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Decision Support System for Risk-Based Inspection and Maintenance Planning for Ship Hull Structures

by

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SUMMARY

This thesis aims to develop a decision support system for inspection and maintenance planning of ship hull structures considering the effects of repair activities performed during the different periodical inspection events through the service life of a ship. Because of the severe environmental conditions in which ships operate, their structure is continually subjected to fatigue and corrosion degradation and as a result of that their strength is reduced.

Corrosion and fatigue cracking represent the most aggressive types of structural damage faced by ship structures, either of which, if not properly repaired or adjusted, can potentially lead to leakage, pollution, fire, critical failures or unanticipated out of service time and economic costs.

For an economic design to be achieved, the ship structures need to be maintained during their life. Building a ship with enough safety margins so that repairs would not be required during its life would be uneconomical and not technically feasible. From the viewpoint of survey and inspection of ship hull structures, improvements in inspection planning, safety and reduction of maintenance costs are the most needed. These issues are addressed in the newly developed decision support system described in this thesis.

Inspection planning may be based on experience (determined by Class Society guidelines), which generally treat all ships with the same inspection program or based on a risk-based maintenance planning program.

In the first case, only some of the knowledge that could be used to predict structural problems, in the case of ship-to-ship variation (construction or use), is gained from the data gathered, while in the second case, risk based maintenance methods can deal with any individual structural component or with overall ship structural integrity.

To bridge the gap between these two approaches, this thesis combines the knowledge gained from currently used practice in ship inspection and maintenance and from risk-based methods which have already been proven as a good practice in several

industrial applications. The newly developed decision support system is employed to calibrate the results of prediction models based on the collected data. To assist in the prediction of structural degradation of ships, a new structural connections catalogue, an inspection oriented ship defects database and a calibration methodology for structural degradation prediction models are developed.

The new system is designed to improve risk-based ship inspection and maintenance planning programs. Application of the newly developed system will benefit inspection companies, class surveyors, ship managers and ship designers by providing a mechanism for the calibration of risk based inspection planning activities

The decision support system developed in this thesis is inherently adaptable and can be applied to many other applications that require a cost effective maintenance (e.g. renewable energy devices, offshore platforms, machinery systems, large structures such as bridges and other transport systems.

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For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

« Aux joyaux de mon cœur, à mes Parents, Yasmine, Amine-Mekyne et Iliane-Mhena »

« To the jewels of my heart, to my Parents, Yasmine, Amine-Mekyne and Iliane-Mhena»

NOMENCLATURE

AP215:2004	Application for Ship Arrangements
AP216:2003	Application for Ship Moulded Forms
AP218:2004	Application for Ship Structure
BMT	British Maritime Technology
BS	British Standard
BV	Bureau Veritas
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAS	Condition Assessment Scheme
CDF	Cumulative Density Function
CMA	Conditional Modelling Approach
COMOD	Computational Module
CP	Cathodic Protection
CSD	Central Statistical Database
DBMS	Database software or database management system
DNV	Det Norske Veritas
EMSA	European Maritime Safety Agency
EU	European Union
EXPRESS	A formal data specification language that specifies the product information to be represented
FD-Waveload	Frequency Domain Waveload Software
grMLH	Generalised Maximum Likelihood Method
GWS	Global Wave's Statistics
HCM	Hull Condition Monitoring Schema
HCM	Hull Condition Data Model
HCMA	Hull Condition Monitoring and Assessment
IACS	International Association of Classification Societies
IMO	International Maritime Organization
IS	International Standard
ISM	International Safety Management
ISO	International Organization for Standardization
LR	Lloyd's Register
MAESTRO	Method for Analysis Evaluation And Structural Optimization; Global Structural Analysis Software
MARPOL	International Convention for the Prevention of Pollution from Ships

MLM	Maximum Likelihood Model
MOU	Paris Memorandum of Understanding on Port State Control
MSC/Circ.	Maritime Safety Committee/Circulars
NDE	Qualification of Non Destructive Evaluation
NDT	Non-Destructive Tests
PDF	Probability Density Function
POD	Probability of Detection
P-P Plot	Probability-Probability Plot
PSCS	Port State Control Surveys
Q-Q Plot	Quantile-Quantile Plot
RISPECT	Risk Based Expert System for Through Life Ship Structural Inspection and Maintenance and New Build Ship Structural Design
SA	Sensitivity Analysis
SIF	Stress Intensity Factor
SMS	Safety Management System
S-N	Stress- Number of cycles to failure
SOLAS	International Convention for the Safety of Life at Sea
SSC	Ship Structure Committee
SSDD	Ship Structural Defect Database
STEP	Standard for the Exchange of Product Model Data; It is the familiar name given for the international standard ISO 10303 Industrial Automation Systems and Integration - Product Model Representation and Exchange. The objective is to provide a mechanism that is capable of describing product model data throughout the life cycle of a product. The standard is a collection of parts, each published separately.
UF	Usefulness Factor
VI	visual inspection
XML	Extensible Markup Language
H_{max}	Maximum Wave High
H_s	Significant Wave Height
T_z	Zero-Crossing Period
h	Wave Height
Cov	Covariance
μ	Mean Value
cv	Coefficient of Variation
ρ	Coefficient of Correlation
σ	Standard Deviation
ω	Weighting Coefficient

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CHAPTER 1: INTRODUCTION

1.1 OVERVIEW AND BACKGROUND

The effect of commercial trading (operation and discharging, repair and maintenance practices, etc.) on hull life and potential structural failure of large vessels have during the last few decades been the subject of considerable interest. There has also been major concern about the loss of large bulk carriers and oil tanker vessels worldwide. A major factor to the cause of these losses is considered to be catastrophic structural failure (ITOPF 2012). In addition, disasters which involve large bulk carriers and oil tankers, are not only counted in terms of loss of human life, the ship and its cargo, and of the environmental damages, but also in terms of ongoing increases in insurance premiums and loss of business caused by bad publicity and loss of reputation.

To some extent, the structural arrangements of modern large bulk carriers and tankers have been extrapolated from structural performance of much smaller deadweight vessels build in the 1960s (Friis Hansen 1997). The requirement for optimised cargo, the use of higher-tensile steels and the introduction of unconventional designs, have further reduced the relevance of these earlier ships as compared to their more sophisticated replacements.

Commercial pressures to reduce turn-round time have led to use of conveyer loading system, and large grabs used for discharge. Bulldozers are also used to dislodge residual ore from bulk carriers' cargo hold. The stresses to the vessel's structure imposed by these practices are exacerbated by the use of higher-strength, thinner-section steel members to maximise these load carrying capacity. Other aspects which also contribute to the structural degradation include corrosive cargoes, such as coal with high sulphur content, which can cause "sweating" of the steel and concentrated corrosion of bulkheads and hull (Gardiner et al. 2003).

Assuring the integrity and reliability of engineering structures continue to challenge the engineering community. Structures and materials deteriorate with time and accumulate a variety of deteriorations such as cracks, corrosion and coating degradation. Exacerbating the situation, economic pressures are requiring the operational life of various aging assets to be extended. Successful life management of these aging systems substantially depends on the ability to predict, identify and quantitatively characterize and predict loading and the behaviour of the structure, materials and defects throughout their life.

Modern design of structures and systems include the use of fatigue and fracture mechanics analysis to quantify damage tolerance and fitness for purpose (Rummel P.E. 2000). Application of damage tolerance assumes the presence of flaws at all critical locations in a structural component/system. Structural integrity is based on assumption that flaws of an assumed design size will not propagate to a size that could induce failure in service. The integrity of component (fitness for service) is therefore dependent on a good prediction for detection and removal of all flaws larger than the assumed design size before the component enters or re-enters service. For safety applications and for those designs incorporating damage tolerance as a design basis, the capability of predicting and quantifying the effects of structural deteriorations is required.

With the new ship designs and construction and with the introduction of the very large ships, the tasks of building, maintaining, inspecting and repairing the ships have become increasingly difficult. Most of these vessels experience varying degrees of corrosion and fatigue cracking problems. These vessels have been in service for some years. Their experience can provide useful information to designers, ship managers and owners.

Though a number of techniques have been developed but not always used, little work has been done on compiling the existing information to help ship inspection, repairer, ship owners and designers and crew to control these problems. The new approach developed in this thesis contributes to a technique which will gather the inspection data, information recorded through life and use this with the prediction models and expert opinion data to help produce better inspection and maintenance strategies to improve the durability of new and existing ships.

1.2 STRUCTURE OF THE THESIS

This thesis is structured in 9 chapters plus references and appendices. A brief outline of the content of each chapter is given below:

- **Chapter 1**, *Introduction*, provides an overview and the background to the research described in this thesis.

- **Chapter 2**, *Objectives and Scope of The Work*, states the aims and objectives that constitute the focus of the work performed in this thesis.

- **Chapter 3**, *Literature Review*, presents a brief history of ship inspection, ship inspection techniques and methods, as well as rules and regulation related to ship inspection. Some guidelines on how to record inspection data are also reviewed in this chapter.

- **Chapter 4**, *Waves Statistical Data: Analytical Model.* In this chapter the results of parameters fitting of an analytical model for wave heights and periods are presented. The analysis provided environmental data to be stored in the database and be used as parameters for the calibration process of the prediction models.

- **Chapter 5**, *Ship Structural Details: Connection Catalogue*. In order to record efficiently inspection data, it was necessary to define a catalogue of structural details in a way that represented their topology and allow the use of knowledge of the behaviour of one detail to inform on the likely behaviour of similar details.

- **Chapter 6**, *Ship Structural Defect Database,* is the core of this research and provides the architecture of the database which is central to the inspection planning tool.

- **Chapter 7**, *Computational Module (COMOD),* explains in detail the functioning of the module attached to the database which computes calibration factors to the deterioration prediction models based on real and expert data.

- **Chapter 8**, *Case Study*, presents examples of two deterioration types: crack and general corrosion to exemplify the model calibration computation process.

- **Chapter 9**, *Conclusions and Future Work*, closes this thesis by summarising the work done during this research and discussing how this work could be extended in the future.

List of Appendices:

- **Appendix A1:** *RISPECT Project*. This Appendix provides an overview of the EU funded RISPECT project to which this work has contributed.
- **Appendix A2:** Tables of results of Chapter 4.
- **Appendix A3:** Extension to Chapter 5.
- **Appendix A4:** *Statistical Notions and Correction of Models Predictions,* provide a self-contained reference to statistical notions used throughout this work.
- **Appendix A5:** Table of results of Chapter 8.
- **Appendix A6:** Extension to Chapter 8: Analysis of effect of sample size.

The logical sequence and interrelations between the chapters of the thesis are illustrated in Figure 1-1.

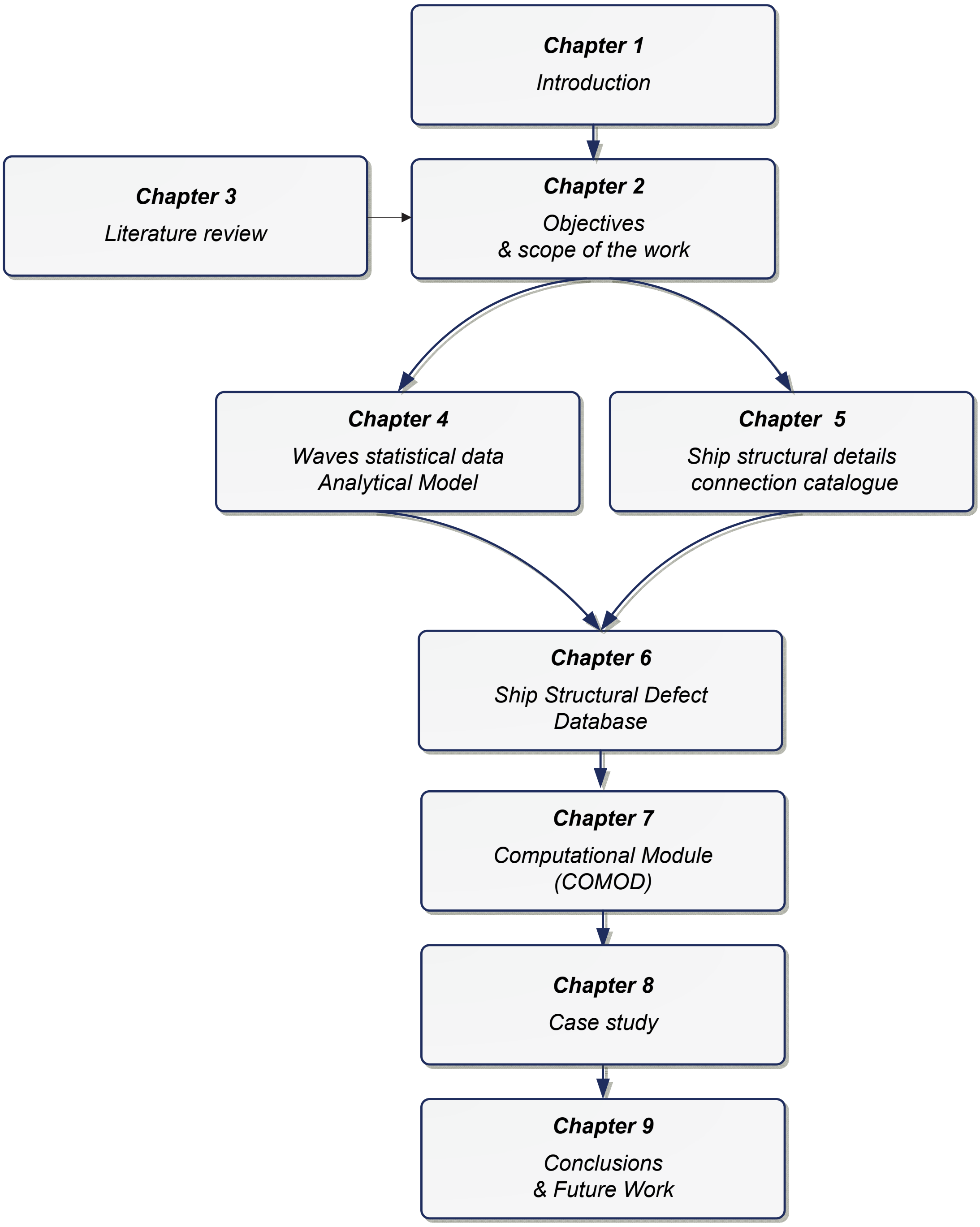

Figure 1-1 Structure of the Thesis

CHAPTER 2: OBJECTIVES AND SCOPE OF THE WORK

Structural failures of ships contribute to the personal risk levels and safety of mariners, pollution and economic costs. Ship structural inspection and good inspection planning are crucial in order to detect structural deteriorations in time and to make decisions about how quickly and cost effective they must be repaired. The accuracy of the data recorded from structural inspection is also very important (Pattofatto 1991; HSE 2009). The inspection planning is based either on experience (determined by class rules) which will treat all the ship with the same inspection program or on first principles reliability based methods.

The aim of the work presented in this thesis is to develop a methodology which will produce a system intended to be used by the inspection companies, class surveyors, ship managers and ship designers. This work is also aiming to address some important aspects of the development of a consistent method for the calibration of predictive models outputs for ship structural inspection and repair. The new system calibrates outputs of models that calculate the structural degradation of ships by using survey results from large numbers of ships (and, in the future, possibly electronic measurements of wave height and structural response). The system then uses these calibrated outputs as input to predict the structural reliability and risk-based maintenance for any individual ship.

Within this calibration, a better methodology and targeted inspection is developed that will (on an ongoing basis) combine (1) detailed analysis of long term experience from large numbers of ships and (2) the Reliability/Risk-Based Methods to work out useful and justifiable Risk-Based Inspection plans (Barltrop et al. 2010; Hifi et al. 2012a), and develop and demonstrate an improved decision making method, based on a combination of experience based Risk and Reliability techniques and statistical analysis, for safe, cost-effective structural inspection and repair of existing ships, which will also be useful for the goal-based design of the new ships. This will lead to better inspection planning, important deteriorations being identified and repaired, fewer pollution incidents and the saving of lives.

To achieve the above aims, the following main objectives are pursued:

- Creation of a database which will store sanitised ship information, inspection result data, statistically analysed data, expert judgment data and defect and degradation prediction models data,
- Develop a new structural defects/deteriorations catalogue to be used to assess structural degradation,
- Make use of information about the behaviour of a defect to assess the likely behaviour of similar defects.
- Develop a mathematical tool to calibrate the output from prediction models.
- Estimate analytical model parameters for wave data for sea areas.
- Demonstrate the use of the newly developed system.

CHAPTER 3: LITERATURE REVIEW

3.1 GENERAL REMARKS

The main objective of this chapter is to review the ship structural inspections, procedures, type of inspection data recorded (corrosion, crack …) and techniques used to record and store inspection data.

Other relevant issues to this thesis such as data storage and implementation will be discussed later in this thesis.

3.2 INTRODUCTION

Structural failures of ships contribute to the personal risk levels and safety of mariners, pollution and economic costs. Ship structural inspection is crucial in order to detect and monitor the structural deteriorations in time, and to allow making decisions about how quickly they must be repaired. The accuracy of the data recorded from structural inspection is also very important for future assessments.

Ships' structures are very complex. Their design is similar to a very large intricate and complicated web formed by different components such as plates, beams, brackets…, welded (at one time riveted) together. The joining points of these components are called connections or structural details (Pattofatto 1991).

Structures that are part of the hull girder are designed for extreme and everyday cyclic "hull girder" loads. Secondary structures, plates and stiffeners, are, during their service life, subject to the overall hull girder loads as well as local e.g. pressure loads. The various loads result in a combination of axial, bending, shear, stable and cyclic with quasi static and occasionally dynamic response[1], all of which in turn have an impact on the connection details.

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[1] A quasi-static response means that although the structure may be subject to cyclic loading the structural response is dominated by its stiffness, as it would be to a steady or statically applied load.
A dynamic response implies that the mass and/or damping have an important effect on the structural response which may then be considerably more or less than the quasi-static response.

Ships have quite a long tradition as regards their design philosophy. Providing their steel is suitably tough, they are usually considered damage tolerant structures and until recently no fatigue calculations would be done during design and even now the problem of propagation of fatigue cracks and the estimation of critical crack sizes (after which particular combinations of temperature and stress might lead to failure) is not directly checked in the design (Glen et al. 1999; Bai 2003; Romanoff et al. 2013).

Material, fabrication and design requirements are foreseen in order to reduce the risk of fatigue, brittle fracture and overall collapse. Non-destructive "tests" and periodic surveys are undertaken – during construction and the operating life in order to detect possible damage (DNV 2013).

Corrosion and fatigue cracking are the most pervasive types of structural problems experienced by ship structures and their details. Each of the damage modes, if not properly monitored and corrected, can potentially lead to catastrophic failure or unanticipated out-of-service time. These problems are a major risk to the structural integrity of the vessels, especially tanker structures and bulk carriers. The importance of monitoring and mitigating corrosion and fatigue has been recognized by classification societies, ship owners and authorities.

Research is still moving toward a solution to many of the ships problems in areas such as: corrosion fatigue, fatigue design of structural details, reliability based fatigue, life expectancy assessment, risk based life cycle management, reliability based optimization of inspection schedule and cost and optimization for inspection.

Soares et al. (2009) proposed a corrosion wastage model based on a non-linear time-dependent corrosion model that is influenced by the effect of different environmental factors contained in the marine atmosphere such as humidity, chlorides, and temperature on the corrosion behaviour of ship steel structures. The model assesses the corrosion short term degradation (under stationary environmental conditions) and the long-term corrosion degradation by considering the succession of the various environmental conditions and the corrosion damage incurred during each of them.

Melchers (2010) developed quantitative models for marine immersion which include the effect of microbiological influences in the prediction of corrosion loss and for maximum pit depth, considering the influence of various environmental and material composition factors and salinity levels. The models have been calibrated to in-situ data from a wide variety of sources, including ships, and are being extended to tidal, atmospheric and inland corrosion environments.

Yamamoto et al. (1998), assume that the phenomena of general corrosion are the results of three sequential processes: degradation of paint coatings, generation of pitting point, and progress of pitting point. Simple probabilistic models for each process are introduced to evaluate the generation and progress of corrosion quantitatively. The estimated behaviour of corrosion progress and dispersion is compared with actual data.

Jordan et al. (1990), developed a guide to assist a designer in selecting sound and cost-effective details. The guide comprises a list of the best details (least expensive details which have given adequate service) from the different arrangements currently in use and also provides the designer with a simple method for determining the approximate construction cost (in terms of man-hours) of a wide range of detail sizes.

Wirsching et al. (1990), describe fatigue crack growth by a fracture mechanics model which parameters and other design factors are considered as random variables. Probability of failure estimates are used for an economic value analysis to establish optimal strategies for design and for a maintenance schedule as it is believed that the integrity of structural systems can be ensured through a program that coordinates, design, inspection and repairs to minimise total lifetime costs.

Ayala-Uraga et al. (2007), sees, in relation to the design of welded structures, the application of the reliability methods as a tool for making decision about the balance between design criteria and optimal plan for inspection and repairs considering inherent uncertainties. The authors propose alternative SN and FM (Fracture Mechanics) formulations of fatigue which include a crack growth formulation based on bi-linear crack growth law. The effect of inspection in the updated reliabilities is illustrated using first and second-order reliability methods as well as Monte Carlo simulation.

Ayyub et al. (2000), discusses a framework and guidelines for managing the life cycle of ships structures. The guidelines, in the form of a risk-based methodology for maintaining and managing the structural integrity of ship systems, provide risk measures to help focusing the attention on the most risk significant degradations modes and locations. Qualitative case studies and examples illustrate the applications of the proposed guidelines.

Ayyub et al. (1990), suggests a methodology of structural life assessment. The methodology is based on probabilistic analysis, using reliability concepts and the statistics of extremes. The result of the methodology is the probability of failure of a structural system as a function of time (i.e. structural life) for identified failure modes. The authors also discusse the effect of inspection strategies on structural life and illustrates the use of the methodology on an example.

Though a number of techniques have been developed but not always used, little work has been done on compiling the information needed to implement the techniques required to help the ship inspectors, repairers, owners and designers, crew or naval architects to control these problems.

3.3 SHIP STRUCTURAL INSPECTION

3.3.1 History of Ship Inspection

Ships as a means of carrying goods and people are very old concepts and were invented before naval architecture and design notions. Ships mainly evolved through empirical design, until recent times, safety and risk prevention policies were based more on experience than on rational thinking, due to a lack of theoretical knowledge.

Shipbuilding (as other fabrication technology) has successfully adopted a “trial and error” process in developing and building ships. This process has been marked by major changes and technological progress which led to developments in existing construction techniques and in-service inspection criteria.

One of the major changes was the use of steel instead of wood as main building material. This, whilst avoiding problems of marine wood-boring animals and rotting and allowing much larger vessels to be built, has introduced fatigue and corrosion which lead to a faster deterioration of the structural integrity. Through time and successive "trials and errors" (including the "cc" corrosion control notation which allowed ship owners to build lighter ships with the notional corrosion margin removed providing they, unrealistically, maintained the ship to avoid corrosion), extra thickness was introduced to compensate for inevitable thickness loss due to corrosion (IACS 2012a; IACS 2012b). In terms of inspection, periodic inspections are used to check for degradation of coatings, corrosion and cracking and other material deteriorations (IACS 2013).

Another important change in the shipbuilding history was the replacement of the rivet by the welding process. This change dramatically improved fabrication efficiency (which was important during the second world war when a lot of ship building was required) but resulted in brittle fracture and fatigue problems as a result of defects, brittleness and stress concentrations at corners introduced by welding and the lack of natural crack stopping in riveted construction. As a result of the Second World War Liberty ship failures it was understood that there was a need to improve the steel properties as there were no means to control cracks from propagating when the rivet stopped being used (Kobayashi et al. 1943).

Over the years improvements in steel properties and performance, welding (techniques and materials) and design of structural details have majorly contributed to the reduction of the occurrence of brittle fractures. At the same time fatigue and corrosion became survivability problems and the resulting strength deterioration needed to be detected and addressed in time to avoid local or overall collapse (Eyres 2007).

This led to a design philosophy that provides a safe life period to the structure to be guaranteed without cracks or in which the growth rate of cracks is sufficiently low so as not to escape timely detection within the given life period. In addition, the structure must still be able to carry a 'predetermined' load under a given amount of damage before it can be detected. In this case, planned inspections should be performed, during the life period, to allow damaged elements to be repaired in time.

Limitation to this approach was the need to keep uninspectable or hidden areas restricted to those areas which are not critical to the safety of the whole structure. This condition, though implied rather than formally demonstrated, was easily satisfied when the ships dimensions were modest and the holds and other important spaces could be properly inspected.

With ships becoming bigger and larger, it has become more difficult and sometimes impractical to perform an adequate global inspection because of the dimensions and or nature of the structure and time constraints: Inspections can be very expensive and time consuming.

Nowadays for a ship to be maintained in class, relevant rules of the Society concerned need to be complied with and surveys are carried out to this end.

Class Society requirements include periodical ("Special") detailed surveys to be carried out every 5 years, the level of severity increasing as the ship age increases (IACS 2013). Special surveys are supplemented by annual bottom/docking surveys aimed at checking the ship's status. If structural damage or other deteriorations occur in the course of ship operations, which the owner is expected to report to the Class Society, additional occasional surveys are usually performed.

An improvement in the periodic inspection philosophy could be obtained by increasing the damage tolerance of the structure; by designing structural details to reduce stress concentration and by reducing the corrosion rate by either coating or cathodic protection so that carefully planned and targeted inspections are sufficient to evaluate the state of health of the whole vessel.

3.3.2 Rules, Regulations and Guidelines for Ship Inspection

In the maritime industry, new regulations are almost always prompted by accidents causing losses of human lives and or environmental pollution (e.g. The sinking of the Titanic in 1912 was the catalyst for the adoption in 1914 of the first International Convention for the Safety of Life at Sea (SOLAS 1914), MARPOL was adopted after the EXXON VALDEZ oil spill).

The oil pollution caused by the sinking of the ERIKA in bad weather due to structural failure, had as impact that the IMO decided to speed up the phase out of older single hull tankers. They also had to pass a Condition Assessment Scheme (CAS) which is a comprehensive survey to determine the true structural condition of the tanker. The Condition Assessment Scheme (CAS) for oil tankers was adopted in 2001 and is applicable to certain oil tankers under the MARPOL convention.

Although the CAS does not specify structural standards in excess of the provisions of other IMO conventions, codes and recommendations, its requirements stipulate more stringent and transparent verification of the reported structural condition of the ship and that documentary and survey procedures have been properly carried out and completed.

The Scheme requires that compliance with the CAS is assessed during the Enhanced Survey Programme of Inspections concurrent with intermediate or renewal surveys currently required by resolution A.744 (18), as amended.

Another development was the launch by the European Union (EU) of three maritime legislations: ERIKA I, ERIKA II and ERIKA III packages, with numerous new or revised directives (European-Commission 2000; 2000b; 2005). One of the important results of these developments was the creation of the centralised European Maritime Safety Agency (EMSA). EMSA was established under the Erika II package. Its function includes providing the European Commission with technical and scientific advice on maritime safety and prevention of vessel source pollution (Ringbom 2001).

The Erika packages also introduced reforms for improving maritime safety and the protection of the maritime environment such as expanded port state control inspection, including a system of banning ships from EU ports that were black-listed by the "Paris Memorandum of Understanding on Port State Control" (MOU) (Frank 2006).

In terms of ship inspection, rules and regulations are set by the IMO, IACS and the individual Classification Societies. The following provides an overview of the existing rules, regulations and guidelines for ship inspection.

3.3.2.1 Rules and Regulations

Procedures on how to conduct hull surveys of tankers, chemical carriers and double hull oil tankers are contained in "IACS; Z10.1 Hull surveys of Oil Tankers ", "IACS; Z10.3 Hull surveys of Chemical Tankers" and "IACS; Z10.4 Hull surveys of Double Hull Oil Tankers".

These documents mainly address Class surveys but they also provide some references and requirements related to the inspections and maintenance to be carried out by owners in between class surveys.

They cover topics such as:

- Surveys schedule & scope (for special, intermediate and annual surveys).
- Preparations for survey (survey program, conditions, access to structures, equipment for survey and survey at sea or at anchorage).
- Documentation regarding the ship hull structure to be provided by the Owners /Managers.
- Extent and procedures for thickness measurements.
- Extent and procedures for close up survey of structural members.
- Reporting and evaluation of the survey.

Also basic mechanical deterioration of a ship structure (corrosion, cracks and buckling) and their causes are identified and suggestion is made to set up a "deterioration monitoring and record keeping system".

IMO MSC/Circ.1070 “Ship Design, Construction, Repair and Maintenance” was prepared to address concerns that, in the absence of a class surveyor, industry shipbuilding and repair standards are not generally applied during repairs. It also reminds companies of their obligations with respect to ship design, construction, repair and maintenance in compliance with SOLAS and Load Lines conventions.

From a statutory point of view, the international regulation which guide the inspections onboard ships is the SOLAS (International Convention for the Safety of Life at Sea) issued by the IMO (2010). In particular, the regulations about the surveys of various types of ships and the issuing of documents signifying that the ship meets the requirement of the convention contained in the “Chapter I - Part b”.

3.3.2.2 Guidelines:

IMO resolution A.744 (18) “guidelines on the enhanced programme of inspections during surveys of bulk carriers and oil tankers” adopted on 4 November 1993, contain the extent of examination, thickness measurements and tank testing. The survey should be extended when substantial corrosion and/or structural deteriorations are found and include additional close-up survey when necessary.

The guidelines cover the following aspects:

- Enhanced surveys carried out during periodical surveys
- Enhanced surveys carried out during annual surveys
- Intermediate enhanced surveys
- Preparations for survey
- Documentation on board
- Procedures for thickness measurements
- Reporting and evaluation of surveys

In these guidelines, critical structural areas are defined as locations identified from calculations to require monitoring or from the service history of the subject ship or from similar sister ships to be sensitive to cracking, buckling or corrosion which would impair the structural integrity of the ship.

In “A guide to managing maintenance; IACS recommendation 74” (IACS 2008), general guidance regarding maintenance procedures is provided. The document gives interpretations and detailed information on the relevant clauses of the International Safety Management (ISM) Code.

“Shipbuilding and repair quality standard for new construction and existing ships. IACS Recommendation 47 Part and B”, addresses in details the following items:

- Repair conditions and repairers capabilities.
- Qualification of welders.
- Qualification of welding procedures.
- Qualification of Non Destructive Evaluation (NDE) operators.
- Requirements for materials.
- Equivalency of material grades.
- Correlation of welding consumables with hull structural steels.
- Requirements for preheating and drying out.
- Dry welding on hull plating below the waterline of vessels afloat.
- Tables with examples for alignment, welding details and repair.

Quality control of ship hull welds during new building is the subject of “Guide for inspection of ship hull welds; IACS Recommendation 20”. This document covers the following aspects:

- Weld joint configuration groups with respect to suitable NDE methods.
- Qualification of personnel.
- Examination techniques.
- Extent of examination in relation to configuration group.
- Quality level and recommended acceptance criteria for each method of inspection.
- Extended examination and corrective actions in case of non-conforming welds.

In “IACS Recommendation 87: Guidelines for Coating Maintenance& Repairs for Ballast Tanks and Combined Cargo/Ballast Tanks on Oil Tankers”, the focus is on survey, maintenance and repair of coatings.

The document addresses the matter of inspection and evaluation of the condition of coatings. It also tackles the maintenance and repair of the coatings and provides tables with recommended maintenance schedules and actions to be carried out.

3.3.3 Inspection Planning

The primary reason for establishing an inspection plan is to provide focus on asset reliability, maintainability, and life cycle cost for the entire ship structure. Structural inspections form an important part of the integrity management process of structures as a means of monitoring their performance to ensure their safety and serviceability. However, inspections can represent a significant cost for ships owners or managers. An accurate estimation of the deterioration propagation and deterioration rates plays an important role for structural designs, planning for inspections, and scheduling for maintenance.

Traditionally inspection planning was based on general guidelines and *engineering judgement* which is prescriptive and does not take into account the structure specific characteristics or make optimum use of the observed performance data. In this approach, the various inspection criteria are combined in a qualitative manner to produce the inspection plan. Such criteria include fatigue lives, member criticality, stress levels, past inspection data, previous experience and cost considerations (Shama 1991). The end result is that a substantial amount of inspections may be ineffective by not focussing on the most critical areas or by not using the most appropriate techniques therefore resulting in uneven safety levels and wastage of limited maintenance resources.

Motivated by the need to optimise maintenance expenditure and achieve better safety level at a lower cost, there have been significant developments in the area of reliability-based inspection planning for complex structures, such as offshore and bridge structures (Lagaros et al. 2007). Work in the area of shipping and offshore structures concentrated initially on fixed steel platforms.

Various tools and methodologies were developed for fatigue reliability analysis and inspection updating (Moses 1977; 1982; Cramer et al. 1991; Enevoldsen et al. 1994). The methods were used for developing optimum inspection plans for individual structures. Following the developments for fixed steel platforms, further research work addressed the development of methodologies for optimised inspection of floating structures and tankers (Ma et al. 1995; Riahi et al. 2011). Methodologies previously developed for fixed platforms were adapted and developed further for floating structures reflecting their special characteristics. Several studies have addressed the application of these techniques to jack-ups (Barltrop 1991; Veldman 1997). For ships, methods for structural inspection and maintenance and repair planning, have been proposed (Skjong 1985; Madsen et al. 1987; Ayyub et al. 2002; Straub et al. 2005), and are being applied to outline Risk/Reliability Based Inspection plans.

It is recognised that reliability based inspections and repair strategies not only improve the cost effectiveness of the maintenance of ship structures but also enable the risk associated with inspections and repairs to be determined quantitatively (Hifi et al. 2008).

In order to maintain a high standard of vessel's structural integrity, inspection, maintenance and repair scheduling need to be carefully planned (Barltrop et al. 2008). For example, Guedes demonstrated the importance and influence of inspection and repair at different points in time on the reliability of the hull girder for tankers (Guedes et al. 1996a) and containerships (Guedes et al. 1996b).

3.3.4 Categories of Deficiencies

The major categories of structural deficiencies for ships are (Sipes et al. 1991):

(1) Deterioration - General or Local.
(2) Hull Defects (Structural Failure).
(3) Hull Damage (Marine Casualty).

Corrosion (which dates back to the year the first ever steel ship was launched) and fatigue represent the major causes of structural deterioration.

For hull defects, a structural failure may consist of either a fracture or a buckle occurring under normal operating conditions.

3.3.5 Techniques of Inspections

Various methods of inspections are used to monitor the performance of structures. These include visual inspection (VI) and Non-Destructive Tests (NDT) (DNV 2011). Both types of inspections are essential in maintaining the reliability of deteriorating structures.

While NDT methods provide more and better quality of information on the performance of the structure, these are usually associated with significantly higher costs and application to smaller areas of the ship than visual inspections. They are generally complemented by the use of reliability-based inspection planning methods which enhance the decision making process. Visual inspections would still be performed as they play an important part of the process of integrity management. For example problem areas which have resulted from gross errors as opposed to general cracking or corrosion are not likely to be detected by NDT regardless of whether optimization has been applied or not. This is one of the areas where visual inspections are necessary.

Another important issue is the quality of different NDT methods which is usually measured by the probability of detection (POD). Within the context of reliability-based optimization of inspections, POD is a very important factor and it comes into play when the reliability of the inspected structural member is updated using the information obtained from inspection.

When it is impossible to ascertain the deterioration of the structure in cases such as general erosion of age and it is required to evaluate and determine to what extent repairs are necessary, the technique used in this case is the thickness measurement.

The thickness of the member in question is measured and compared with its original thickness. This comparison is usually expressed in terms of percentage of wastage from the original scantling.

Thickness measurement is made by ultrasonic measurement. This is achieved through the application of ultrasonic vibrations and observations of the resulting reflection of the vibrations from the material. The ultrasonic waves are sound waves of a frequency well above the audible range. These waves are reflected within the material either by its opposite side or by a flaw or discontinuity, so that the thickness of most parts can be measured.

3.3.6 Inspection Procedure of ship structure

A major requirement for any marine structure is to have low initial and operational costs, to be reasonably safe and not to have catastrophic failure nor to have much trouble in service due to frequent minor failures.

Once commissioned and operating, ships must satisfy the requirements of a Class Society, which specifies that ship surveys be undertaken to determine if vessels are suitable, seaworthy, and safe for the purpose intended (Macewen 1953), where safety is not only concerned with the structure itself, but also with external damage that may result as a consequence of failure.

Inspections are performed by surveyors of classification societies, by crew or owner's superintendents, by vetting inspectors and by thickness measurement companies. A survey is conducted to determine two factors:

(1) That the vessel is safe and has a reasonable chance of remaining so until the next scheduled survey.

(2) To cover all aspects of vessel machinery and equipment used in operating and outfitting of the vessel and all non-structural and structural elements of vessel that may require repair.

Structural inspections typically cover: the state of coating, the assessment of possible structural deteriorations and the remaining thickness of plates and profiles. For many years, there have been clear procedures for measuring and assessing thickness values (IACS URZ). Nevertheless, despite the large number of measurements which have to be taken during class renewal for aging tankers or bulk carriers (see IMO MEPC.94(46) and Resolution A.744(18)), measurement preparation, reporting and assessment are all typically performed manually, or with minimal IT support (e.g. Excel tables).

When in the course of an inspection, one or more deficiencies are encountered, the surveyor must first evaluate if seaworthiness has been compromised. This calls for considerable discretion because the line of demarcation between what is seaworthy and what is not, is necessarily approximate and subject to some range of interpretation. The following factors must be weighed in this determination:

(1). The extent and degree of deterioration.

(2). The period of time involved before the next scheduled inspection of the area in question. A progressing condition which may be acceptable in one area would not be acceptable in another without repair.

(3). Whether the repair work contemplated is necessary to restore seaworthiness or is a maintenance measure to insure prolonged utilization of the vessel.

(4). Once a decision has been reached by the surveyor that repair is necessary, the specific requirement is submitted to ship manager for further action.

(5). The general rule is to "renew as original", i.e., to replace the defective structure so as to restore its original design and condition. However, in cases where the necessity for repair apparently stems from an unsatisfactory structural feature, this feature should be corrected in making the repairs.

