0.443	0.103
10-14	0.493	1.367	1.650	2.457	0.571	0.613	1.749	2.009	3.144	0.730
14-18	3.447	9.564	11.546	17.192	3.998	3.504	10.004	11.492	17.986	4.175
SUM	**4.3**	**11.8**	**14.3**	**21.3**	**4.9**	**4.2**	**12.0**	**13.8**	**21.6**	**5.0**

SPEED (kn.)	Sea State 3					Sea State 4				
	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following
0-6	0.125	0.286	0.330	0.548	0.123	0.000	0.000	0.000	0.000	0.000
6-10	0.467	1.066	1.232	2.045	0.461	1.285	2.968	3.568	5.686	1.293
10-14	7.089	16.186	18.702	31.036	6.990	5.956	13.757	16.538	26.351	5.991
14-18	18.637	42.549	49.163	81.588	18.376	15.857	36.628	44.032	70.159	15.950
SUM	**26.3**	**60.1**	**69.4**	**115.2**	**26.0**	**23.1**	**53.4**	**64.1**	**102.2**	**23.2**

SPEED (kn.)	Sea State 5					Sea State 6				
	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following
0-6	0.000	0.000	0.000	0.000	0.000	0.061	0.103	0.137	0.221	0.049
6-10	0.639	1.530	1.818	2.898	0.661	1.641	2.779	3.690	5.938	1.308
10-14	3.317	7.940	9.430	15.035	3.428	5.633	9.540	12.669	20.388	4.490
14-18	9.891	23.676	28.121	44.833	10.223	6.085	10.306	13.686	22.024	4.850
SUM	**13.8**	**33.1**	**39.4**	**62.8**	**14.3**	**13.4**	**22.7**	**30.2**	**48.6**	**10.7**

SPEED (kn.)	Sea State 7					SPEED (kn.)
	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following	
0-6	0.941	0.843	1.651	2.268	0.456	0-6
6-10	1.254	1.125	2.201	3.024	0.608	6-10
10-14	2.509	2.249	4.402	6.049	1.216	10-14
14-18	0.627	0.562	1.100	1.512	0.304	14-18

SUM	**5.3**	**4.8**	**9.4**	**12.9**	**2.6**	**100**

Now, with the combinations of stationary conditions (combinations of speed, heading and sea state) identified with an associated frequency of occurrence, it is necessary to evaluate the responses for each combination. The fact that some of the probabilities are zero, or very small, reduces the number of conditions for which the response needs to be evaluated. Out of 140 stationary condition combinations, 75 responses were evaluated. Responses were again obtained using the linear strip theory code SHIPMO 7. Output for each condition includes the RAO (response amplitude operator) and the RMS value of the vertical bending moment. RMS values were generated using a two parameter Bretschneider Spectrum (suitable for fully developed seas), with the sea states defined in Table 6.2.7, and a peak period of 7.5 seconds for all runs.

Table 6.2.8 summarizes computed results. Columns two through seven indicate sea state, speed and vessel's heading for each run. Next two columns are values of RMS and corresponding period T_z. There are three additional columns in the table: standardized frequency of occurrence (px1000), number of wave bending moments (or wave peaks) in ship's life at each condition (N), and nominal deck stress (σ_d) where the section modulus at the deck was taken as 15.94 m^3.

In this example, only the Southbound operational profile was analyzed. To complete the long term distribution of wave loading, it would be necessary to repeat the procedure described for the northbound voyage. For our example, this implies another 82 SHIPMO 7 runs. This was not undertaken as the demonstration of the procedure was already highlighted. The end product would be two histograms of wave loading, one for the northbound and one for the southbound leg of the voyage (see Table 6.2.9). The lifetime (long term) wave loading distribution is obtained by multiplying each bin of the histograms by appropriate weighting factor which reflect time spent at each transit leg (noting that there is a variation in loading condition also).

For the case of the TAPS tanker profile, the weighting factors are: 2161/4344 = 0.497 for the northbound leg and 2183/4344 = 0.503 for the southbound leg. These values are based on the total number of hours in each loading condition (see Table 4.1).

Thus, it will be understood that for the fatigue reliability assessment described in the next section, the wave loading distribution of the southbound leg of the voyage, shown in Figure 6.2.1 is assumed to be vessel's lifetime distribution of wave loading.

Table 6.2.8: Long Term Response Values - Strip Theory Analysis

			Heading					SHIPMO7 Data				Nom. Stress.
Run #	Sea State	Speed (kn.)	**180**	**135**	**90**	**45**	**0**	**RMS**	**Tz**	p* 1000	N	Deck σ_d (Pa)
1	1	8	0	0	0	1	0	1300.6	10.7	1.067	8.5E+04	8.2E+04
2	1	12	0	1	0	0	0	1007.1	6.3	1.367	1.1E+05	6.3E+04
3	1	12	0	0	1	0	0	1079.5	7.4	1.650	1.3E+05	6.8E+04
4	1	12	0	0	0	1	0	1649.3	12.5	2.457	2.0E+05	1.0E+05
5	1	16	1	0	0	0	0	752.7	4.3	3.447	2.7E+05	4.7E+04
6	1	16	0	1	0	0	0	990.6	5.7	9.564	7.6E+05	6.2E+04
7	1	16	0	0	1	0	0	1158.4	7.4	11.546	9.2E+05	7.3E+04
8	1	16	0	0	0	1	0	2025.5	15.5	17.192	1.4E+06	1.3E+05
9	1	16	0	0	0	0	1	1108.2	22.0	3.998	3.2E+05	7.0E+04
10	2	12	0	1	0	0	0	6042.8	6.3	1.749	1.4E+05	3.8E+05
11	2	12	0	0	1	0	0	6476.7	7.4	2.009	1.6E+05	4.1E+05
12	2	12	0	0	0	1	0	9895.9	12.5	3.144	2.5E+05	6.2E+05
13	2	16	1	0	0	0	0	4576.2	4.3	3.504	2.8E+05	2.9E+05
14	2	16	0	1	0	0	0	5943.7	5.7	10.004	8.0E+05	3.7E+05
15	2	16	0	0	1	0	0	6950.6	7.4	11.492	9.1E+05	4.4E+05
16	2	16	0	0	0	1	0	12153	15.5	17.986	1.4E+06	7.6E+05
17	2	16	0	0	0	0	1	6649.2	22.0	4.175	3.3E+05	4.2E+05
18	3	12	1	0	0	0	0	13302	5.3	7.089	5.6E+05	8.3E+05
19	3	12	0	1	0	0	0	17625	6.3	16.186	1.3E+06	1.1E+06
20	3	12	0	0	1	0	0	18890	7.4	18.702	1.5E+06	1.2E+06
21	3	12	0	0	0	1	0	28863	12.5	31.036	2.5E+06	1.8E+06
22	3	12	0	0	0	0	1	18043	17.1	6.990	5.6E+05	1.1E+06
23	3	16	1	0	0	0	0	13172	4.3	18.637	1.5E+06	8.3E+05
24	3	16	0	1	0	0	0	17336	5.7	42.549	3.4E+06	1.1E+06
25	3	16	0	0	1	0	0	20273	7.4	49.163	3.9E+06	1.3E+06
26	3	16	0	0	0	1	0	35447	15.5	81.588	6.5E+06	2.2E+06
27	3	16	0	0	0	0	1	19393	22.0	18.376	1.5E+06	1.2E+06
28	4	8	1	0	0	0	0	29181	6.5	1.285	1.0E+05	1.8E+06
29	4	8	0	1	0	0	0	39215	7.0	2.968	2.4E+05	2.5E+06
30	4	8	0	0	1	0	0	37315	7.5	3.568	2.8E+05	2.3E+06
31	4	8	0	0	0	1	0	50984	10.7	5.686	4.5E+05	3.2E+06
32	4	8	0	0	0	0	1	31285	12.7	1.293	1.0E+05	2.0E+06
33	4	12	1	0	0	0	0	28505	5.3	5.956	4.7E+05	1.8E+06
34	4	12	0	1	0	0	0	37768	6.3	13.757	1.1E+06	2.4E+06
35	4	12	0	0	1	0	0	40479	7.4	16.538	1.3E+06	2.5E+06
36	4	12	0	0	0	1	0	61849	12.5	26.351	2.1E+06	3.9E+06

Table 6.2.8: Long term Response Values - Strip Theory Analysis (Continued)

			Heading					SHIPMO7 Data				Nom. Stress.
Run #	Sea State	Speed (kn.)	**180**	**135**	**90**	**45**	**0**	**RMS**	**Tz**	p* 1000	N	Deck σ_d (Pa)
37	4	12	0	0	0	0	1	38666	17.1	5.991	4.8E+05	2.4E+06
38	4	16	1	0	0	0	0	28226	4.3	15.857	1.3E+06	1.8E+06
39	4	16	0	1	0	0	0	37148	5.7	36.628	2.9E+06	2.3E+06
40	4	16	0	0	1	0	0	43441	7.4	44.032	3.5E+06	2.7E+06
41	4	16	0	0	0	1	0	75958	15.5	70.159	5.6E+06	4.8E+06
42	4	16	0	0	0	0	1	41557	22.0	15.950	1.3E+06	2.6E+06
43	5	8	1	0	0	0	0	50581	6.5	0.639	5.1E+04	3.2E+06
44	5	8	0	1	0	0	0	67972	7.0	1.530	1.2E+05	4.3E+06
45	5	8	0	0	1	0	0	64679	7.5	1.818	1.4E+05	4.1E+06
46	5	8	0	0	0	1	0	88373	10.7	2.898	2.3E+05	5.5E+06
47	5	8	0	0	0	0	1	54226	12.7	0.661	5.3E+04	3.4E+06
48	5	12	1	0	0	0	0	49408	5.3	3.317	2.6E+05	3.1E+06
49	5	12	0	1	0	0	0	65464	6.3	7.940	6.3E+05	4.1E+06
50	5	12	0	0	1	0	0	70164	7.4	9.430	7.5E+05	4.4E+06
51	5	12	0	0	0	1	0	107205	12.5	15.035	1.2E+06	6.7E+06
52	5	12	0	0	0	0	1	67020	17.1	3.428	2.7E+05	4.2E+06
53	5	16	1	0	0	0	0	48926	4.3	9.891	7.9E+05	3.1E+06
54	5	16	0	1	0	0	0	64390	5.7	23.676	1.9E+06	4.0E+06
55	5	16	0	0	1	0	0	75299	7.4	28.121	2.2E+06	4.7E+06
56	5	16	0	0	0	1	0	131660	15.5	44.833	3.6E+06	8.3E+06
57	5	16	0	0	0	0	1	72033	22.0	10.223	8.1E+05	4.5E+06
58	6	8	1	0	0	0	0	77817	6.5	1.641	1.3E+05	4.9E+06
59	6	8	0	1	0	0	0	104573	7.0	2.779	2.2E+05	6.6E+06
60	6	8	0	0	1	0	0	99507	7.5	3.690	2.9E+05	6.2E+06
61	6	8	0	0	0	1	0	135959	10.7	5.938	4.7E+05	8.5E+06
62	6	8	0	0	0	0	1	83425	12.7	1.308	1.0E+05	5.2E+06
63	6	12	1	0	0	0	0	76012	5.3	5.633	4.5E+05	4.8E+06
64	6	12	0	1	0	0	0	100714	6.3	9.540	7.6E+05	6.3E+06
65	6	12	0	0	1	0	0	107945	7.4	12.669	1.0E+06	6.8E+06
66	6	12	0	0	0	1	0	164931	12.5	20.388	1.6E+06	1.0E+07
67	6	12	0	0	0	0	1	103108	17.1	4.490	3.6E+05	6.5E+06
68	6	16	1	0	0	0	0	75270	4.3	6.085	4.8E+05	4.7E+06
69	6	16	0	1	0	0	0	99062	5.7	10.306	8.2E+05	6.2E+06
70	6	16	0	0	1	0	0	115844	7.4	13.686	1.1E+06	7.3E+06
71	6	16	0	0	0	1	0	202553	15.5	22.024	1.8E+06	1.3E+07
72	6	16	0	0	0	0	1	110820	22.0	4.850	3.9E+05	7.0E+06