While it is logical to expect more issues on the older vessels and on vessels which have seen rough service, inspection of the newer vessels is also required, because some of these deteriorations can occur even after relatively short service period. Special attention should be given in conducting a hull examination for most of the critical areas and particular connection details points.

In an increasing cost and safety conscious environment, ship operators are constantly seeking ways to rationalise inspection costs whilst maintaining a high level of structural integrity. Ideally, these objectives can be met by inspecting only the correct details at the instant a defect became detectable.

The location and frequency of connections details inspections could be determined by a subjective appraisal of fatigue life, surveyor experience, service history, consequence of failure, etc. (Basar et al. 1990; Mansour et al. 1996; DNV 2002; Lee et al. 2007).

3.3.6.1 Class/Statutory Inspections

They are divided into:

- special visits;
- intermediate visits;
- visits dedicated to the inspection of a particular section of the ship.

Frequency and severity of these inspections are connected to the age of the ship, ship's dimensions and type of voyage.

3.3.6.2 Extra-Class Inspections

These surveys are carried out when requested by insurance companies or charterers and they are always carried out by the insurance company Surveyor or by the Charter Company Inspector together with a Company Superintendent.

The inspections could be classified in two groups:

- written;
- not written

Written inspections are the visits to the ships in accordance with the procedures contained into the Safety Management System (SMS). This system is specific to each kind of ship.

Not written inspections are routine visits that are performed on board a ship for the regular maintenance management. These kinds of visits can be further divided into two categories:

a) visits performed for the planned maintenance of the ship;
b) visits performed in preparation of works and repairs to be done on board.

Also and in particular for tankers reference is made to the vetting, i.e. some inspections required from the charterer independently from class obligations, in order to have major guarantees about the ship.

3.3.6.3 Kind of Surveys

Sources and origin of 'other surveys' are the following:

- Safety Management System and/or other management systems adopted by the company.

  Based on IMO resolution A741 (18), company inspections are frequently carried out (within 6 months (+/- 2 months). They usually consist of a checklist to which an inspection report is attached.

- Events and damages due to the loading/unloading operations;
- Events and damages due to accidents (impacts, grounding, etc.);
- Findings during routine inspections by the seafarers;
- Surveys ordered by Port State Control Surveys (PSCS) SMS Chapter 9.3

  Surveys by the Port State Authority are performed when the ship is in a foreign port, according to the SOLAS Convention or the "Memorandum of Understanding on Port State Control" (Paris and other countries Memorandum of Understanding "MOU").

- CAS (Condition Assessment Scheme)

  The CAS is to verify that the structural condition of the hull is acceptable and will be acceptable providing an appropriate maintenance.

- Inspections Ordered By Shippers or Charterers (Hatch Covers, Loading Areas Close Condition Assessment, Etc.).

3.3.7 Techniques Used To Record and Store Inspection Data

3.3.7.1 Hull Condition Monitoring and Assessment

According to the *Oxford* dictionary, the *"Hull"* is the main body of the ship including the bottom, sides and deck, excluding the superstructure, machinery and other fittings.

The *Hull Condition Monitoring and Assessment (HCMA)* as defined in (Jaramillo et al. 2007) is "*the continuous process during the service life of a vessel, in which the condition of structural parts of the ship, especially those affecting the overall strength, is determined and evaluated with respect to the corresponding functional purpose for which they have been designed"*.

The authors descried the HCMA process as comprising different phases (preparation, data collection, reporting, assessment, and analysis of trends) and involving several actors; some directly involved: ship owner, classification society and measurement company and others indirectly involved in the process: shipyard, vetting company, flag state administration, port state authority, regulatory bodies (IMO, IACS, ...). All of which have different user requirements according to their respective roles in the process.

3.3.7.2 Defect Diagnosis

The possibility of carrying out defect diagnosis will depend on the structure type, configuration and environmental conditions. A defect may be indicated by a change in one or more of the baseline values.

The following criteria may be used to perform defect diagnosis:

- experience of similar structures;

- realistic statistical and/or other numerical models;
- deviation from required minimum or maximum values;
- from discussion between the builder (constructor) and the owner (operator).

3.3.7.3 Measurement Procedure and Data Processing

a) Measurement Technique

For the particular measurable parameter considered applicable, one or more measurement techniques may be appropriate. The particular technique chosen then needs to be assessed as to the practicalities of implementation, and the type of condition monitoring system required.

b) Feasibility of Measurement

Consideration should be given to the feasibility of acquiring the measurement including ease of access, complexity of required data acquisition system, level of required data processing, safety requirements, cost, and whether surveillance or control systems exist which are already measuring parameters of interest.

c) Environmental Conditions during Measurements

Measurements of different parameters should be taken wherever possible at the same time, or under the same environmental conditions. For variable loadings (duty), it may be possible to achieve similar measurement conditions by varying the extent, speed and/or density of the loading.

Monitoring should be taken where possible when the structure has reached a predetermined set of environmental conditions (e.g. seasonal midday temperature). These are also conditions which may be used for a specific structure configuration to establish baselines. Many engineering structures and their baseline parameters show a very strong dependency on temperature, hence measurements should either be taken at the same temperature conditions or the dependency of the baseline parameters on temperature should be known. Subsequent measurements are compared to the baseline values to detect changes. The trending of measurements is useful in highlighting the development of deteriorations.

d) Data Acquisition Rate

For steady state conditions, the data acquisition rate should be fast enough to capture a complete set of data before conditions change. During transients, high speed data acquisition may be necessary. Consideration should also be given to the duration of the measurement, the interval between measurements, and whether periodic or continuous sampling is required. A preliminary estimate will need to be made, based on an analysis of how the structure is likely to perform, and the type of deteriorations and their rate of propagation. Subsequently the duration may need to be revised as the monitoring proceeds, if the structural performance differs significantly from that anticipated.

e) Record of Monitored Parameters

Records of monitored parameters should include as a minimum the following information: essential data describing the structure, the measurement position, the measured quantity units and processing, and date and time information. Other information useful to allow comparison includes details of the measuring systems used and the accuracy of each measuring system. It is recommended that details of structure configuration and any component changes are also included.

f) Measurement Locations

Measurement locations should be chosen to give the best possibility of deterioration location. Measurement points should be identified uniquely. The use of a permanent label, or identification mark, is recommended.

Factors to take into consideration are:

- safety;
- high sensitivity to change in deterioration condition;
- reduced sensitivity to other influence;
- repeatability of measurement;

- attenuation or loss of signal;
- accessibility;
- environment;
- cost.

3.3.8 Data recording

As briefly mentioned in the section (3.3.6) analysis and synthesis of measurements and inspections data records are mainly done manually.

Surveyors, during inspections, fill in forms (check lists, diagrams, etc…) and tables with their findings. Data are kept in paper forms and are sometimes transferred to a computerised format (MS Excel tables) for storage and further analysis.

There is a clear lack of IT support for handling inspection data in general and thickness measurements in particular, but some attempts have been made recently for an integrated electronic support such as the EU-project Condition Assessment Scheme for Ship Hull Maintenance (*EU-CAS Project*), which focussed on comprehensive IT support for hull inspection and maintenance in general – and the thickness measurement process in particular. In the project, major stake holders of the thickness measurement process cooperated to devise an enhanced process, design a data model for the exchange of measurement data and implement prototype tools to examine possible benefits of the new procedure.

The Hull Condition Data Model (HCM) enables capturing all information required for determining and analysing the corrosion status of a vessel as required in current mandatory regulations. A major design goal of the HCM is that it shall not be necessary to enter more information in preparation and conduction of measurements than is currently recorded. The information content of an HCM file can therefore reflect the amount of information contained today in a typical thickness measurement report. On the other hand, a 3D geometrical model of a ship can simplify assessment of measurement results when used for their visualization. For that reason such a model can be stored in HCM, but again in a very simple form. In contrast to a full structural model of the ship, a data model for Hull Condition Monitoring Assessment

(HCMA) needs no topological information (connectivity of plates) and only low precision with respect to the exact location of plate boundaries. HCM is therefore held simple as compared to structural models such as STEP-AP218 (STEP-AP218 2004), which specifies the use of the integrated resources necessary for the scope and information requirements for the exchange of product definition data and its configuration and approval status information for ship structural systems; its complexity is tailored to the HCMA process.

HCM shall provide support for all phases of HCMA; Planning, Recording, Reporting and Assessment. The chosen XML-based approach ensures extensibility in future versions of the data model, which will need to be adapted to new available methodology for ship inspections (e.g. robotics), new regulatory requirements (IMO, EMSA, IACS) as well as to innovations in Information Technology in both soft- and hardware that will have an impact on the process. In spite of possible extensions, it shall always be possible to use HCM in a minimal way, i.e. by storing only that information about the ship structure and the gaugings, which can be captured during a typical measurement campaign as it is performed today.

HCM is implemented in form of a set of Schema Documents based on the W3C XML Schema Specification (Biron et al. 2004; Fallside et al. 2004; Thompson et al. 2004).

3.3.9 Recorded Data from Inspections

The range of findings normally detected and recorded in occasion of ‘other surveys’ includes the following (with relevant information provided in the occasion of report from the inspection company):

3.3.9.1.1 Cracks

Information normally associated to cracks in a survey report is:

a. material,
b. original thickness,
c. current thickness,

d. location,
e. structural details,
f. dimensions of the crack,
g. orientation of the crack
h. Identification of structural details of ship structure
i. Appropriate history of ship structures
j. Crack growth material data
k. Information about quality performance of structural details (*if available*)

3.3.9.1.2 Indent/Deformations:

This kind of failure can be referred to stiffeners/girders and/or to plates (associated or not to stiffeners/girders). It can be the result of some different origin:

a. Due to impact (contact with other ships, contact with quay, contact with other external bodies/objects, use of loading/unloading tools like grabs, etc.)
b. Due to structural collapse

Information normally associated to the dent in a survey report:

a. Material,
b. Original thickness,
c. current thickness,
d. geometrical representation of the areas (including stiffeners/girders),
e. dimension and shape of the stiffeners,
f. detail of the deformation,
g. general conditions (corrosion/coating) of the interested area/surface

3.3.9.1.3 Thickness Reduction/Corrosion:

This is normally related to plates and to stiffeners. It can be the result of several causes like: stress, fatigue, superficial wear, erosion, electro-chemical, coating degradation.

Information associated to thickness reduction in a survey report is:

1. Location and extension of the area in terms of:
    a. Compartment name (from capacity plan and/or from general arrangement plan).
    b. Other areas like: side shell, deck. Longitudinal position (frames intervals) - Transversal position, height (distance from a chosen reference).
    c. Geometrical details of the interested item (if it is stiffener, girder etc.).
2. Material
    a. Original thickness
    b. Current thickness
    c. Description of the surface corroded
    d. General coating state/conditions
    e. Eventual presence of cathodic protection

3.3.9.1.4 Coating Degradation

The coating degradation can refer to several cases:

- *Coating thickness reduction:* due to normal wear and/or erosion, and/or chemical aggression.
- *Coating breaks:* due to ageing, stresses and elastic deformation, erroneous original coating cycle, inadequate original steel preparation of the surfaces, application mistakes (too high thickness); mechanical impacts, temperature.

Information associated to coating in a survey report:

i. Location and extension of the inspected area.
ii. Percentage of the degraded surface with respect to the whole surface (codified terms can be adopted: fair, good, and poor).
iii. Description of the degradation type.

CHAPTER 4: WAVES STATISTICAL DATA: ANALYTICAL MODEL

4.1 SCOPE

Ships operate in different sea conditions where their structure is affected wind, climatic conditions such as temperature range, and waves. The latter are the most disturbing forces in the ship environment (Rawson 2001).

Air and sea temperatures and solar radiation are also important factors as they affect the structural steel temperature making it more likely to affect the corrosion rate and fracture toughness (Melchers 2002; Barltrop et al. 2008) but many other chemical factors also affect the degradation of the different structural components of the ship (Garbatov et al. 2006; Soares et al. 2009).

Wave loading statistics (including impact effects), air and internal temperature are used in the fatigue and fracture calculations.

In design, the practice in most cases is to apply the ideal mathematical formulations of the sea state as defined by the observed significant wave height and period.

In a Joint Industry Project (DNV) (Nestegard et al. 2006), the various nautical zones (areas: Marsden squares) that defined the distribution parameters for the Omni-directional wave model have been expressed and recommended. But this recommendation does not include the parameters for the directional wave.

The objective of the present work is to estimate the parameters of the mathematical model for the wave height and period for each direction and for the 104 areas.

This chapter will discuss the analytical models for the wave environmental data for different sea areas derived from BMT's Global Wave's Statistics (GWS) data (Hogben et al. 1986).

An initial study, which results were presented in (Ma et al. 2012), was carried out to derive analytical models for some areas for a specific ship route in order to use them within an extreme loading and fatigue calculations program. Data from BMT's GWS atlas were transformed into Ms Excel sheets which were then used to derive the parameters of the analytical models. .

The work undertaken in this part of the thesis is a study of the wave environmental data which includes all the areas and also proposes models parameters for sea areas for which data is missing.

The output will be used as a parameter to characterise the wave conditions for different ship routes. This information will be stored in the database (which will be described in Chapter 6) and will be used as part of the calculation of ship to ship correlation during the calibration process of the prediction models.

4.2 INTRODUCTION

According to casualty statistics, one of the major causes of ship losses is bad weather (Guedes Soares et al. 2001), which stresses the importance of taking extreme sea state conditions adequately into account in ship design. Therefore, a correct and thorough understanding of meteorological and oceanographic conditions, most notably the extreme values of relevant wave and wind parameters, is of paramount importance to maritime safety. Thus, there is a need for appropriate statistical models to describe these phenomena.

Ocean basins cover approximately 71% of Earth's surface or about 361 million square kilometres (140 million square miles). Their average depth is 5,000 meters (16,000 feet), and the total volume is about 1.35 billion cubic kilometres (322 million cubic miles). There are five major subdivisions of the world ocean: the Pacific Ocean, Atlantic Ocean, Indian Ocean, Southern Ocean, and Arctic Ocean (Figure 4-1). The Pacific, Atlantic, and Indian Oceans are conventional ocean basins and are bounded by the continental masses or by ocean ridges and currents; they merge below 40° South latitude in the Antarctic Circumpolar current, or west Wind Drift, at the Southern (or Antarctic) Ocean. In the North Polar Region, the Arctic Ocean is considered as the fifth ocean subdivision (Ruth et al. 1989).

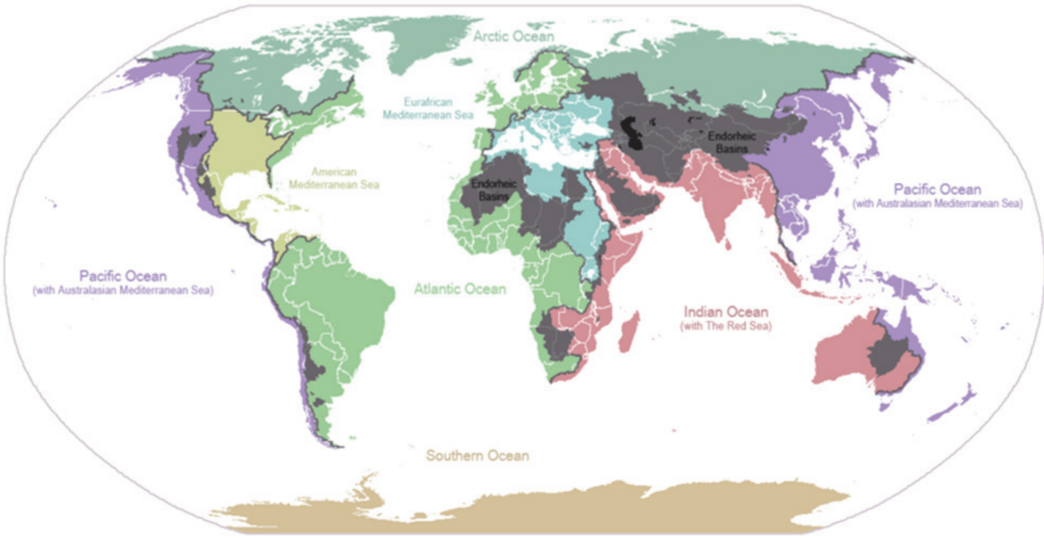


Figure 4-1: Major features of the ocean basins (adapted from Wikipedia).

4.3 OCEAN-SEA WAVE AND AREA

Wave data is important during the design of floating or fixed ocean structures. One important stage in the design of floating structures, such as ships, involves the calculations of motion characteristics in waves. This will enable designers to predict the performance of the vessel in waves and hence its operability. In the design of offshore structures an assessment of wave loadings is made to determine the ability of the structure to sustain heavy weather and hence its reliability. A very important input for both design calculations is good and reliable wave data in the form of probability of occurrence of wave heights and periods.

Fatigue failure of a structure is caused by repeated loads. In the design and analysis of some ship structural details such as the connections of deck longitudinal to transverse webs, the ocean waves are considered to be the main source of fatigue damage.

To develop a better understanding for the offshore fatigue life, it is essential to analyse the sources of variability of fatigue life and to understand the extent of the variability. The first step, to derive a fatigue design procedure, is to determine how to evaluate fatigue strength and how to calculate the working stress and wave load sequence introduced by wave load acting on the structural members. In order to calculate the working stress on the ship structure, there is a need for a wave scatter diagram (wave height, period, and direction) and ship's course within a given navigation area. This is because working stress on structural members varies not only by wave height and period, but also by the angle at which a ship encounters wave (Tomita et al. 2005). In general the probability of occurrence of significant wave heights is normally enough for most engineering design calculations. The significant wave height (Hs) is the value determined by decomposing a wave record obtained during a certain period into individual waves, estimating those heights, rearranging the heights in descending order in size, and averaging the heights for the top one-third.

However, in some cases such as the use of sea spectra to estimate downtime of floating vessels, data regarding wave periods is required. Wave direction as well as the wave height is important, such as in the case of harbour planning with entrance at point 'O' (Goda 2000).

Marine wind and wave data have different characteristics expressed as quality, accuracy, errors present in the data, geographical distributions, and quantity of data and there are four main sources of data available to the user:

(a) visual observations from ships,

(b) data measured from buoys or platforms,

(c) data measured by remote instruments on board of high altitude flying satellites, and

(d) meteorological and wave models operational at the various meteo-oceanographic centres.

The data considered in this work is based on the visual observations of commercial ships (known as VOS, Volunteer Observing Ships), which have been analysed and compiled in statistics on geographical areas. Hogben et al. (1967) have published these statistics in atlases such as ‘Ocean Wave Statistics’. The more commonly used ‘Global Wave Statistics’ (GWS) by Hogben et al. (1986) is the environmental data for different sea areas, which have been established using the improved version of Ocean Wave Statistics (OWS) and published by British Maritime Technology, BMT (Hogben et al. 1986). GWS is based on an analysis of 55 million VOS observations collected from 1854 to 1984 (Cees Leenaars et al. 2000).

BMT’s GWS atlas consists of the worldwide database, which contains 104 Marsden squares (Figure 4-2). Each square contains seasonal and directional scatter diagrams. In fact, the database includes 4 seasonal data sets and one annual data for each direction (8 + Omni direction) for each area (104) scatter diagrams (total of 4680). The 104 sea areas are derived by a quality enhancing analysis of a very large number of visual observations of both waves and winds reported from ships in normal service all over the world. Although it does not present any kind of data, the analysis procedures used involved modelling of the statistical relationships between the wave and wind observations (Hogben et al. 1986). The data are presented in terms of probability distributions of wave heights, periods and directions for the global selection of sea areas. The heights and periods for which statistics are given have been shown to correspond to measured values of the so-called ‘significant wave heights’ and ‘zero crossing periods’.

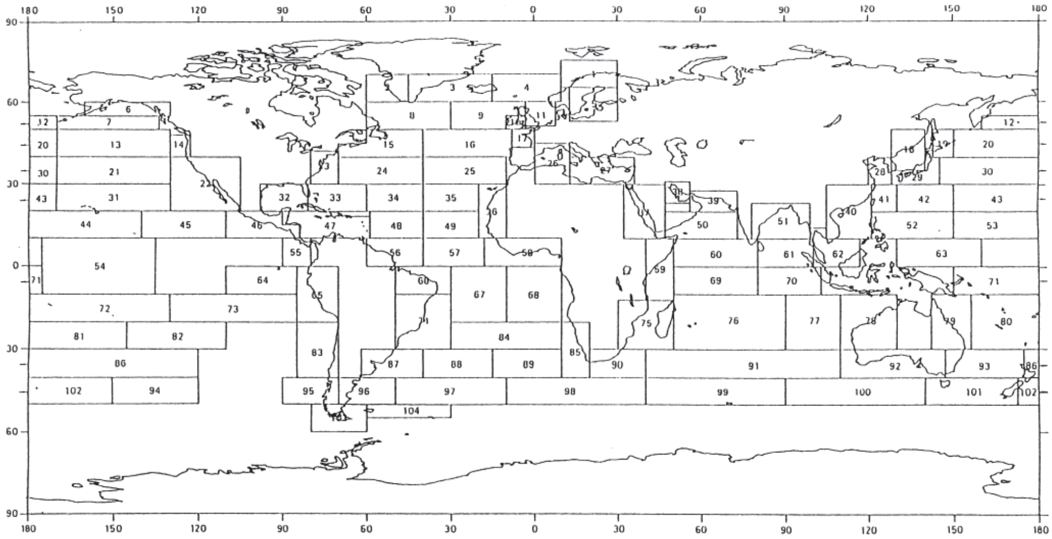


Figure 4-2: GWS Climatologically Areas

Actual wave data records are available only for limited ocean areas. In this study, it is proposed to estimate the parameters for an analytical model and to assess the data for the missing area and for each direction (8 + all directions).

4.3.1 World Meteorological Organization sea state code

The WMO sea state code largely adopts the 'wind sea' definition of the Douglas Sea Scale (Eurometeo).

Table 4-1: State of the sea

WMO Sea State Code	*Wave Height (meters)*	*Characteristics*
0	*0*	*Calm (glassy)*
1	*0 to 0.1*	*Calm (rippled)*
2	*0.1 to 0.5*	*Smooth (wavelets)*
3	*0.5 to 1.25*	*Slight*
4	*1.25 to 2.5*	*Moderate*
5	*2.5 to 4*	*Rough*
6	*4 to 6*	*Very rough*
7	*6 to 9*	*High*
8	*9 to 14*	*Very high*
9	*Over 14*	*Phenomenal*

Table 4-2: Character of the sea swell

Character of the sea swell	
Low	0. None 1. Short or average 2. Long
Moderate	3. Short 4. Average 5. Long
Heavy	6. Short 7. Average 8. Long 9. Confused

4.3.2 Wave Statistics

Wave statistics are indispensable to evaluate the service performance of the structure for the offshore or costal engineering, or naval architects requiring wave climate statistics for areas where reliable instrumental data are not available in order to predict high waves. Understanding ocean wave height statistics is particularly useful and becomes an important matter for engineering, especially for safety and prevention reasons.

In general and as discussed in the previous paragraph, wave statistics are given as a scattering table of significant wave heights and mean wave periods. These parameters are commonly obtained by analysing wave records which contain wave characteristics measured by data acquisition systems (Capitao et al. 1995). To simplify use of the table, researchers have proposed analytical distribution of wave statistics (Naito 2003). They have often applied the log-normal, gamma and Weibull distributions.

4.3.3 Wave Height Distribution

The surface elevation of sea waves is a non-stationary Gaussian process. Therefore, the description of sea water is derived into a short-term and long-term description. Short-term refers to a time interval short enough to consider the sea state to be stationary and long enough to obtain statistically reliable results. A short-term sea state, referred to as a 'wave field', can be characterised by specified parameters like significant wave height and characteristic wave period. The long-term statistical description characterises the variability of these specified parameters, which are assumed constant in short-term description.

On a long term time scale (e.g. one year), symmetric probability distributions, such as the normal distribution, are not suitable to describe the long term distribution of the significant wave heights, Skewed distributions, such as the Gumbel and Weibull distribution, fit much better, (Battjes 1972).

The probability distributions of the individual wave heights on a short term time scale (e.g. three hours), is given by a Rayleigh distribution (Figure 4-3), given a few easily-satisfied, boundary conditions (such as stationary conditions) (Longuet-Higgins 1956).

4.3.3.1 Short Term Wave Height

The short term wave statistics in deep water are well described by several authors. They showed that the wave heights of Gaussian waves with a narrow banded frequency spectrum obey the Rayleigh distribution. Comparisons of the Rayleigh distribution with measured wave heights by several authors (Longuet-Higgins 1956; Goodnight et al. 1963; Collins 1967; Chakrabarti et al. 1971; Longuet-Higgins 1980), shows that this distribution produces acceptable results for most of the storms.

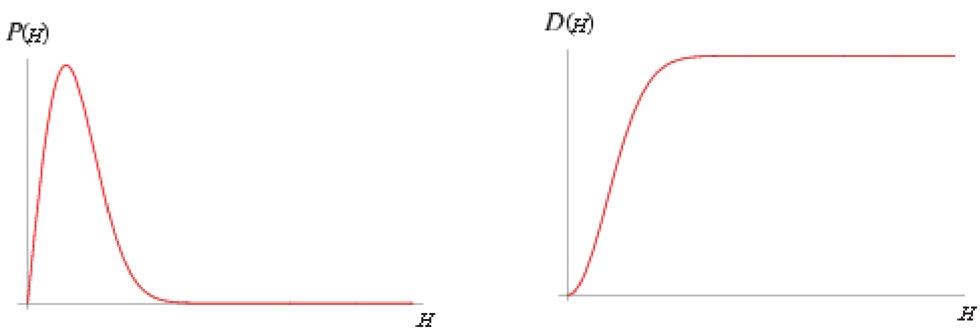


Figure 4-3: Rayleigh Probability Density Function (P) and Cumulative Distribution Function (D)

The Rayleigh Probability Density Function (PDF) can be written:

$$P(H) = \frac{H}{m_0} \times e^{\frac{-H^2}{2 \times m_0}} \quad (H > 0) \qquad \text{Eq. 4-1}$$

and the Cumulative Distribution Function (CDF):

$$D(H) = 1 - e^{\frac{-H^2}{2 \times m_0}} \quad (H > 0) \qquad \textit{Eq. 4-2}$$

in which m_0 is the variance of the water surface elevation.

4.3.3.2 Long Term Wave Height

Long-term wave statistics plays an important role for the design of marine systems, and provide the load spectrum data which are needed for fatigue analysis, since the accumulation of responses of a marine system in each short-term sea state over its lifetime provides information vital for evaluating fatigue loads of the system. The methods for estimating long-term individual wave statistics and a marine system's long-term response are essentially the same (Ochi 1998). For the latter case, however, the effects of additional conditions such as loading, heading to waves, speed, etc., have to be considered.

The long-term statistics of individual wave height is an accumulation of the statistics for all short-term sea conditions, taking into account the frequency of occurrence of each short-term sea state. The Weibull probability function is a flexible distribution to use to account for nonlinearities of wave crests and heights (note that a Rayleigh distribution is a special case of the Weibull distribution) and as discussed earlier, it has been applied by several authors (Goda 1974; Kuo et al. 1974; Hughes et al. 1987). Unless data indicate otherwise, a 3-parameter Weibull distribution can be assumed for the marginal distribution of significant wave height Hs, (Nordenstrøm 1973; DNV 2010).

The significant wave height is modelled by a 3-parameter Weibull Probability Density function:

$$f_{H_S}(h) = \left(\frac{h-\gamma}{\alpha}\right)^{\beta-1} \times e^{-(\frac{h-\gamma}{\alpha})^{\beta}} \qquad \textit{Eq. 4-3}$$

where α is the scale parameter, β is the shape parameter, and γ is the location parameter.

The distribution parameters are determined from site specific data by some fitting techniques.

In the context of this research, it was assumed that the location parameter is equal to zero ($\gamma = 0$) and carried out the work with the 2-parameters Weibull Probability Density Function:

$$f_{H_S}(h) = \left(\frac{h}{\alpha}\right)^{\beta-1} \times e^{-(\frac{h}{\alpha})^{\beta}} \qquad \textit{Eq. 4-4}$$

And the Weibull Cumulative Distribution Function is given by:

$$F_{H_S}(h) = 1 - e^{-(\frac{h}{\alpha})^{\beta}} \qquad \textit{Eq. 4-5}$$

4.3.3.3 Wave Height and Associated Period

A sea state is traditionally characterized by significant wave height Hs and the characteristic zero-crossing period Tz. The concept of characteristic zero-crossing period Tz is a generalization of the period of a pure sinusoidal wave. The real sea surface may be modelled as made up of a superposition of a large number of sinusoidal waves with random heights and periods. At any given position the resulting surface necessarily moves up above and down below the level of the undisturbed surface (denoted as the zero level). This movement is not periodic for example in the sense that there is a constant time interval between an up-crossing and the next up-crossing of the zero level. The time intervals vary randomly around an average value denoted Tz and measured during the considered time chosen for a sea state duration. For technical evaluations the subdivision into sea states is convenient even though the real situation is a gradual and continuous change of the character of the sea surface geometry (Ditlevsen 2003).

Although the long-term distributions of Hs provide a probabilistic description of the sea state severity, it is often necessary to also describe the associated mean period and direction. On other occasions, joint distributions of waves and storm surges are required or joint distributions of waves, wind and current (Guedes Soares et al. 2003). Different approaches have been developed for specific applications, but possibly the most widely used is the conditional modelling approach in which the joint density function is defined in terms of a marginal distribution and a series of conditional density functions modelled by parametric functions that are fitted to the conditioned data by some form of estimation process.

The most used joint distributions of wave parameters Hs and Tz are the bivariate probability density. Different approaches for establishing a joint environmental model exist: The Maximum Likelihood Model (MLM) (Prince-Wright 1995), and the Conditional Modelling Approach (CMA) (Bitner-Gregersen et al. 1991), which are available for different areas of the ocean and coastal areas. The MLM uses a Gaussian transformation to a simultaneous data set while in the CMA, a joint density function is defined in terms of a marginal distribution and a series of conditional density functions.

Most wave data banks provide information of the scatter diagram at a point, although some also provide directional information, and in this case the scatter diagram is given for each of eight directional sectors when data is available (GWS). In this case, the joint distribution for the wave height, period and direction is given by:

$$g(H_S, T_Z, \theta) = f((H_S, T_Z)/\theta) \times h(\theta) \qquad \text{Eq. 4-6}$$

where θ indicates the wave direction.

The joint (or bivariate) distribution of significant wave height and mean period is constructed from a conditional distribution of average or peak periods and a marginal distribution of significant wave height given by:

$$f_{H_S,T_Z}(H,T) = f_{H_S/T_Z}(H/T) \times f_{H_S}(H) \quad \text{Eq. 4-7}$$

The zero-crossing wave period conditional on significant wave height is given by the log-normal density function as follow.

$$f_{T_Z,H_S}(t/h) = \frac{1}{\sigma t\sqrt{2\pi}} e^{-\left\{\frac{(\ln(t)-\mu)^2}{2\sigma^2}\right\}} \quad \text{Eq. 4-8}$$

where:

$$\mu = E(\ln(t)) = a_0 + a_1 h^{a_2} \quad \text{Eq. 4-9}$$

$$\sigma = Std(\ln(t)) = b_0 + b \times e^{(b_2 h)} \quad \text{Eq. 4-10}$$

and the distribution parameters μ and σ are functions of the significant wave height (Bitner-Gregersen et al. 1989; Nestegard et al. 2006). Experience shows that the following model often gives good fit to the data. The parameters a_i, b_i, $i=0, 1, 2,$ are determined from actual data.

4.3.4 Directional Consideration

Floating systems experience quite different responses to waves on their direction of approach, and so it is usually necessary to take this direction into account, in the fatigue analysis. Permanent installations which cannot rotate with the weather will obviously have a fixed heading with respect to wave climate. And even mobile systems such as semi-submersible drilling vessels will usually moor pointing into a specific direction (usually the anticipated direction of the severest weather), and this leads to directional bias in the weather condition they experience.

The fatigue analysis needs to take into account the distribution of these wave directions about the vessel axis, and indeed the analysis usually takes benefit from the fact that the waves (stress) are not always in the same direction. By the same token, any tendency of the wave to most often approach from a prevailing direction also needs to be taken into account (Barltrop 1998).

4.3.5 Parameters Estimation

As in all statistical modelling, a crucial prerequisite for any sensible modelling and reliable analysis is the availability of statistical data. The BMT's GWS atlas wave data records are available only for limited ocean areas. In some cases, the contents of individual tables have been omitted due to insufficient data.

In the present work, the fitting of the significant wave height and conditional period-wave data to a Weibull and log-normal distributions respectively for each direction and area was performed.

The distributions parameters for the global wave model were estimated in order to derive the data for the missing area and for each direction (8 + all directions), using the Maximum Likelihood Method and other statistical analysis tool for fitting.

Parameters for the univariate probability distribution model of significant wave height and the joint probability distribution of significant wave height, mean zero crossing period, maximal wave height during a sea state, have been estimated.

The data used in the fitting process are based on the measured sea state data published in the GWS atlas.

In this study, the 'Generalised Maximum Likelihood' (grMLH) method was used to calculate the parameters values of the Weibull distribution for the significant wave height, when scatter diagram data was available, and regression methods have been used to estimate the parameters when data was missing.

The grMLH approach used to estimate the two parameters of the Weibull distribution is based on the ranking function (Jacquelin 1994). The parameters for the conditional distribution of the zero-crossing period Tz given the significant wave height, Hs were computed using equations (Eq. 4-9) and (Eq. 4-10), where a_0= 0.7 and b_0= 0.07 (Nestegard et al. 2006).

The sample of significant wave height has been obtained by randomly generating data for each direction on each yearly area, using as a reference each bin reported in the scatter diagram (wave height, range and number).

The data generated was then fitted to the Weibull distribution, and its parameters have been estimated using the grMLH.

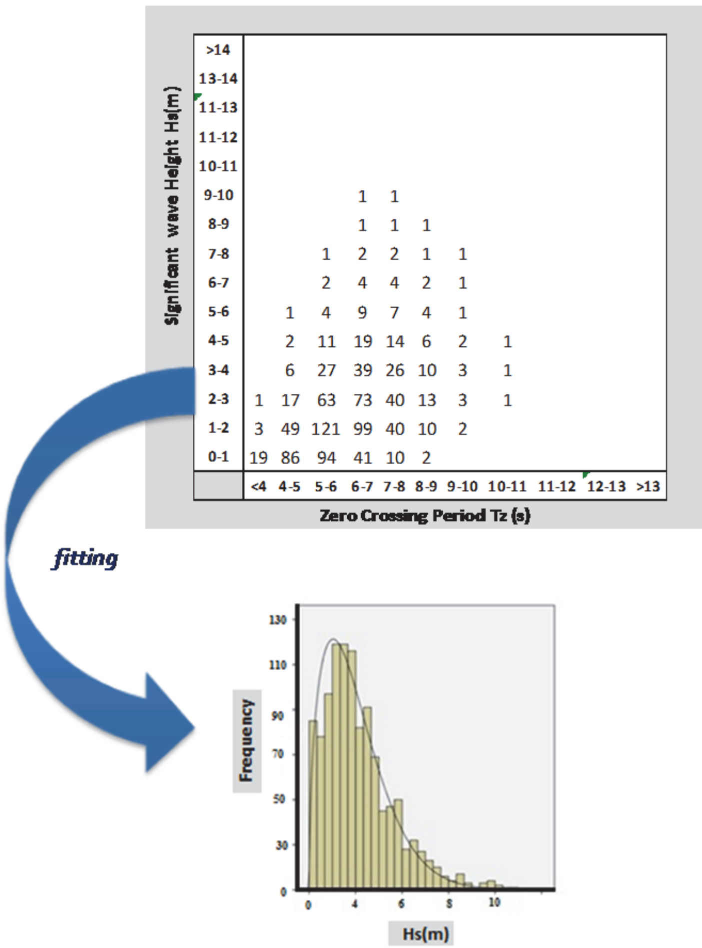


Figure 4-4: Fitting of the significant wave height from the scatter diagram

In addition a combined directional wave has been defined in order to validate the approach by comparing it to DNV omini-directional as well as the scatter diagram. The combined directional wave (referred to as combined in the rest of the section) is obtained using the following formulas:

$$combined\ H_s = \sum_{i=1}^{9} p_i \times H_{s_i} \qquad \text{Eq. 4-11}$$

$$combined\ (T_z|H_s) = \sum_{i=1}^{9} p_i \times (T_z|H_s)_i \qquad \text{Eq. 4-12}$$

Where:

- p_i is the probability of occurrence of the wave direction as given in the scatter diagram and reproduced in Appendix A.2 for:

  $$i \in \{NE, N, NW, W, SW, S, SE, E, unknown\}$$

  For the *unknown* direction, Omni-directional data from the scatter diagram has been used to generate the missing information.
- H_{s_i} is the estimated significant wave height for direction i.
- $(T_z|H_s)_i$ is the estimated zero-crossing wave period conditional on significant wave height for direction i.

4.3.6 Extreme wave conditions

Extreme wave conditions, likely to occur during the life of any offshore or coastal structure, must be considered during the design stage. Extreme wave conditions are usually represented in terms of wave heights and wave periods:

- The significant wave height H_s.
- The zero-crossing period, T_z.

When carrying out extrapolations of the design parameters to obtain some estimate of their extreme values the question arises as to what return period to use for the design condition. Structures designed to withstand almost anything are necessary in certain situations, but in others they are more expensive than weaker structures, for which the cost of periodical repair is included. By taking costs into account in this way it is possible to establish an acceptable level of risk of the design condition occurring within a given number of years. Where the consequences of failure are as severe as to be unacceptable at other than for very low probabilities then such structures should be able to withstand design conditions with return periods of the order of 1000 years or more (BS-6349 2003).

In the extreme value analysis the random variable X and the corresponding distribution function f(x) is generally continuous in which case:

$$\mathrm{Prob}(X \le x) = F(x) = \int_{-\infty}^{x} f(u)du \qquad \text{Eq. 4-13}$$

There exist several functions used for extreme values distributions. One of the most common is the Weibull distribution.

The return period T_R is defined as the period that, on average, separates two events occurrences (this does not mean that exactly T_R years will separate two such occurrences). For example, an event with a return period of 1000 years, there is a 0.1% probability of occurrence in any one year, even the one following a previous occurrence, and there is approximately 1.8 % chance of occurrence in a 20-year period. For a time interval equal to the return period there is a 6.3 % probability of occurrence within the return period.

The significant wave height for the return period (number of designed years) T_R can be defined as the $(1 - 1/(nT_R))$ quantile of the distribution of significant wave heights, where n is the number of sea states per year. It is denoted H_{S,T_R} and is expressed as:

$$H_{S,T_R} = F_{H_s}^{-1}(1 - \frac{1}{nT_R}) \qquad \text{Eq. 4-14}$$

4.4 RESULTS AND DISCUSSION

4.4.1 Parametric models results

Results verification ensures that the estimated parameters allow the model to meet its intended requirements in terms of the results obtained. The ultimate goal of this verification is to make the results useful, in the sense that the model provides accurate information about the system being modelled, so the parameters could be widely used.

For this analysis, the fitting of significant wave height to the Weibull distributions using the GWS data, is further sustained by the use of histograms of the data in comparison with the corresponding Weibull probability density function.

Values of the parameters per direction and for the 104 areas are reported in Appendix A.2.

Not all areas are discussed in this section but only results from area 1 and area 11 are presented. Area 1 was chosen to represent all the areas with missing directional data (not available in GWS) in order to demonstrate the extent of the analysis as well as the extrapolation when not all the information is available. While Area 11 has been chosen as it is part of the North Sea and all the data is available.

Figure 4-5 shows the cumulative density function (CDF) of the wave height for every direction as estimated from the scatter diagrams as well as the combined direction for area 1.

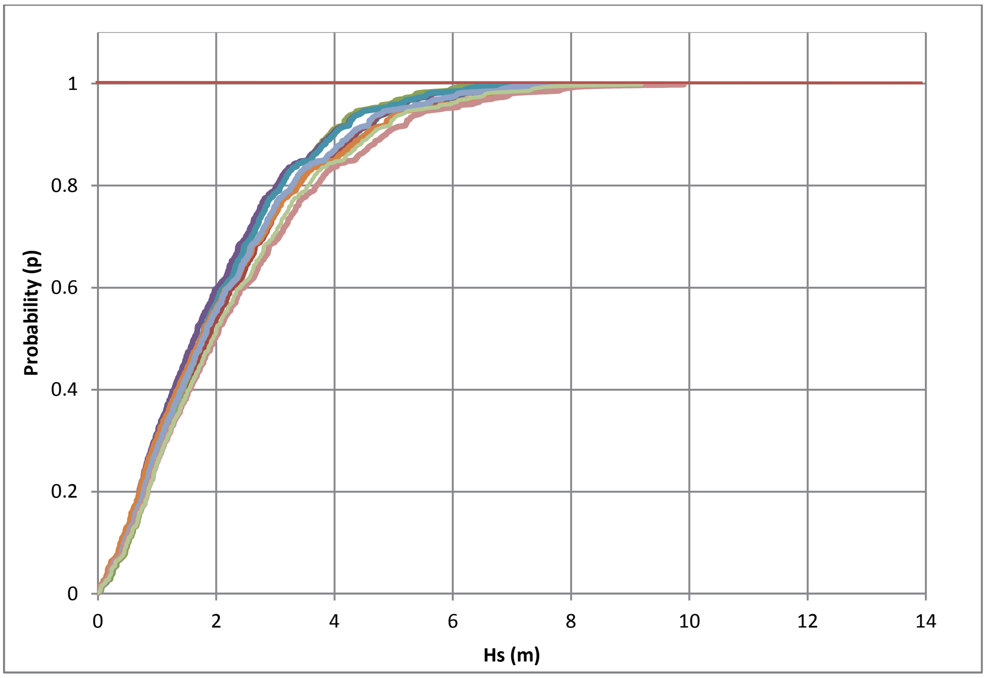


Figure 4-5: H_s CDF directional and combined directions for Area 1

Figure 4-6 shows wave height cumulative density function (CDF) for the combined directions, the DNV omni-directional and the estimated omni-directional from the scatter diagram for area 1. This figure shows a very good agreement between the combined directions and the DNV omni-directional (curves are almost superimposed). This is further shown in Figure 4-7 which presents the results from the regression analysis for the combined directions versus DNV omni-directional.

The combined directions curve shows a slight over estimation but in general it has also a good agreement with the curve for the omni-directional data from the scatter diagram and Figure 4-8 shows the results from the regression analysis for the combined directions versus the omni-directional from scatter diagram data.

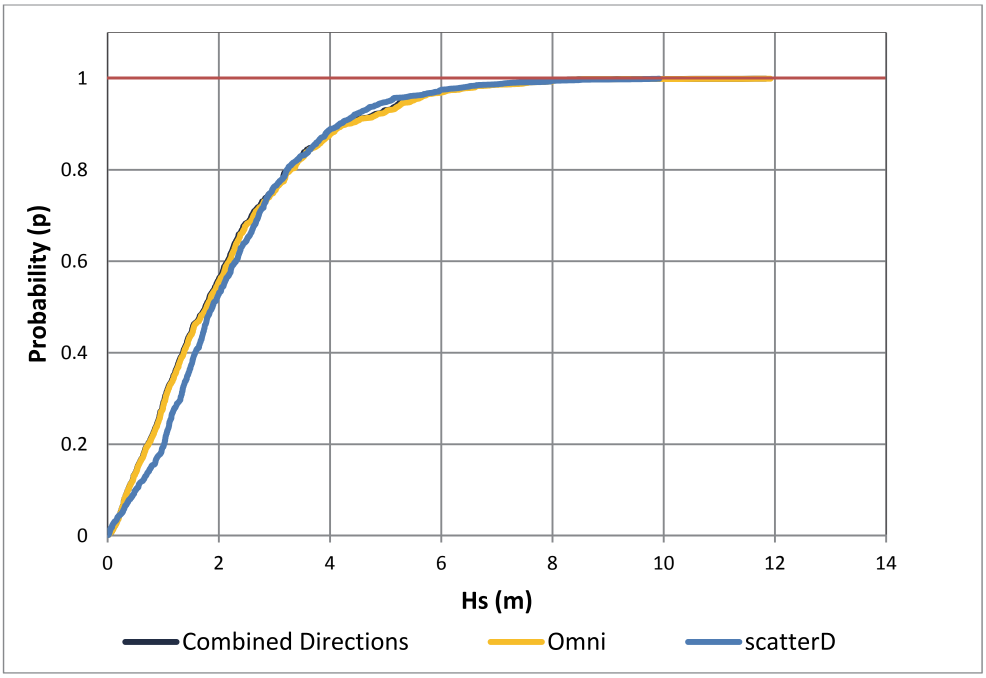


Figure 4-6: CDF Hs Combined directions, Omni-direction (DNV parameters) and scatter diagram for Area 1

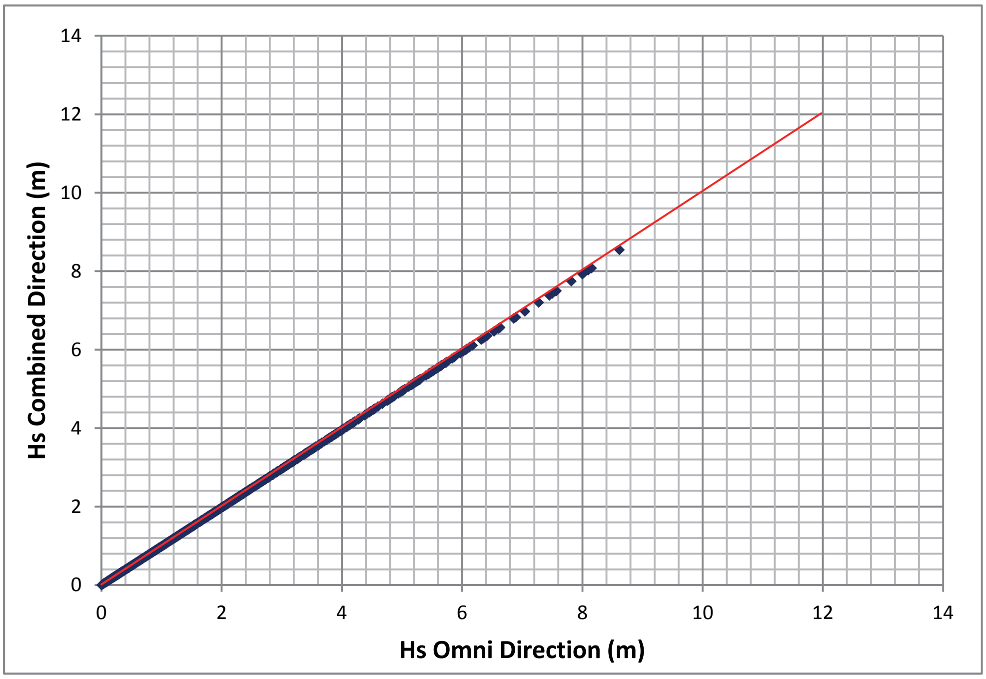


Figure 4-7: Combined directional H_s data versus Omni-direction (DNV parameters) for Area 1

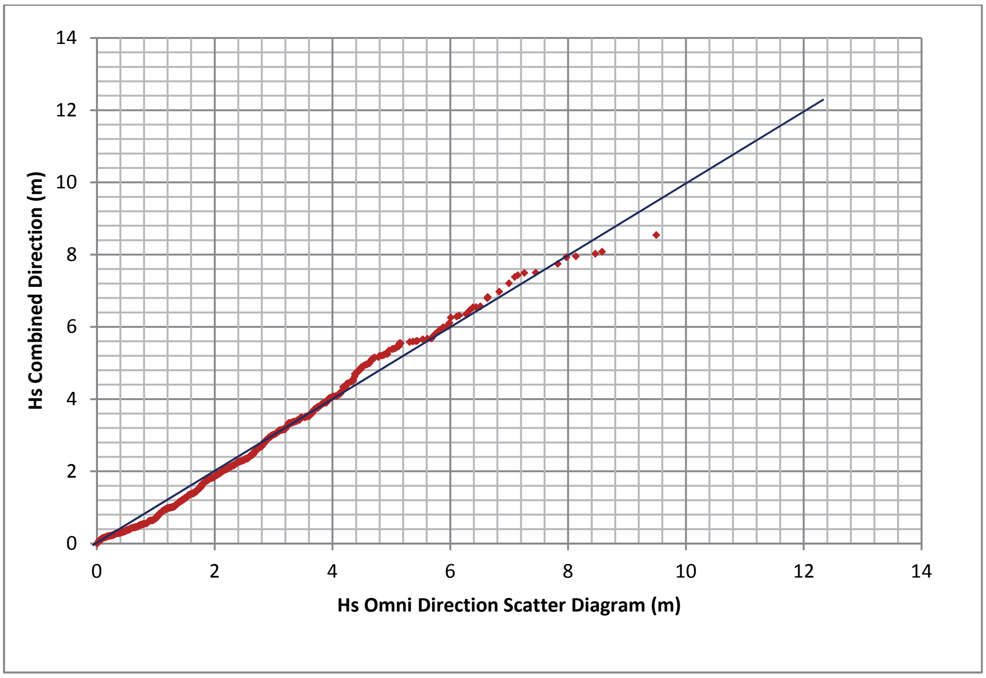


Figure 4-8: Combined directional Hs data versus scatter diagram Hs for Area 1

For area 11, Figure 4-9 shows the cumulative distributions of each direction as well the combined directional one.

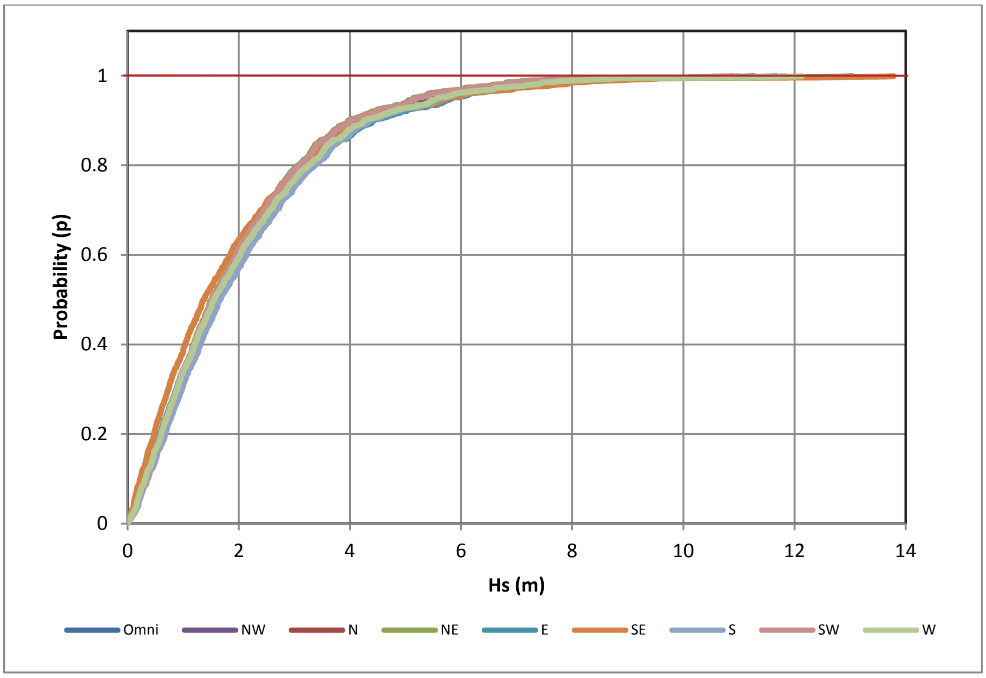


Figure 4-9: Area 11- Comparing directional data with Omni-directional (combined)

Figure 4-10 shows the cumulative curves for the combined directions versus, DNV omni-direction and the omni-direction from the scatter diagram. The results are quite similar to those of area 1 as the curve for the combined directions is almost the same as DNV omni-directional curve and the combined direction shows a good agreement with the one obtained from the data of the scatter diagram. In addition, data from the scatter diagram has been compared to the combined directions and the DNV omni-directional as shown in Figure 4-11. Both curves are in a very good agreement for H_s up to 5 m. From 5m to 7m, both curves slightly overestimate the wave height and after that the two curves give an underestimation of the wave height with the combined direction giving a better estimate.

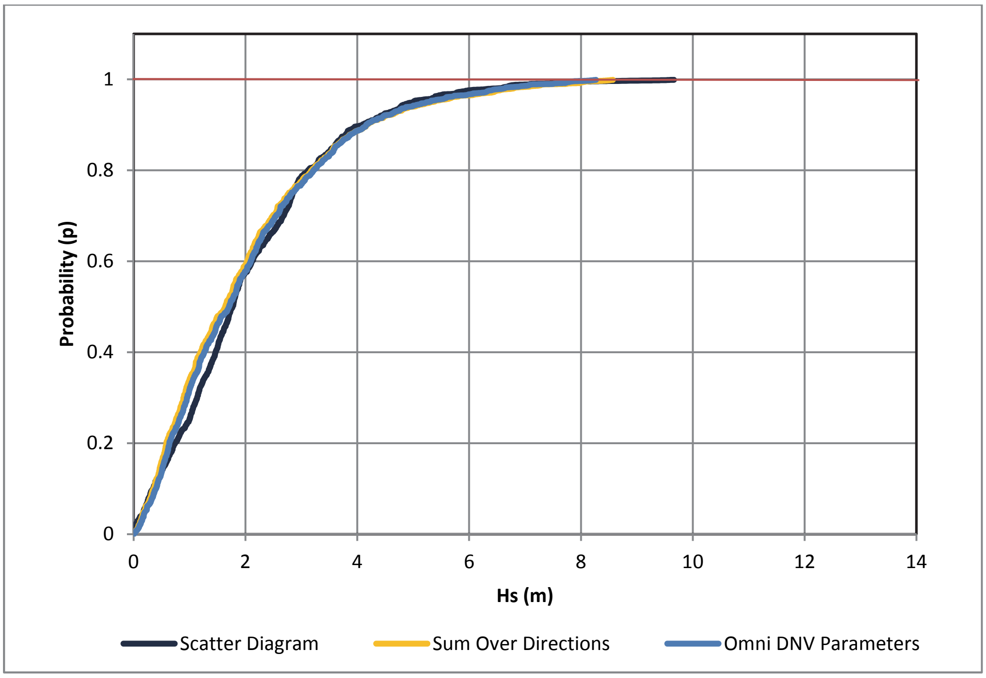


Figure 4-10: Combined directional predicted H_s data versus Omni-direction (DNV parameters) H_s and Scatter diagram data for Area 11

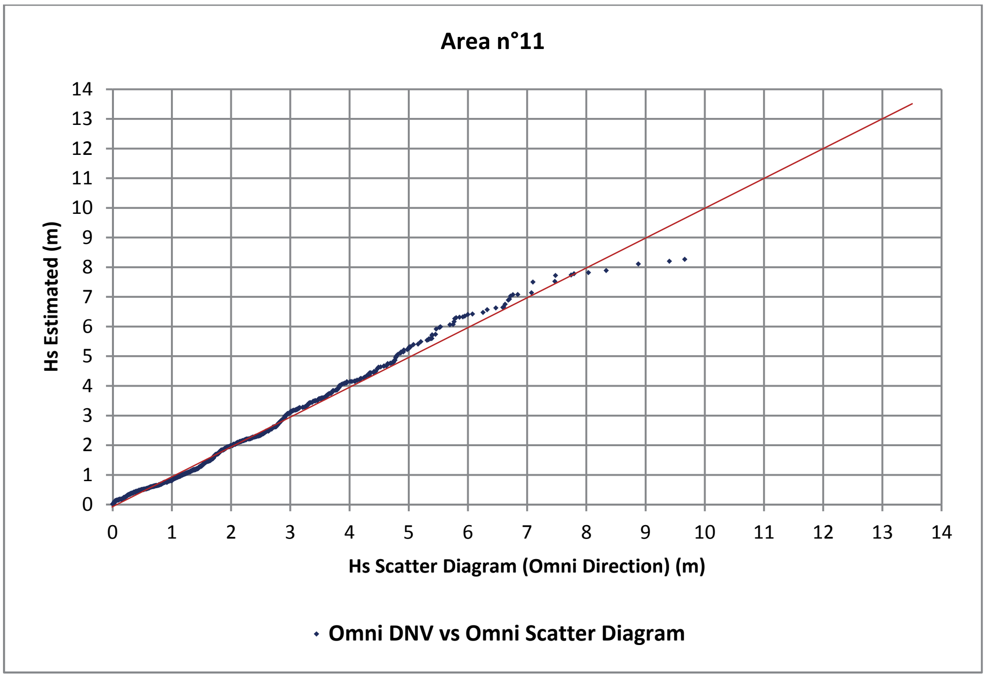


Figure 4-11: Area 11- Comparing Omni-directional data

In addition the *Probability-Probability* (P-P) plot which is a graph of the empirical Cumulative Distribution Function (CDF) values plotted against the theoretical CDF values and the *Quantile-Quantile* (QQ) plot which is a graph of the input data values plotted against the theoretical (fitted) distribution quantiles are used to test the fitting of the data to the Weibull distribution. Both axes of the PP and QQ plots are in units of the input data set. The plots are approximately linear if the specified theoretical distribution is the correct model.

The corresponding QQ and PP plots for the wave height fitting for area 11 for every direction have been plotted and are shown below. They confirm that the GWS data fit the Weibull distribution.

The QQ plots (Figure 4-12 to Figure 4-14) shows a very good agreement between the fitted data particularly for the North direction.

The PP plots (Figure 4-15 to Figure 4-17) also show a very good agreement between the CFDs and in particular for the West direction (Figure 4-17).

The agreement between the GWS data (scatter diagram) and those generated using the Weibull distribution with the estimated parameters and P-P and Q-Q plots, reinforce the conclusion that the estimated parameters for the Weibull distribution are a good approximation.

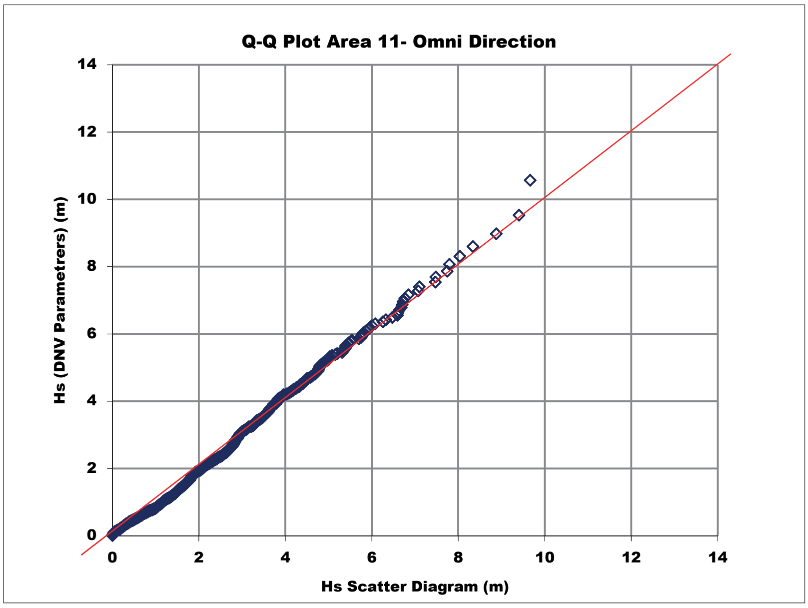


Figure 4-12: Q-Q plot of DNV omni-directional Hs data versus scatter diagram

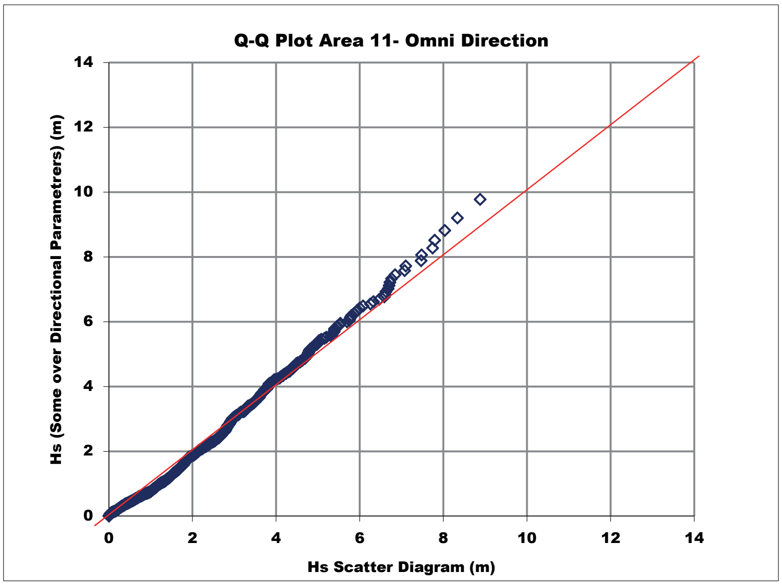


Figure 4-13: Q-Q plot of combined directions Hs data versus scatter diagram

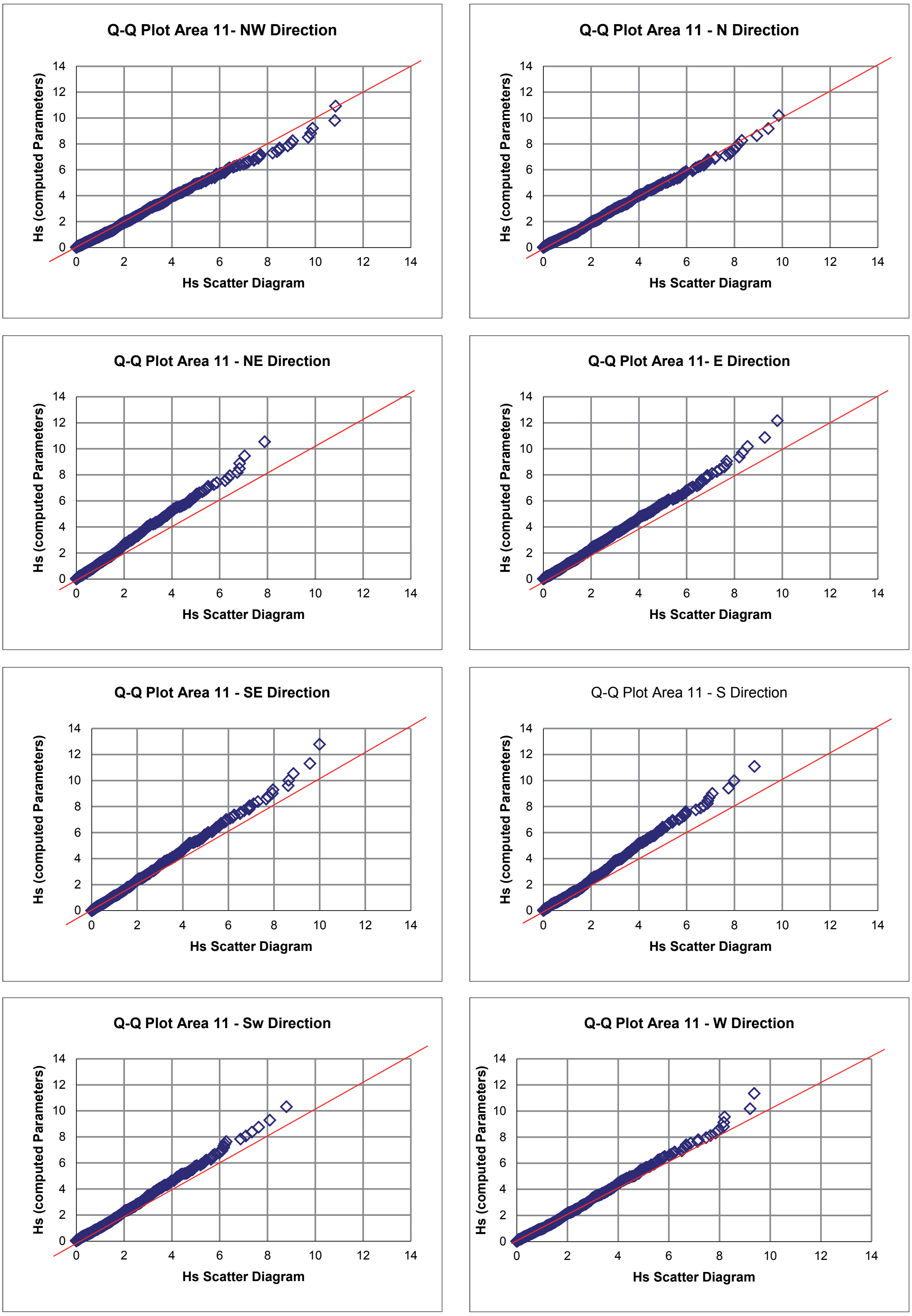


Figure 4-14: Q-Q plot of the directional Hs (m) data estimated with the scatter diagram for North-west, North, North-East, East, South-East, South, South-West and West

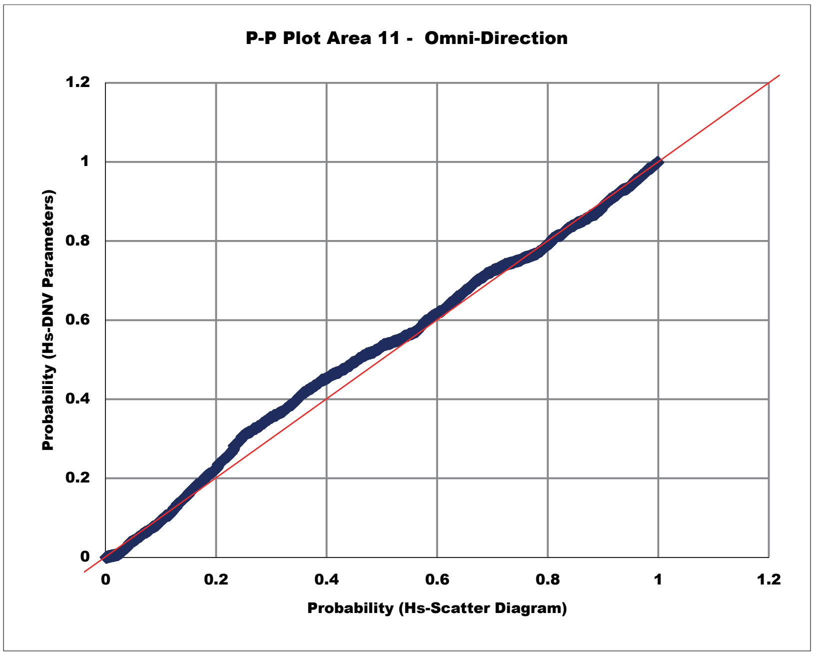


Figure 4-15: P-P plot of the DNV omni-directional Hs data with the scatter diagram

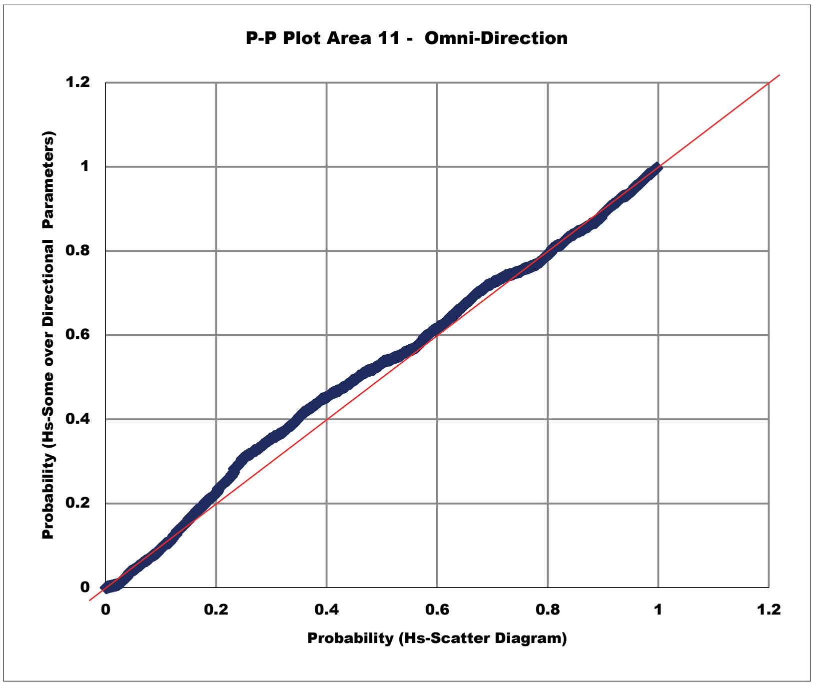


Figure 4-16: P-P plot of the combined directional predicted H_s data with the scatter diagram

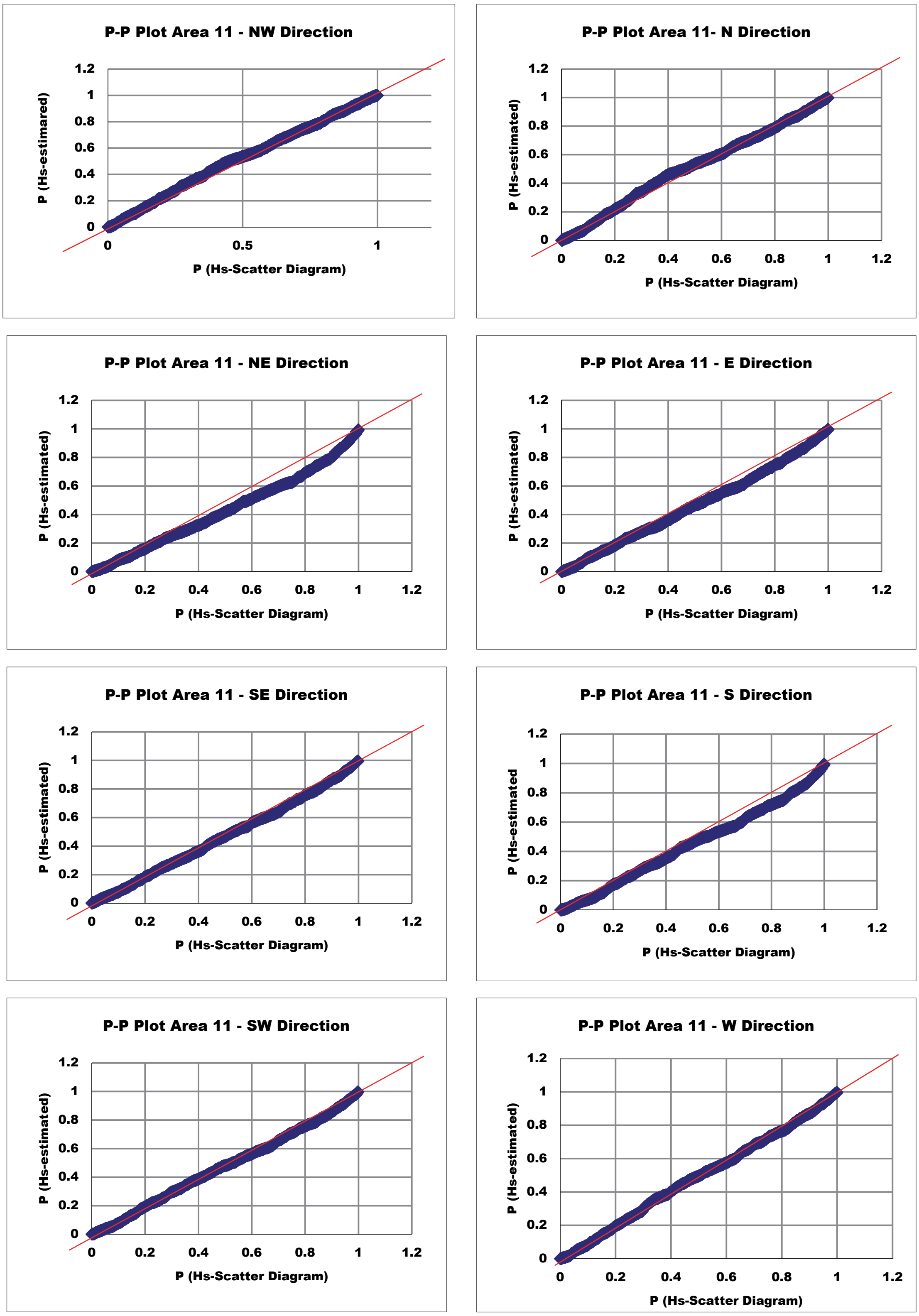


Figure 4-17: P-P plot of the directional Hs data estimated with the scatter diagram for North-west, North, North-East, East, South-East, South, South-West and West

4.4.2 Extreme wave conditions results

In addition to the verification of the fitting results with those of DNV presented above, computation of the extreme wave height for a 1000 years return period using the estimated combined distribution was performed and compared to that of DNV omni-directional. Data for Area 11 was used in this calculation.

Considering a return period of 3 hours per 1000 years, the value of H_s for the return period is calculated by equating the Weibull distribution with a chance of a three hours storm in 1000 years.

The wave height h which is expected to be exceeded is given by:

$$\begin{aligned} P(H_s > h) &= 1 - F_{H_S}(h) \\ &= e^{-\left(\frac{h}{\alpha}\right)^{\beta}} \\ &= P(3\ hours\ in\ 1000\ years) \end{aligned} \qquad \text{Eq. 4-15}$$

And the maximum wave height H_{max} is then computed as follows:

$$H_{max} = 1.86 \times H_s \qquad \text{Eq. 4-16}$$

Plotting H_{max} obtained using the probability distribution for the combined directions against the ones obtained using DNV's for the 104 areas gives the chart shown in Figure 4-18 below.

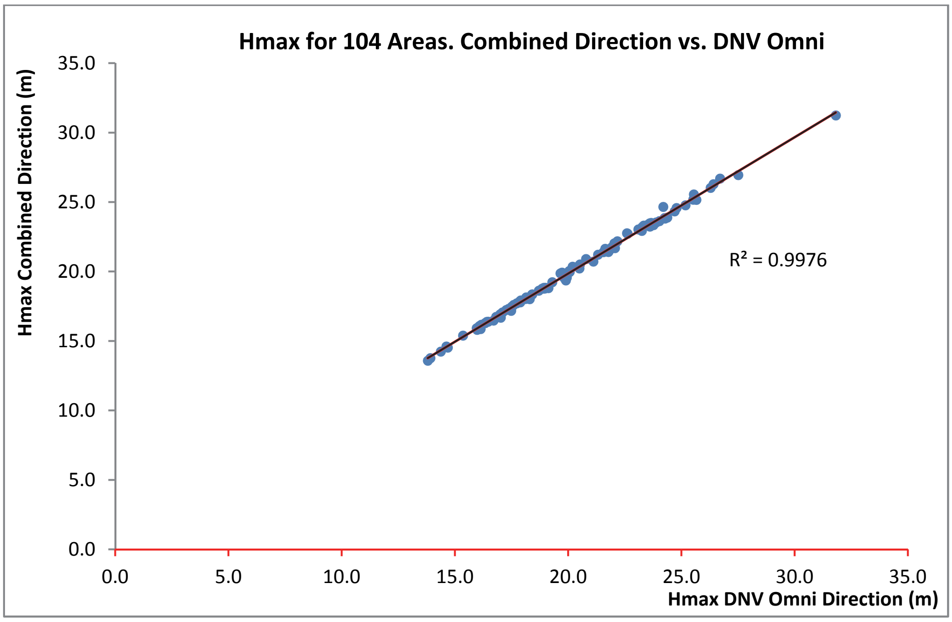


Figure 4-18 Area 11-Hmax; Combined directional data vs. DNV Omni direction

The values of H_{max} obtained from the combined directions are very close to those obtained from DNV omni- dierctional. For this data, the sum of the square errors (error could be due to fitting, computation, etc…) was found to be 1.24% which is almost insignificant.

4.5 SUMMARY

This chapter has presented analytical models for the wave environmental data for different sea areas derived from BMT's Global Wave's Statistics data. Using the advance maximum likelihood method, parameters of the mathematical model for the wave height and the wave period for each direction and for the 104 areas have been calculated. Using the estimated distribution parameters for the global wave model, data for the missing area for each direction have been derived.

The fitting of the significant wave height and conditional period-wave data to a Weibull and log-normal distributions respectively for each direction and area was performed.

Parameters for the univariate probability distribution model of significant wave height and the joint probability distribution of significant wave height, mean zero crossing period, maximal wave height during a sea state, have been estimated.

Results obtained from this analysis compared to DNV's results as well as the GWS data show a good agreement and the estimated parameters of the Weibull distribution for the individual directions are deemed a good approximation.