Table 6.2.9: Lifetime Wave Loading – Southbound Operational Profile

Moment $x10^5$ kNm	Bin#	Number of observations per 1000 events (p*1000)
0.0075-0.1352	1	132.077
0.1352-0.2629	2	151.966
0.2629-0.3906	3	196.959
0.3906-0.5183	4	99.021
0.5183-0.6460	5	50.688
0.6460-0.7737	6	144.367
0.7737-0.9014	7	5.847
0.9014-1.0291	8	23.536
1.0291-1.1568	9	39.823
1.1568-1.2845	10	13.686
1.2845-1.4122	11	50.771
1.4122-1.5399	12	0
1.5399-1.6676	13	20.388
1.6676-1.7953	14	0
1.7953-1.9230	15	0
1.9230-2.0507	16	22.024

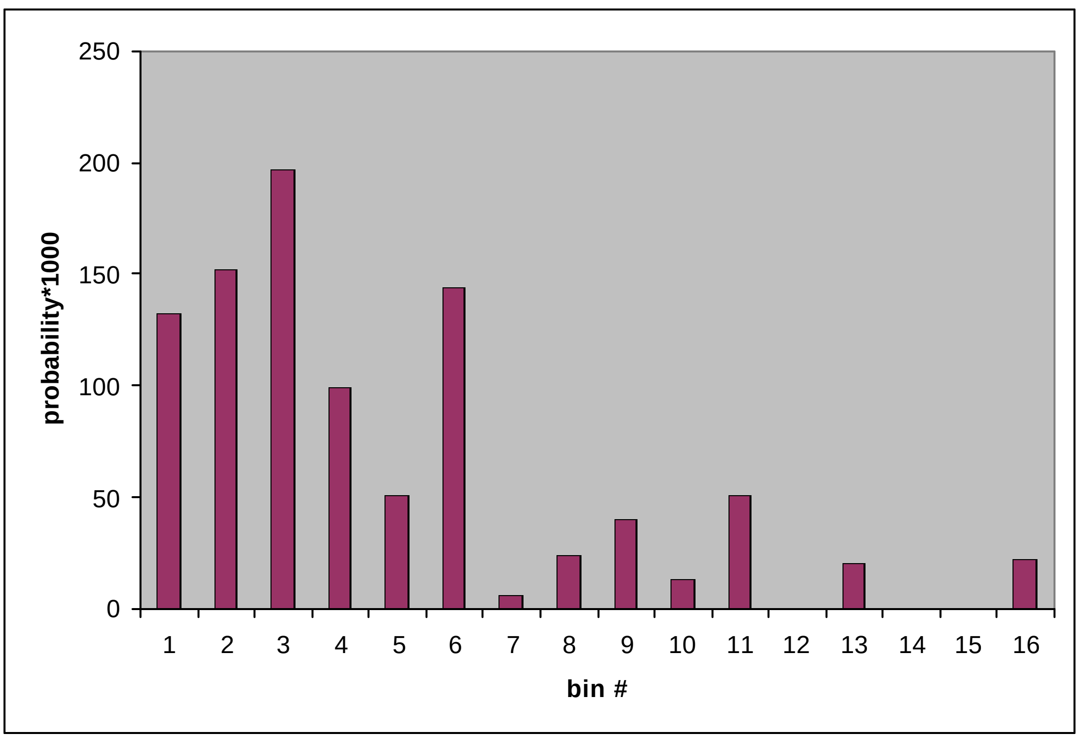


Figure 6.2.1: Lifetime Wave Loading - Southbound Operational Profile (Histogram)

Step 4: Fatigue Reliability Assesment (Case #2)

In the development of the simplified fatigue assessment, it will be assumed that the lifetime load spectrum of wave induced vertical bending moment represented in Figure 6.2.1 is the only source of cyclic stresses in ship structure. The approach used for the fatigue analysis was the Palmgren-Miner approach based on the S-N curves. The S-N curves describe the number of constant amplitude stress cycles to failure, as a function of the fluctuating stress amplitude. Such curves are of the form:

$$N\ S^m = K \qquad (6.10)$$

where N is the number of cycles to failure, S is the constant amplitude stress range, m is the inverse slope of the S-N curve (fatigue strength exponent), and K is the fatigue strength coefficient.

Each structural detail type has an S-N curve. In this example, fatigue assessment was performed for the hatch opening structural detail classified as belonging to class F2[1] with the S-N curve defined as:

$$\log N = \log K - m \log S \qquad (6.11)$$

with $K=0.43\times10^{12}$, and m=3.0.

Accumulation of fatigue damage D is assumed to be described by a linear damage accumulation rule (Palmgren-Miner):

$$D = \Sigma\ n(S_i)/N(S_i) \qquad (6.12)$$

where $n(S_i)$ is the number of stress cycles at stress S_i , and $N(S_i)$ is the number of cycles to failure at stress S_i. The summation is over all stress ranges experienced by the structural detail. When D=1, failure occurs.

Estimates of the hull girder bending stresses produced by the vertical bending moment are based on the flexure formula. To account for gross structural geometry surrounding the detail (e.g., hatch opening), the stress concentration factor is used.

$$\sigma_v = K_G\ M_v\ z / I_v \qquad (6.13)$$

where σ_v is the total hull girder stress due to vertical bending, M_v is the vertical bending moment amplitude at the location under consideration, z is the vertical distance from the neutral axis of the hull cross section to the location under consideration, I_v is the moment of inertia of the hull cross section about the transverse neutral axis, and K_G is the global stress concentration factor.

[1] BS 5400: Part10. Code of practice for fatigue, British Standards Institution

Table 6.2.10 gives the fatigue assessment results. In the calculations K_G =3 was used, and relevant sectional properties were the same as in Case Study #1 (e.g., z=11.09 m, and I_v = 176 m^4). Accumulation of fatigue damage, indicated by summation over all stress ranges (D=0.66), shows that for the hatch opening detail fatigue damage is not critical.

Table 6.2.10: Fatigue Assesment Results

Moment **x10e5 kNm**	Stress Nominal	Bin#	Stress* tot. (Pa)	Stress (Mpa)		cycles to failure N	n	n/N	p*1000
0.0075-0.1352	447577.1	1	1342731	1.3427	11.25	1.78E+11	9.99E+06	0.00	132.08
0.1352-0.2629	1248637	2	3745910	3.7459	9.91	8.18E+09	1.15E+07	0.00	151.97
0.2629-0.3906	2049696	3	6149088	6.1491	9.27	1.85E+09	1.49E+07	0.01	196.96
0.3906-0.5183	2850755	4	8552266	8.5522	8.84	6.87E+08	7.49E+06	0.01	99.02
0.5183-0.6460	3651815	5	10955445	10.9554	8.51	3.27E+08	3.83E+06	0.01	50.69
0.6460-0.7737	4452874	6	13358623	13.3586	8.26	1.80E+08	1.09E+07	0.06	144.37
0.7737-0.9014	5253934	7	15761801	15.7618	8.04	1.10E+08	4.42E+05	0.00	5.85
0.9014-1.0291	6054993	8	18164980	18.1649	7.86	7.17E+07	1.78E+06	0.02	23.54
1.0291-1.1568	6856053	9	20568158	20.5681	7.69	4.94E+07	3.01E+06	0.06	39.82
1.1568-1.2845	7657112	10	22971336	22.9713	7.55	3.55E+07	1.03E+06	0.03	13.69
1.2845-1.4122	8458172	11	25374515	25.3745	7.42	2.63E+07	3.84E+06	0.15	50.77
1.4122-1.5399	9259231	12	27777693	27.7776	7.30	2.01E+07	0.00E+00	0.00	0.00
1.5399-1.6676	10060290	13	30180871	30.1808	7.19	1.56E+07	1.54E+06	0.10	20.39
1.6676-1.7953	10861350	14	32584050	32.5840	7.09	1.24E+07	0.00E+00	0.00	0.00
1.7953-1.9230	11662409	15	34987228	34.9872	7.00	1.00E+07	0.00E+00	0.00	0.00
1.9230-2.0507	12463469	16	37390406	37.3904	6.92	8.23E+06	1.67E+06	0.20	22.02

* Stress concentration factor K_G=3 **SUM:** 0.66

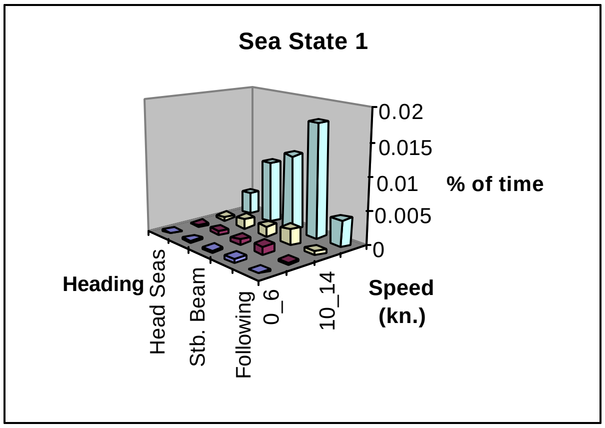
6.2.2 Discussion of Case Study #2 (Long Term Analysis)

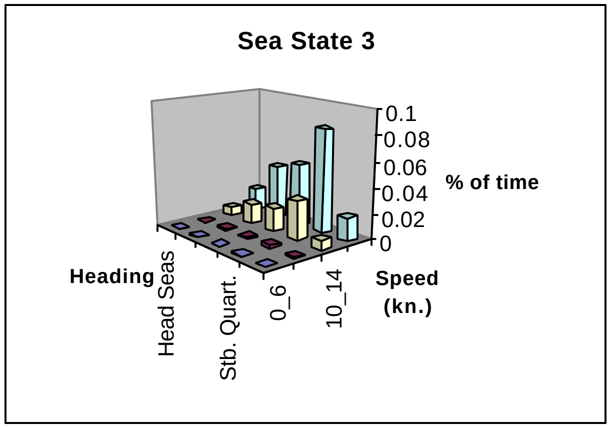
A step-by-step procedure to determine the probability distribution of wave loads during the service life of a ship has been demonstrated. The purpose of this commentary is to make the reader aware of the simplifications used in the example, and outline the required volume of calculations needed to fully complete the analysis.

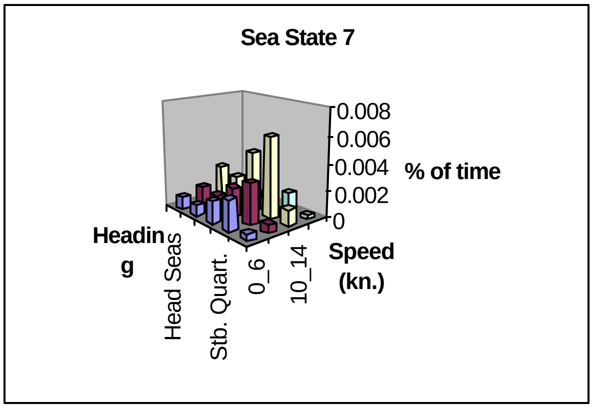
In the example, only the southbound operational profile was analyzed. To complete the long term analysis, it would be necessary to repeat the procedure for the northbound voyage. This would require another 82 SHIPMO 7 runs. Also, all wave information in the region was combined in a single wave height distribution regardless of wave period. For a comprehensive application, it would be necessary to repeat the same analysis for every wave period given in the scatter diagrams of the operational zones (Marsden Zones). In the analysis, it was assumed that vertical wave-induced bending moment is the only source of cyclic stresses. For comprehensive calculations lifetime distribution of horizontal and torsional bending moments need to be incorporated, as well as local and secondary cyclic load sources.

In many recent reliability-based analyses of ships, speed and heading are assumed to be independent quantities. Methodology used in this report to define operational profiles provided a framework in which assumption of speed and heading independence can be reviewed. Joint probability of vessel speed and sea state, and joint probability of vessel heading and sea state define each operational profile. Combining these two probabilities (for each sea state) together with the probability of combined Marsden Zone, three-dimensional probability of speed, heading and sea state is obtained. This procedure was demonstrated in the Case Study #2. If the relationship between heading and speed exist, it would become apparent by plotting the histograms (joint probability) of speed and heading for each sea state. For example, by plotting the data for Sea State 1, 3 and 7 from Table 6.2.7 it can be observed that at Sea State 1, relationships between speed and heading exist at 14-18 knots speed range, while at smaller speeds probability of heading and speed is very small. At intermediate Sea State 3, the speed/heading relationship begins to appear at 10-14 knots speed range. At Sea State 7 joint probabilities of speed and heading are comparable over the whole range of speed and headings.

Based on this data and in Case Study #2, heading/speed relationships exist at certain speeds, which in the Case Study #2 correspond to the speed range at the limit of the operational profile. This relationship is not unique, as it changes with Sea States, and different ships. Heading/Speed relationship for all four vessels is shown in Appendix B. If the vessel's operational profile is defined in the terms of speed and sea state and heading and sea state, and the procedure outlined in Case Study 2 is followed, then the analyst need not to worry about this relationship. Combined heading and speed histograms derived from the operational data can be used as a check in the calculations. Thus the definition of the heading/speed relationship is mainly a concern when a designer is creating a hypothetical operational profile.







Case Study #3

In this example, the procedure demonstrated in Case Study #2, under steps 1 to 3, will be employed to develop three dimensional probabilities for four operational profiles of the *HAMILTON Class* Cutter. Assumed percent time spent in the Marsden Zones for the four operational profiles are given in Table 6.3.1, and the distribution of wave heights probabilities for the Marsden Zones are presented in Table 6.3.2.

Table 6.3.1: Time Percentages in Marsden Zones

	Marsden Zone 23	Marsden Zone 24	Marsden Zone 33
Operational Profile #1	100%	~	~
Operational Profile #2	100%	~	~
Operational Profile #3	50%	~	50%
Operational Profile #4	40%	20%	40%

Table 6.3.2: Distribution of Wave Height Probabilities (f_{mi}) for Marsden Zones

Hs[m]	Marsden Zone		
	23	**24**	**33**
0-1	0.1959	0.0831	0.1612
1-2	0.3559	0.2641	0.4122
2-3	0.2389	0.2691	0.2652
3-4	0.1169	0.1811	0.1072
4-5	0.0519	0.1011	0.0362
5-6	0.0219	0.0511	0.0112
6-7	0.0099	0.0251	0.0042
7-8	0.0049	0.0121	0.0012
8-9	0.0019	0.0061	0.0012
9-10	0.0010	0.0031	0.0000
10-11	0.0009	0.0021	0.0000
11-12	0.0000	0.0011	0.0000
12-13	0.0000	0.0011	0.0000
SUM:	1.0000	1.0000	1.0000

For simplicity, detailed calculations of composite distribution of wave height probabilities (f_{mc}) and the joint probabilities of speed and wave height for each profile are not shown here (see steps 1 to 3 in Case Study #2). The process of calculation can be easily automated using any spreadsheet program. Matrices of three dimensional probability of simultaneous occurrence of speed (V), and heading (ϕ) for the given wave height (H_s) in the combined Marsden Zone for operational profiles 1 to 4 are given in Tables 6.3.3 to 6.3.6, respectively. As in Case Study #2, probabilities shown are normalized such that they represent number of observation per 1000 events.

Table 6.3.3: Operational Profile #1 - Joint Probabilities Speed, Heading, Wave Height

SPEED (kn)	0-0.31 (m)					0.31-0.61 (m)				
	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following
0-3.75	10	8	16	8	4	7	11	29	9	6
3.76-7.50	3	3	6	3	2	2	3	8	3	1
7.51-11.25	2	2	4	2	1	4	6	16	5	3
11.26-15.00	6	5	11	5	3	2	4	10	3	2
15.01-18.75	0	0	1	0	0	1	1	3	1	1
18.76-22.50	0	0	0	0	0	--	--	--	--	--
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	22	**17**	**37**	**18**	**10**	**15**	**26**	**65**	**21**	**13**

SPEED (kn)	0.61-0.92 (m)					0.92-1.22 (m)				
	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following
0-3.75	8	7	21	6	5	0	0	0	0	0
3.76-7.50	2	1	4	1	1	4	2	2	1	0
7.51-11.25	5	5	14	4	3	9	5	4	3	0
11.26-15.00	7	6	18	5	4	21	11	10	7	0
15.01-18.75	0	0	0	0	0	13	7	6	4	0
18.76-22.50	--	--	--	--	--	--	--	--	--	--
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	23	**20**	**58**	**17**	**13**	**47**	**25**	**22**	**16**	**0**

SPEED (kn)	1.22-1.53 (m)					1.53-1.83 (m)				
	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following	Head Seas	Stb. Bow	Stb. Beam	Stb. Quart.	Following
0-3.75	--	--	--	--	--	--	--	--	--	--
3.76-7.50	--	--	--	--	--	--	--	--	--	--
7.51-11.25	5	11	23	11	--	--	--	--	--	--
11.26-15.00	5	10	21	11	--	--	--	--	94	--
15.01-18.75	--	--	--	--	--	--	--	--	324	--
18.76-22.50	--	--	--	--	--	--	--	--	--	--
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	10	**20**	**44**	**22**	**0**	**0**	**0**	**0**	**418**	**0**

Table 6.3.4: Operational Proflile #2 - Joint Probabilities Speed, Heading, Wave Height

SPEED (kn)	0-0.31 (m)					0.31-0.61 (m)				
	Head Seas	Strbd Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	3	2	3	6	1	1	1	1	1	1
3.76-7.50	2	1	2	4	1	3	5	3	3	2
7.51-11.25	6	5	6	14	2	13	20	13	12	9
11.26-15.00	5	4	5	11	2	5	8	5	5	4
15.01-18.75	3	3	3	7	1	4	7	4	4	3
18.76-22.50	0	0	0	1	0	0	0	0	0	0
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	20	**16**	**19**	**43**	**7**	**28**	**41**	**27**	**24**	**20**

SPEED (kn)	0.61-0.92 (m)					0.92-1.22 (m)				
	Head Seas	Strbd Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	1	1	1	1	0	1	7	2	2	1
3.76-7.50	3	4	3	3	1	1	4	1	1	0
7.51-11.25	12	13	11	10	3	3	18	6	4	1
11.26-15.00	9	10	8	7	2	3	20	6	4	1
15.01-18.75	6	7	5	5	2	2	12	4	3	1
18.76-22.50	0	0	0	0	0	0	1	0	0	0
22.51-26.25	0	0	0	0	0	--	--	--	--	--
26.26-30	0	0	0	0	0	--	--	--	--	--
	33	35	29	26	8	10	62	19	13	5

SPEED (kn)	1.22-1.53 (m)					1.53-1.83 (m)				
	Head Seas	Strbd Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	3	11	4	4	3	--	--	--	--	--
3.76-7.50	1	3	1	1	1	2	4	3	4	2
7.51-11.25	3	13	6	5	3	3	5	4	5	3
11.26-15.00	3	12	5	4	3	6	11	8	10	5
15.01-18.75	1	3	1	1	1	0	0	0	0	0
18.76-22.50	0	0	0	0	0	--	--	--	--	--
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	11	43	18	15	10	12	21	16	19	10

SPEED (kn)	1.83-2.14 (m)					2.14-2.44 (m)				
	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	--	--	--	--	--	--	--	--	--	--
3.76-7.50	--	--	--	--	--	0	2	2	2	1
7.51-11.25	7	11	--	--	--	1	3	3	3	2
11.26-15.00	20	29	--	--	--	2	10	9	8	6
15.01-18.75	--	--	--	--	--	--	--	--	--	--
18.76-22.50	--	--	--	--	--	--	--	--	--	--
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	27	**40**	**0**	**0**	**0**	**3**	**16**	**13**	**12**	**9**

SPEED (kn)	2.44-2.745(m)				
	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	--	--	--	--	--
3.76-7.50	--	--	--	--	--
7.51-11.25	--	220	--	--	--
11.26-15.00	--	--	--	--	--
15.01-18.75	--	--	--	--	--
18.76-22.50	--	--	--	--	--
22.51-26.25	--	--	--	--	--
26.26-30	--	--	--	--	--
	0	**220**	**0**	**0**	**0**

Table 6.3.5: Operational Proflile #3 - Joint Probabilities Speed, Heading, Wave Height