CHAPTER 5: SHIP STRUCTURAL DETAILS – Connection Catalogue

5.1 CLASSIFICATION OF SHIP STRUCTURAL DETAILS

5.1.1 Introduction

Ship structural details connect structural components that are parts of the basic hull girder. The structural components are designed for primary hull girder loading, and secondary axial forces, moments and shear forces, e.g. from locally applied pressures.

Ship structural details are important because:

- their layout and fabrication represent a sizable fraction of hull construction costs;
- details are often the source of cracks and local failure which can lead to serious damage to the hull girder;
- the trend towards decreasing ship hull scantlings has the potential of increasing the frequency and seriousness of cracks and failures at details;
- analysis of structural details has been neglected, partly because of large numbers of configurations, functions, etc.; and
- details influence the performance of the primary structural components.

This chapter deals with the classification of structural details for Oil Tanker and Bulk Carrier vessels. These two types of ships were chosen, as they are the ones most affected by structural degradation (Rispect 2008). It is an extension of the work done by the Ship Structure Committee (SSC et al. 1990), and Lloyd's Register (LR-Shipping 2013).

This chapter includes the principle details, gathered to propose a catalogue to be used for the description of the ship details and to be integrated into ship database and statistical database, as defined in following chapters 6-8.

This research proposes a different classification of structural connections and cracks to record efficiently inspection data.

Details are represented by their constituent elements (gussets, cuts-out, etc…) which reduces the number of connection types to record. The proposed new system allows for making use of the knowledge of the behaviour of one detail to predict the likely behaviour of similar details and the assessment of fatigue performance in comparison with expected fatigue performance can be compared and calibration factors for prediction models can be derived.

It is proposed to use this new system to replace the existing classification of structural details.

5.1.2 Vessel's Structure Subdivision

Corrosion and fatigue cracking are the most pervasive types of structural problems experienced by ship structures. Each of the damage modes, if not properly monitored and then corrected, can potentially lead to catastrophic failure or unanticipated out-of-service time. These problems are a major risk to the structural integrity of the vessels, especially tanker structures and bulk carriers.

To assess the damage that can occur to the vessel's structure, a *catalogue for vessel sub-division* (into parts and areas) *of the structural detail failures* is proposed in this section. The catalogue is based on IACS document "*Guidelines for Surveys, Assessment and Repair of Hull Structure"(IACS 1999).*

The vessel has been sub-divided into parts and areas to be given particular attention during the surveys (Figure 5-1):

Part 1 Cargo hold region

Area 1: Deck structures:

a) On deck

b) Under deck

Area 2: Top side tank structures;

Area 3: Side structures;

Area 4: Transverse bulkhead including stool structures;

Area 5: Double bottom including hopper tank structures;

i. **Part 2 Fore and aft end regions**

Area 1: Fore end structure;

Area 2: Aft end structure;

Area 3: Stern frame, rudder arrangement and propeller shaft support;

ii. **Part 3 Machinery and accommodation spaces**

Area 1: Engine room structure;

Area 2: Accommodation structure;

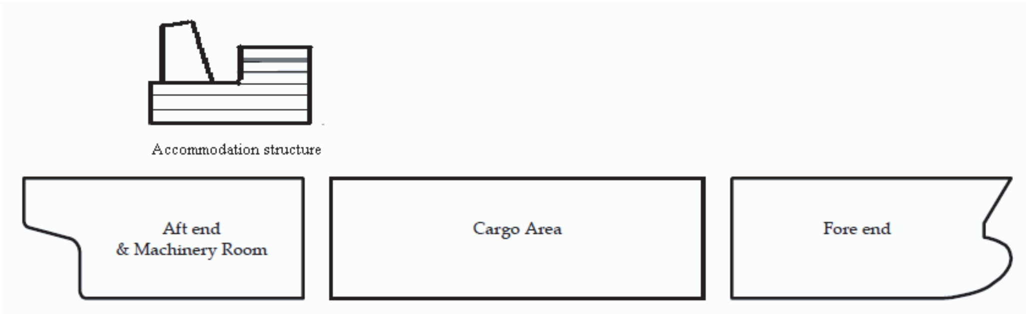


Figure 5-1 Vessel's Structure Subdivision

5.1.3 Ship Structural Details

There are hundreds of structural detail configurations in existence; this chapter will only provide examples of the most common details. The generic ship types dealt with are:

- Double hull Tankers
- Bulk Carriers

In order to find failure trends in the various features, structural details for the oil tanker and bulk carrier vessels reported in (Jordan et al. 1990), were grouped within each family according to their similar or related characteristics. Thus, each family is composed of two or more detail groups, containing related configurations, which were designed to perform the same function, but differ from each other in one or more geometric features. This grouping method resulted in twelve detail families being subdivided into forty-five separate groups with a total of 300 distinct configurations (189 for the cargo area) (see Table 5-1).

The detail variations are identified by their assigned position in the individual families, i.e., the first number(s) is the family number, the letter is the group number and the last number(s) is the variation number. Each family is presented according to the above grouping with sketch for each observed configuration. An over view of structural framing is illustrated in Table 5-1.

Considering the three parts of the ship, the total number for the different structural configurations recorded for the Bulk Carrier and Oil Tanker vessels is about 300 details. The cargo area (Part 1) for the two categories of vessels encloses 190 details as illustrated in Figure 5-2 below.

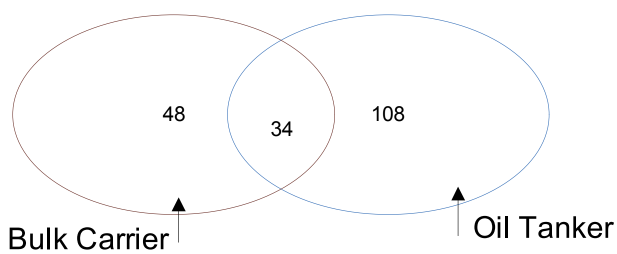
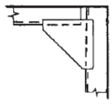
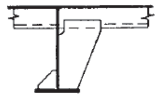
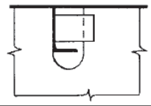
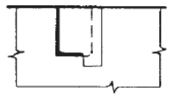
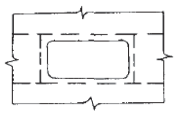
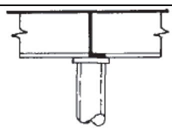
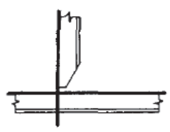


Figure 5-2: Details Repartition of Cargo Area

Table 5-1 Classification of ship structural details (adapted from (Jordan et al. 1985))

DETAIL FAMILLY N°	FAMILLY NAME	FUNCTION-PROVIDES	TYPICAL CONFIGURATION
1	BEAM BRACKETS	END CONSTRAINT FOR FRAMING	
2	TRIPPING BRACKETS	LATERAL SUPPORT	
3	NON-TIGHT COLLARS	SHEAR CONNECTION FOR CONTINUOUS FRAMING	
4	TIGHT COLLARS	SAME AS #3 AND A TIGHT PENETRATED PLATE	
5	GUNWALE CONNECTIONS	CONNECTION OF STRENGTH DECK TO SIDE SHELL	
6	KNIFE EDGE CROSSING	NO USEFUL FUNCTION (A PROBLEM TO AVOID)	
7	MISCELLANEOUS CUTOUTS	HOLES FOR ACCESS, DRAINAGE, EASE OF FABRICATION, CABLEWAYS, PIPES, AIR HOLES, ETC.	
8	STIFFENER CLEARANCE CUTOUTS	FOR PASSING ONE MEMBER THROUGH ANOTHER AND A SHEAR CONNECTION	
9	STRUCTURAL DECK CUTS	PASSAGE THROUGH DECKS FOR ACCESS, TANK CLEANING, PIPING, CABLES, ETC.	
10	STANCHION ENDS	LOAD PATH BETWEEN STANCHION AND DECK	
11	STIFFENER ENDS	DESIGNED END RESTRAINT LOAD CARRYING MEMBERS	
12	PANEL STIFFENERS	STABILITY TO PLATING	

5.1.4 Beam bracket details-family n°. 1

FUNCTION-PROVIDES: *"END CONSTRAINT FOR FRAMING"*

Variations in beam bracket configurations are grouped according to similar characteristics: continuous (groups A and B), corner (groups C, D, E, F and G), end (groups H, J and K), and transition (groups L, M, N and P). Details include:

1. *STRUCTURALLY CONTINUOUS – PHYSICAL INTERCOSTAL BEAMS*
   - Plate Bracket Without Bulkhead Stiffener
   - Built-Up Bracket Without Bulkhead Stiffener
   - Plate Bracket In Way of Bulkhead Stiffener
   - Built-Up Bracket In Way of Bulkhead Stiffener
   - Built-Up Bracket In Way of Girder

2. *STRAIGHT CORNER BRACKETS*
   - Plate
   - Flanged
   - Built-Up

3. *CURVED CORNER BRACKETS*
   - Plate
   - Built-Up

4. *HATCH GIRDER END BRACKETS - BEAM END BRACKETS*
   - At "Soft" Plating
   - At Structural Sections
   - Plates at Rigid Structure
   - Flanged at Rigid Structure
   - Built-up at Rigid Structure

5.1.5 Tripping Brackets Family N°2

FUNCTION-PROVIDES: *"Lateral Support"*

Tripping brackets used to prevent lateral instability failures of webs or flanges of longitudinal, beams or girders are placed in three general groups:

- Group "A' consists of single plate brackets on one side of the web only;
- Group "B" consists of single plate brackets of the same type located- on both sides of the web; and
- Group "C" consists of flanged brackets on one side of the web only.

5.1.6 Non-Tight Collars Details Family N°3

FUNCTION-PROVIDES: *"Shear Connection for Continuous Framing"*

The different variations of non-tight collars for the Oil Tanker and Bulk Carrier vessels were separated into three general groups, based on the method of attachment used to connect it to the through members:

- Group "A" has one connection to the through members;
- Group "B" has two connections to the through members; and
- Group "C" has three connections to the through members.

Details include:

a) Bars
b) Bulb Flats
c) Angles
d) Tees (A11, B5)

5.1.7 Tight Collars Details Family N°4

FUNCTION-PROVIDES: *"Same As #3 and a Tight Penetrated Plate"*

Different configurations for the tight collars recorded and classified in four family groups and include:

a) Bars
b) Angles

Note that group "D" contains slots, which accommodate through members and are considered as "tight collars" in this document.

5.1.8 Gunwale Connections Details Family N°5

<u>FUNCTION-PROVIDES:</u> *"Connection of Strength Deck to Side Shell"*

Throughout the history of ship design and construction, emphasis has been placed on the connection of the side shell strength deck in an effort to eliminate the possibility of crack propagation that could result on such catastrophic structural failure that the ship would be ultimately lost. These gunwale connections have been accomplished by either riveting or welding.

5.1.9 Knife Edge Crossing Details Family N°6

Not classified for the Oil Tanker and Bulk Carrier vessels.

5.1.10 Miscellaneous Cut-outs Details Family N°7

<u>FUNCTION-PROVIDES:</u> *"Holes for Access, Drainage, Ease Of Fabrication, Cableways, Pipes, Air Holes, Etc."*

Functional groups in the miscellaneous cut-out family are access openings, air escapes, drain holes, lapped web openings, lightening holes, pipeways, wireways, and weld clearances. Sketches of the miscellaneous details are represented in the eight family groups (A to H).

The family was deliberately limited to these cases in order to omit data on unique one-of-a-kind geometries.

Each individual detail is placed in only one group according to the detail's major function regardless of the number of duties it may fulfil on the ship.

Details include:

a) Access Openings
b) Lapped Web Openings
c) In Way of Corners
d) In Way of Plate Edge
e) Miscellaneous

5.1.11 Clearance Cut-outs Details Family N°8

<u>FUNCTION-PROVIDES</u>: *"For Passing One Member through Another and a Shear Connection"*

Each cut-out detail was placed in one of the four family groups (B, C, D and E) according to its geometrical shape or attachment to the interrupting structural member. Details include:

a) Bars
b) Angles

5.1.12 Structural Deck Cuts Details Family N°9

<u>FUNCTION-PROVIDES:</u> *"Passage Through Decks For Access, Tank Cleaning, Piping, Cables, Etc."*

The different deck cut-outs are represented in three groups A, B and C. Groups "A" and "B" are relatively small deck openings that are normally used for access. Group "A" has openings with the surrounding deck plate edges unsupported except by a stiffening member a few inches from the hole. Group "B" has the plate edges supported by a flat bar either centred with, or on one side of, the deck plating. Group "C" configurations are deck cuts at corners of large hatch openings.

5.1.13 Stanchion Ends Details Family N°10

<u>FUNCTION-PROVIDES:</u> *"Load Path between Stanchion and Deck"*

The different details for stanchion ends include the connections at the top of the circular stanchions, all of the stanchion bottom connections, and all of the connections at the top of "H" stanchions and classified in three groups.

5.1.14 Load Carrying Stiffener End Details Family N°11

<u>FUNCTION-PROVIDES:</u> *"Designed End Restraint Load Carrying Members"*

The stiffener ends included in this family are the ends of load carrying structural angles on tees that are attached to panels of plating. Details include:

a) Full Connection
b) Padded
c) Lapped
d) With End Chocks
e) With Clips

5.1.15 Panel Stiffeners Details Family N°12

<u>FUNCTION-PROVIDES:</u> *"Stability to Plating"*

Panel stiffeners include those structural angles, tees, and flat bars welded to large panels of plating for the explicit purpose of preventing local instability of the plate. They are non-direct load carrying members. According to its shape and the function of the structural member it is attached to, each of observed variations are classified in five groups and include:

a) Flat Bars
b) Shapes
c) Flat Bars on Girder Webs In Way of Longitudinal
d) Flat Bars on Girder Webs
e) Flanged

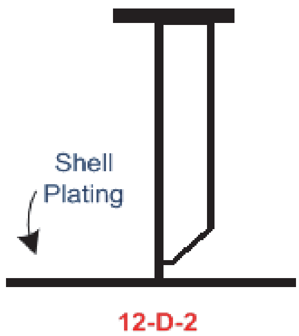


Figure 5-3: Representation of the detail number 12-D-2 (Oil Tanker)

Representation of details number for each family (oil tankers and bulk carriers) is illustrated in Appendix A.3.

5.2 DETAILS LOCATION ALONG THE VESSEL STRUCTURE

This section contains a table of data arranged by family group for each of the detail variations recorded for the Oil Tanker and Bulk Carrier vessels. The table gives general information about the location along the vessel structure “forward, aft and midship” for recorded details introduced earlier in the document. The midships (Mid) cover the entire cargo section. The following Figure 5-2 shows details-location for the Beam Brackets family. Each configuration is represented using:

1) Detail family number
2) Geometrical sketch
3) Location on ship
4) Position on the ship

Details location for other families are illustrated in Appendix A.3.

5.3 LOCATIONS AND POSITIONS DESCRIPTION

This study is focussing mainly on the cargo hold area of both Oil Tanker and Bulk Carrier vessel. The following Table 5-3 gives the common coding used to represent the compartments.

Table 5-2: Detail Family: Beam Brackets

Detail Family Number	Ship Type	Location on Ship		
1-A-5	**Tanker**		**Mid**	
1-A-6	**Tanker**		**Mid**	
1-A-9	**Tanker**	**Fwd**	**Mid**	**Aft**
1-B-1	**Tanker**		**Mid**	
1-B-3	**Tanker**		**Mid**	**Aft**
1-B-4	**Tanker**		**Mid**	**Aft**
1-B-5	**Tanker**		**Mid**	
1-B-6	**Tanker**		**Mid**	**Aft**
1-B-7	**Bulk Carrier**		**Mid**	
1-B-8	**Tanker**		**Mid**	
1-B-10	**Tanker**		**Mid**	**Aft**
1-B-11	**Tanker**		**Mid**	
1-B-13	**Bulk Carrier**		**Mid**	
1-C-9	**Bulk Carrier**	**Fwd**	**Mid**	**Aft**
1-C-17	**Bulk Carrier**	**Fwd**	**Mid**	
1-D-1	**Bulk Carrier**	**Fwd**	**Mid**	**Aft**
1-D-2	**Bulk Carrier**	**Fwd**	**Mid**	**Aft**
1-E-2	**Bulk Carrier**	**Fwd**	**Mid**	**Aft**
	Tanker		**Mid**	
1-E-7	**Tanker**		**Mid**	**Aft**
1-F-1	**Tanker**		**Mid**	
1-F-2	**Tanker**		**Mid**	
1-H-7	**Bulk Carrier**	**Fwd**	**Mid**	
1-H-8	**Bulk Carrier**	**Fwd**	**Mid**	**Aft**
1-J-4	**Bulk Carrier**		**Mid**	
1-J-6	**Bulk Carrier**		**Mid**	
1-K-4	**Tanker**		**Mid**	
1-K-6	**Tanker**		**Mid**	
1-L-4	**Bulk Carrier**		**Mid**	
1-N-1	**Bulk Carrier**		**Mid**	
1-N-5	**Bulk Carrier**		**Mid**	
1-P-1	**Tanker**		**Mid**	
1-P-4	**Bulk Carrier**		**Mid**	

Table 5-3: Coding of compartment

n	Compartment type	Symbol
1	Ballast	B
2	Dry Cargo	D
3	Liquid Cargo	L
4	Liquid Cargo/Ballast	X
5	Dry Cargo/Ballast	Y

5.4 CLASSIFICATION OF CRITICAL LOCATIONS & DETAILS *(Bulk Carrier & Tanker)*

5.4.1 Structural Damage and Deterioration

IMO-IACS Guidelines (IMO 2004) define structural damages and deterioration as being caused by:

- excessive corrosion;
- design faults;
- material defects or bad workmanship;
- navigation in extreme weather conditions;
- loading and unloading operations, water ballast exchange at sea;
- wear and tear;
- contact (with quay side, ice, touching underwater objects, etc.).

and not as a direct consequence of accidents such as collisions, groundings and fire/explosions.

Deficiencies are considered to be:

- Material wastage;
- Fractures;
- Deformations.

Material wastage is essentially caused by *corrosion*, which can be:

- General, and in this case it appears as friable rust, which can form uniformly on uncoated internal surfaces of hold or tank. The layer of rust continually breaks off, exposing more metal to corrosive attack. Usually thickness loss cannot be evaluated visually until excessive loss has occurred. Mill scale when left during construction of the ship can accelerate corrosion during the service life. Severe general corrosion in all types of ships, can lead to insufficient strength and the need for extensive steel renewals.

Figure 5-4: Corrosion in way of the buckled lower end of the web in a lower wing tank (Adapted from Amtec)

- Grooving corrosion often found in or beside welds is caused by the galvanic current generated from the difference of the metallographic structure between the heat affected zone and base metal. Because welds coating is generally less effective compared to other areas due to roughness of the surface, this can worsen the corrosion. Grooving corrosion may lead to stress concentrations and further accelerate the corrosion process. Grooving corrosion may be found in the base material where coating has been scratched or the metal itself has been mechanically damaged.
- Pitting corrosion is often found in the bottom plating or in horizontal surfaces in ballast tanks. It normally starts due to local breakdown of coating and takes the form of cavities limited to a point or small area. Once pitting corrosion starts it is heightened by the galvanic current between the pit and other metal.

Figure 5-5: Pitted steel surface (Adapted from SteelConstruction.info)

Erosion (wearing effect of flowing liquid) in conjunction with corrosion and abrasion, (caused by mechanical actions), could also be a cause of material wastage.

Fractures are found in most cases, at locations where stress concentration occur. (Technology 2012). Weld defects, flaws, and where lifting fittings used during ship construction are not properly removed are often areas where fractures are found. Additionally, they can occur in way of notches, openings or slots. Fractures that grow under repeated stresses, which are below the yielding stress, are called fatigue fractures (IMO 2004).

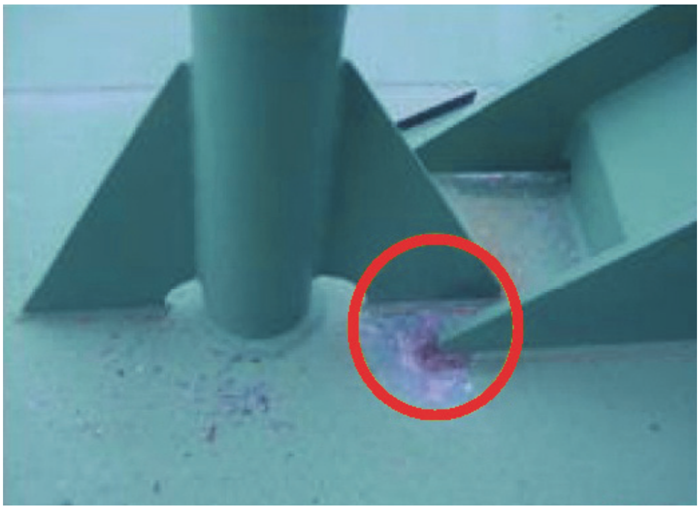


Figure 5-6: Cracks at the toe of the brackets (Original Picture Adapted from officerofthewatch.com)

Fatigue may start at a single point or several points, depending on the shape of the critical section and the type of loading (Molzen et al. 2000). When a component is subjected to torsion and/or bending loads, tensile stress is highest at the surface of the material, which is where the overwhelming majority of cracks initiate. In addition to the cyclic stresses induced by wave forces, fatigue fractures can also result from vibration forces introduced by main engine(s) or propeller(s), especially in the afterward part of the hull. Fracture initiating as latent defects in welds more commonly appears at the beginning or end of a run of welds, or rounding corners at the end of a stiffener, or at an intersection. Special attention should be paid to welds at toes of brackets, at cutouts, and at intersections of welds (Bostina et al. 2012).

Undercutting the weld in way of stress concentrations could also contribute to the initiation of a fracture. Although now less common as they have been found to be susceptible to corrosion related damage, intermittent welding may cause problems because of the introduction of stress concentrations at the ends of each length of weld (IACS 1999).

Fatigue crack and failure are often considered to be the most serious type of defect in working parts, as they occur during normal service without overloaded (Lovejoy 1993). Fatigue crack can lead to failure without warning if it is not detected and maintained at an early stage, which is not always easy. Fractures and in particular fatigue fractures due to repeated stresses, could lead to serious damages such as the loss of watertight integrity.

A fracture or crack that has extended under the effect of fatigue may become unstable and grow rapidly when a critical crack length is reached, at a specific applied load. This unstable 'fast' fracture mechanism may be brittle or ductile in its nature, depending on the material properties and the temperature at the time of the fast fracture. The rate of crack propagation depends on many factors, such as: (1) material, (2) environment, (3) service load history, (4) crack geometry, (5) local structural configuration (Toor et al. 1995).

As ships operate in different environment around the world, most of their structural components are subjected to fluctuating load and invariably operate in various environments. Tour et al. (1995) highlighted the importance of behaviour of metals in various environments, and refer- the corrosion fatigue behaviour of a given environment-material system, to the characteristics of the material under fluctuating loads in the presence of a particular environment.

Figure 5-7: Merchant vessel 'Mol Comfort' splits into two off Mumbai coast, crew rescued June 2013 (Original Pictures adapted from felixstowedocker.blogspot.co.uk)

IMO-IACS Guidelines (IMO 2004) pointed that d*eformation* of structure is caused by in-plane load, out-of-plane load or combined loads. Such deformation is often identified as local deformation, (deformation of panel or stiffener), or global deformation, (deformation of beam, frame, girder or floor, including associated plating).

If in the process of the deformation large deformation is caused due to small increase of the load, the process is called buckling.

Deformations are often caused by impact loads/contact and inadvertent overloading. Damages due to bottom slamming and wave impact forces are, in-general, found in the forward part of the hull, although stern seas have resulted in damages in way of the after part of the hull.

In the case of damages due to contact with other objects damages to the shell plating may look small from the outboard side but in many cases the internal members are heavily damaged.

Permanent buckling may arise as a result of overloading, overall reduction in thickness due to corrosion, or contact damage. Elastic buckling will not normally be directly obvious but may be detected by evidence of coating damage, stress lines or shedding of scale. Buckling damages are often found in webs of web frames or floors. In many cases, this may be attributed to corrosion of webs/floors, wide stiffener spacing or wrongly positioned lightening holes, manholes or slots in webs/floors.

There are three modes of buckling (Camotim et al. 2000; DNV 2004):

1) *Flexural Buckling* (also called Euler Buckling) where members are subject to flexure, or bending, when they become unstable.
2) *Local Buckling* occurs when some parts of the cross section of column are so thin that they buckle locally in compression before the other modes of buckling can occur.
3) *Flexural torsional buckling* may occur in columns that have certain cross sectional configurations. These columns fail by twisting (torsion) or by a combination of torsional and flexural buckling.

There are six primary modes of stiffened panel collapse that could be mentioned, namely:

1. *Mode I:* Overall collapse of plating and stiffeners as a unit;
2. *Mode II:* Collapse under predominantly biaxial compression;
3. *Mode III:* Beam-column type collapse;
4. *Mode IV:* Local buckling of stiffener web;
5. *Mode V:* Tripping of stiffener;
6. *Mode VI:* Gross yielding

The inadvertent overloading might cause significant damages. In general, however, major causes of damages are associated with excessive corrosion and contact damage (IMO 2004).

5.5 FATIGUE CRACK LOCATION & ORIENTATION IN TYPICAL TANKER STRUCTURE

The following figure (Figure 5-8) describes a few typical crack location and orientation for tanker structure.

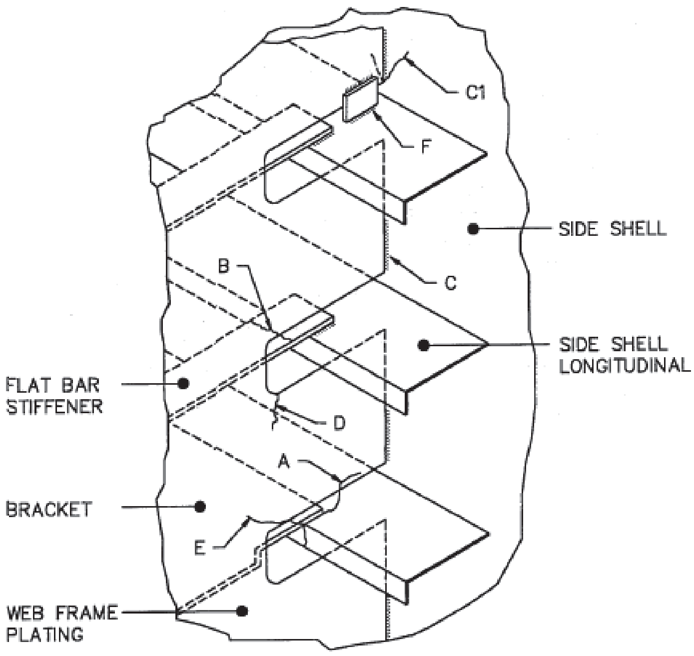


Figure 5-8 Typical example of fatigue cracking in ship structural details (adapted from (Stambaugh et al. 1994))
A Longitudinal, B Flat Bar Stiffener Crack, C Shell Plate to Web Weld Cracked, C1 Crack extending into shell plate, D Web frame Cracked, E Bracket Cracked, F Lug cracked (Typical detail)

5.5.1 Fatigue Crack Location & Orientation in Typical Bulk Carrier Structure

The following figure illustrates typical crack location and orientation for bulk carrier structure.

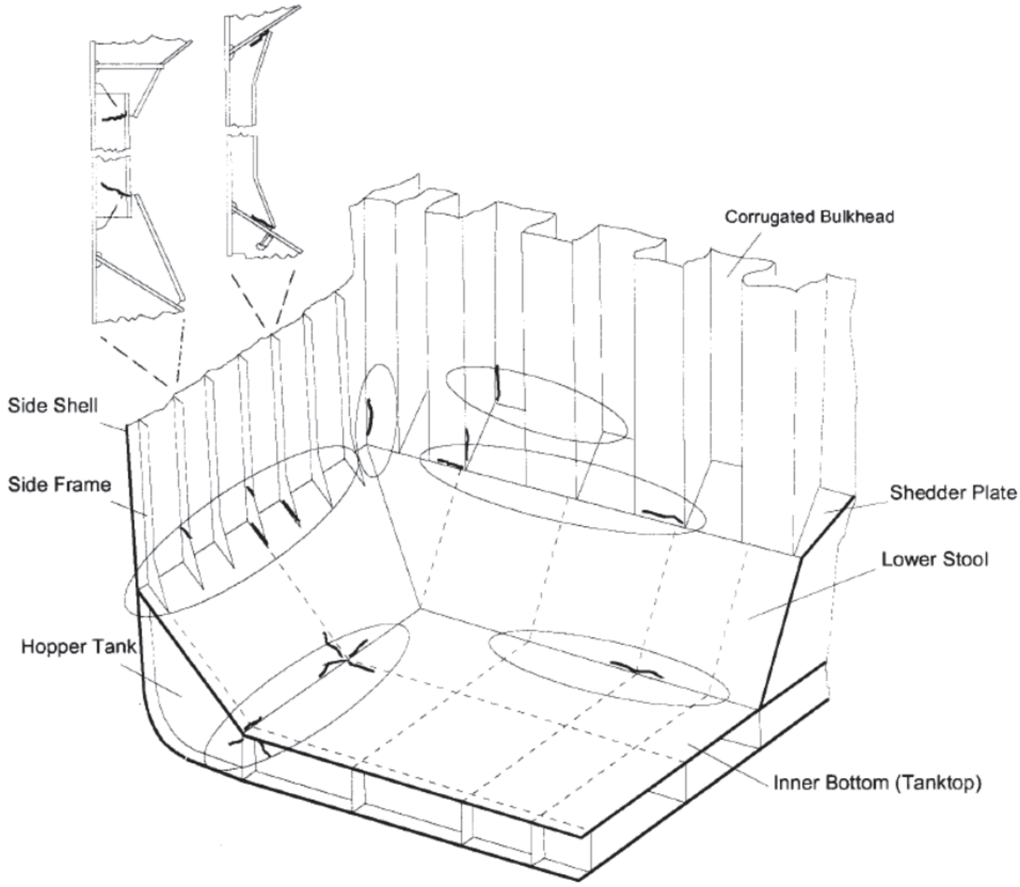


Figure 5-9 Fatigue Crack Location & Orientation in Typical Bulk Carrier Structure (adapted from (Glen et al. 1999))

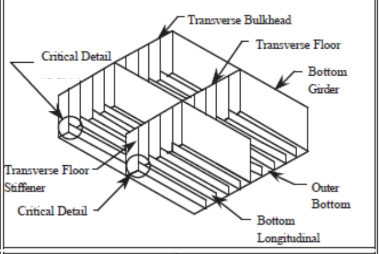
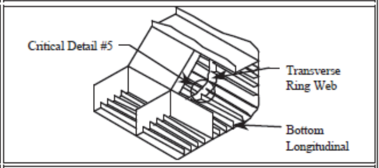
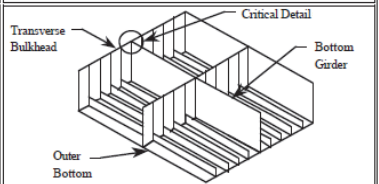
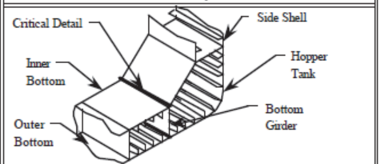
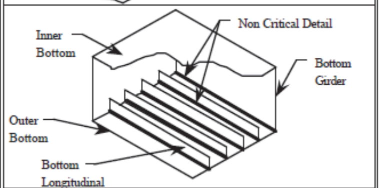
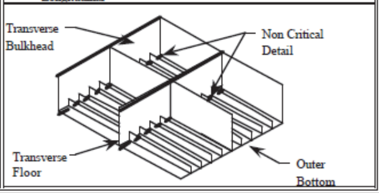
Cracking begins in small imperfections where the material is most stressed (could be near the surface and in conjunction with indentations).

Cracks formed due to fatigue will continue to grow until the point where the remaining material cannot support the given load. At that point, the material will shear off.

5.5.2 Critical Structural Details for Ship

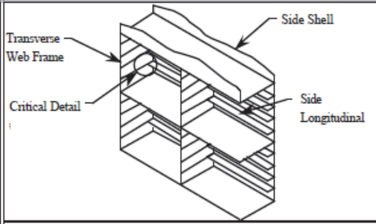
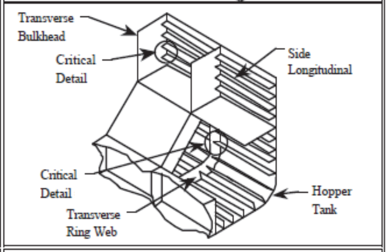
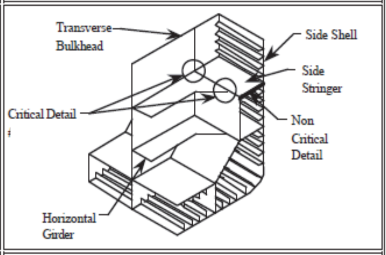
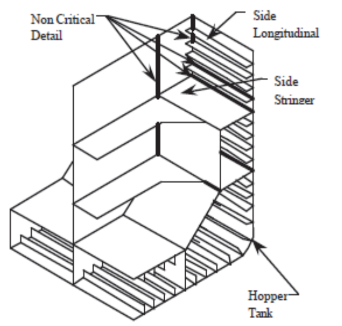
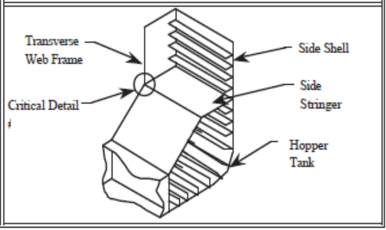
The following Table 5-4 illustrates Critical Structural Details for Double Bottom structure.

Table 5-4 Critical Structural Details for Double Bottom (LR-Shipping 1996)

<table>
<tr><th colspan="2">Critical Structural Details</th><th></th><th>Detail Figure</th></tr>
<tr><td rowspan="2">Inner/Outer Bottom Longitudinals</td><td>Transverse Floor Stiffener
- Asymmetric Longitudinal
- Symmetric Longitudinal</td><td></td><td rowspan="2"></td></tr>
<tr><td>Transverse Bulkhead
- Plane Oil Tight Transverse Bulkhead
- Corrugated Oil Tight Transverse Bulkhead</td><td></td></tr>
<tr><td>Bottom Longitudinals</td><td>Transverse Ring Web
- Transverse Ring Web Tripping Bracket</td><td></td><td></td></tr>
<tr><td>Bottom Girders</td><td>Transverse Bulkhead
- Plane Oil Tight Transverse Bulkhead
- Plane Oil Tight Transverse Bulkhead Vertical Stiffener End Brackets and High Strength Steel Girders</td><td></td><td></td></tr>
<tr><td rowspan="5">Inner/Outer Bottom Plating</td><td>Hopper Tank and Tranverse Floor
- Welded Knuckle
- Radiused Knuckle</td><td></td><td></td></tr>
<tr><td>Bottom Longitudinal</td><td></td><td rowspan="2"></td></tr>
<tr><td>Bottom Girder</td><td></td></tr>
<tr><td>Transverse Floor</td><td></td><td rowspan="2"></td></tr>
<tr><td>Transverse Bulkhead</td><td></td></tr>
</table>

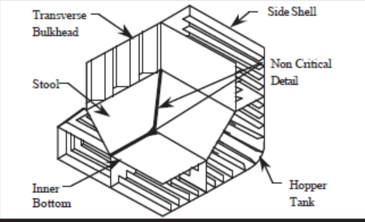
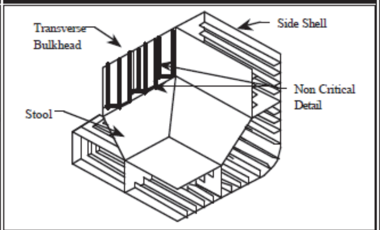
The following Table 5-5 illustrates Critical Structural Details for Double Side Structure.

Table 5-5 Critical Structural Details for Double Side (LR-Shipping 1996)

<table>
<tr><th colspan="2">Critical Structural Details</th><th></th><th>Detail Figure</th></tr>
<tr><td rowspan="3">Side Shell Longitudinals</td><td>Transverse Web Frame Stiffener
- Asymmetric Longitudinal
- Symmetric Longitudinal</td><td></td><td></td></tr>
<tr><td>Transverse Ring Web
- Transverse Ring Web Tripping Bracket</td><td></td><td rowspan="2"></td></tr>
<tr><td>Transverse Bulkhead
- Transverse Bulkhead Horizontal Stiffener</td><td></td></tr>
<tr><td rowspan="2">Side Stringers</td><td>Transverse Web Frames</td><td></td><td rowspan="2"></td></tr>
<tr><td>Transverse Bulkhead
- Plane Oil Tight
- Corrugated Oil Tight</td><td></td></tr>
<tr><td rowspan="5">Side Shell Plating</td><td>Hopper/Topside Tank</td><td></td><td rowspan="5"></td></tr>
<tr><td>Side Longitudinals</td><td></td></tr>
<tr><td>Side Stringers</td><td></td></tr>
<tr><td>Transverse Web Frames</td><td></td></tr>
<tr><td>Transverse Bulkhead</td><td></td></tr>
<tr><td>Transverse Web Frames</td><td>Hopper/Topside Tanks
- Welded Side Longitudinal Bulkhead Plating
- Knuckled Side Longitudinal Bulkhead Plating</td><td></td><td></td></tr>
</table>

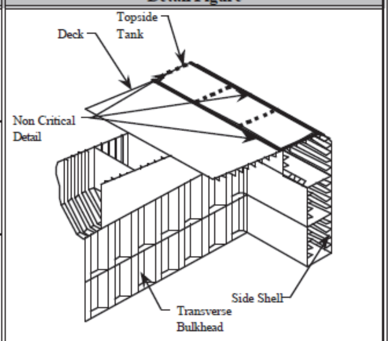
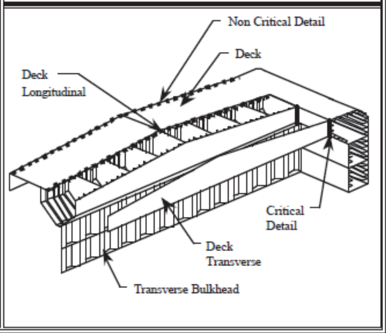
The following Table 5-6 illustrates Critical Structural Details for Transverse Bulkhead structure.