SPEED (kn)	0-0.31 (m)					0.31-0.61 (m)				
	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	0	0	0	0	0	0	1	0	0	0
3.76-7.50	1	0	1	1	1	1	3	2	1	1
7.51-11.25	4	1	2	3	2	2	4	3	2	1
11.26-15.00	6	3	4	5	3	6	14	11	6	3
15.01-18.75	11	4	7	9	6	13	29	23	12	6
18.76-22.50	1	0	1	1	1	2	3	3	1	1
22.51-26.25	0	0	0	0	0	--	--	--	--	--
26.26-30	0	0	0	0	0	--	--	--	--	--
	23	**9**	**14**	**19**	**12**	**24**	**54**	**42**	**22**	**11**

SPEED (kn)	0.61-0.92 (m)					0.92-1.22 (m)				
	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	--	--	--	--	--	0	0	0	0	0
3.76-7.50	0	1	1	1	1	0	0	0	0	0
7.51-11.25	1	5	7	5	4	1	5	7	5	1
11.26-15.00	1	5	7	5	3	2	7	9	8	1
15.01-18.75	5	18	24	19	12	5	17	22	18	2
18.76-22.50	1	4	6	4	3	1	2	3	2	0
22.51-26.25	--	--	--	--	--	0	0	0	0	0
26.26-30	--	--	--	--	--	--	--	--	--	--
	9	34	44	35	23	9	31	41	34	4

SPEED (kn)	1.22-1.53 (m)					1.53-1.83 (m)				
	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	--	--	--	--	--	--	--	--	--	--
3.76-7.50	0	0	0	2	1	--	--	--	--	--
7.51-11.25	1	2	2	10	3	--	--	--	--	--
11.26-15.00	1	2	2	9	3	15	--	16	16	--
15.01-18.75	4	5	5	25	8	11	--	12	12	--
18.76-22.50	1	2	2	10	3	--	--	--	--	--
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	8	12	12	55	17	26	0	27	29	0

SPEED (kn)	1.83-2.14 (m)					2.14-2.44 (m)				
	Head Seas	Strbd Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	--	--	--	--	--	--	--	--	--	--
3.76-7.50	--	--	--	--	--	--	--	--	--	--
7.51-11.25	--	--	--	--	--	--	--	--	--	--
11.26-15.00	25	4	--	11	2	--	18	--	36	--
15.01-18.75	16	3	--	7	1	--	--	--	--	--
18.76-22.50	--	--	--	--	--	--	--	--	--	--
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	41	7	0	17	3	0	18	0	36	0

SPEED (kn)	2.44-2.745 (m)				
	Head Seas	Strbd Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	--	--	--	--	--
3.76-7.50	--	--	--	--	--
7.51-11.25	--	--	--	--	--
11.26-15.00	--	198	--	--	--
15.01-18.75	--	--	--	--	--
18.76-22.50	--	--	--	--	--
22.51-26.25	--	--	--	--	--
26.26-30	--	--	--	--	--
	0	198	0	0	0

Table 6.3.6: Operational Proflile #4 - Joint Probabilities Speed, Heading, Wave Height

SPEED (kn)	0-0.31 (m)					0.31-0.61 (m)				
	Head Seas	Strbd .Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	3	3	3	2	1	2	4	3	2	1
3.76-7.50	3	3	3	2	2	6	11	9	5	3
7.51-11.25	3	4	3	2	2	6	11	9	5	3
11.26-15.00	4	4	4	2	2	5	9	8	4	2
15.01-18.75	3	3	3	2	1	6	11	9	5	3
18.76-22.50	0	0	0	0	0	0	1	1	0	0
22.51-26.25	--	--	--	--	--	0	0	0	0	0
26.26-30	--	--	--	--	--	--	--	--	--	--
	16	16	16	10	7	25	47	40	20	12

SPEED (kn)	0.61-0.92 (m)					0.92-1.22 (m)				
	Head Seas	Strbd .Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	1	2	2	2	1	0	0	0	0	0
3.76-7.50	4	6	6	5	3	4	5	5	4	2
7.51-11.25	9	14	13	11	6	7	9	9	7	3
11.26-15.00	6	9	9	7	4	8	10	10	8	3
15.01-18.75	3	4	4	3	2	3	4	4	3	1
18.76-22.50	0	1	1	1	0	0	1	1	0	0
22.51-26.25	0	0	0	0	0	0	0	0	0	0
26.26-30	--	--	--	--	--	--	--	--	--	--
	23	36	34	27	15	23	29	29	24	10

SPEED (kn)	1.22-1.53 (m)					1.53-1.83 (m)				
	Head Seas	Strbd Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	0	1	0	0	0	1	0	0	0	0
3.76-7.50	3	5	2	3	1	5	4	2	2	1
7.51-11.25	4	8	3	4	2	7	5	2	2	2
11.26-15.00	6	13	5	6	3	8	7	3	3	2
15.01-18.75	5	10	4	5	2	9	7	3	3	2
18.76-22.50	1	1	0	1	0	0	0	0	0	0
22.51-26.25	0	0	0	0	0	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	19	38	15	19	8	30	23	10	10	7

SPEED (kn)	1.83-2.14 (m)					2.14-2.44 (m)				
	Head Seas	Strbd .Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	1	1	0	0	0	1	1	0	0	0
3.76-7.50	4	6	2	2	2	2	2	1	1	1
7.51-11.25	5	7	3	2	2	5	4	2	1	1
11.26-15.00	5	7	3	2	2	5	4	2	1	1
15.01-18.75	4	5	2	2	2	6	5	2	1	1
18.76-22.50	--	--	--	--	--	1	1	1	0	0
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	17	26	10	7	9	21	16	9	5	5

SPEED (kn)	2.44-2.745 (m)					2.745-3.05 (m)				
	Head Seas	Strbd Bow	Strbd. Beam	Strbd. Quart.	Following	Head Seas	Strbd. Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	--	--	--	--	--	--	--	--	--	--
3.76-7.50	14	10	--	1	4	6	1	3	--	5
7.51-11.25	5	3	--	0	1	4	1	2	--	4
11.26-15.00	1	1	--	0	0	--	--	--	--	--
15.01-18.75	--	--	--	--	--	4	1	2	--	4
18.76-22.50	2	1	--	0	0	--	--	--	--	--
22.51-26.25	--	--	--	--	--	--	--	--	--	--
26.26-30	--	--	--	--	--	--	--	--	--	--
	22	16	0	2	7	14	4	7	0	12

SPEED (kn)	3.05-3.66 (m)				
	Head Seas	Strbd Bow	Strbd. Beam	Strbd. Quart.	Following
0-3.75	--	--	--	--	--
3.76-7.50	49	7	--	--	35
7.51-11.25	32	5	--	--	23
11.26-15.00	--	--	--	--	--
15.01-18.75	--	--	--	--	--
18.76-22.50	--	--	--	--	--
22.51-26.25	--	--	--	--	--
26.26-30	--	--	--	--	--
	82	12	0	0	58

The number of stationary conditions (combination of speed, heading and wave height) in the tables is 1400 (240-OP#1, 360-OP#2, 360-OP#3, and 440-OP#4). As can be seen, some of the probabilities are small, and some are zero (indicated by “--“). This reduces the number of conditions for which the response needs to be evaluated. There are total of 602 non-zero entries (92-OP#1, 159-OP#2, 130-OP#3, and 221-OP#4).

Once the response is evaluated for 602 stationary conditions, four wave loading histograms (four operational profiles) can be constructed. To obtain lifetime long distribution of wave loading , each bin of the histograms needs to be multiplied by the appropriate weighting factor which reflects time spent at each operational profile (see data in Table 4.1).

In this exercise, it was observed that the wave heights reported in the ship log (wave heights used in development of operational profiles) are smaller than the wave heights given in the Marsden Zones for the same area. For example, in Marsden Zone 23, the largest observed wave height (on an annual basis) is between 10-11m, while maximum wave heights reported for the operational profile #2 are between 2.44-2.745m. In order to affect this for calculation purposes, probabilities for wave heights greater than 2.745m were lumped together.

7. DISCUSSION OF FINDINGS

In this section, we review the outcome of this work, in relation to the objectives set.

7.1 Objective 1

(Develop a methodology for determining sea operational profiles)

Sea Operational Profiles have been developed from log data for four ships of different type and function. A total of ten (10) operational profiles have been developed for these four ships.

For commercial ships, sea operational profiles are expressed in terms of the vessel's *loading condition*, heading, sea state (wave height) and speed. For the government-operated vessel, operational profiles are defined in terms of vessel's *mission*, heading, sea state (wave height) and speed. In order to put the operational profiles into the environmental context, the vessel's routes are described in terms of Marsden Zones visited, and the time spent in each zone is documented.

Operational profiles have been organized in the following manner:

i) joint probability (two-dimensional probability) of speed and wave height or sea state;
ii) joint probability (two-dimensional probability) of heading (relative to wave) and wave height or sea state;
iii) a listing of Marsden Zones, traversed by the vessel and relative time spent in each zone.

7.2 Objective 2

(*Generate lifetime and mission oriented profiles)*

Two operational profiles have been identified for all commercial ships. The basis for the definition was the loading condition (ballast or fully loaded) with the exception of SS *SEALAND McLEAN* for which operational profiles were defined as Eastbound and Westbound trips. In the case of the *HAMILTON Class* USCG cutter, four mission specific operational profiles were developed for a total of ten.

Operational Profile Summary:

SS SEALAND McLEAN	2 Profiles (Eastbound, Westbound)
ARCO CALIFORNIA	2 Profiles (Northbound, Southbound)
MV THORNHILL	2 Profiles (Loaded, Ballast)
USCG HAMILTON Class	4 Profiles (Short Training, Long Training, Patrol, and Enforcement/Rescue)

Three case study examples were completed to demonstrate the reliability-based structural analysis approaches for the vessel load data collected. Case Study #1 and Case Study #2 deal with the short and long term analysis procedures, respectively, outlined in SSC-398 report, "Assessment of Reliability of Ship Structures". Case Study #3 deals with the application of the long term procedure for mission oriented operational profiles.

The short term method seeks to establish the extreme wave height that will be encountered during the period of interest (ship's life). The implicit assumption is that the highest wave height yields the highest load. The results of the short term analysis indicate that wave height encounter probabilities are highly dependent on the time spent in Marsden Zones as well as the route of a ship. If it is suspected that a ship's operational profile may change over the lifetime of the ship (e.g., change in time spent in Marsden Zones and/or route of the ship), and sensitivity analysis of the short term approach is recommended. Once the procedure is set up on the spreadsheet, it is quite easy to change the parameters of the operational profile and investigate the changes in the encounter probabilities, and thus in design wave height.

In evaluating the vessel response in the short term analysis care should be taken as to which theoretical or experimental method is used in the calculations as the response to the extreme design wave is expected to be non-linear.

The approach for the long term analysis fully employed all the data collected for the operational profiles. A step-by-step procedure was demonstrated with the final result being the lifetime distribution of wave loading. This was done by obtaining vessel response for each stationary condition and multiplying this by the probability of the stationary condition (three-dimensional probability of speed, heading, and sea state). This information was used for the simplified fatigue assessment of a ship's structural detail.

In the long term analysis, several simplifications were used to maintain clarity of the procedure. These include:

- only one operational profile was used in the analysis;
- all of the wave information in the regions of interest were combined in a single wave height distribution regardless of the period; and,
- vertical bending moment was taken as the only source of cyclic loading;

As these simplifications are relaxed, the volume of the required calculations is expected to rise dramatically.

7.3 Objective 3

(Relationships of a vessel's operational profile factors and comparison against the assumptions employed in recent reliability studies)

Assumptions of speed/heading independence need not be used in the reliability-based analysis. With data collected form ship's logs, and compiled into operational profiles, the relative probability of heading and speed combinations for different profiles can be obtained.

Some recent reliability studies use parametric equations for wave load estimation, and then Weibull distribution is used to provide a model for the stress range spectrum. In a long term analysis described here, the end product is the lifetime distribution of wave loading based on the operational profiles, wave climate of interest, and the response is evaluated based on the particulars of the hull form in question. This represents a more rigorous way of wave load estimation and it alleviates the need for shape parameters of the Weibull distribution to describe the stress range spectrum.

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APPENDIX A - INDEX OF DATA FILES

A.1 Introduction

This CD-ROM has been produced by Fleet Technology Limited for the SSC project entitled, "Sea Operational Profiles". The CD-ROM contains an electronic version of the report, as well as the full data set of operational profile data. The data includes ship's log data as well as reduced and analysed data and statistical distributions. This data may be accessed for subsequent analysis.

The data covers the four vessel classes/types used in the report, as summarized below in Table A-1.

Table A-1: Principal Characteristics of Selected Vessels

Ship Name	Ship Type	Length	Displacement
ARCO CALIFORNIA	Tanker	290 metres	220,808 tons
SS Sealand Mclean	Container Ship	288 metres	51,220 tons
MV Thornhill	Panamax bulk carrier	194 metres	48,075 tons
US Coast Guard Cutter Hamilton	High Endurance Cutter	115.2 metres	3,050 tons

A.2 Organization of Data Files

Each of the vessel types has a main ship name directory (see Table A-2).

Ship name directory for:

- *ARCO CALIFORNIA* **arco ***
- *SS Sealand Mclean* **mclean***
- *MV Thornhill* **thornhil***
- *USCG HAMILTON Class Cutter* **hamilton***

* throughout this Appendix, file/directory names are printed in **bold** exactly as they appear on the CD-ROM.

Each vessel has two main subdirectories: **rawdata** and **analysis**. **rawdata** contains the original data files from which analysis has been made. **analysis** contains files of data that has been evaluated and correlated.

Index of Files of Vessels

The files **arcindex.doc, mclindex.doc, thoindex.doc** and **hamindex.doc** list all the files in the subdirectories for *ARCO California*, *SS Sealand Mclean*, *MVThornhill* and *USCGC Hamilton* respectively with explanations of what the files are and what the filenames refer to. Please refer to the *.index.doc files before accessing the appropriate subdirectories. Finally, there is a **readme.doc** file that should be read before accessing the files.

Table A-2: CD-ROM Directories Organization

Directory	**Subdirectories**	**Description**
report	**Final Report**	Text for final report
	Appendix A	Index of Data Files
	Appendix B	Speed and Heading Data
arco	**rawdata**	Rawdata of *ARCO California*
	analysis	Analysed data of *ARCO California*
sealand	**rawdata**	Rawdata of *SS Sealand Mclean*
	analysis	Analysed data of *SS Sealand Mclean*
thorn	**rawdata**	Rawdata of *M.V. Thornhill*
	analysis	Analysed data of *M.V. Thornhill*
hamilton	**Chase**	Rawdata of *USCGC Chase* (not analyzed)
	rawdata	Rawdata pf *USCGC Hamilton*
	analysis	Analysed data of *USCGC Hamilton*

A.3 DESCRIPTION OF INDIVIDUAL DIRECTORIES

A.3.1. Directory for *ARCO California* - **arco**

A.3.1.1 **arco/rawdata**

Subdirectory contains original log data for the *ARCO California*

A.3.1.2 **rawdata**

The **rawdata** subdirectory for the *ARCO California* contains 15 subdirectories that have dates in their titles (e.g., **nov92**).

These subdirectories contain individual files for individual days. Filename format is a 3 digit prefix then a 2 digit number for the day followed by the letter of the month in question and the year (2 digits). An example is: 26903d92.xls which means the file number 269 on the 3rd of December, 1992, and the extension indicates it is an EXCEL file. ***Please note that this format only applies to the arco files.***

- **north** This directory has only northbound voyages for specific months with one exception which has the suffix MIX in the title.

Files within the **rawdata** subdirectory

- **buoys.doc** List of all buoys on ARCO California's routes

A.3.1.3 **arco/analysis**

Subdirectory contains analysis of raw data of the ARCO California

- **arconato.xls** Converts Marsden zone data of wave heights to NATO types
- **headwave.xls** Relative wave direction to ship
- **marstotl.xls** Total time spent in Marsden zones
- **ntstsvss.xls** North & southbound voyages, speed in sea states
- **seastate.xls** Sea states during north and southbound voyages
- **seavsspd.xls** Ship's speed for NATO sea states for all ARCO voyages
- **spdvswvd.xls** Ship's course for north & southbound voyages
- **tvthednt.xls** Ship's speed for north & southbound voyages & total

A.3.2. Directory for *SS Sealand Mclean* - **mclean**

A.3.2.1 **mclean/rawdata**

Subdirectory contains unanalysed data for the *SS Sealand Mclean*

- **sealand.xls** Data file for all years combined

Subdirectory - **year1raw** contains one (1) file:

- **sealand1.xls** Data file for first year of *SS Sealand Mclean*

Subdirectory - **year2raw** contains one (1) file:

- **sealand2.xls** Data file for second year of *SS Sealand Mclean*

Subdirectory - **year3raw** contains one (1) file:

- **sealand3.xls** Data file for third year of *SS Sealand Mclean*

A.3.2.2 **mclean/analysis**

Subdirectory - **mclean/analysis** - contains analysis of the data on the *SS Sealand Mclean*

Subdirectory - **year1**

- **marstime.xls** First season data, only one that recorded lat. and long.
- **relhtwd1.xls** Wave direction relative to ship for certain voyages, 1st season
- **sealand1.xls** All voyages, ship speed and heading histogram, 1st season
- **seasinmz.xls** First season data, only one that recorded lat. and long.
- **seastat1.xls** NATO sea states encountered for each Marsden zone, 1st season
- **seavsp11.xls** Tables of ships speed for given sea states, 1st season
- **seavspd3.xls** Tables of ship's speed for given sea states, 1st season
- **shipsped.xls** Ship speed for total voyage time and docking, 1st season
- **spdvswd1.xls** Tables of speed vs. relative wave direction E and W, 1st season
- **spdvwd11.xls** Histogram of speed vs. wave direction all voyages, 1st season
- **tothtwd1.xls** Histogram of total wave directions during all voyages, 1st season
- **totshsp1.xls** Histogram of ship speed during voyage plus docking, 1st season
- **totstat1.xls** Histogram of total sea states encountered, all voyages, 1st season

Subdirectory - **year2**

- **relhtwd2.xls** Wave direction relative to ship for certain voyages, 2nd season
- **seastat2.xls** NATO sea states encountered for each Marsden zone, 2nd season
- **seavspd2.xls** Tables of ship's speed for given sea states, 2nd season
- **shipspd2.xls** Ship speed for total voyage time and docking, 2nd season
- **spdvswd2.xls** Tables of speed vs relative wave direction, 2nd season

Subdirectory - **year 3**

- **marstim3.xls** Total time spent in each Marsden zone, 3rd season
- **relhtwd3.xls** Wave direction relative to ship for certain voyages, 3rd season
- **seastat3.xls** NATO sea states encountered for each Marsden zone, 3rd season
- **seavspd3.xls** Tables of ship's speed for given sea states, 3rd season
- **shipspd3.xls** Ship speed for total voyage time and docking, 3rd season
- **spdvswd3.xls** Tables of speed vs relative wave direction, 3rd season
- **tothtwd3.xls** Wave direction relative to ship, all NE, SW voyages, 3rd season

Subdirectory - **total**

- **hdtowd-t.xls** All 3 seasons head to wave directions
- **seavsp-t.xls** All 3 seasons of ship speed against sea state
- **sestat-t.xls** All 3 seasons of sea states encountered
- **shsp3s-t.xls** All 3 seasons of recorded ships speed
- **sl-7nato.xls** Observed vs. expected sea states in each Marsden zone (3 seasons)
- **spvswd-t.xls** All 3 seasons of ship speed against head to wave directions

A.3.3 Directory for Thornhill - **thornhil**

A.3.3.1 **thornhil/rawdata**

Subdirectory contains unanalysed data on the vessel

- **thornhil.xls** All voyage data pertaining to *M.V. Thornhill*

A.3.3.2 **thornhil/analysis**

Subdirectory contains analysis of raw data for the vessel

- **abstowd.xls** Takes wind direction correlated with course
- **brokzone.xls** Lists all Marsden zones ship was in with time in each
- **headtowd.xls** Absolute wave direction for each voyage
- **marstime.xls** Time spent in each zone for each voyage
- **mzprobab.xls** Table of probabilities of sea states in each Marsden zone
- **seastate.xls** Tables of sea states encountered during each voyage
- **seatota2.xls** Histogram of total sea states for all voyages combined
- **seavsspd.xls** Tables of ship speed vs. sea state for each voyage
- **shipsped.xls** Histogram of total ship speed recorded during all voyages
- **spdvswvd.xls** Tables of ship speed vs. relative wave direction, each voyage
- **sped&hed.xls** Tables and graphs for each voyage, speed and course
- **spvwdtot.xls** Histogram of total data for ship speed vs. relative wave direction
- **tothtowd.xls** Histogram for relative wave direction
- **totsvssp.xls** Histogram of ship speed vs. sea state recorded

A.3.4 Directory for *USCG Hamilton* Class Cutters - **hamilton**

A.3.4.1 **hamilton/chase**

Subdirectory USCG Cutter Chase raw data.

Note: The data for the USCGC Chase was not analysed. Only the *USCGC Hamilton* data was analysed.

- **chaseraw.xls** Raw data of operations from 10/31/87 to 8/23/88

A.3.4.2 **hamilton/rawdata**

Subdirectory USCG Cutter Hamilton raw data

All files prefixed **ssc#*.xls** are raw data files.