Table 5-6 Critical Structural Details for Transverse Bulkhead (LR-Shipping 1996)

Critical Structural Details			Detail Figure
Upper/Lower Bulkhead Stool	Deck/Bottom Plating		
	Topside/Hopper Tanks		
Transverse Bulkhead	Upper/Lower Bulkhead Stool		
Transverse Bulkhead Plating	at Corrugations		

The following Table 5-7 illustrates Critical Structural Details for Deck structure.

Table 5-7 Critical Structural Details for Deck (LR-Shipping 1996)

Critical Structural Details			Detail Figure
Deck Plating	Topside Tank		
	Side Shell Plating		
	Transverse Web Frame		
Deck Transverse End Brackets	Transverse Web Frames - Toe Connection		
Deck Transverse	Deck Longitudinals		

5.6 CRACK TYPE DEFINITION

5.6.1 First approach

The first approach to define the crack discussed in this section, is based on data from different studies undertaken within the shipping domain (Jordan et al. 1979; Glen et al. 1999), and extended in this research. This approach focuses on the definition of the cracks for each single component of the structure, this could end with a large number of cracks types, which would be very difficult to handle, especially in term of data inspection record and storage.

The following table and examples illustrate the idea behind the first approach.

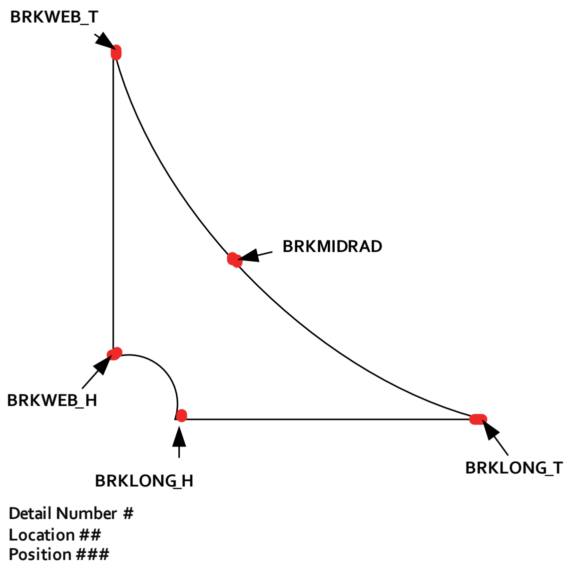


Figure 5-10. Crack Types at Brackets

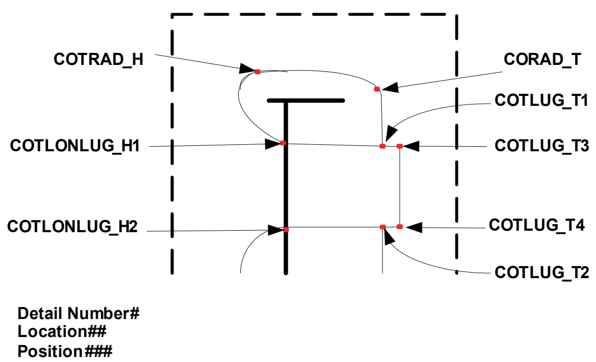


Figure 5-11. Crack Types at Cutout

Table 5-8. First Approach for the crack definition

	Description	**Short name**
1	Bottom Girder Flange Crack	CRBGF
2	Bottom Girder Plating Crack	CRBGP
3	Bottom Longitudinal Flange Crack	CRBLF
4	Bottom Longitudinal Web Crack	CRBLW
5	Bottom Plating Crack	CRBPL
6	Bracket Crack	CRBRK
7	Bottom Transverse Flange Crack	CRBTF
8	Bottom Transverse Web Crack	CRBTW
9	Deck Girder Flange Crack (Beam)	CRDGF
10	Deck Girder Web Crack	CRDGW
11	Deck Longitudinal Flange Crack	CRDLF
12	Deck Longitudinal Web Crack	CRDLW
13	Deck Plating Crack	CRDLP
14	Flat Bar Crack	CRFBC
15	Inner Bottom Plating Crack	CRIBP
16	Inner Bottom Floor Plating Crack	CRILF
17	Inner Bottom Longitudinal Flange Crack	CRILF
18	Inner Bottom Longitudinal Web Crack	CRILW
19	Inner Bottom Transverse Flange Crack	CRITF
20	Inner Bottom Transverse Web Crack	CRITW
21	Longitudinal bulkhead longitudinal flange Crack	CRLBF
22	Longitudinal bulkhead plating Crack	[illegible]
23	Longitudinal bulkhead longitudina[illegible]	
24	Other Cra[illegible]	
25		

OTHER ACRONYMS

Table 5-9. Other acronyms for crack definition

CUT OUTS	**COT**
HEEL	**H**
LONGITUDINAL	**LON**
LUG	**LUG**
OPENING, HOLES	**OPN**
PLATE	**PLT**
PILLARS	**PLR**
RADIUM	**RAD**
SEAMS	**SEM**
TRANSVERSE	**TRA**
TOE	**T**
WEB FRAME	**WEB**
others ++	

Example:

a) *BRKWEB_T:* Crack at the end bracket (Toe) connection with web.

b) *BRKWEB_H:* Crack at the notch (Heel) connection with web.

c) *BRKLON_T:* Crack at the end bracket (Toe) connection with web.

And so on….

The first tentative alternative was to use the first approach by replacing the crack acronym with a simplified one that could be used for the data storage. This would not reduce the number of crack types to define nor the number of connections. Figure 5-12 and Figure 5-13 give respectively an example of crack types at beam bracket details and the first approach for the storage of crack data. Table 5-10 summarises the data recorded proposed for the first approach.

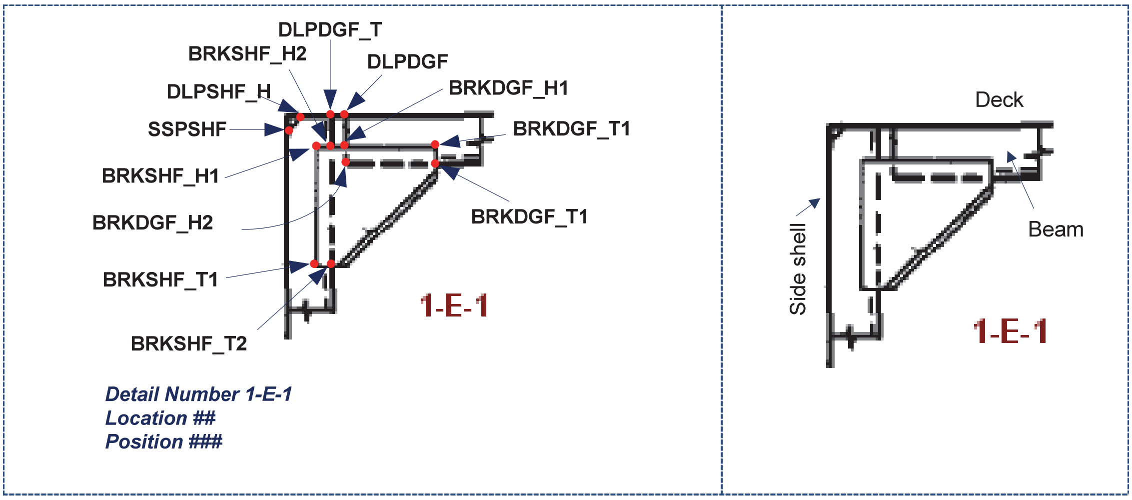


Figure 5-12. Crack Types at Beam Bracket Details (1-E-1)

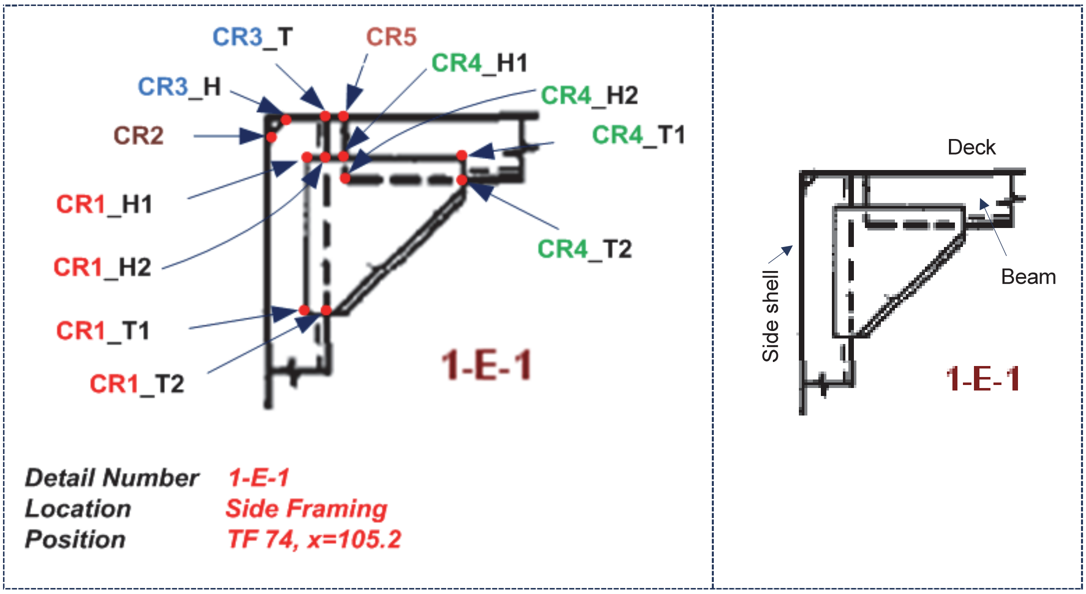


Figure 5-13. First Approach for the Storage of crack data

Table 5-10. First approach, crack data record

Frame n°	*Beam n°*	*Side*	*Crack type*	*Crack Dimension/Direction*					
				x1	*y1*	*z1*	*x2*	*y2*	*z2*
...									

The definition used in this attempt will need a very complex database to store the data recorded. It would not be easy also for ship inspector to remember all the crack details that have been defined according to each structural detail. Due to the complexity of this first approach, in term of number of crack types to be defined, which would be very difficult to handle, costly and time consuming to record the associated data, it has been decided to work out a less complex approach. This second approach, discussed in the next section, is aiming at simplifying the number of crack types defined, and rather than focusing on the different structural elements, the second approach considers the structural connections that will be assessed on the basis of the forces that are the most important for each part of the connection.

5.6.2 Second Approach

This approach is aiming at:

1) Simplifying the complexity of the connection and crack types definition and data inspection records, data storage and retrieval.

2) Providing a classification system that allows inferences to be made between different connection details that nevertheless have some similarity.

A substantial change in the connection type definition and a reordering and addition of cracks type has been introduced.

5.6.2.1 Crack Introduction Logic

- The structural connections will be assessed based on the forces that are the most important for each part of the connection.
- For stiffener connections and fatigue of the stiffener or supporting gussets the most important forces are in the stiffener closest to that part of the connection.
- Looking along any particular stiffener the connection may look like a corner, a stem or top of a tee or an X.
- The same connection may appear as a Tee stem from one stiffener or a Tee top from another stiffener.

- The crack type definition as presented in
- Table 5-8 and Table 5-9 define how possible types of crack are introduced in the analysis.

5.6.2.2 *Crack Type General Definition*

The following Table 5-11 gives a general definition of the crack types used for the second approach.

Table 5-11. Crack type definition

Acronym	Designation
T1	**Toe Crack perpendicular to member**
T2	**Toe Crack parallel to member**
T3	**Toe End bracket and parallel to member**
T4	**End bracket and perpendicular to member**
H1	**Heel Crack perpendicular to member**
H2	**Heel Crack parallel to member**
H3	**Heel End bracket and parallel to member**
H4	**Heel End bracket and perpendicular to member**

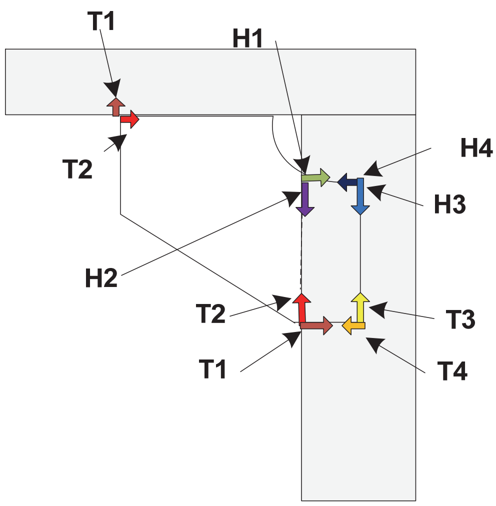


Figure 5-14. Cracks Type General Definition

The definition and use of crack types are summarised in Table 5-12 Illustrations of the different types of crack are shown in Figure 5-15 to Figure 5-21.

Table 5-12. Definition and Use of Cracks Type

Acronym		Designation
1	T1L	Toe Crack 1 at Lap joint
2	T1B	Toe Crack 1 at Butt joint
3	T2	Toe Crack 2
4	T3E	Toe Crack 3 at end of Edge stiffener
5	T3S	Toe Crack 3 at end Side stiffener
6	H1L	Heel Crack 1 at Lap joint
7	H1B	Heel Crack 1 at Butt joint
8	H2	Heel Crack 2
9	H3	Heel Crack 3
10	C1	Cutout Crack 1
11	C2	Cutout Crack 2
12	C3	Cutout Crack 3
13	C4	Cutout Crack 4
14	C5	Cutout Crack 5
15	C6	Cutout Crack 6
16	C7	Cutout Crack 7
17	C8	Cutout Crack 8
18	P1	Plate Crack 1
19	P2	Plate Crack 2
20	P3	Plate Crack 3
21	P4	Plate Crack 4
22	P5	Plate Crack 5
23	R1	Radius Crack 1
24	R2	Radius Crack 2
25	R3	Radius Crack 2
26	S1	Bend/Swaged Flange Crack1
28	C9	Cutout Crack 9
29	C10	Cutout Crack 10
30	C11	Cutout Crack 11
31	C12	Cutout Crack 12
32	B1	Crack Type B1
33	B2	Crack Type B1

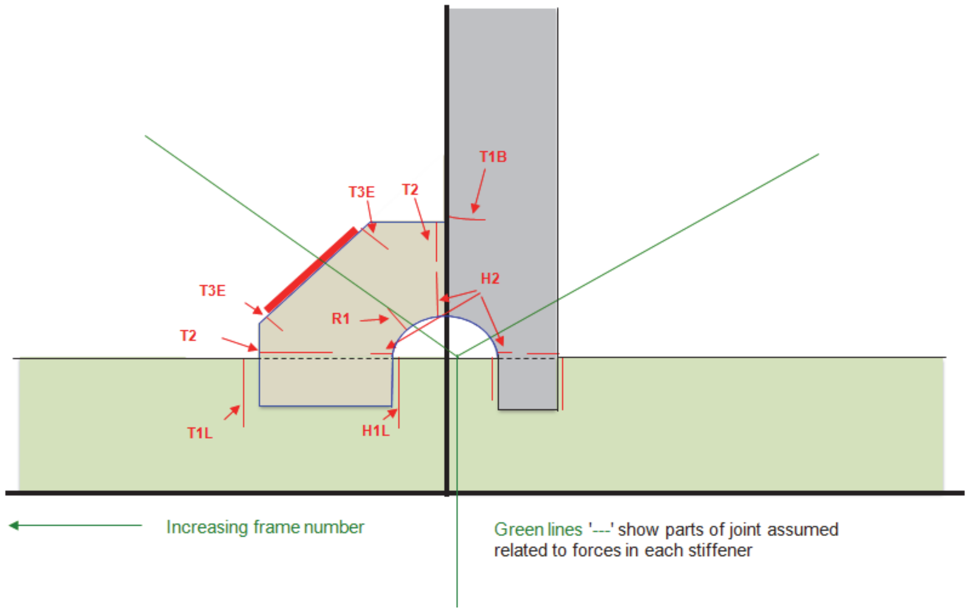


Figure 5-15. Illustration of TL1, T1B, T2, T3E, H1L, R1 and H2 Crack Types (see Table 5-12)

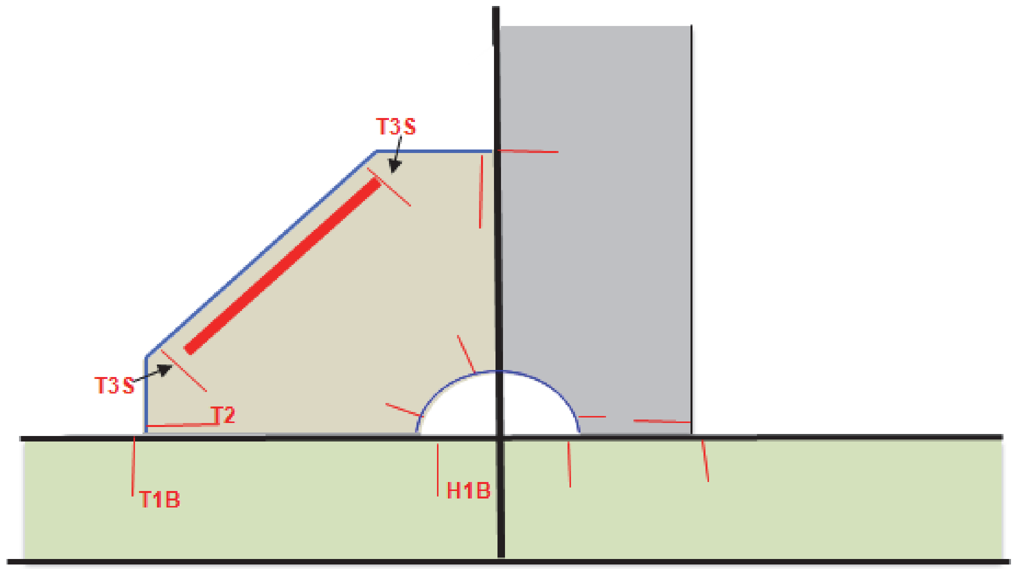


Figure 5-16. Illustration of T3S, T1B, H1B and T2 crack Types (see Table 5-12)

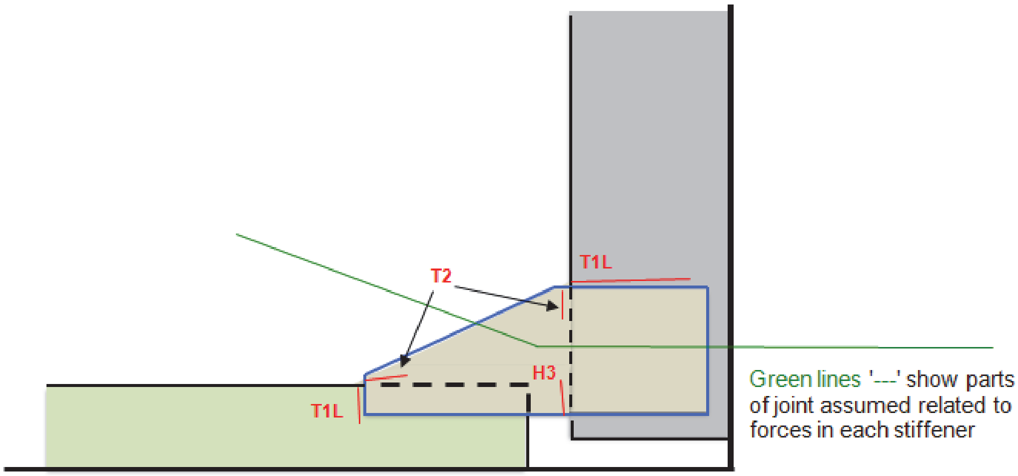


Figure 5-17. Illustration of H3, T1L and T2 Crack Types

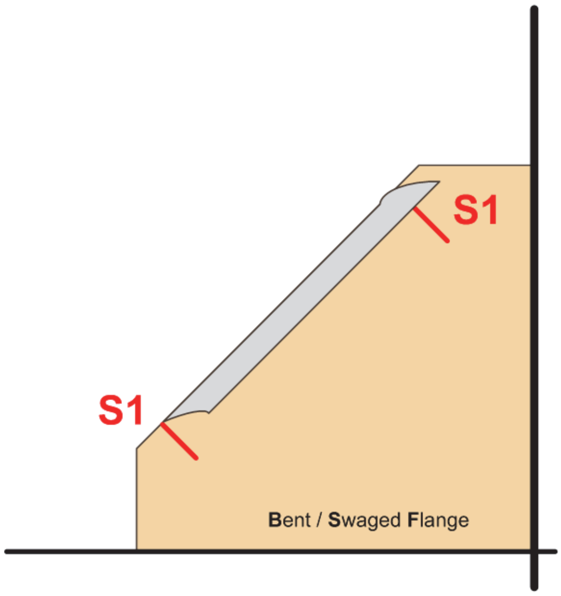


Figure 5-18. Illustration of S1 Crack Type

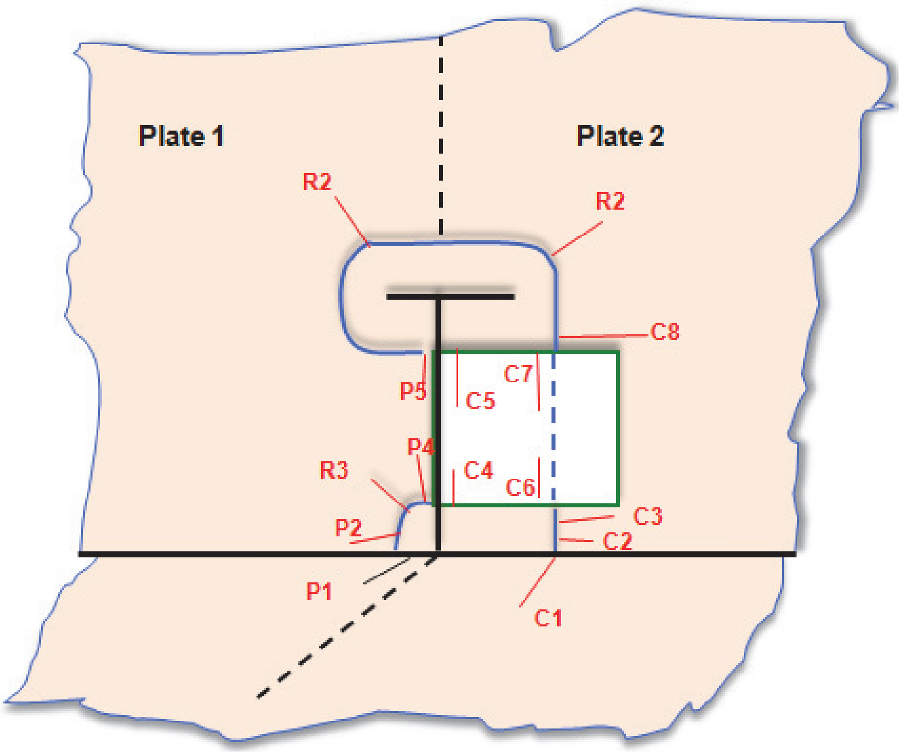


Figure 5-19. Illustration of C1-C8, P1, P2, P4, P5, R2 and R3 Crack Types (see Table 5-12)

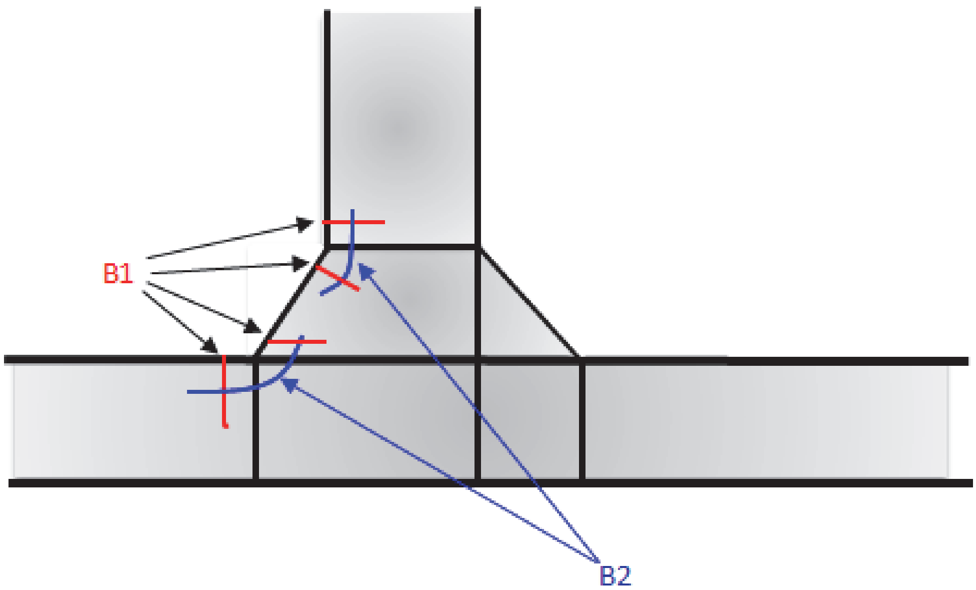


Figure 5-20. Illustration of B1, B2 Crack Types

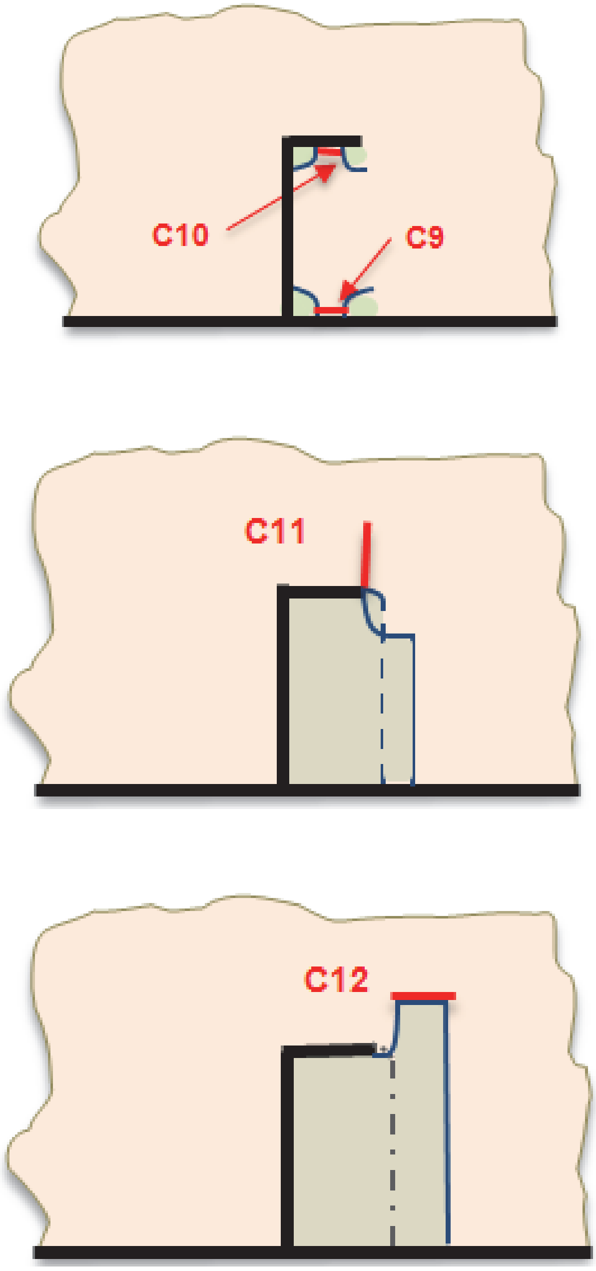


Figure 5-21. Illustration of C10-C12 Crack Types

5.6.2.3 Definition of Connection Type

1. **<u>Overall connection type</u>**

Detail	*Description*
1.1	Corner
1.2	T stem
1.3	T top
1.4	X

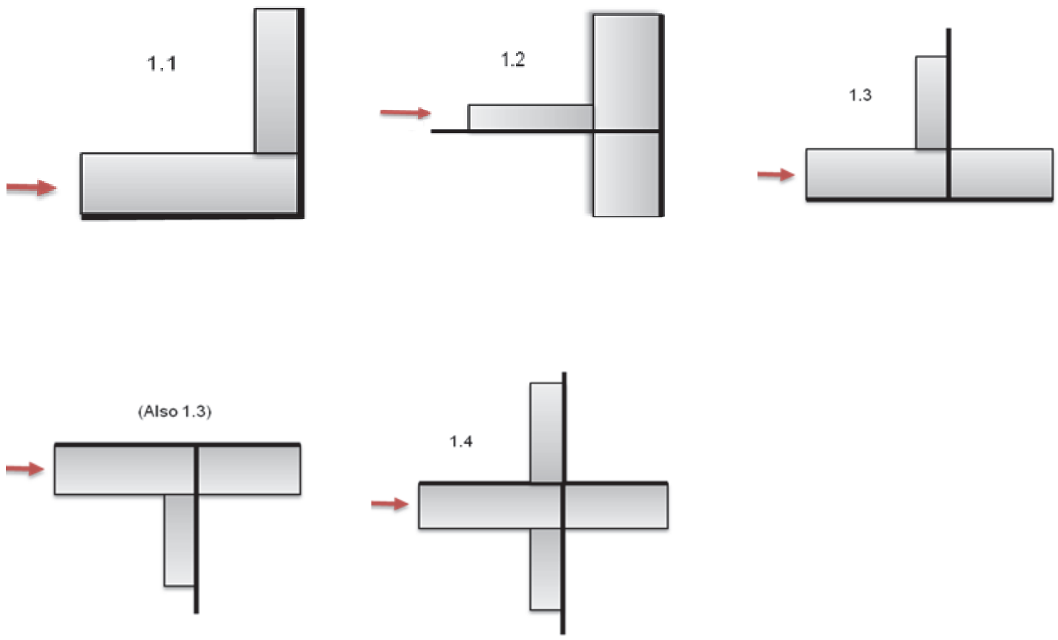


Figure 5-22. Overall connection types

2. Primary Stiffener connection

Detail	Description	Cracks introduced(Crack Types)
2.1	Cut	H1, H2
2.2	Cut & lapped	T1, T2, H1, H2
2.3	Continuous	T1, H1
2.4	Full flange no web stiffener	B1, B2
2.5	Full flange + web stiffener	B1, B2
2.6	Frame end	T1, T2, H1, H2

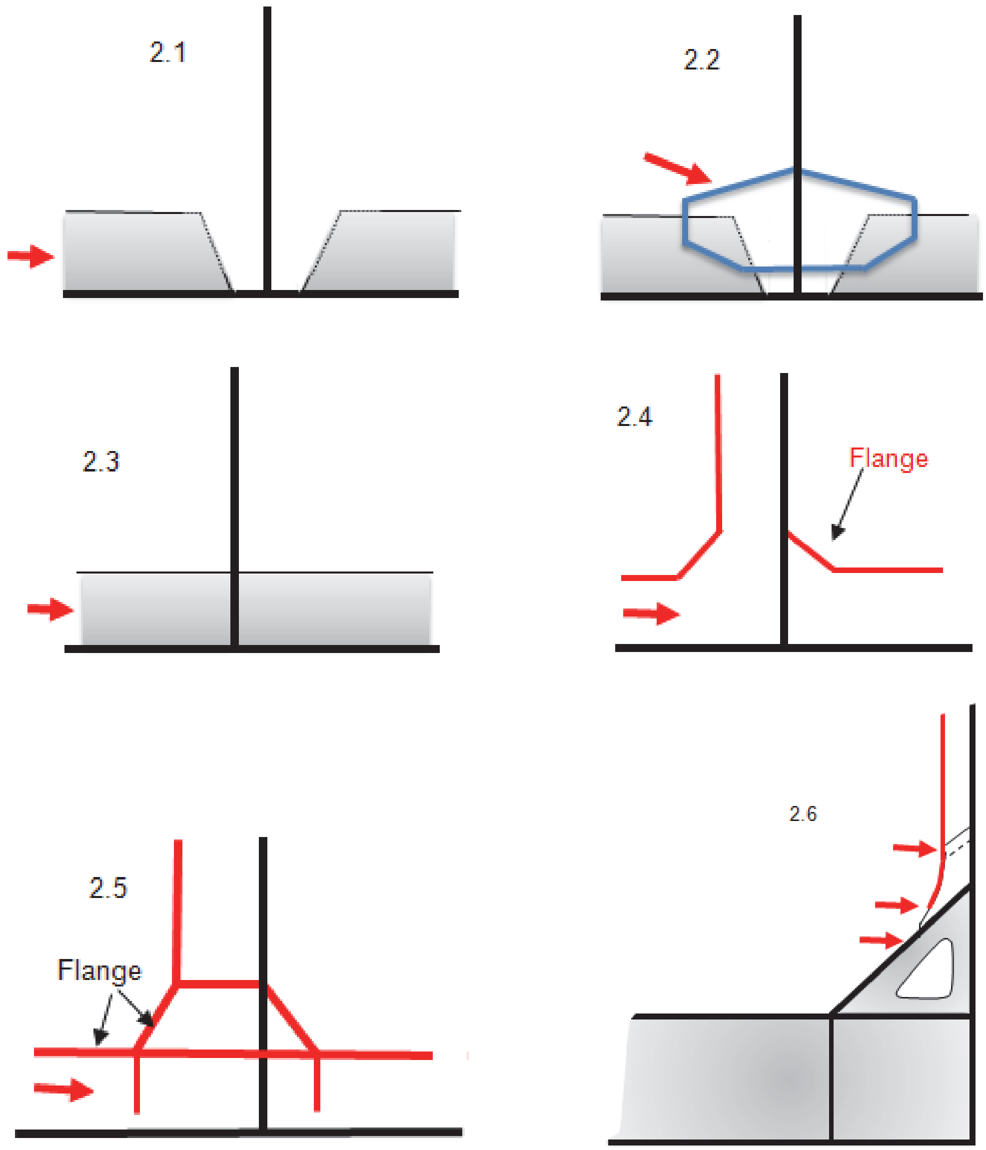


Figure 5-23. Primary Stiffener connection

3. Gusset/transverse stiffener symmetry

Detail	Description
3.1	None
3.2	This side only
3.3	Far side only
3.4	2 sides

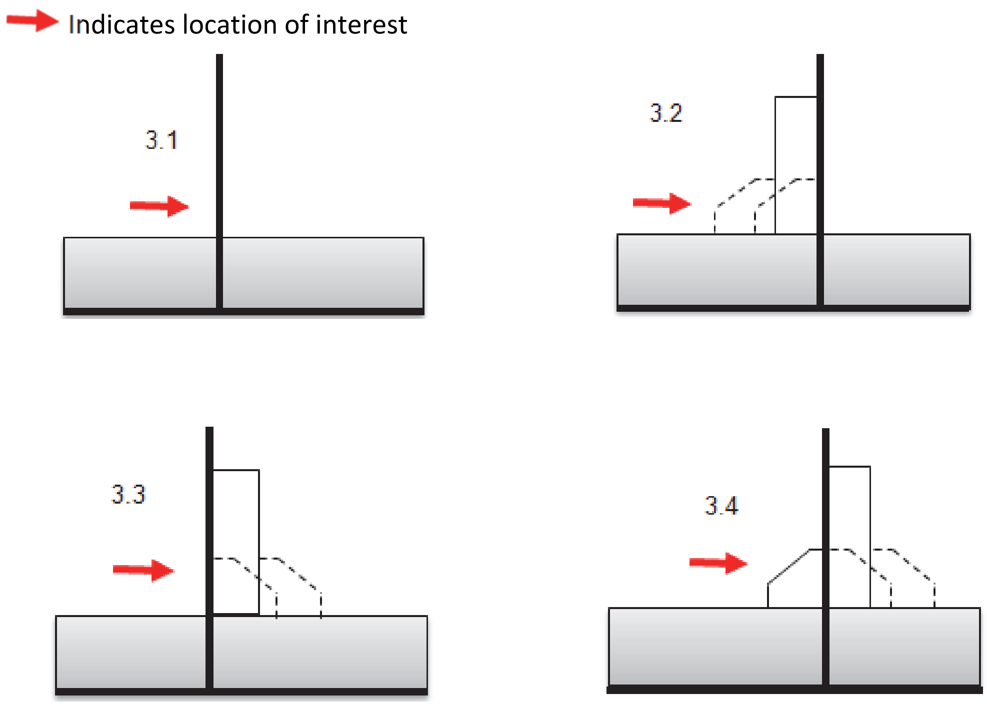


Figure 5-24. Gusset/transverse stiffener symmetry

4. <u>Gusset Shape</u>

Detail	*Description*
4.1	Lap Fillet
4.2	Lap Radius
4.3	Butt Fillet
4.4	Butt Radius

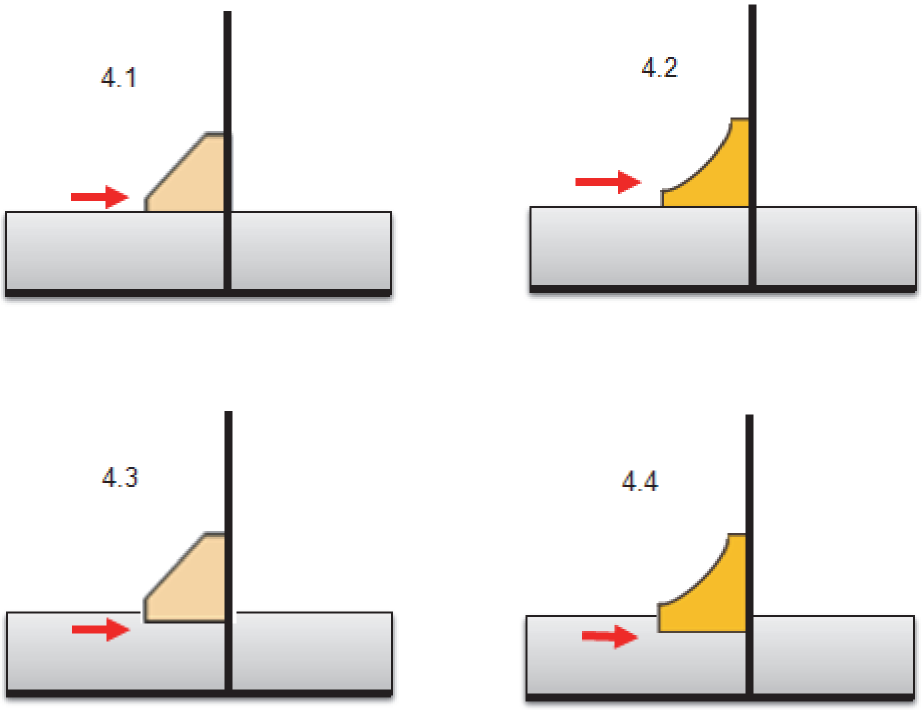


Figure 5-25. Gusset Shapes

5. Gusset edge stiffening

Detail	Description	Cracks introduced(Crack Types)
5.1	Unstiffened	None
5.2	Stiffened Flange	T3E
5.3	Stiffened Side	T3S
5.4	Stiffened Bent	S1