- **ssc1a.xls** Sheets H1 and H2 have data that is not entirely correct
- **ssc1acor.xls** Sheets H1 and H2 for ssc1a.xls are corrected in this file

A.3.4.3 **hamilton/analysis**

Subdirectory *USCG Hamilton Cutter* analysed data

Files with **_an** suffix on the filename are Stage 1 Analysis (see report).

Other filenames in subdirectory - **hamilton/analysis**

- **hmltn1&2.xls** Operational profiles #1 and #2 summary
- **hmltn3.xls** Operational profile #3 summary
- **hmltn4.xls** Operational profile #4 summary
- **ham_opr.xls** Operational profile analysis of all 4 operational profiles
- **sumdata2.xls** Explanation and tables of operational profiles

APPENDIX B – SPEED AND HEADING DATA

B.1 *SS SEALAND McLEAN*

The first set of data, which covered three seasons of operation in North Atlantic service, belonged to the *SS SEALAND McLEAN*. This data covered dates between October 1972 and March 1975. The data was reported at 4-hour intervals, as is usual with ship's logs. This particular ship was rated at a maximum speed of 33 knots during its operational lifetime.

During the first season of data collection, October 8, 1972 to April 4, 1973, two speed ranges were noticed. During the first four voyages, the ship's speed dropped below 28 knots only one time, due to a Beaufort wind force of 10. During the fifth voyage, the vessel lost her port engine and following replacement, the ship did not exceed speeds over 30 knots. Fifty-seven percent of the vessel's speed was recorded above 28 knots and 28% between 24 and 28 knots. The amount of time spent between 24 and 28 knots is mainly due to the reduced speed after the engine replacement. Speeds were below 24 knots for about 15% of the time, the loss of the port engine accounting for most of this time and the rest due to a storm where winds of 55 knots were recorded, and due to dense fog. It must be noted that other storms were recorded during the first season but the ship kept its speed between 28 and 30 knots.

During the second season, September 1973 to March 1974, the ship appeared to slow down for two major storms, but continued at a speed above 26 knots for the balance of the voyages. In fact 87% of the speeds recorded during the second season were above 26 knots. The storms encountered causing reduction in speed were recorded at Beaufort winds of 11 and 12, which corresponds to 60 knot winds and greater. It was noticed that for winds of up to 50 knots, the ship continued at the regular speed between 28 and 32 knots.

The third season of data, January 1975 to March 1975, showed much the same result as the first two. The weather encountered during the final season was less severe than that of the first two. However, the ship did spend more time between 14 and 20 knots than at its usual speed of 28 to 32 knots. This change came about as a result of an operating policy (higher fuel costs) than operational constraints.

B.2 *ARCO CALIFORNIA*

The second vessel analyzed was the *SS ARCO CALIFORNIA*. The voyages recorded for this vessel took place between November 1992 and July 1994. The vessel belongs to the Trans-Alaskan Pipeline Service and operates on a year-round basis. The data available for the *ARCO CALIFORNIA* was mostly electronic, 10 minute intervals for every voyage recorded. Those voyages not covered by the electronic data were taken from the ship's logs.

This ship was designed for a maximum speed between 15 and 16 knots. From the operational data, the speed was shown to remain between 12 to 16 knots for about 85% of the recorded time. A further breakdown of the data shows that 67% of the speed was greater than 14 knots and 18% was between 12 and 14 knots. Any speed that was recorded below 10 knots was storm related except for really low speeds (0-6 knots) which relate to dock approach and departure and on one occasion, for boiler repairs. Analysis showed the ship reduced speed on a few occasions due to high winds, but spent the same or greater amount of time at higher speeds for the same wind force. It was felt that this difference may have been due to ship's heading relative to the sea, or loading condition. However, these were examined to try and clarify such results, and although some changes were recorded, no significant pattern emerged and no firm explanation could be found.

There was also an in-house study conducted by the ARCO staff on the subject of speed reduction due to bad weather. Similar to the findings from the above analysis, they confirmed no significant change in the vessel's speed during a voyage. Once the vessel reaches its initial transit speed, little regard is given to any changes in the weather encountered along the route [Ref. MT].

B.3 *MV THORNHILL*

The third ship examined was the *MV THORNHILL*. The data obtained for this vessel covered a time period between August 1996 and August 1997 and was reported in daily summaries for each day during a voyage. This vessel operates on a worldwide route and is designed for a service speed of 15 knots.

Although the vessel was designed for a service speed of 15 knots, most of the voyage speeds recorded were between 12 and 14 knots. In fact, 93% of the vessel's time was spent at speeds above 12 knots. Any speed that was recorded below 10 knots was due to contact with a severe weather system.

B.4 *USCG CUTTER HAMILTON*

The fourth ship examined was the *US Coast Guard Cutter HAMILTON*. The statistics used covered the period February 1989 to January 1991 because these showed a significant amount of transitting time. The operating area of the Hamilton extended from the East Coast of the United States to the Caribbean.

The vessel sailed over a wide range of speeds in varying sea states with no correlation between speed reduction and wind speed or wave height. During a 3-day period, the ship was travelling at 17 knots with wind speeds rising from 14 to 36 knots. No speed reduction was undertaken. At other times, in very calm conditions, the vessel would travel at 6 knots.

The highest wave height recorded was 6 feet and the vessel maintained a 17-knot speed during this entire period. The variability of the statistics is likely due to the vessel's mission profile, e.g., transitting to a particular area at cruising speed, remaining in the area for a certain length of time to carry out a task and then transitting to another location.

B.5 DESCRIPTION OF US COAST GUARD OPERATIONAL PROFILES

B.5.1 Operational Profile #1 - Short Training Activity

The following activities were undertaken: training, gun exercise, man overboard drill, machinery testing and patrol. These were carried out over 1-6 days with the vessel operating within a 100 NM radius.

B.5.2 Operational Profile #2 - Long Training Activity

The duration of this activity was 3-8 days at sea with the vessel operating in a 500 NM radius. Training, gun exercise, sonar work, machinery testing, patrol and transit were carried out during this period.

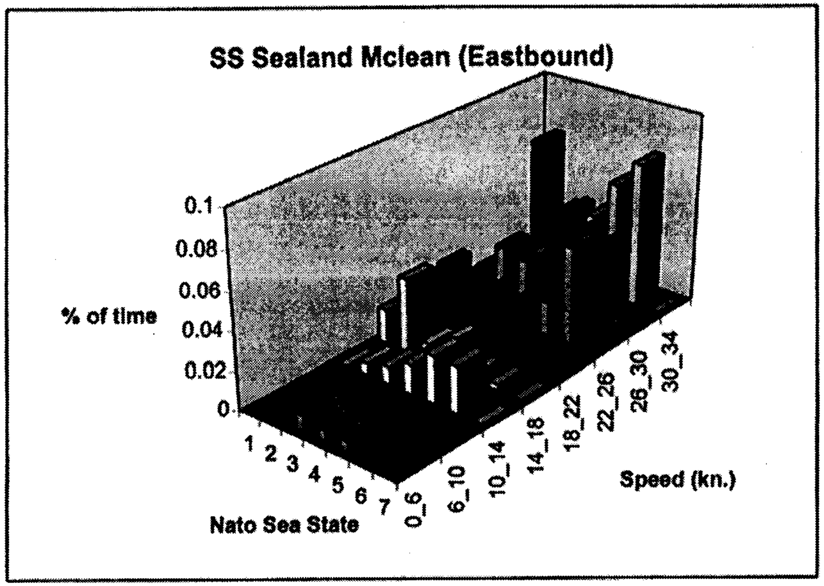
B.5.3 Operational Profile #3 - Patrol

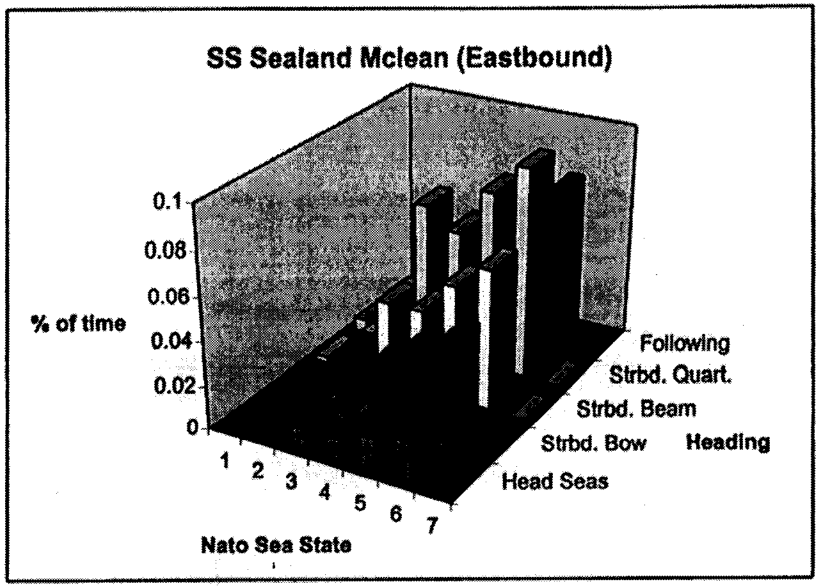
The vessel spent 1-6 days at sea and operated over a 1300 NM radius. The activities carried out included transit, patrol and training exercise.