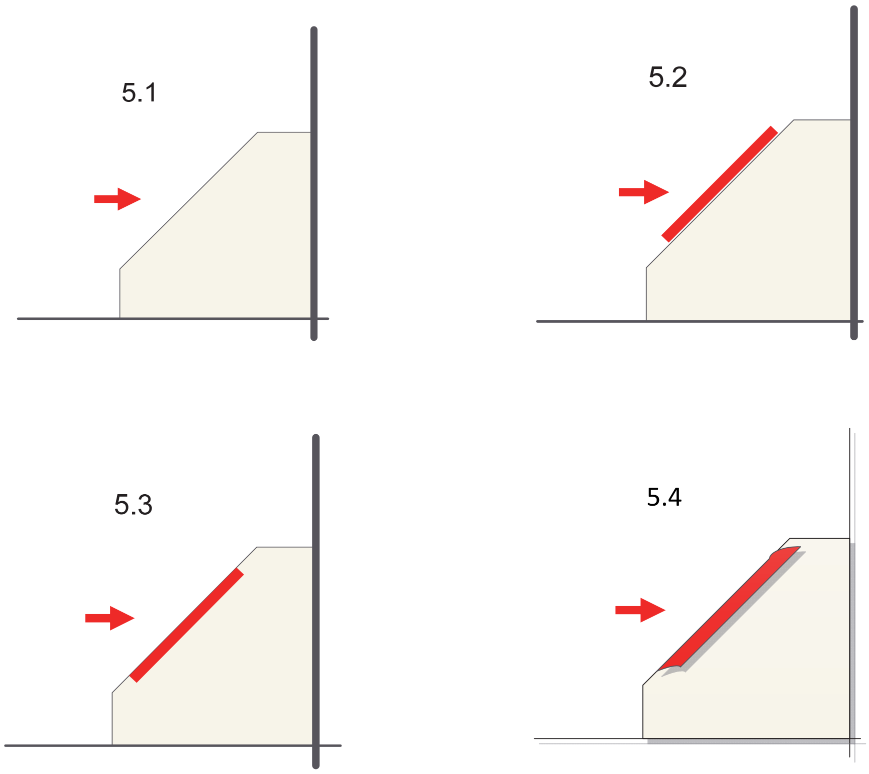


Figure 5-26. Gusset edge stiffening

6. Stiffener type

Detail	Description
6.1	Flat bar
6.2	Bulb
6.3	Angle
6.4	Tee

6.1 6.2 6.3 6.4

Figure 5-27. Stiffener Types

7. Cut out

Detail	Description	Cracks introduced(Crack Types)
7.1	No connection	C1 C2 R2
7.2	Connect 1 side web	C1 C2 P1 P2 P4 P5 R2 R3
7.3	Connect 1 side web and flange	C1 C2 P1 P2 P4 P5 R2 R3
7.4	Connect both sides (not flange)	P1 P2 P4 P5 R2 R3
7.5	Connect all round	P1 P2 P4 P5 R2 R3
7.6	Connect all round & watertight	C11 C13

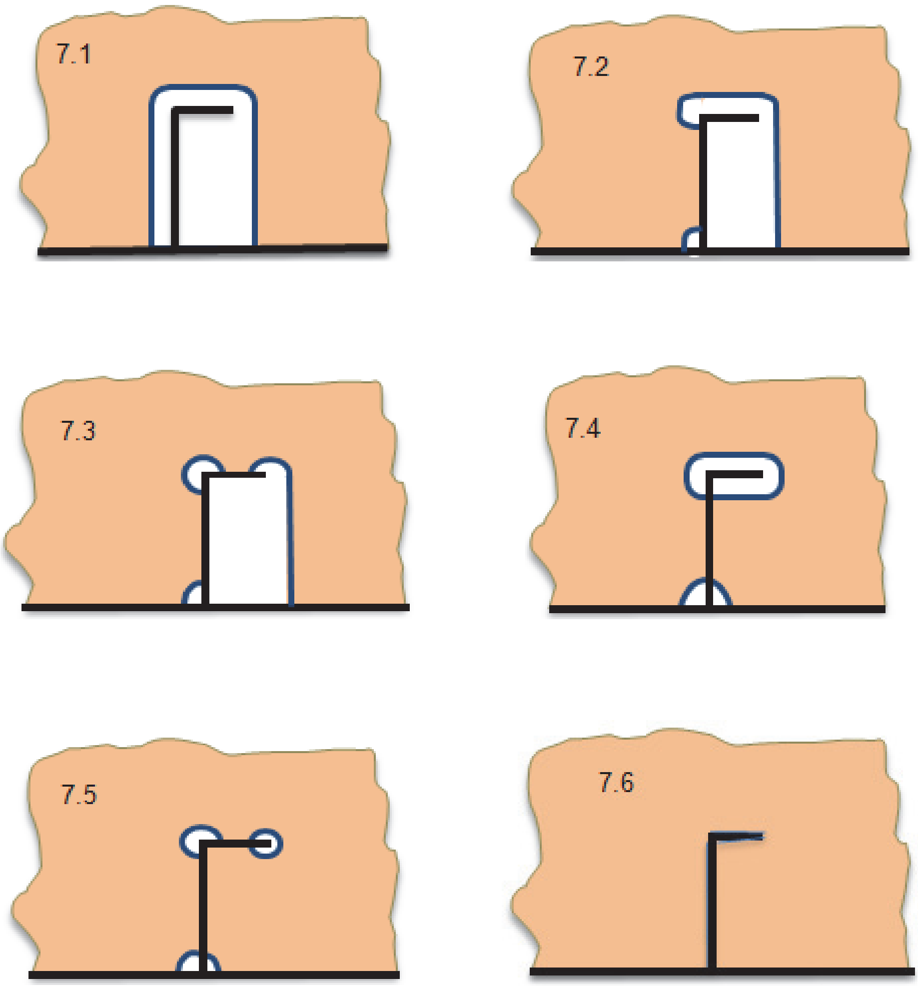


Figure 5-28. Cutout Configurations

8. Collar

Detail	Description	Cracks introduced(Crack Types)
8.01	Non tight, One side Fit to web	C3 C4 C5 C6 C7 C8
8.02	Non tight, One side Fit web & plate	C5 C7 C8
8.03	Non tight, One side Fit web and flange	C3 C4 C6 C11 C12
8.04	Non tight, One side Fit all	C6 C11 C12 C13
8.05	Non tight, One side Fit all + Mouseholes	C3 C4 C5 C6 C7 C8
8.06	Non tight, Both sides Fit to web	C3 C4 C5 C6 C7 C8
8.07	Non tight, Both sides Fit web & plate	C5 C7 C8
8.08	Non tight, Both sides Fit web and flange	C3 C4 C6 C11 C12
8.09	Non tight, Both sides Fit all	C6 C11 C12 C13
8.10	Non tight, Both sides Fit all + mouseholes	C3 C4 C5 C6 C7 C8
8.11	Tight	None

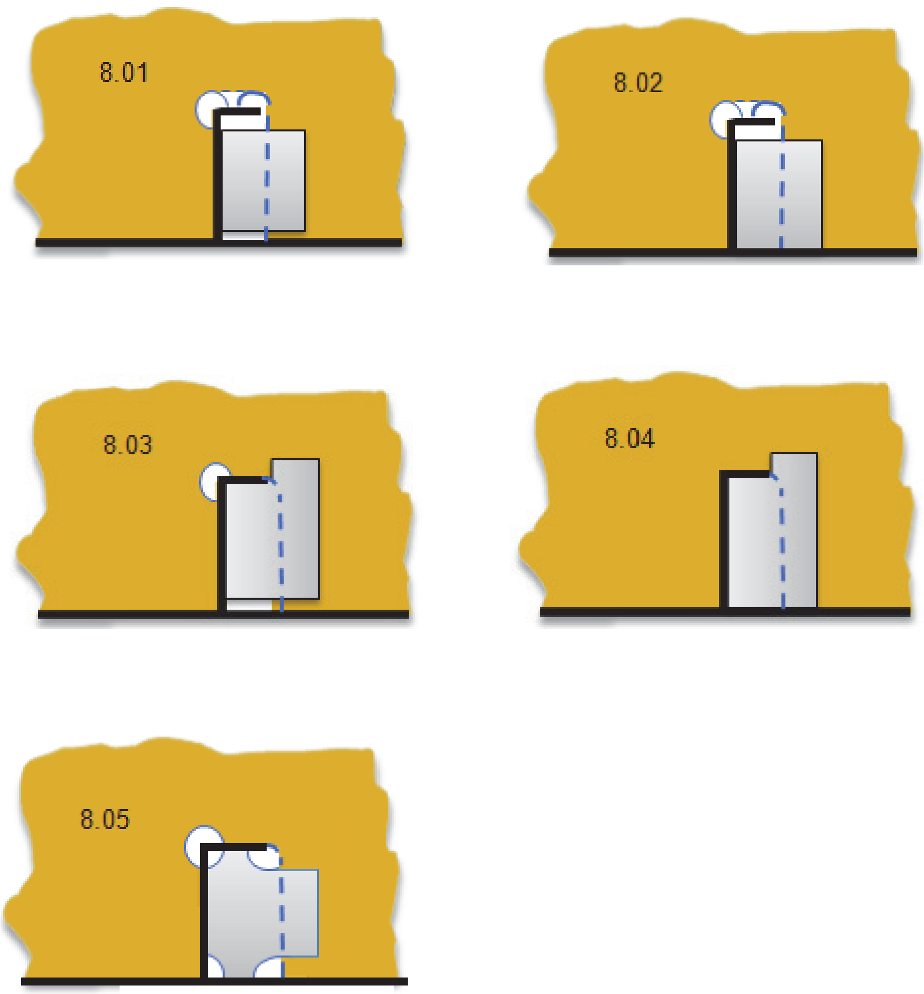


Figure 5-29. Collar configurations

9. <u>Holes For Access, Drainage, Ease Of Fabrication, Cableways, Pipes, Air Holes</u>

Detail	*Description*	*Cracks introduced(Crack Types)*
9.1	Hole for access	R2, P2, P4
9.2	Hole	R3
9.3	Drainage	B1, B2
9.4	Hole	B1, B2

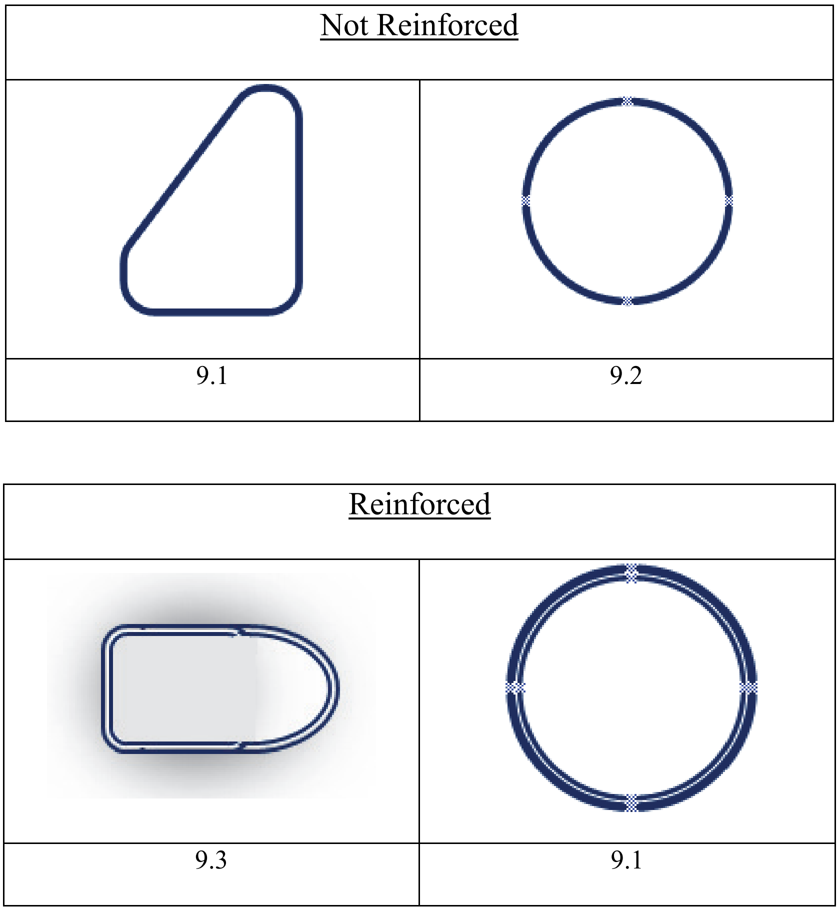


Figure 5-30. Hole configurations

5.6.2.4 *Future possible coding and nomenclature - not used at present,*

1. **Stiffener code**

1	Stiffener on arm being analysed
2	Stiffener at right angle
3	2nd stiffener at right angle
4	Continued stiffener

2. **Dimension code**

DS	Stiffener depth,
BS	Stiffener flange width
TW	Stiffener web thickness
TF	Stiffener flange thickness or inner plate thickness
TP	Plate thickness
GL	Gusset plate length measured in direction of stiffener end being assessed
GH	Gusset plate height
LO	Sum of lengths of gussets and depth of transverse stiffener
GS	Gusset plate sniped height
GO	Gusset plate overlap height
LS	Length of transverse stiffener

5.7 SUMMARY

This chapter has given an overview of the classification of structural details for Oil Tanker and Bulk Carrier vessels, based on the previous studies done by “The Ship Structure Committee” (SSC), and Lloyd Register (LR).

This work has proposed a different classification of structural connections and cracks. It is based, not on the detail as a whole but on its elemental gussets, lugs, cut outs etc. It is simpler yet more versatile than previous classification systems.

The high number of existing details, and the effort that the ship inspectors would need to memorise all the connections types will be eased by the new classification system, however computer logging of details may make this less important as the inspector could simply click on the appropriate detail without needing to remember codes.

More importantly, the new system contributed to the RISPECT defect data management and analysis system (EU Project (Appendix A.1)).

The identified principal details are assembled in a catalogue to be used for the description of the ship details and to be integrated into the ship structural defect and statistical database.

CHAPTER 6: SHIP STRUCTURAL DEFECTS DATABASE

6.1 INTRODUCTION

The objective of this chapter is to develop a database that will hold data about ships, structural joint details (connections), defects and deteriorations data, inspection data, results of structural degradation prediction models and information to calibrate their results. The existing structural databases are more construction oriented (product model) than inspection oriented, and for a better use of the data collected during the inspection and ship monitoring, a more appropriate database structure for recording and storing the data is needed. In this work, the new developed database will be known as the Ship Structural Defects Database (SSDD).

The SSDD will also have a statistical computation module attached to it which will be further explained in the next chapter.

The challenge of this part of the research is to produce a suitable and flexible database structure that will cater for the present and future needs in terms of data storage and will make the exchanges with any outside module (computational/other databases) efficient.

This chapter will introduce databases notions and definitions before describing in details the SSDD architecture and its different components.

6.2 DATABASE: NOTIONS AND DEFINITIONS

A database is an organized collection of data (D*atabase File*) for one or more purposes, usually in digital form. The data are typically organized to model relevant aspects of reality, in a way that supports processes requiring this information. However, not every collection of data is a database; Data will need a D*atabase Management System*, a complex software system, to be exploited and maintained (Klaus 1988; Zaniolo 1997; Date 2000; Rob 2009).

Databases are needed for:

- Storage of big volume of data
- Structured data storage
- Retrieve specific data easily when needed
- Ease of use and exploitation
- Eliminate duplication
- Identify which data should be deleted or archived
- Provide backup of the full and partial data
- Disaster recovery
- Security and privacy
- Migration from one system to another

A *Database file* is defined as a collection of related records. A database file is sometimes called a *table* or an *entity type* or *set*. Files are frequently categorized by the purpose or application for which they are intended. Files may also be classified by the degree of permanence they have: Transition files are only temporary, while master files are much more long-lived.

An *entity* is a member or element or instance of the entity type or set. Each entity within the entity type will have the same set of *attributes*, which are the data about the entity that is to be kept in the database, but will have in general different attribute values.

The attribute that uniquely identifies each entity from all the others in the entity type is known as the *primary key*. In some cases more than one attribute is needed to identify the entity. In this case a *composite key* is needed.

The data stored in a database file is independent from the application programs which use and process the data.

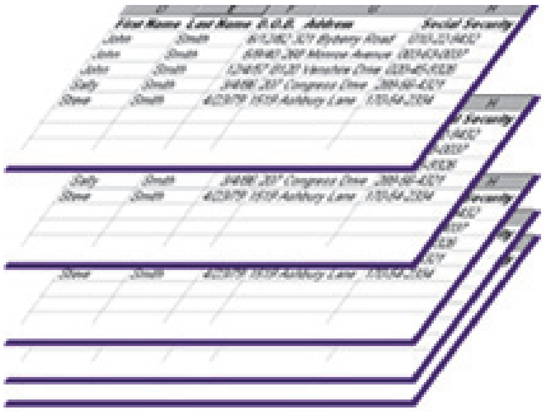


Figure 6-1 Database File

Database software or database management system (DBMS), is the phrase used to describe any software that is designed for creating databases and managing the information stored in them. Database software tools are primarily used for storing, modifying, extracting, and searching for information within a database. Database software is used for a number of reasons in any industry from bookkeeping, compiling client lists to running online Web site (Narang 2006).

Because they have so many uses, there are dozens of database software programs available, some of the most popular database software applications include desktop solutions like Microsoft Access and FileMaker Pro and server solutions like MySQL, Microsoft SQL Server and Oracle, DB2, Informix, Ingres, Java DB…

There exist different types of database management systems:

- Hierarchical Databases
- Network databases
- Relational Databases
- Object-oriented Databases

These are further explained below.

Hierarchical Databases is one of the oldest methods of organizing and storing data. It is organized in a pyramid fashion, like the branches of a tree extending downwards (Figure 6-2) (Svolba 2006; Singh 2011).

Related fields or records are grouped together so that there are higher-level records and lower-level records. Based on this analogy, the parent record at the top of the pyramid is called the root record. A child record always has only one parent record to which it is linked but a parent record may have more than one child record linked to it. Each child can also be a parent with children underneath it.

Hierarchical databases work by moving top down. A record search is conducted by starting at the top of the pyramid and working down through the tree from parent to child until the appropriate child record is found.

The advantage of hierarchical databases is that they can be accessed and updated rapidly because the tree-like structure and the relationships between records are defined in advance.

The disadvantage of this type of database structure is that each child in the tree may have only one parent, and relationships or linkages between children are not permitted.

Hierarchical databases have a rigid design: adding a new field or record requires redefining the entire database (Setrag et al. 1996; Silberschatz et al. 2011).

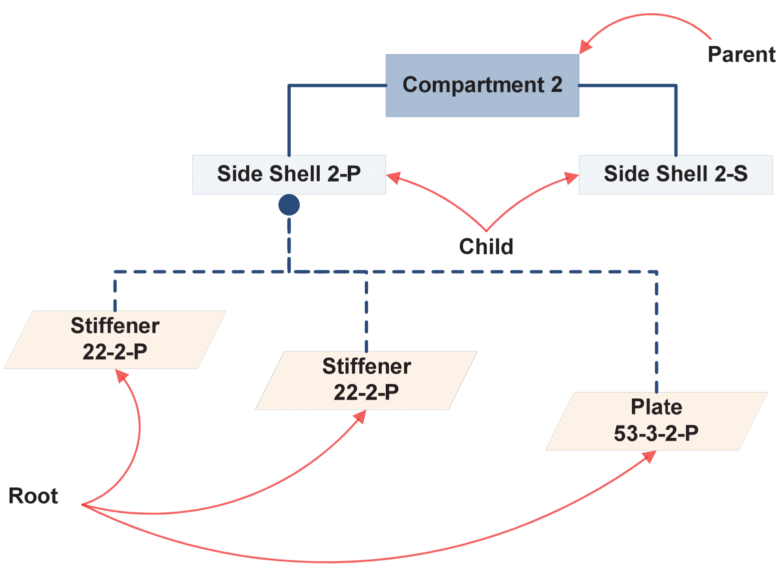


Figure 6-2 Hierarchical Database

Network Databases are similar to hierarchical databases (have a hierarchical structure); they do not look like an upside-down tree but more like an interconnected network of records. In network databases, children are called members and parents are called owners. Each child or member can have more than one parent (or owner).

Network databases are more flexible because more connections can be made between different types of data (Figure 6-3). However, two limitations must be considered when using this kind of database: network databases must be defined in advance and there is a limit to the number of connections that can be made between records (Setrag et al. 1996).

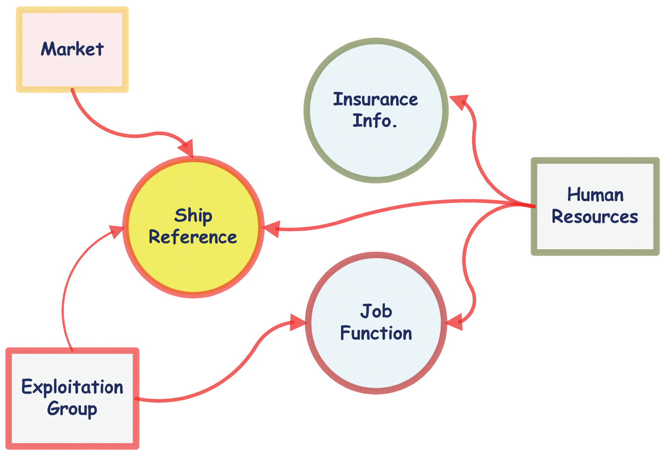


Figure 6-3 Network databases

In ***Relational Databases,*** relationship between data files is relational not hierarchical. Relational databases connect data in different files by using common data elements or a *key field*. Data in relational databases is stored in different tables, each having a key field that uniquely identifies each row (Figure 6-4). Relational databases are more flexible than either the hierarchical or network database structures. In this case, tables or files filled with data are called relations, tuples designates a row or record, and columns are referred to as attributes or fields. The relational database is quite popular for two major reasons. First, relational databases can be used with little or no training. Second, database entries can be modified without redefining the entire structure.

The disadvantage of using a relational database is that searching for data can take time (Sumathi et al. 2007).

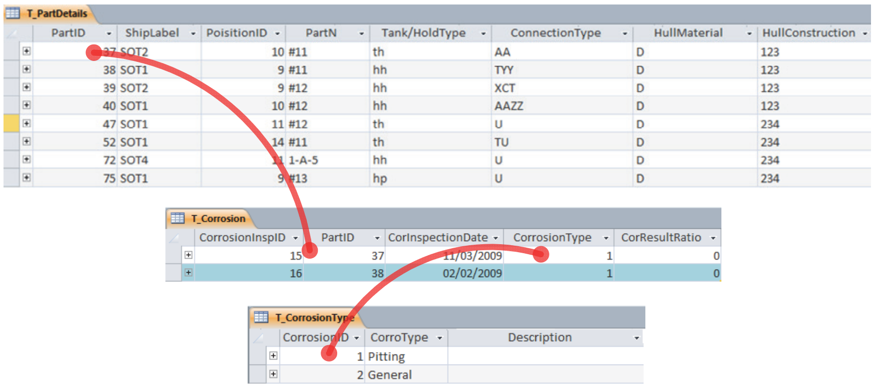


Figure 6-4 Relational database

Object Oriented Databases are able to handle many new data types, including graphics, photographs, audio, and video. They represent a significant advance over the other database types. They can also be used to store data from a variety of media sources and produce output in a multimedia format.

Object-oriented databases have two disadvantages.

- Costly to develop.
- Most organizations are not ready to abandon or convert from databases in which they have already invested money.

The benefits to object-oriented databases could be numerous because of the multimedia capability (Singh 2009; Silberschatz et al. 2011).

In this research the relational database was used to develop the Ship Structural Defects Database (SSDD) and the Java NetBeans and Java DB (NetBeans) software were chosen for the development.

6.3 SHIP STRUCTURAL DEFECTS DATABASE (SSDD)

As discussed in the introduction of this chapter the database will hold information about ships, structural details and connections, defects and deteriorations data, inspection data, results of structural degradation prediction models and results of the calibrations process of the prediction models.

The purpose being to have a researchable database which holds information about ships degradations, which is accessible to different stakeholders (ship owners, classification societies, inspection companies, ship yards, etc…) to draw up experience-based design, inspection plans and maintenance rules. Up to now this information has mainly been kept in class society survey reports and its availability restricted as it has not been typical for large scale information to be shared in the maritime industry. Also classification societies themselves have found their data difficult to analyse.

The general shape of the database is shown in the Figure 6-5 below.

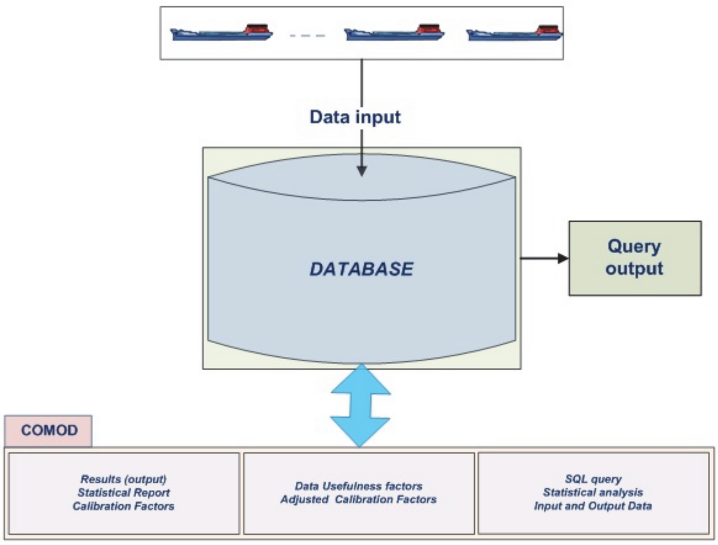


Figure 6-5 Ship Structural Defects Database

The database to be developed would need to satisfy the following requirements:

1. Confidentiality

Confidentiality of the information in the database will be ensured through the use of sanitised or double sanitised data. This point is further discussed later in this chapter.

2. Access Control

Different access rights to the database can be set such as:

a. list: allow to find out about existence of data

b. read: allow to access the data

c. write: allow to modify the data (or: create a new version)

d. delete: allow to mark the data as deleted (in a version tracking environment no real physical removal will be possible)

e. administrate: allow full access, including low level physical modification of data

6.4 DATABASE ARCHITECTURE

The database was conceived to allow an efficient storage and access to the data especially by the computational module (COMOD) that calculates the calibration factors and which will be explained in Chapter 7.

The database consists of the data about the ship defects and deteriorations, and for confidentiality of the information, the ship label or tag replaces all the vessel information. The different components of the database are:

- Ship label
- Length category
- The longitudinal frame-table
- Tonnage Category
- Type of vessel
- Cargo Types
- Connection details
- Coating defect and deterioration data

- Corrosion data
- Crack data
- Anode degradation data
- Connection type definition
- Crack types
- Corrosion types
- Coating types
- Anode types
- Material data
- Inspection data
- Model Prediction data
- Expert correction factors
- Computed correction factors
- Stiffener definition
- Plates definition
- World Metocean data (Wave data)
- Other.

The main component of the database is the defect and deterioration (corrosion, crack and coating breakdown) data and the database was built around it.

Each element that constitutes the database is explained in details in what follows.

The main inflow of constructs of database is from:

- ISO 10303-215 (compartments)
- ISO 10303-216 (general ship design)
- ISO 10303-218 (ship structures)
- HCM rev. 0.71
- Rispect Database (Appendix A.1)
- Extensions of geometry definitions
- Extensions of material definition attributes
- Corrugated structures (integrate ISO and HCM models)

In order to construct the database, first the ship compartmentalisation is defined and is characterised by:

- coordinate system: frames, longitudinal positions,
- major dividers (bulkheads, decks…).

Then the structure functional layout is defined (shell plating, deck/bulkhead plating). And finally hull cross sections, stiffeners and connections types are defined.

6.4.1 Ship information

In the database, a ship is defined by the following (Figure 6-6):

(1). Identification (Label)
(2). LBP category
(3). Tonnage category
(4). Ship Type and purpose
(5). Cargo type
(6). Frame Data
(7). Year of build
(8). Ship Routes

Each element is further detailed hereafter.

- As ship information is one of the most sensitive data in the shipping industry, to preserve the confidentiality of the data, the ship identification (ship name, IMO number, owner, flag, call number, etc….) is replaced by a label or a tag (*ShipId*) and its main particulars: length between perpendiculars (LBP) and weight are replaced by a range: *LBPCategory*, *TonnageData*.

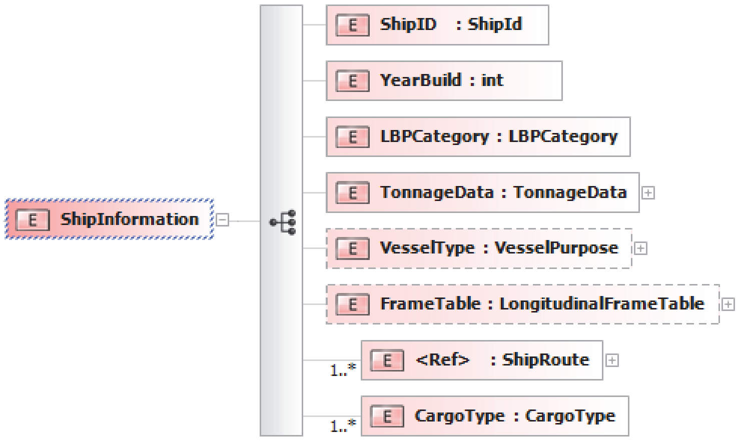


Figure 6-6 Ship Information Records

Tonnage and length categories are defined based on ship classifications. Table 6-1 shows and example of weight ranges for Oil Tankers. In

Table *6-2* the ranges used for the lengths are given.

Table 6-1: Double hull oil Tankers Classification

Size category	Dead weight range (tonnes)
Product	<50K
Panamax	50-80K
Aframax	80-120K
Suezmax	120-160K
VLCC	160-320K
ULCC	>320K

Table 6-2: LBP Categories

Abbreviation	Length Ranges
LBP1	under 120m
LBP2	between 120m and 180m
LBP3	between 180m and 220m
LBP4	between 220m and 270m
LBP5	between 270m and 300m
LBP6	over 300m

- *VesselType* is a list of all different types of vessels (Figure 6-7). This research focuses mainly on Oil Tankers and Bulk Carriers which are part of the *CarrierVessel* type.

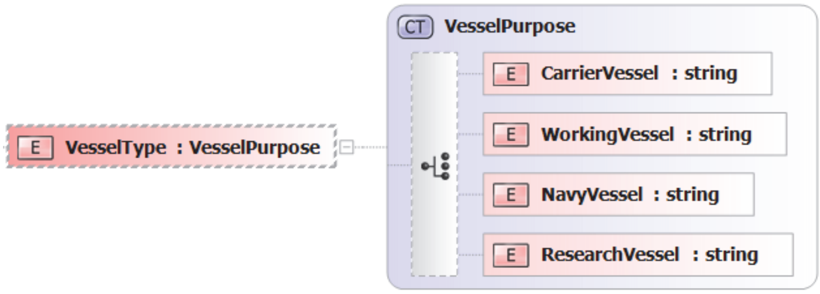


Figure 6-7 Vessel Types and Purpose

- A *SpacingPosition* is a location on one of the global coordinate axes of the ship that is used as a reference point for any geometrical or structural item during the design and manufacture of the ship (STEP-AP218 2004).

  A *LongitudinalFrameTable* is a type of *SpacingTable* that has positions that reference the location of frames that are located along the global X-axis. (STEP-AP218 2004).

  The *FrameTable* (Figure 6-8) gives the spacing positions of the longitudinal frames where each frame is defined by a name and coordinates. Frame numbering is used as reference.

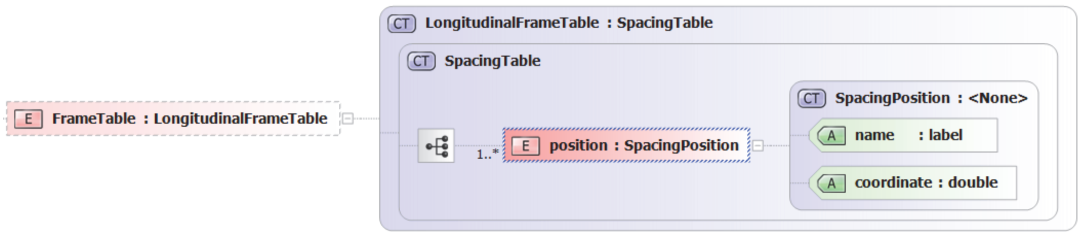


Figure 6-8 Frame Table

- *ShipRoute* (Figure 6-9) provides information about the routes the ship trades in as well as the time spent in a particular navigation area. This in turn is linked to the navigation areas (Marsden squares as defined in Chapter 4).

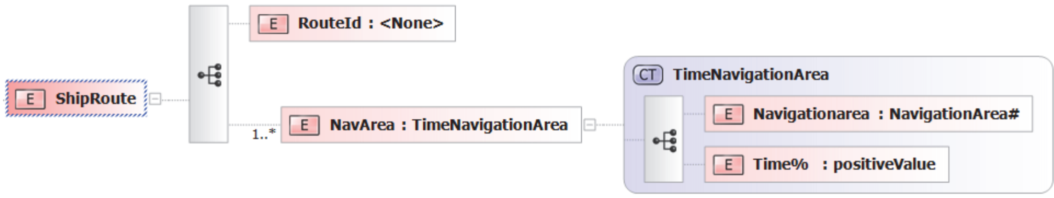


Figure 6-9 Ship Route

- *Cargotype* (Figure 6-10) is used to record the different type of cargo carried by the ship.

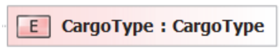


Figure 6-10 Cargo Types

6.4.2 Ship Data Records

As introduced earlier, the ship defect/deterioration is the main element of the database. To efficiently represent it in in the database structure an entity called *ShipData* is defined. The *ShipData* groups the ship defects, COMOD (computational module) results and the data from inspections, experts and prediction models as shown in Figure 6-11.

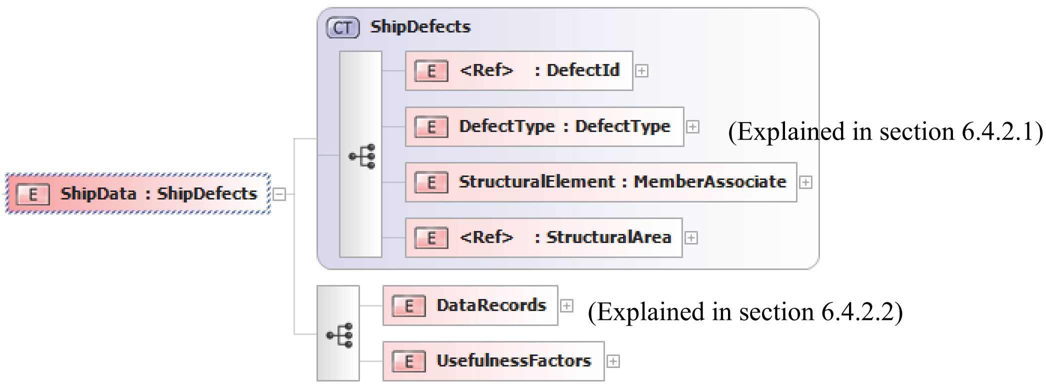


Figure 6-11 Ship Data Record

Each component of the *ShipData* record is further explained below.

6.4.2.1 *Ship defects*

ShipDefect is used to record all structural defects/deteriorations of the ship (Figure 6-12). Each defect/deterioration is given a unique identification (*DefectId*), type, structural element associated to it and the location (structural area).

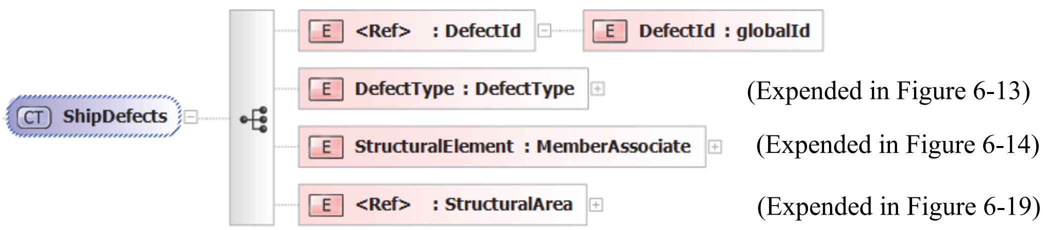


Figure 6-12 Ship Defects

a) DefectType Entity

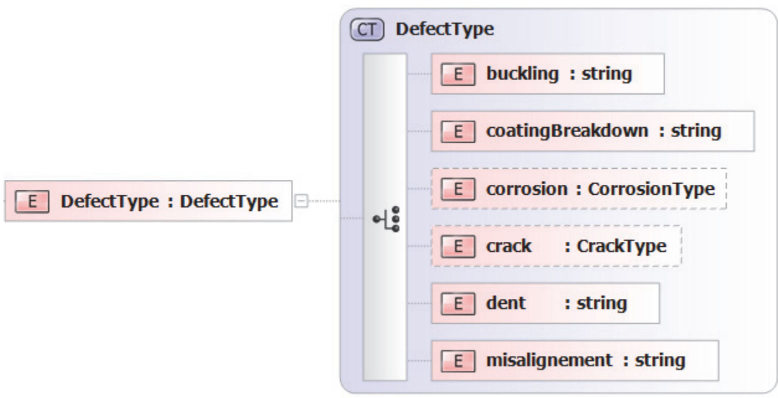


Figure 6-13 Ship Defect Types

DefectType groups the different defect/deterioration types (Figure 6-13). There is a record in the database for each defect/deterioration as defined in Chapter 4. The corrosion types are given below as illustration:

```
<xs:simpleType name="CorrosionType">
  <xs:restriction base="xs:string">
    <xs:enumeration value="General " />
    <xs:enumeration value="Grooving" />
    <xs:enumeration value="Pitting" />
  </xs:restriction>
</xs:simpleType>
```

b) *StructuralElement Entity*

This entity has several functions depending on its use in the database structure. When dealing with defect/deterioration as illustrated in Figure 6-14, *StructuralElement* will Group all plates and stiffeners affected by the defect/deterioration. Plates and stiffeners entities are expended below.

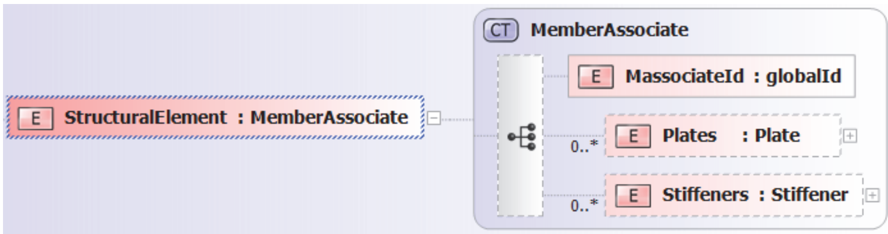


Figure 6-14 Ship Structural Element

c) *Plate Entity*

This entity defines plate characteristics (Figure 6-15). Each plate is represented by a unique reference (*MemberId*), name, strake number, plate number, ship side, original thickness, maximum thickness diminution, plate type and material property.

In the case of plate replacement, the *RenewalMember* keeps track of the changes.

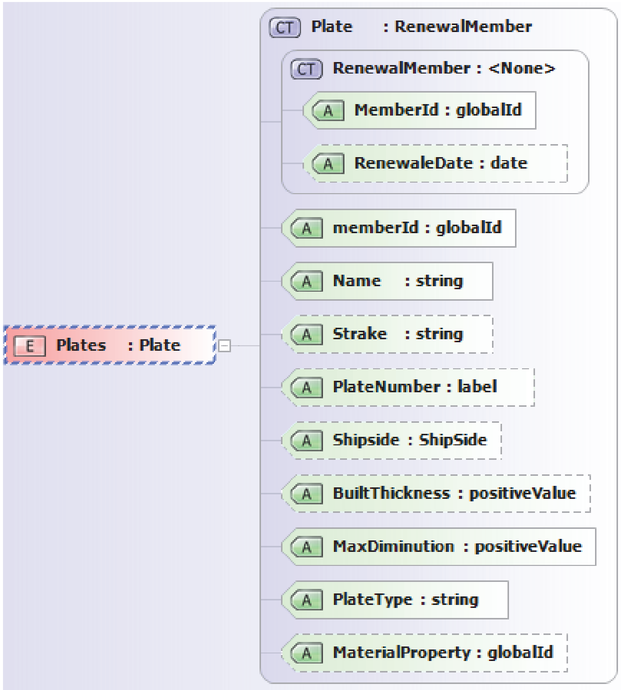


Figure 6-15 Ship Plate

The material properties data of the ship structure are given (Figure 6-16) by:

- the steel grades (for example A, AH, D, DH, E, EH)
- Tensile strength
- Yield strength
- Elastic Modulus
- Others.

Figure 6-16 Material property

d) Stiffener Entity

Data defining stiffeners is in the stiffener entity as shown in Figure 6-17. The stiffener is represented by a unique reference (*StiffId*), name, orientation, web and flange (width, thickness, maximum diminution and material property), flange with upper and lower, stiffener length and type and ship side. As in the plate entity, the *RenewalMember* keeps track of the changes when the stiffener is replaced.

Figure 6-17 Ship Stiffener

e) StructuralArea Entity

A structural area is defined as the surface allocated between two frames and two stiffeners which constitute its boundary as illustrated in Figure 6-18.

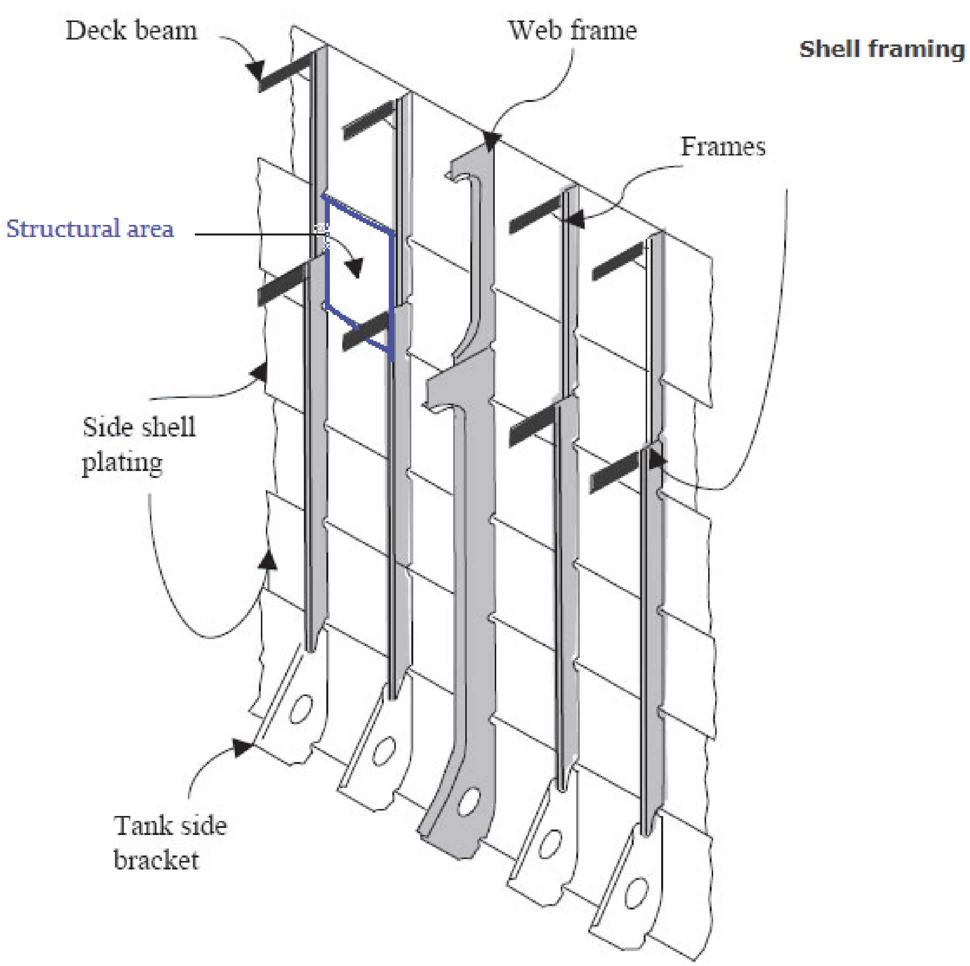


Figure 6-18 Ship Structural area (modified from original Picture adapted from Transport Canada)

Its representation in the database is done through the *StructuralArea* Entity. This entity gives the location in the structure and has several components as shown in Figure 6-19.

The *StructuralArea* is represented by a unique reference, Member (*StructuralComponent*), frames and stiffeners. The key identification for the frames and stiffeners delimiting the area are used to link the stiffeners and frames to respectively, the stiffener entity and frame table defined earlier. *Structural component* is further detailed below.

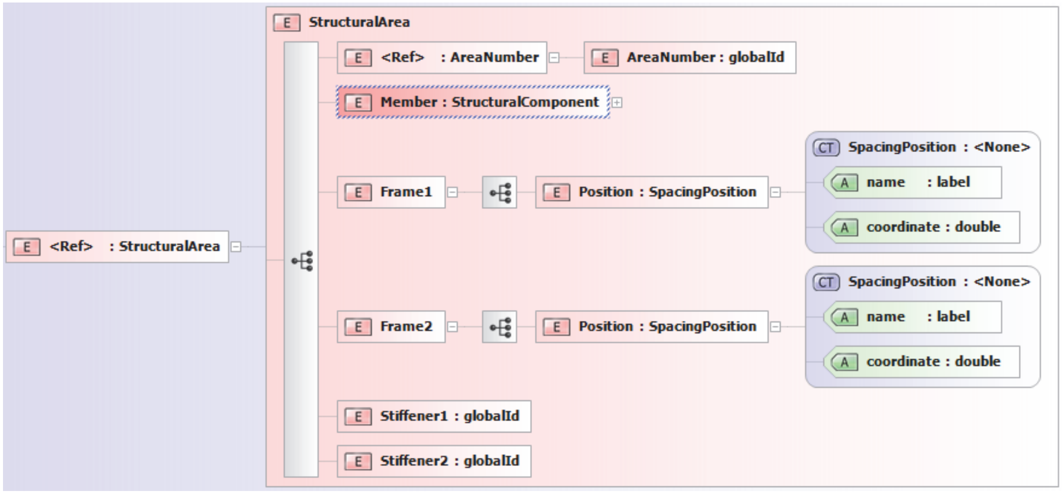


Figure 6-19 Structural Area Entity

f) StructucturalComponent Entity

The *StructucturalComponent* represents an element of the ship structure and has a unique reference, Name, Location, purpose (*MemberFunctionProperty*), and description (Figure 6-20).

The Entity *MemberFunctionalProperty* is an enumeration of type "string" which represents the denomination of the functional property or role of a structural member of the ship. The values are based on STEP Application Protocol 218. The location (*Compartment* Entity) is extended below.

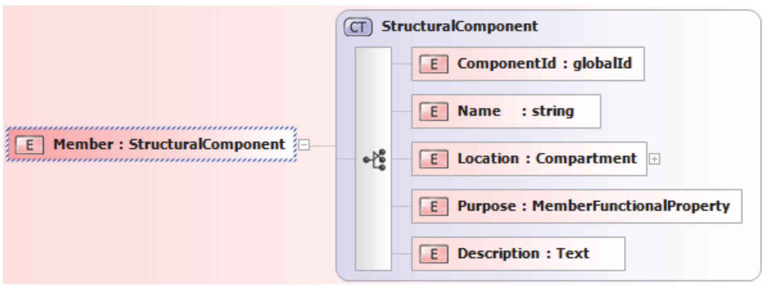


Figure 6-20 StructuralComponent

g) Compartment Entity

The *Compartment* entity (Figure 6-21) has a unique reference, purpose, ship side, associated: Member (Figure 6-14), Frames (Figure 6-8), and connections (explained below), and related ship (Figure 6-6).

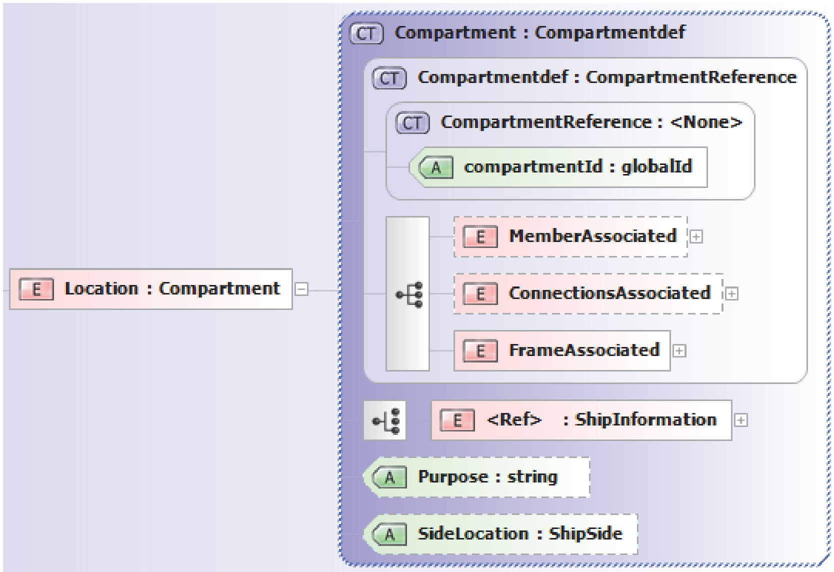


Figure 6-21 Compartment

h) ConnectionAssociated (Connection) Entity

As explained in Chapter 5, the definition of a catalogue of details (connections) was necessary to implement the methodology developed in this research. The storage of the structural details in the database is done through the Connection entity. This entity has a unique reference, connection type, crack type associated to the type of connection, *MemberAssociated* to the connection and coordinates.

When linked to the *Compartment* entity, *ConnectionAssociated* entity (Figure 6-22) is a list of connections associated to a compartment.

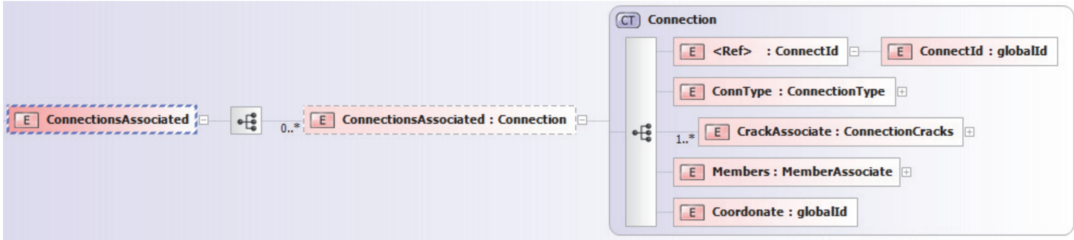


Figure 6-22 Structural Connection

6.4.2.2 DataRecords Entity

Part of the *ShipData* entity (Figure 6-11), the main purpose of the *DataRecords* entity is to hold information used in the interaction between the database and the COMOD. *DataRecords* entity (Figure 6-23) will hold data about the different types of defects/deteriorations where each type of defect/deterioration has its own entity.

All the defect/deterioration entities are constructed on the same model and only the *CrackDefects* entity is explained hereafter.

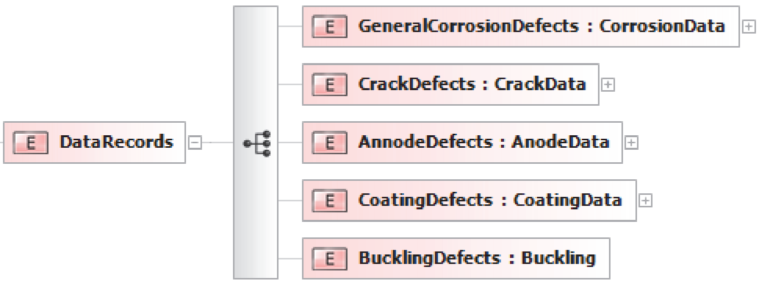


Figure 6-23 Ship Defects Records

a) CrackDefects Entity

CrackDefects entity (Figure 6-24) is organised to record the input to COMOD and the computational results for the calibration process. It has a link to the model ID used to predict the crack size which is characterised by the crack length and depth where each one of them has an entity associated to it: *CrackLenght* and *CrackDepth*. Both entities have the same structure and hold information related to computed factors, expert correction factors and correction factors which are further expended below (Figure 6-25 to Figure 6-28). Definitions and details of the computation of these factors are given in Chapter 7.

The *Date* entity keeps track of when data was recorded following inspection.

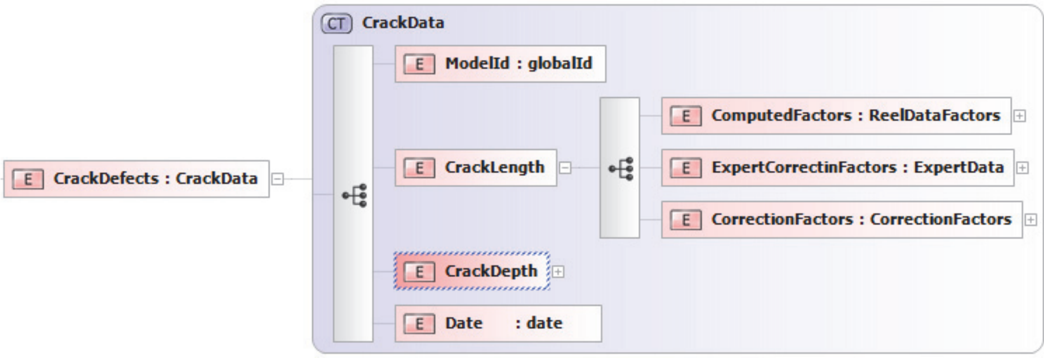


Figure 6-24 Crack Defects Records

b) ComputedFactors Entity

This entity will mainly store output of the COMOD in relation to the inspection data. These consist of : ratios[2], mean ratios, coefficient of variation of the ratios, bias factors, confidence interval for the bias, coefficient of variation of the bias factors and their confidence intervals.

In addition the entity will hold data from inspection and prediction model (in this case crack length).

[2] *For sanitised data, ratios will be computed by the COMOD and returned to the database for storage. For double sanitised data, ratios will be given as input. This is explained in more details later in the chapter.*

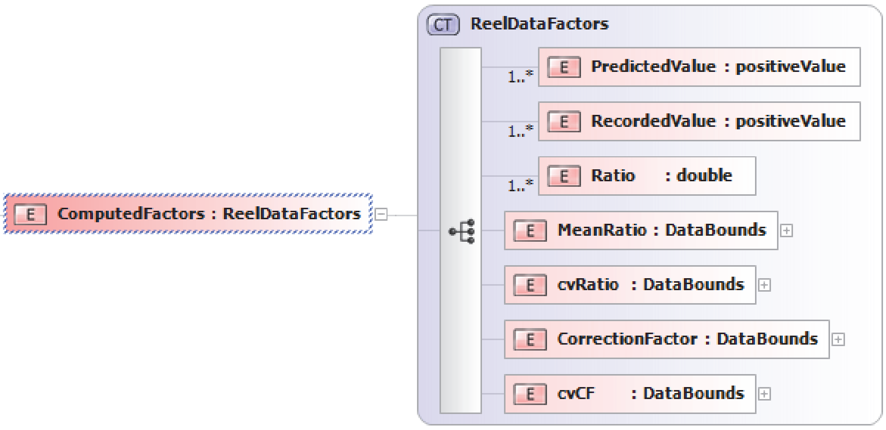


Figure 6-25 Computational Factors

c) DataBounds Entity

The *DataBound* entity is used to store a parameter (mean or coefficient of variation) value and the bounds (upper value and lower value) of its confidence interval.

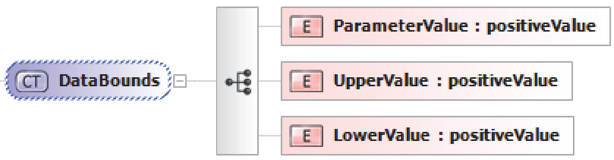


Figure 6-26 Data Bounds

d) ExpertCorretionFactors Entity

The *ExpertCorretionFactors* entity is used to store the models correction factors provided by experts whith knowledge of the given model error of the estimated data. This entity consists of the correction value and its coefficient of variation and their confidence intervals (Figure 6-27).

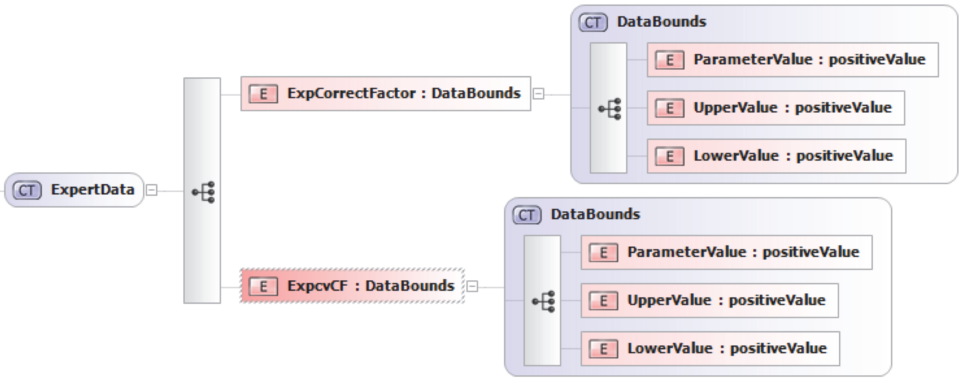


Figure 6-27 Expert Judgement Corrections Factors

e) CorrectionFactors Entity

The *CorrectionFactors* entity is used to store the combined correction factors provided by experts and those computed from real data. This entity consists of the correction value and its coefficient of variation and confidence intervals (Figure 6-28).

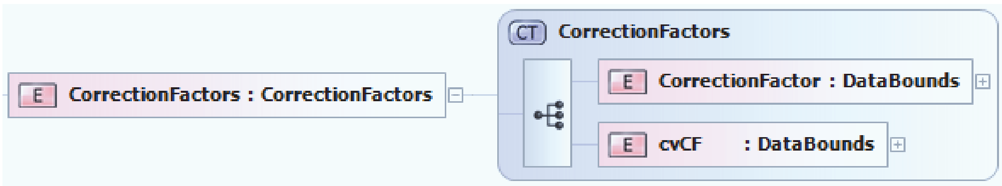


Figure 6-28 Correction Factors

f) UsefulnessFactors Entity

Also part of the *ShipData* entity (Figure 6-11), the *UsefulnessFactors* entity holds information computed by COMOD used in assessment of defect/deterioration behaviour in a particular situation based on information of its behaviour in another situation (from a given element/part to another). The usefulness factors considered in this research are computed for ship to ship variation, crack types, ship routes, general corrosion by locations and coating. The usefulness factors are not just limited to what is illustrated in Figure 6-29, but could be extended to include compartment to compartment, material properties and so on.

All the usefulness factors entities have the same structure and the *Ship2Ship* entity is explained hereafter.

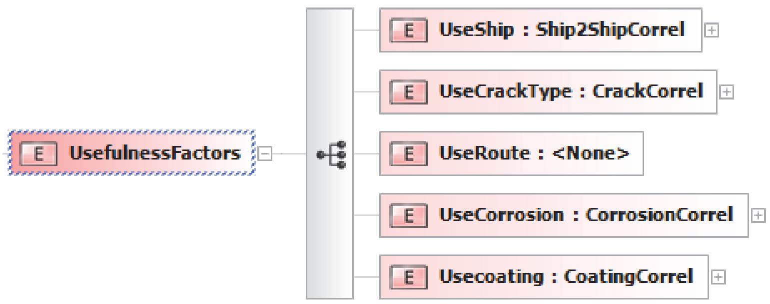


Figure 6-29 Usefulness Factors

g) Ship2Ship Usefulness Factors

Ship2Ship Usefulness Factors entity (Figure 6-30) records the data of the calibration process.

The entity holds information related to computed usefulness factors from real data, expert usefulness factors and the combined factors.

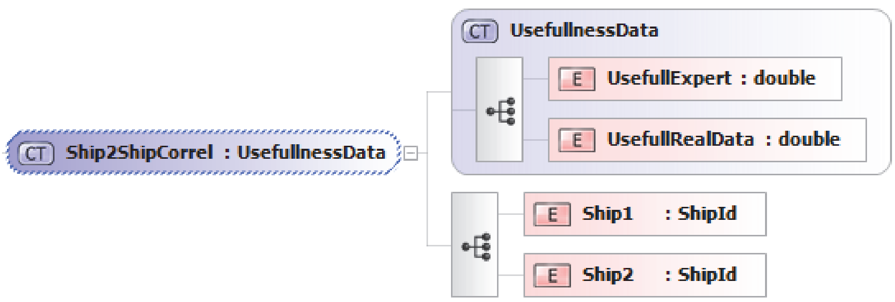


Figure 6-30 Ship Usefulness Factors

6.5 DATA EXCHANGE WITH THE SSDD: INPUT AND OUTPUT

The SSDD holds information about ships and structural deterioration that is either measured (inspection data), predicted (degradation prediction models) or estimated (expert judgment). The database has also a computational module attached to it which purpose is to calibrate the prediction models results with the real data and or expert data and with which, the database exchanges information. The output of the computation module (calibration factors) is then stored in the database.

Care should be taken to avoid the same information being repeated in the database e.g. when a ship's name, owner or class changes. Also there is a need to ensure that relevant data from a scrapped ship is maintained on the Database and that the data is used intelligently e.g. if manufacturing processes fundamentally change, data from before the change is less relevant to ships built after the change.

The following explains how data are recorded in the database as well as the type of information that is exchanged with the computational module.

6.5.1 Recording Information in the Database

When recording a new ship in the database a label is provided to identify the ship.

When a ship changes owner, different actions could be considered:

a) The new ship owner holds the historical data of the ship including the reference registered in the database; in this case the sanitised ship data stored in the SSDD will be compared with the owner's historical data, and updated with any missed records, and with the newly recorded data.

b) The new ship owner does not hold the historical data of the ship but have the ship reference in SSDD database; in this case the database data for the ship will also be updated with the newly recorded data using the database-ship reference.

c) The ship owner does not hold either the historical data or the ship reference in the database; in this case, , the ship will be considered as a new record for the SSDD database which will be started with the limited information provided by the previous owner. In the event of the ship being already recorded, the existing data would stay in the database and could be used for calibration purposes.

6.5.2 Input to the SSDD and Dealing with Sensitive Data

Ships data contains confidential and sensitive information. For this reason input to the database consists of sanitised or double sanitised ship specific survey information (*Figure 6-31*).

Each ship is given a unique reference number.

When the data is double sanitised survey information is given in the form of ratios, not absolute values e.g.:

- Crack life/predicted life;
- Measured corrosion/predicted corrosion;
- Coating breakdown/expected breakdown

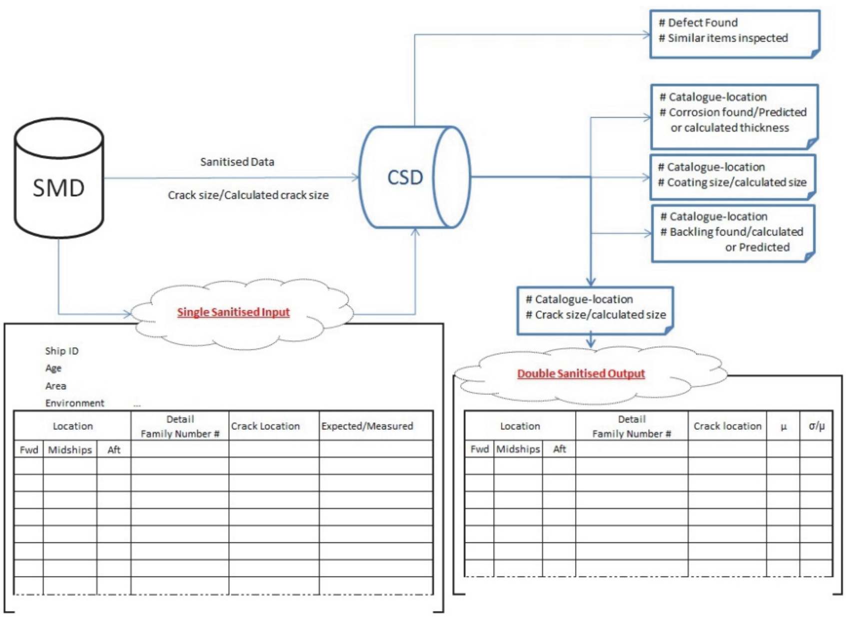


Figure 6-31 Data Sanitisation

Sanitised data derived from a particular ship will be processed by the computational module COMOD (subject of next chapter), attached to the database and the overall statistical results from this and other ships will be stored in the database.

6.5.3 SSDD and Computational Module Data Exchange

When calibrating the prediction models results, survey and or expert data and predicted data are retrieved from the database. When data is double sanitised it is the ratios of actual defect(/deterioration) / expected defect(/deterioration) that is retrieved.

The computational module then calculates the calibration factors. It will weight each piece of data according to its relevance for calibration purposes and then return the weighted mean and coefficient of variation values required for calibration.

6.5.4 SSDD Output

The information that can be retrieved from the database through queries can be different and numerous depending on the need.

Data stored in the database can be accessed to check the ship condition for example.

Depending on the calculations required there may be a requirement to:

1. Provide all data relating to a particular plate or stiffener.
    a. For a tanker this will require all data for the particular cross section that the plate or stiffener is on.
    b. For a bulk carrier data will be required for all locations in the hold and the holds either side of the detail in question.
2. Provide all data relating to parts of the ship surveyed between particular dates.
    a. As for 1. data will be required for surrounding parts of the ships.
3. Provide all data for the whole ship.

The user will specify the parts to be checked and the order in which the results are required. Data in the database will effectively define the additional information that is available (e.g. other data for the same cross section).

It may be that, in order to make the calculation process efficient, the order of doing the calculations will not be the same as that requested by the user. For example if the user defines a whole series of calculations for stiffener number 7 at frames 23, 24, 25 and then calculations for stiffener 8 at the same frames the inspection planning program should first check stiffeners 7 and 8 at frame 23 then at frame 24 then at frame 25.

6.6 DATABASE EXTENSIONS

In addition to route data, ship voyage data could also be stored in the database. This information consists of: time in this service, speed, speed reduction in storms, draft, cargo details (e.g. weight in each hold, temperature, liquid/granular), measures to reduce slamming, port of departure, via a way point, elapsed days from start, port of arrival.

The database developed within this work has the flexibility to incorporate in the future the ship voyage data.

Automatically recorded voyage data

Although not defined during this research, voyage data such as the following could be acquired automatically to be stored in the database.

- Strain measurements on the deck
- Strain measurements on side shell
- Strain measurements on internal structure
- Water pressure measurements

In order to achieve this, permanent sensors to measure the required information would need to be added to the ship in addition to a storing device to record the data.

Details of the implementation for the automatically recorded voyage data could be the subject of future development.

6.7 SUMMARY

This chapter has presented the architecture and components of the Ship Structural Defect Database (SSDD) which was designed to hold ship information in addition to ship inspection and prediction data. The database was constructed to be flexible enough for future additions and to allow for efficient exchanges with external units.

In addition a computational module is attached to the database which computes calibrations factors for the predictions models based on inspection data which are also stored in the database.

Data exchanges between the database and the computational module have also been explained in this chapter.

The newly developed database described in this work is mainly oriented towards ship structures but could also be developed for any other type of structure or inspection data records that require cost effective maintenance.

CHAPTER 7: COMPUTATIONAL METHODOLOGY (COMOD)

7.1 INTRODUCTION

Inspection planning is either based on experience or on reliability and risk-based methods.

Part of the research presented in this thesis attempts to develop a method to calibrate the reliability models (defect/deterioration prediction models) using the data from experience based methods (inspection and expert judgment data), to be incorporated in a decision support system to be used at the design stage and for inspection planning to improve the ship structural performance and make inspections cost-effective.

To achieve this goal it is important to (a) study structural details as discussed in Chapter 5 and to (b) define the correlation between the different details which would allow assessing their behaviour.

The methodology to calibrate the reliability models is explained in this chapter.

7.2 COMPUTATIONAL PROCESS AND DATABASE

As introduced in the previous chapter (Chapter 6), the Ship Structural Defect Database (SSDD) contains sanitised ship data, and holds information on the structural degradation (predicted and measured), expert judgement data and calibration results for each detail of each ship in the database.

The previous chapter discussed in details the data information relevant to the input and output from and to the SSDD. This chapter gives details of the calibration methodology.

7.3 UPDATING PREDICTION MODEL FOR INSPECTION PLANNING

The goal of this work is to provide a technique which will gather the inspection data and information recorded through life to combine that with the prediction models to help produce better inspection and maintenance strategies to improve the durability of new and existing ships.

After an inspection is performed in a ship structure, the results can be classified as "no defect/deterioration recorded" or "defect/deterioration recorded". In the latter case the defect/deterioration type and measured size define the defect/deterioration. Each inspection result gives additional information on the in-service condition of the ship structure. The additional information leads to changes of the predicted values and the basic random variables affecting the reliability. Therefore, it is necessary to update models predictions with the additional information.

Inspection planning is either based on experience (determined by class rules) which will treat all the ship with the same inspection program or on first principles Reliability based methods (Figure 7-1).

- In the first case, no knowledge which could be used to predict structural problems in case of ship to ship variation (construction or use) is gained from the data gathered.
- In the second case, reliability models (methods) can deal reasonably well with individual part but they do not give a good estimate of the overall reliability of the ship and they lack the 'experience database' that the experience-based, methodology uses so the reliability models are not calibrated by reality.

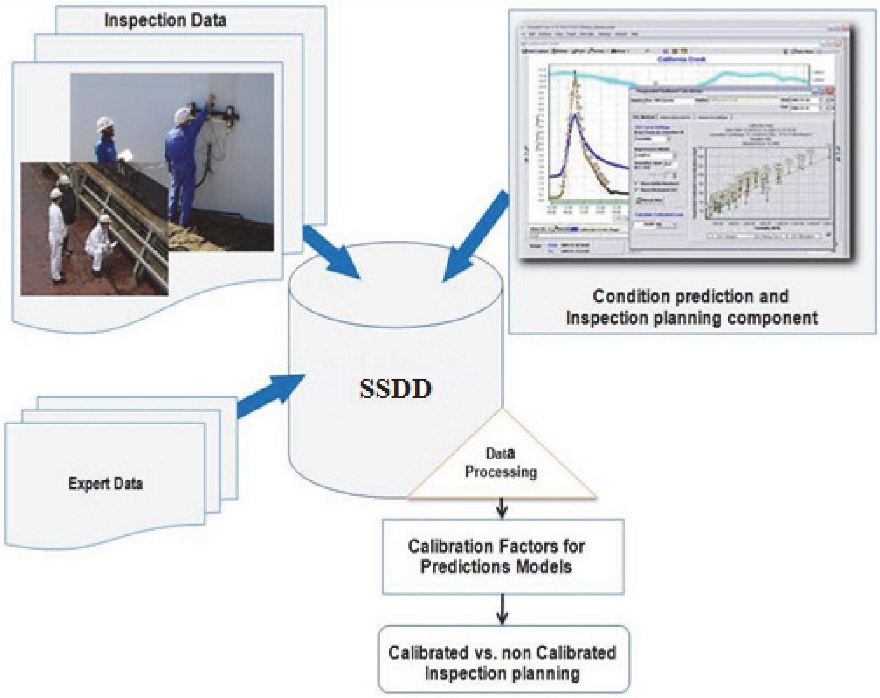


Figure 7-1. Ship Structural Defect Database- Data Flow

In order to make full use of the inspection data in the prediction models, it is necessary to correct the systematic prediction models biases. However, not much attention has been paid to this problem in the past.

To demonstrate that, two approaches could be considered to effectively reduce these biases:

The first approach for model calibration is the process of modifying or updating the model parameters using inspection data until the output from the model matches an observed set of data. This technique is used when there is enough data available but it is not always easy, especially when the parameters information is not directly measured.

The second approach (used in this research) is to consider the model as a black box (Figure 7-2) and that the model output is calibrated using the inspection data through a statistical process as explained later in in this chapter.

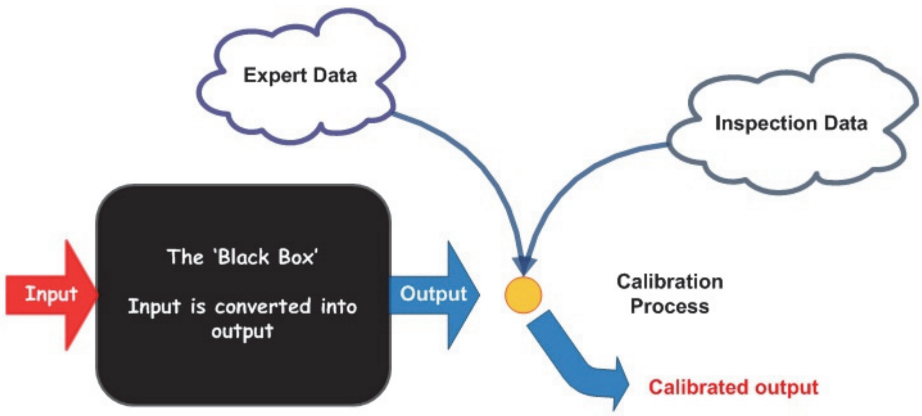


Figure 7-2. Black box Model

7.4 DETAILS AND DEFECTS IN THE COMPUTATIONAL PROCESS

The importance of defining a catalogue for the structural details and defects/deteriorations to be considered in this research was discussed in Chapter 5. The structure of the database which includes different details, different categories of defect (corrosion, crack, coating …), positions and locations of the defects and details in the ship was discussed in Chapter 8. For ease of understanding, a reminder of the information needed in the computational process is provided below (Figure 7-3):

For each detail in a particular ship:

a) Locations on the ship (mid-section, web frame...);

b) Position on the ship ((x, y, z), frame number...);

c) Categories of defect/deterioration related to the detail:

  i. Corrosion and its types (Pitting, Grooving, Dents);

  ii. Coating degradation and its types;

  iii. Crack and its types;

  iv. Others;

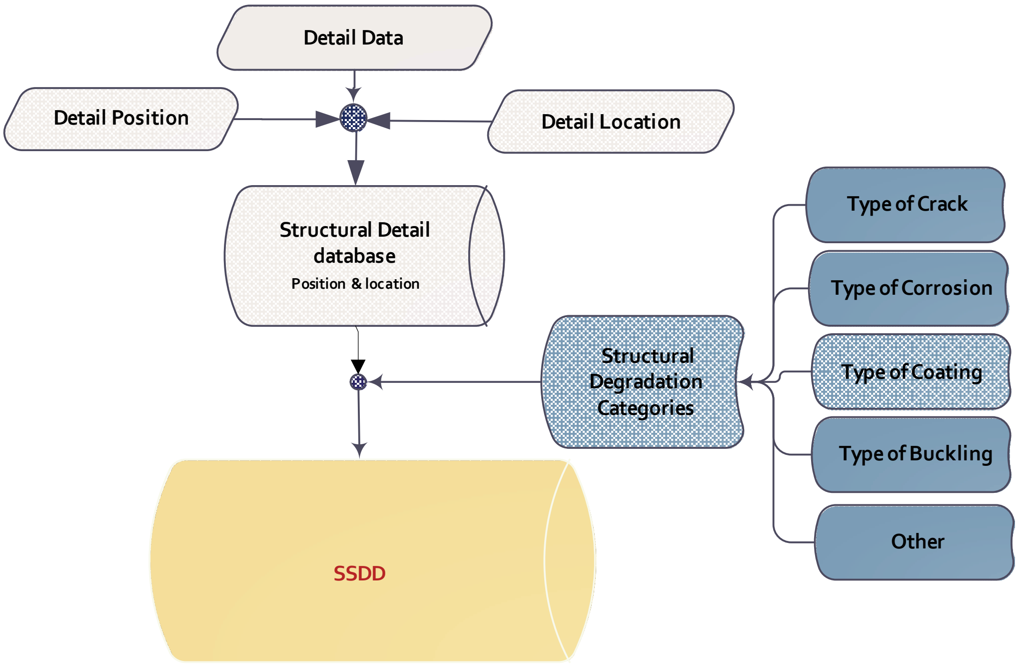


Figure 7-3 Structural deteriorations data flow

7.5 COMPUTATIONAL PROCEDURE

Prediction models of structural deteriorations in ships (cracks, corrosion…) usually produce data which are incompatible with the recorded measurements of the defects/deteriorations. This is caused by systematic model biases that affect their reliability. Without an effective method to reduce the mismatch between data predicted and recorded, the model is prevented from achieving its optimal predictive capability.