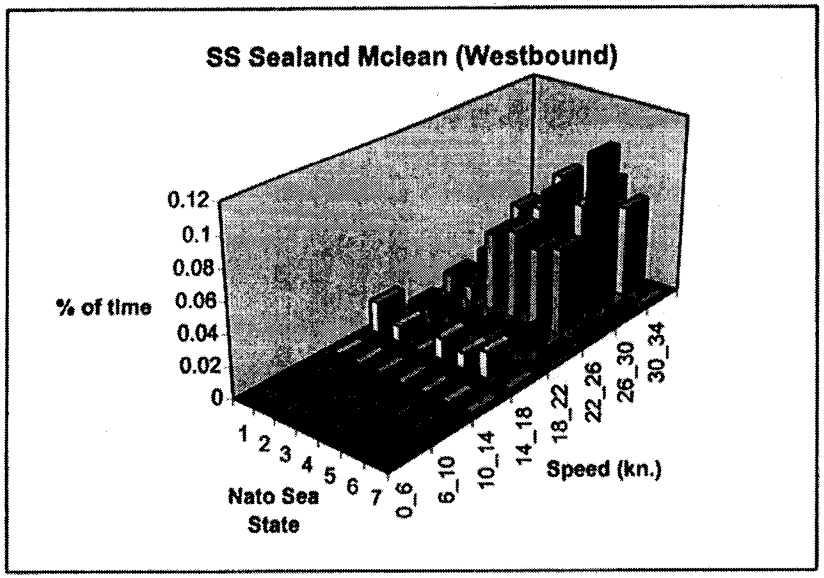
B.5.4 Operational Profile #4 - Enforcement/Rescue

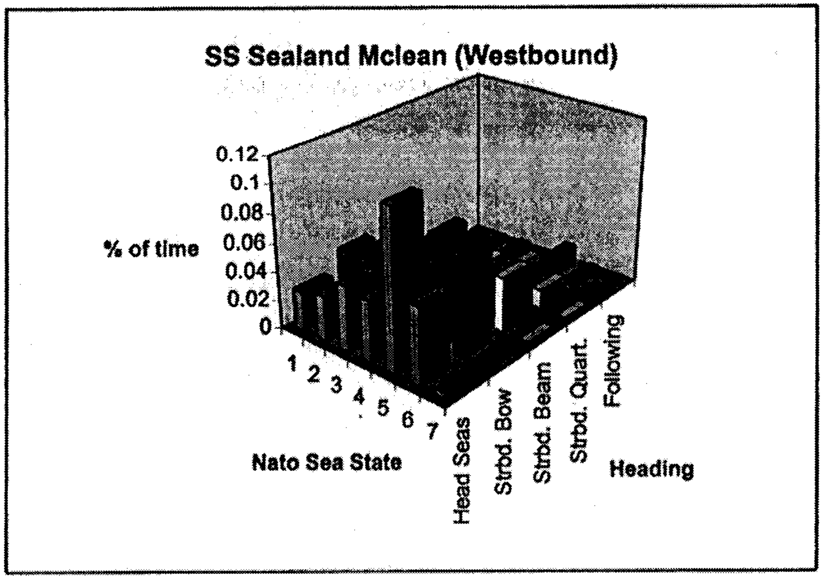
During this period, the vessel carried out law enforcement, hurricane relief, transit and training. The vessel was at sea for between 2 and 30 days and operated over a radius of up to 2500 NM.

Operational Profile of SS Sealand Mclean

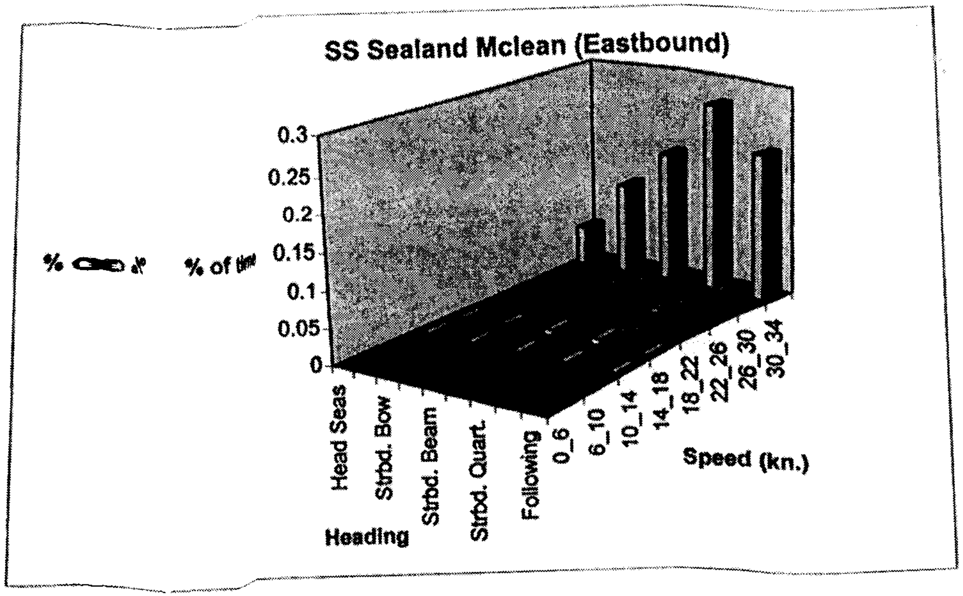


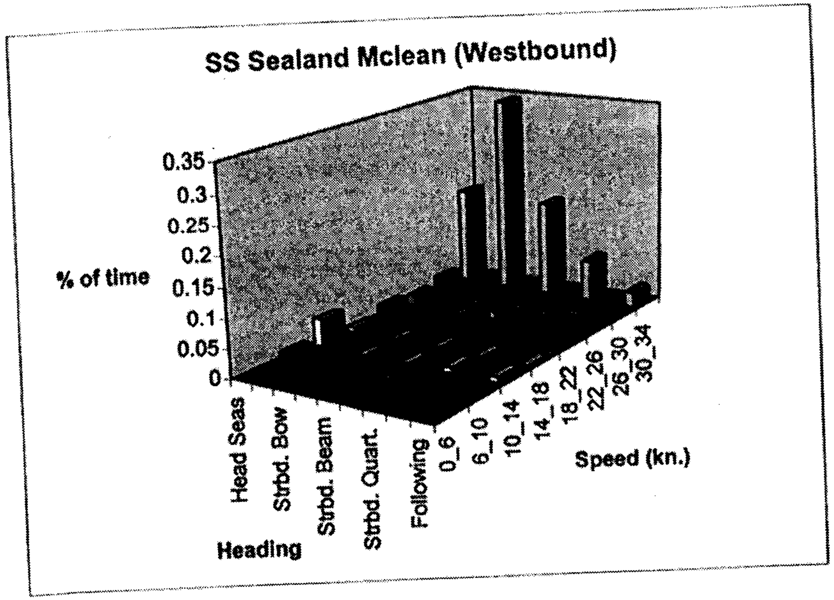




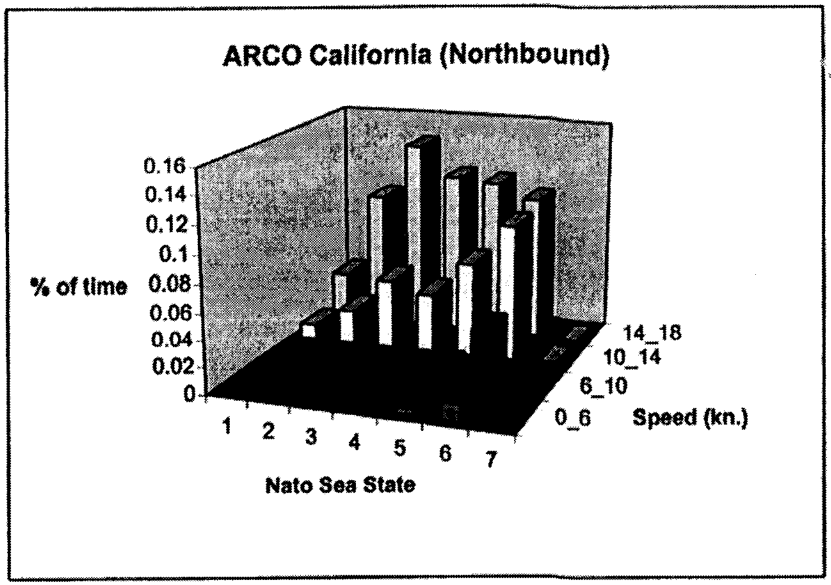


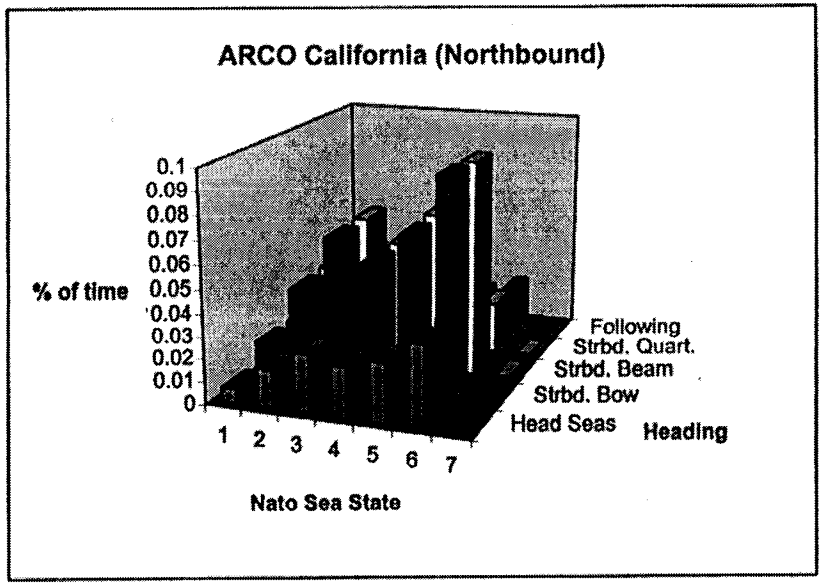
Correlation between Heading and Speed for SS Sealand Mclean

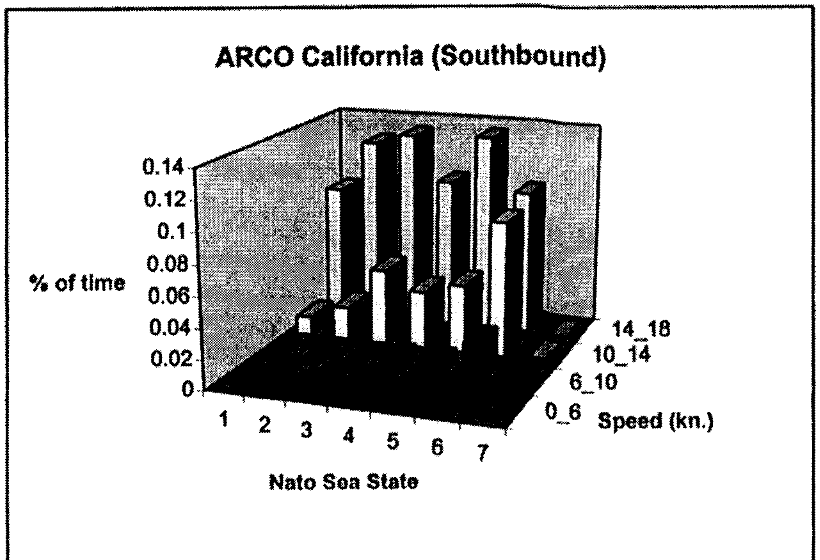


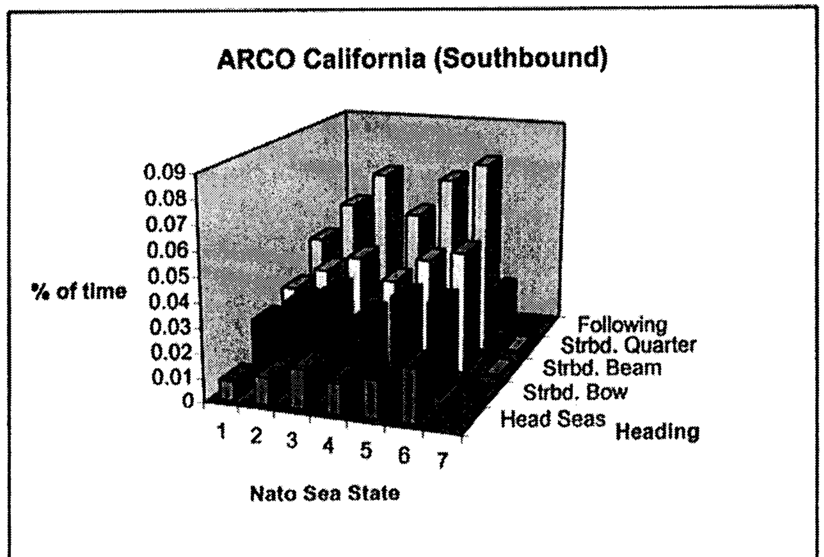


Operational Profile of ARCO California

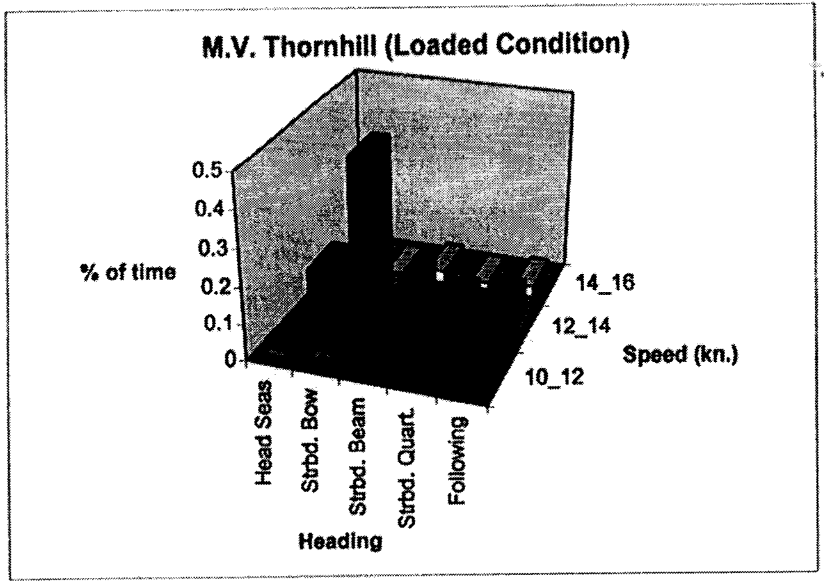


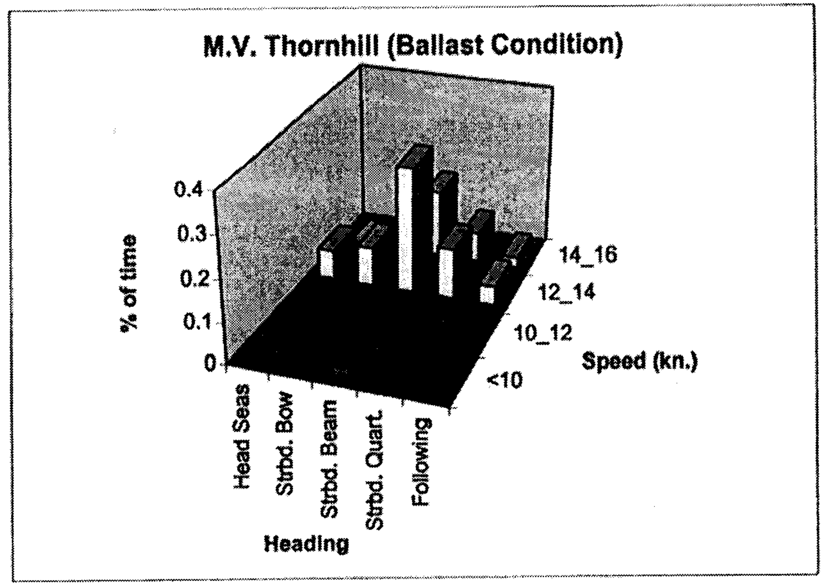




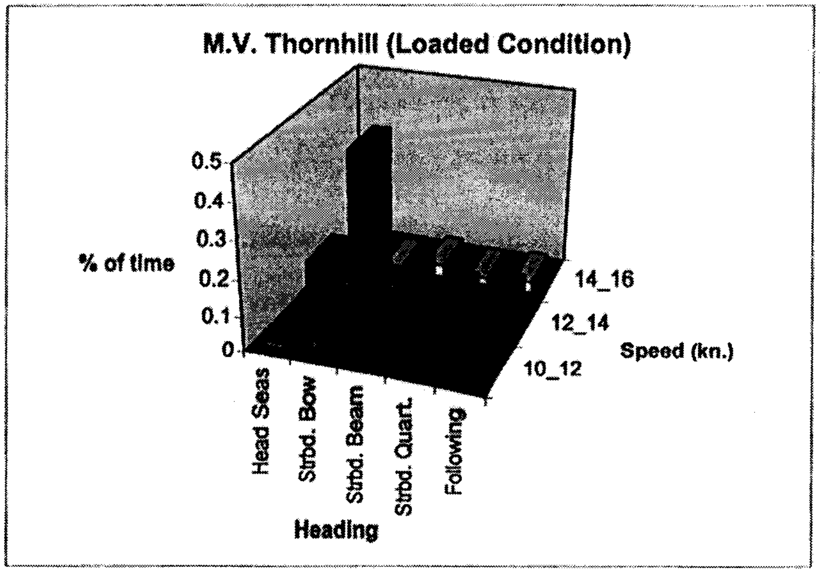


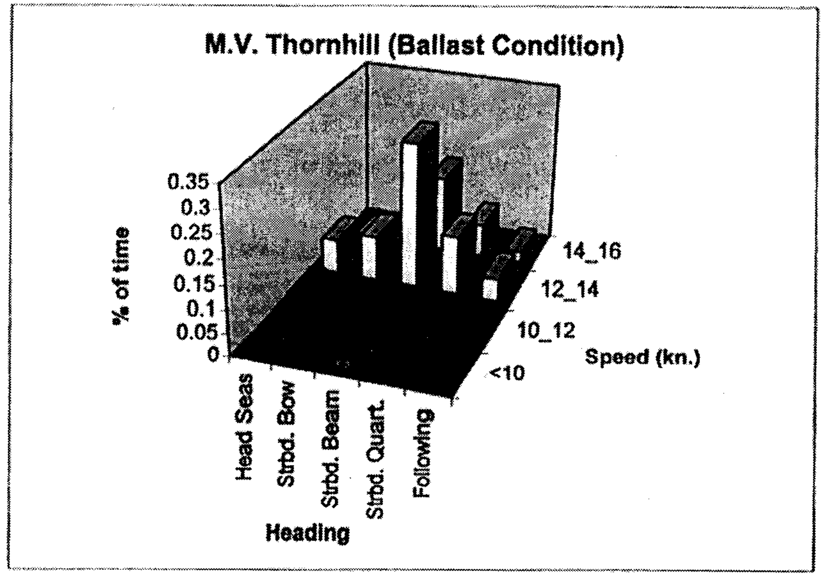
Correlation between Heading and Speed for M.V. Thornhill





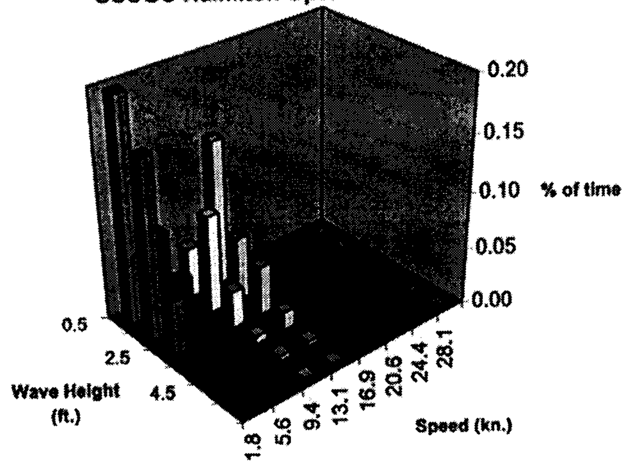
Correlation between Heading and Speed for M.V. Thornhill



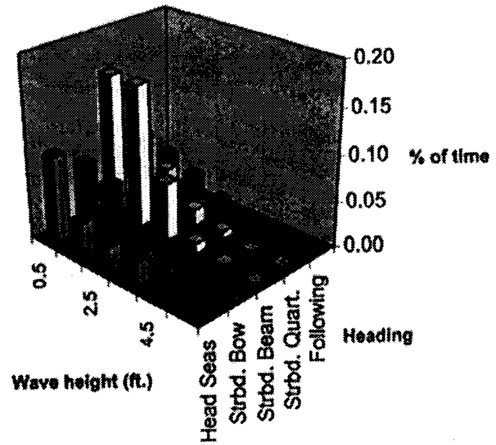


USCGC Hamilton Operational Profiles 1 and 2, Short and Long Training Activity

USCGC Hamilton Operational Profile #1



USCGC Hamilton Operational Profile #1



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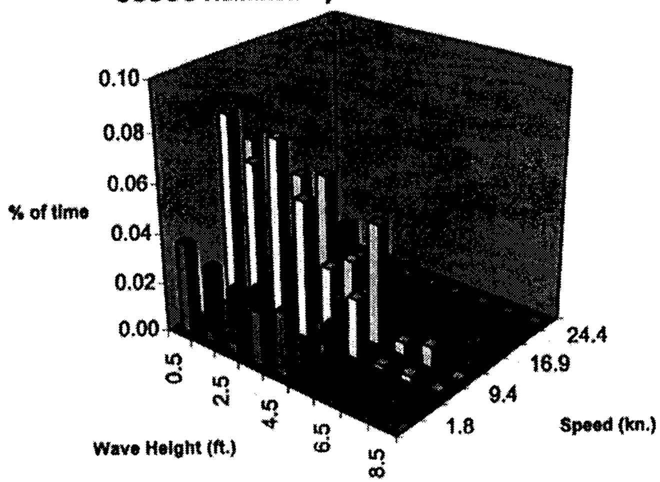
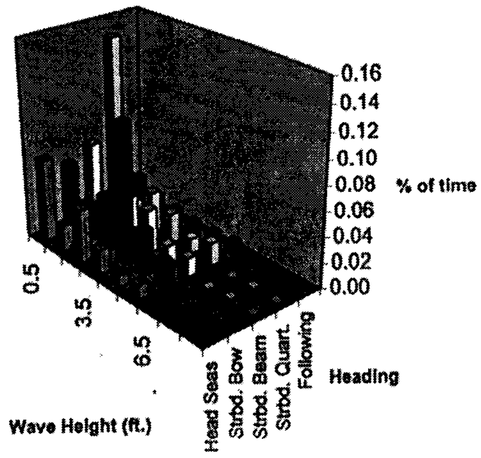


USCGC Hamilton Operational Profile #2



USCGC Hamilton Operational Profiles 3 and 4, Patrol and Enforcement/Rescue Activity