The complexity of the overall system for ship inspection planning arises due to the use of both the ship specific and other ship statistical data.

The system as demonstrated below in Figure 7-4, include several ships, one ship Manager and one Classification society.

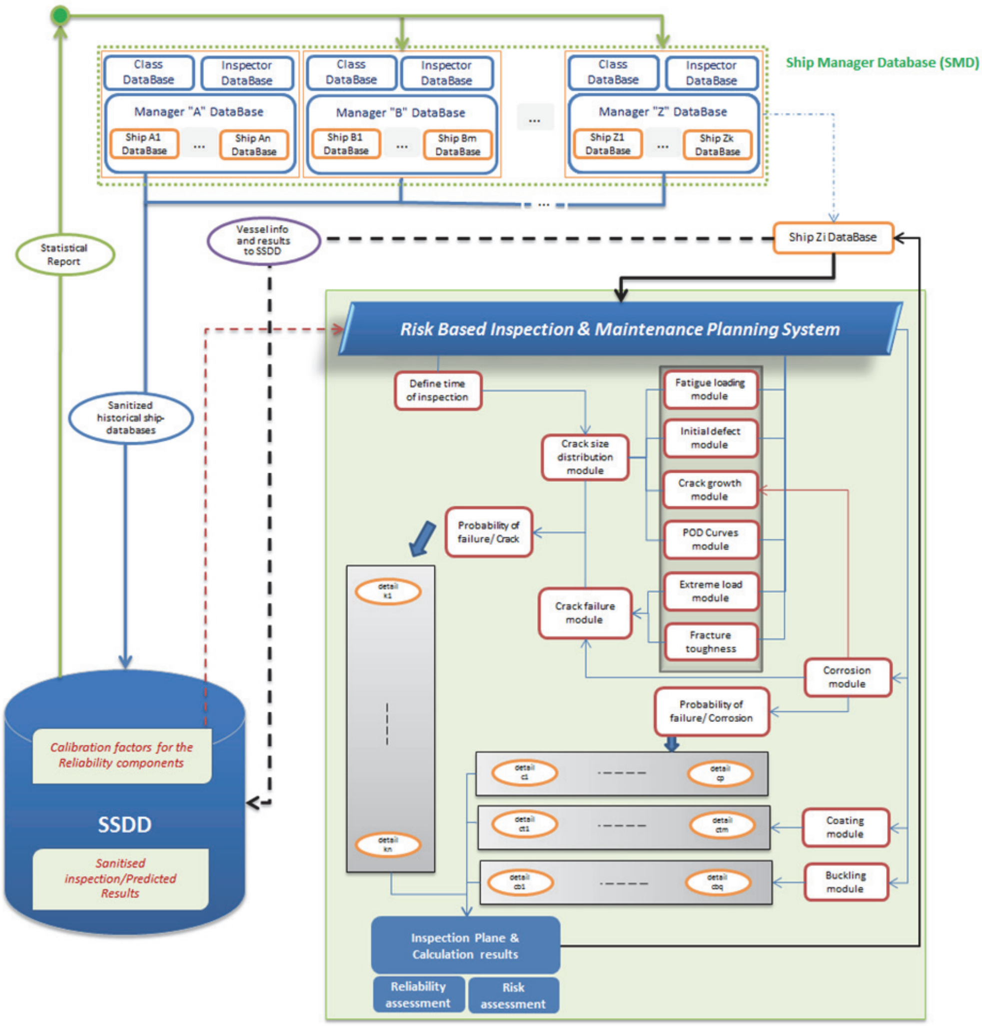


Figure 7-4 SSDD within the Risk Based Inspection & Maintenance Planning System

In order for the computational module of the central database (Figure 7-5) to operate, it needs the following inputs:

- Vessel info.
- Inspection data and outputs from the prediction models or if data is double sanitised (as explained in Chapter 6) ratios of measured/predicted defect/deterioration data.
- Expert data.

The computational process then:

- Computes the ratios if not provided as inputs.
- Computes and updates the correlation factors per
  - Ship type
  - Route
  - Details
  - Type of defect/deterioration
  - Space
  - Location
  - etc…
- Computes the bias Matrix (and confidence intervals).
- Computes the correction factor by combining expert bias with computed bias.

Once the computation is performed the following output are produced:

- For Inspection planning: calibration factors for failure prediction models (crack growth calculations, corrosion calculations, etc…)
- Summary report
- Detailed printout

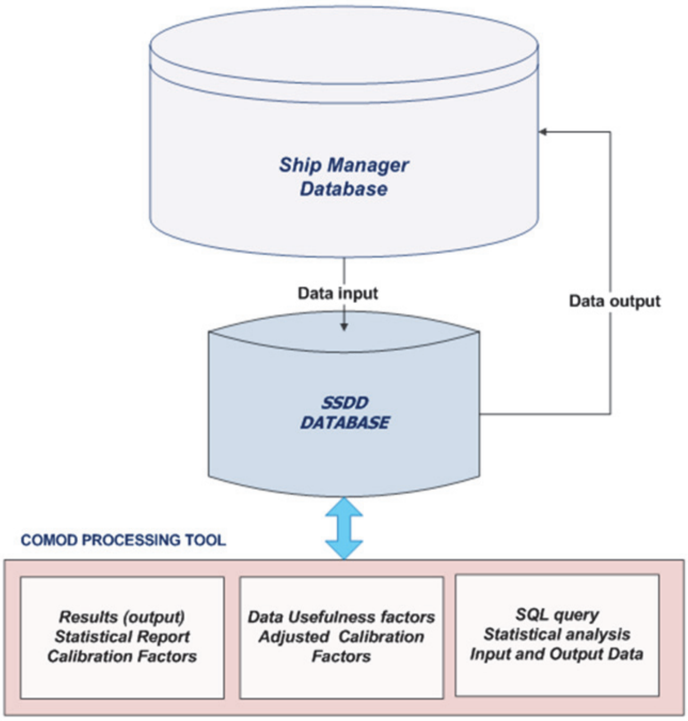


Figure 7-5 SSDD & Ship Manager Database Interactions

7.6 STATISTICAL PROCESSING TO PROVIDE CALIBRATION FACTORS

The data used to perform the computation of the calibration factors is in the form of ratios of actual deterioration (cracking or coating breakdown or corrosion) / expected deterioration.

For a particular detail, using only the most relevant data may not be best because the quantity of data may be insufficient to have statistical confidence in the resulting calibration factors. And using too broad a range of data will result in a lack of confidence because much of the data will not be relevant. Therefore the SSDD program (COMOD) will weight each piece of SSDD data according to its relevance (usefulness) for calibration purposes and then return the weighted mean and coefficient of variation values required for calibration.

The usefulness factors will vary from 100 to 0, where 100 means numbers are directly applicable and 0 means there is no applicability.

If the specificities of different ships need to be taken into account, the usefulness factors could be multiplied by a ship dependent Oceanographic data quality factor/100.

The whole computational process as illustrated in Figure 7-6 can be summarised with the following steps:

Step 0		Input from prediction models.
Step 1		Determination of the ship characteristic (from the input Step 0): ship type, route, type of cargo, type of defect/deterioration *(ex. crack)*...
Step2		Extract inspection and expert data with the same ship characteristic from the data stored in SSDD: *Inspection data:* ▪ Measurement data for the defect/deterioration. ▪ Ratios *Recorded/Predicted* if data double sanitised. *Expert Data:* ▪ Subjective value for defect/deterioration ratio

		(Recorded/Predicted). ▪ Correlation factors for ship details. ▪ Correlation factors for defects. ▪ Ship Location correlation factors. ▪ Ship space correlation factors.
<u>*Step 3*</u>		Computational steps A. <u>*For real data*</u> ▪ If data are single sanitised compute the ratios *Recorded/Predicted* else use ratios given as inputs. ▪ Compute measures of central tendency (*averages - mean, median and mode*) and measures of variability about the average (*range and standard deviation*) for the ratios. ▪ Compute coefficient of variation. ▪ Compute Correlation coefficients and usefulness factors. ▪ Perform statistical tests to help deductions to be made from the data collected, to test hypotheses set and relating findings to the group or family of the details. ▪ Compute confidence intervals for the mean and the coefficient of variation. ▪ Compute calibration factors (weighted mean) and weighted standard deviation. B. <u>*For expert opinion data*</u> ▪ Combine correlations if given separately. ▪ Compute confidence intervals for the mean and the coefficient of variation assuming a number *N* of data. ▪ Compute calibration factors (weighted mean) and weighted standard deviation
<u>*Step 4*</u>		Combining calibration factors obtained in <u>*Step 3A*</u> (inspection data) with calibration factors obtained in <u>*Step 3B*</u> (expert data) and compute their coefficient of variation and associated confidence intervals.
<u>*Step 5*</u>		Export the calibration parameters to the condition planning and prediction modules for new evaluation.
<u>*Step 6*</u>		Export the statistical report.

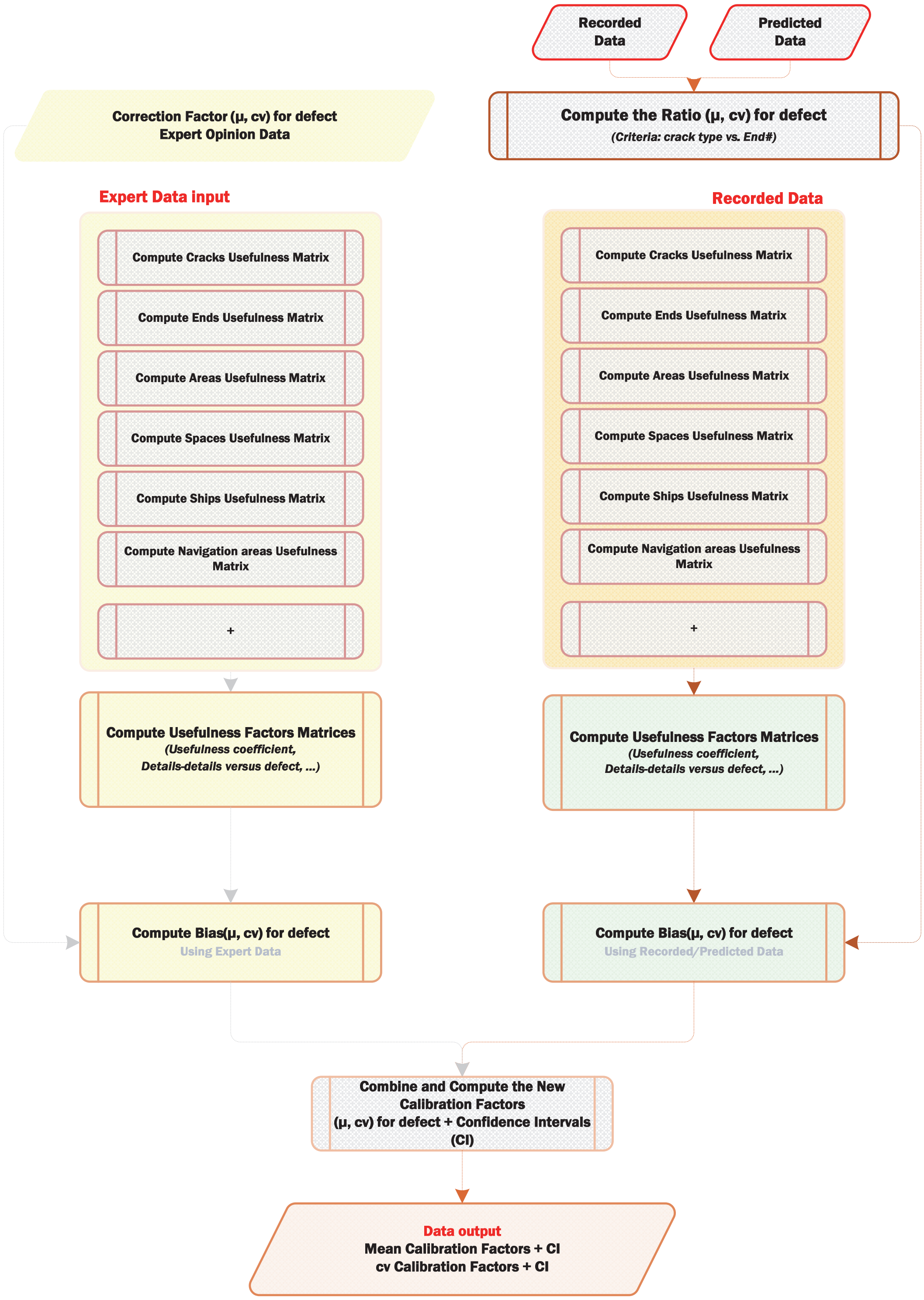


Figure 7-6. COMOD Computational Steps

Each step is explained in details in the following subsections.

7.6.1 Input Results from Reliability Models and Retrieving Data from the Database

This subsection explains the input to the computational module (Step 0 to Step 2).

Data from inspections and prediction models will consist of:

- Date of Inspection/year of prediction
- Location (e.g. Frame#3-4, side shell stiffener#22, end#1)
- Defect/deterioration type and extent (Coating condition, General corrosion, Grooving corrosion, Pitting corrosion, Cracks: description of location, type and size)

Data from expert judgment are in the shape of ratio (bias values) with mean and coefficient of variation. Data includes subjective values for defect ratios and for correlation as explained later in the following subsections.

7.6.2 Computational Methodology

This subsection explains *Setp3- Computational steps*.

For every set of data (differences in handling expert data and real data are explained in following subsections) the following is computed:

- mean μ and coefficient of variation cv of the ratios only for real data.
- correlation (usefulness) factors.
- confidence intervals for μ and cv.
- Weighted mean (calibration factors) and standard deviation.

When computing the correlation factors the number of data items (sample size) matters and is taken into account in determining the truth of the correlation factor (hypotheses test). In addition and specifically for crack defects, to allow meaningful correlations to be calculated an extensive system of coding structural components and crack locations has been developed as explained in Chapter 5.

7.6.3 Data Analysis Based on Recorded Data

This subsection explains *Step3A* of the computational process which uses analytical computation, and provides descriptive statistics for analysed data including measures of central tendency and measures of variability about the average (Figure 7-7).

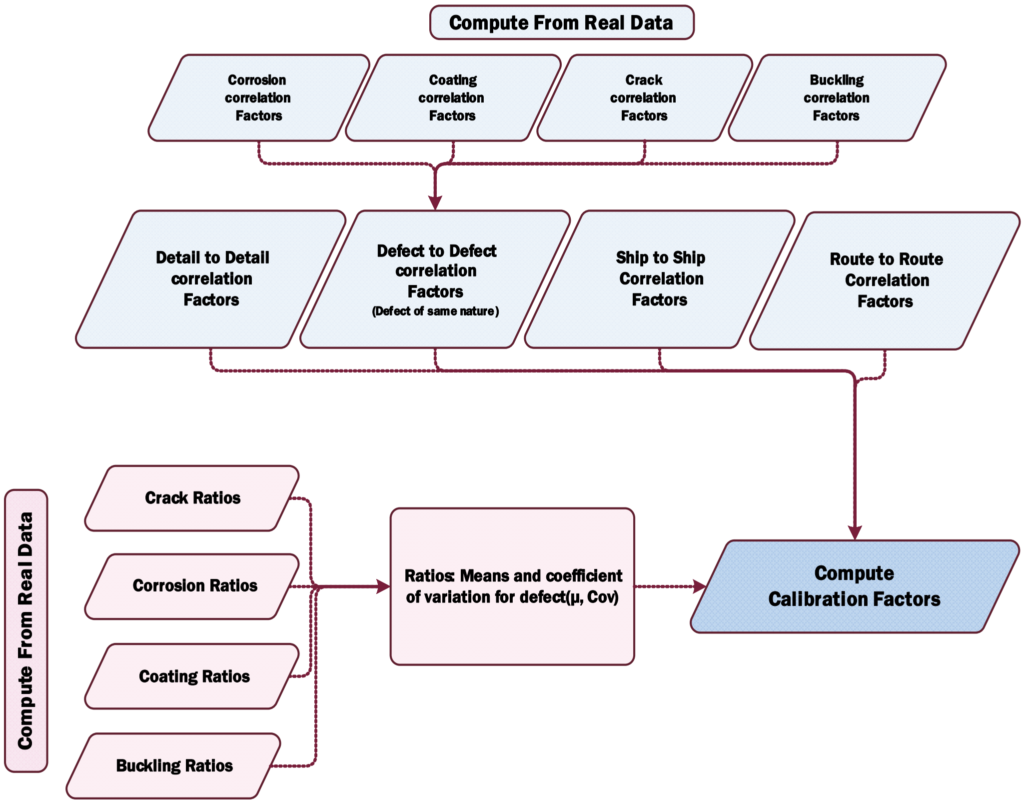


Figure 7-7 SSDD computational steps: Real Data

The defect/deterioration ratio is calculated using data from inspections and predictions. When data is double sanitised these ratios are provided as input.

The mean and coefficient of variation parameters (μ, cv) of the ratios and their associated confidence intervals are then computed statistically considering the defect type, detail type, location etc.

The correlation coefficients and usefulness factors including the correlation tests and confidence intervals are then calculated as detailed below (Figure 7-8).

1) Ship's Details Correlation factors

The correlation factors between two ships details $\mathrm{d_1}$ and $\mathrm{d_2}$ are calculated using the data for the defects associated with the details and is given by:

$$\rho_{\mathrm{details}_{(d_1,d_2)}} = \frac{\mathrm{Cov}(d_1, d_2)}{\sigma_{d1} \times \sigma_{d2}} \qquad \text{Eq. 7-1}$$

where $\mathrm{Cov}(d_1, d_2)$ is the covariance for (d_1, d_2).

*2) Defects/*deteriorations *Correlation factors*

The correlation factors between two defects/deteriorations $\mathrm{C_1}$ and $\mathrm{C_2}$ are calculated using the data for the defects/deteriorations recorded with each detail-location (detail-connection) on ships and is given by:

$$\rho_{\mathrm{DefectType}_{(C_1,C_2)}} = \frac{\mathrm{Cov}(C_1, C_2)}{\sigma_{C1} \times \sigma_{C2}} \qquad \text{Eq. 7-2}$$

3) Ship Location correlation factors

The correlation factors between two different locations $\mathrm{L_1}$ and $\mathrm{L_2}$ on a ship are calculated using the data for the defects-details recorded with each location (detail-connection) on the ship and is given by:

$$\rho_{\mathrm{Location}_{(L_1,L_2)}} = \frac{\mathrm{Cov}(L_1, L_2)}{\sigma_{L1} \times \sigma_{L2}} \qquad \text{Eq. 7-3}$$

4) Ship's Space correlation factors

The correlation factors between two ships compartments $\mathrm{Cm_1}$ and $\mathrm{Cm_2}$ are calculated using the recorded defects/deteriorations data by defect/deterioration types and compartment types.

$$\rho_{\mathrm{Compartment}_{(L_1,L_2)}} = \frac{\mathrm{Cov}(Cm_1,Cm_2)}{\sigma_{Cm1} \times \sigma_{Cm2}} \qquad \text{Eq. 7-4}$$

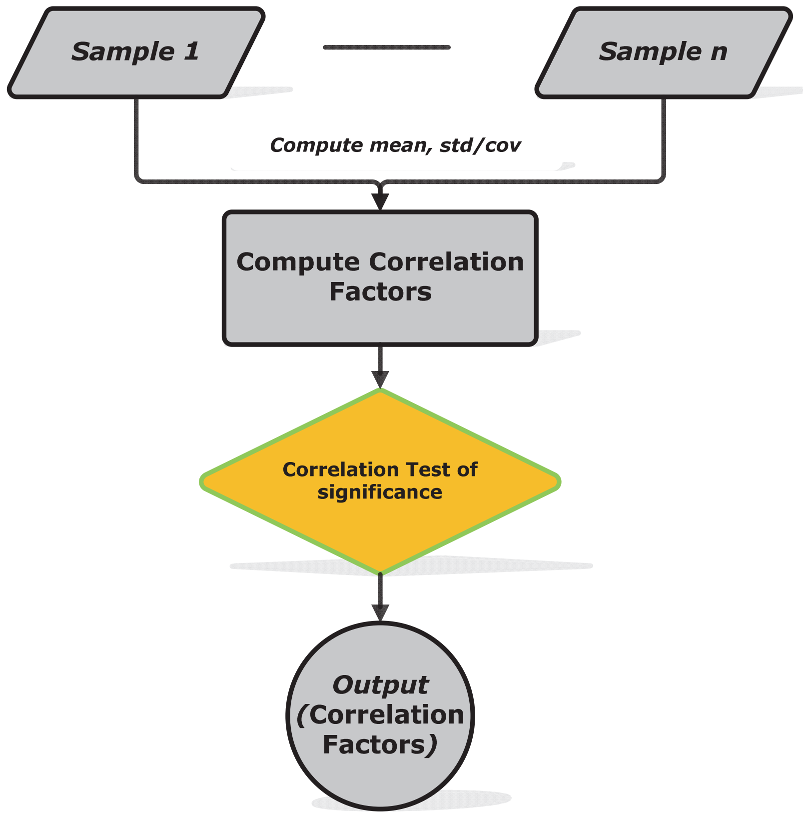


Figure 7-8 SSDD computational steps: Correlation Factors

The usefulness factor (UF) to assess the behaviour of defect/deterioration type related to any considered element (ship, location, detail, etc…) is computed using the square of the correlation factor which describes the proportion of variance in common between the two variables as explained in Appendix A.4 and given by:

$$\mathrm{UF} = \rho^2 \times 100 \qquad \text{Eq. 7-5}$$

The confidence factors for the computed calibration factors are determined using the Z- test (that the distribution is normal). The confidence factor is given by:

$$\mathrm{CF} = \mathrm{p\_value} * 100 \qquad \text{Eq. 7-6}$$

The calibration factors (bias) are then calculated using the weighted mean of the mean $\overline{x_i}$ of the defect ratios (x_i), where the usefulness factors (ω_i) are used as weighting factors for the different elements considered.

The bias (mean) is given by:

$$M(x_1, x_2, \dots, x_N) = \frac{\sum_{i=1}^{N} \omega_i \times \overline{x_i}}{\sum_{j=1}^{N} \omega_j} \quad ; \quad \omega_i \geq 0 \qquad \text{Eq. 7-7}$$

The weighted standard deviation is given by:

$$S(x_1, x_2, \dots, x_N) = \sqrt{\frac{\sum_{i=1}^{N} {\omega_i}^2 \times {\sigma_i}^2}{\left(\sum_{j=1}^{N} \omega_j\right)^2}} \quad ; \quad \omega_i \geq 0 \qquad \text{Eq. 7-8}$$

where σ_i is the standard deviation of the defect ratios (x_i).

The coefficient of variation is given by:

$$cv\,(x_1, x_2, \dots, x_N) = \frac{S(x_1, x_2, \dots, x_N)}{M(x_1, x_2, \dots, x_N)} \qquad \text{Eq. 7-9}$$

7.6.4 Data Analysis Based on Expert Opinion Data

This subsection explains Step 3B of the computational process. The analysis is performed based on the expert opinion data for the different types of structural deteriorations (Crack, Corrosion, Coating, Anodes, Buckling, and Others…) (see Figure 7-9).

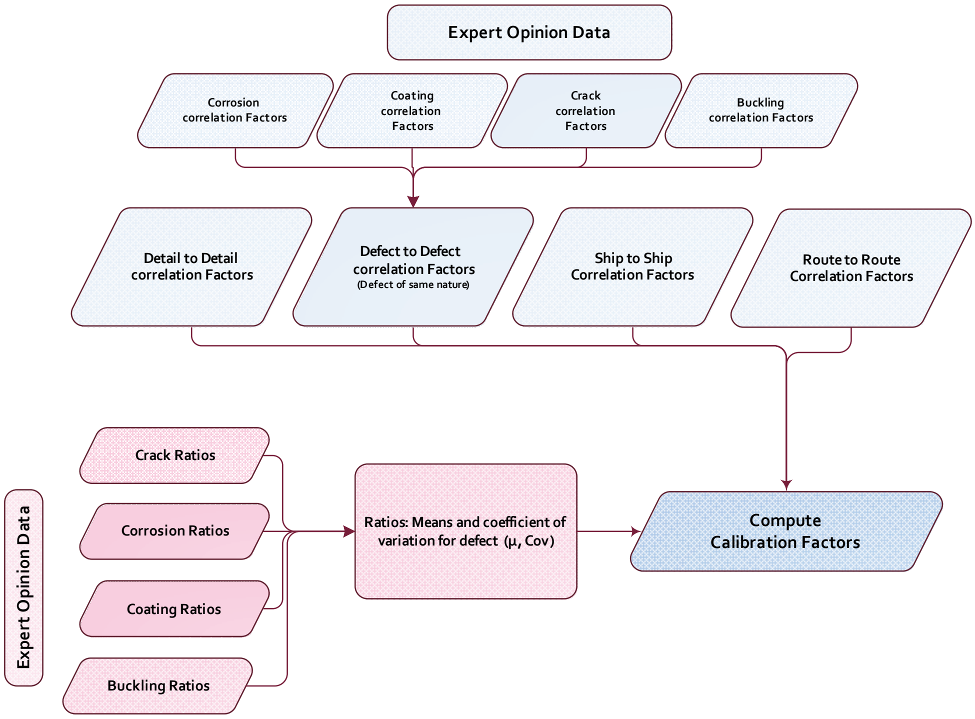


Figure 7-9. SSDD computational steps: Expert judgment Data

The input needed for the computation of expert data includes the following:

a. *Subjective value for defect/*deterioration *Ratio (Recorded/Predicted)*

The subjective data consists of the defect/deterioration mean ratios that the experts can accumulate from their experience. In this case the model developer could contribute as he/she already has an idea of how his model is behaving in terms of overestimating or underestimating the real life. This ratio will contribute to correct the model outputs. Experts also provide their confidence for the subjective data.

b. Subjective value for Correlation data

Subjective values, provided by experts, of correlations for different elements such as:

- ✓ Ship's details correlation factors,
- ✓ Defect/deterioration types correlation factors,
- ✓ Ship's location correlation factors,
- ✓ Ship's compartments correlation factors, and
- ✓ Other…

The correlations describing the common behaviour between the elements considered will be combined to estimate the correlation coefficients using the Partial correlation method (Kline 2004). For example, the correlation matrix between details for each crack type can be calculated using the Partial correlation method as follows:

$$\rho_{D_i,D_j/C_{kl}} = \begin{cases} \dfrac{\rho_{D_i,D_j} - \rho_{D_i,C_{kl}} \times \rho_{D_j,C_{kl}}}{\sqrt{\left(1-(\rho_{D_i,C_{kl}})^2\right)} \times \sqrt{\left(1-(\rho_{D_j,C_{kl}})^2\right)}} & if\ i \neq j \\ \rho_{D_i,D_i} & else \end{cases} \qquad \text{Eq. 7-10}$$

Where: ρ_{D_i,D_j} is the correlation coefficient between details types i and j and $\rho_{D_i,C_{kl}}$ is the correlation coefficient between crack types k and l given the detail D_i.

As discussed in Appendix A.4, the squared correlation factor (multiplied by 100) is considered as a usefulness factor which is used to assess the applicability of data from one ship/compartment type/detail/defect to another.

The calibration factors and the coefficient of variation are as previously defined (Eq. 7-7 to Eq. 7-9).

The expert opinion data will be used when real data is not available, and will be combined with and eventually be automatically superseded by real data collected from inspection and model prediction, when they become available.

7.6.5 Combining Expert and Recorded Data

Step 4 of the computation process combines expert and recorded data and this is done after computing the calibration factors parameters (μ, cv) and their confidence intervals for the expert and real data. The overall calibration factor is computed as a weighted sum of the real data calibration factor and the expert data calibration factor.

Let μ_{real} and μ_{expert} be the calibration factors for the real data and the expert data respectively and let σ^2_{real} and σ^2_{expert} be the associated variance for the real and expert data respectively.

Based on the inverse variance weighting method (Hartung et al. 2008; Higgins et al. 2011), let ω_{real} and ω_{expert} be the weights associated to μ_{real} and μ_{expert} respectively they are defined as follows:

$$\omega_{real} = \frac{1/\sigma^2_{real}}{1/\sigma^2_{real} + 1/\sigma^2_{expert}} \qquad \text{Eq. 7-11}$$

$$\omega_{expert} = \frac{1/\sigma^2_{real}}{1/\sigma^2_{real} + 1/\sigma^2_{expert}} \qquad \text{Eq. 7-12}$$

The combined calibration factor is then given by:

$$\mu_{combined} = \mu_{real}\omega_{real} + \mu_{expert}\omega_{expert} \qquad \text{Eq. 7-13}$$

7.6.6 Calibration of Prediction Models When Data is Missing

Over the lifetime of a ship, if no data (real or from expert) is available for a particular year, the calibration factor from the previous year is used.

7.6.7 Statistical Report and Output

Step5 and *6* are about the output of the computational module.

The data output will consist of:

1) Inspection Planning Calculation Process
   a. Calibration factors for corrosion calculations (μ_c, cv_c)
   b. Calibration factors for crack growth calculations (μ_c, cv_c)
   c. Calibration factors for coating degradation calculations (μ_c, cv_c)
   d. Calibration factors for buckling calculations (μ_c, cv_c)
2) Summary report
3) Detailed printout

The statistical report indirectly includes data information relevant to the data input and output from and to the Ship Structural Defect Database and models used to assess the ship structural reliability.

The report output and printout will be produced by query.

(a) *Output to the prediction models*

For each part or location to be checked, the μ_c and cv_c values will be used as an integral part of the reliability assessment.

(b) Overall Statistical Summary Report

- The statistical report will provide information about the data in the SSDD. In most cases the statistics will be of the observed/expected results with options for different subsets of data to be considered.
- Metocean data – statistics of input data quality (detailed vs. estimated)
- Corrosion

- Crack growth
- Coating breakdown
- Other

(c) Detailed Print Outs From the SSDD

Various printed reports that summarize the data and show all the data can be produced.

7.7 SUMMARY

This chapter has presented a methodology to calibrate the prediction models of structural deteriorations using data from experience-based methods and expert judgement. Correlations between deteriorations and details, locations.., have been used to deduce the usefulness of available information in the assessment of potential defects/deteriorations. This methodology is to be used to improve inspections planning and make them cost-effective.

The method used in the development of the calibration methodology is mainly based on statistical analysis but could also be done using other methods such as classical Bayesian updating (Harney 2003; Holmes et al. 2008).

CHAPTER 8: CASE STUDY

8.1 INTRODUCTION

This chapter demonstrates, using a simplified small example, how the calibration process is performed.

Confidence in using statistical data from similar -rather than identical details/plates- will be evaluated with the help of usefulness factors.

Both crack and general corrosion deteriorations will be used in the case study.

It was hope that during the course of the Rispect project real measurement data of deteriorations would be available, which would have been used in this research to demonstrate the calibration of the deterioration prediction models. Unfortunately it was not possible to obtain such data, so for this study it was decided to use simulated data for the crack example (practical application would involve hundreds or thousands of crack measurements from many ships.). For the corrosion case study, simulations were used to produce values representing measurements.

8.2 COMPUTATION

8.2.1 Application to Crack defects

This example will demonstrate how the calibration of the prediction model is performed. It is assumed that data is available from measurements and from experts.

For this case study and so that the reader can follow the methodology, only two (02) crack types at 4 different structural details (connections) are considered (Figure 8-1).

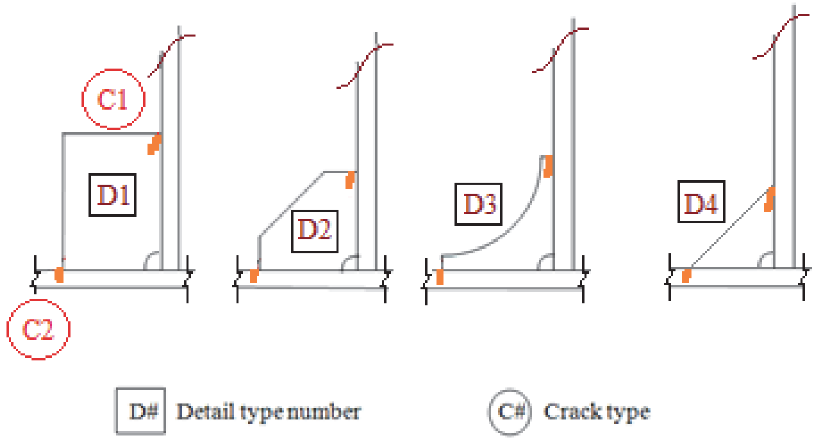


Figure 8-1 Details and crack locations (subject to similar stresses)

All data used for the computations of calibration factors for the crack defects are simulated data. It is assumed that all details and cracks are subject to similar stresses and environmental corrosion.

The step by step computation procedure is explained hereafter.

8.2.1.1 Step A: dealing with measurement data

<u>Input data from measurements</u>

We assume that 8 measurements are available for each crack type at each detail. Data from measurements are assumed to be as in Table 8-1 below.

Table 8-1: Crack size recorded data (mm)

Predate Data	Detail1	Detail2	Detail3	Detail4
PredictedData_C1	0.072	0.056	0.049	0.071
	0.071	0.065	0.055	0.068
	0.059	0.071	0.068	0.059
	0.064	0.078	0.066	0.055
	0.066	0.072	0.059	0.051
	0.059	0.049	0.052	0.048
	0.052	0.055	0.071	0.070
	0.043	0.068	0.062	0.059
PredictedData_C2	0.058	0.061	0.074	0.069
	0.074	0.070	0.054	0.052
	0.060	0.068	0.073	0.072
	0.074	0.063	0.064	0.069
	0.076	0.067	0.056	0.041
	0.069	0.059	0.062	0.068
	0.055	0.045	0.060	0.067
	0.063	0.058	0.056	0.065

Data from prediction model are assumed to be as follows.

Table 8-2: Crack size predicted data (mm)

Recorded Data	Detail1	Detail2	Detail3	Detail4
PredictedData_C1	0.066	0.066	0.059	0.061
	0.068	0.056	0.075	0.081
	0.055	0.061	0.078	0.069
	0.066	0.071	0.068	0.050
	0.056	0.067	0.052	0.055
	0.069	0.054	0.072	0.058
	0.072	0.065	0.067	0.072
	0.049	0.066	0.058	0.065
PredictedData_C2	0.066	0.066	0.059	0.061
	0.068	0.056	0.075	0.081
	0.055	0.061	0.078	0.069
	0.066	0.071	0.066	0.050
	0.056	0.077	0.062	0.055
	0.065	0.054	0.052	0.058
	0.072	0.065	0.067	0.072
	0.049	0.066	0.058	0.055

Step 1A:

Ratios of measured size /predicted size are computed and are presented in Table 8-3 below.

Table 8-3: Crack ratios

Ratio Recorded-Predicted data	Detail1	Detail2	Detail3	Detail4
Ratio_C1	0.917	1.179	1.204	0.859
	0.958	0.862	1.364	1.191
	0.932	0.859	1.147	1.169
	1.031	0.910	1.030	0.909
	0.848	0.931	0.881	1.078
	1.169	1.102	1.385	1.208
	1.385	1.182	0.944	1.029
	1.140	0.971	0.935	1.102
Ratio_C2	1.138	1.082	0.797	0.884
	0.919	0.800	1.389	1.558
	0.917	0.897	1.068	0.958
	0.892	1.127	1.031	0.725
	0.737	1.149	1.107	1.341
	0.942	0.915	0.839	0.853
	1.309	1.444	1.117	1.075
	0.778	1.138	1.036	0.846

Mean and coefficient of variation of the ratios for every detail per crack type are computed and are summarised below.

Table 8-4: Means and coefficient of variation of ratios per detail per crack type

Recorded-Predicted data		μ	cv
Crack Type C1	Detail1	1.047	0.157
	Detail2	0.999	0.127
	Detail3	1.111	0.164
	Detail4	1.068	0.113
Crack Type C2	Detail1	0.954	0.183
	Detail2	1.069	0.175
	Detail3	1.048	0.162
	Detail4	1.030	0.257

Step 2A:

Then correlations per crack type are computed and the usefulness factors as defined in Appendix A.4 (Section A.4.2.9) are calculated and are shown in Table 8-5.

Table 8-5: Usefulness factors for crack defect based on measurement data.

Recorded-Predicted data		Crack Type C1				Crack Type C2			
		Detail1	Detail2	Detail3	Detail4	Detail1	Detail2	Detail3	Detail4
Crack Type C1	Detail1	100.0	30.4	1.7	0.6	31.9	32.1	0.5	8.3
	Detail2	30.4	100.0	0.0	16.0	55.7	29.8	37.8	10.7
	Detail3	1.7	0.0	100.0	13.5	1.4	60.5	0.4	1.4
	Detail4	0.6	16.0	13.5	100.0	12.8	27.9	16.7	17.5
Crack Type C2	Detail1	31.9	55.7	1.4	12.8	100.0	21.0	3.0	1.2
	Detail2	32.1	29.8	60.5	27.9	21.0	100.0	2.2	5.5
	Detail3	0.5	37.8	0.4	16.7	3.0	2.2	100.0	60.5
	Detail4	8.3	10.7	1.4	17.5	1.2	5.5	60.5	100.0

Step 3A:

Weighted mean and standard deviation are computed using usefulness factors per detail per crack. If the method has collected a lot of data then these values should be reliable. The values are presented below.

Table 8-6: Calibration factors based on measurements data

Recorded-Predicted data		Calibration factor	Associated *cv*
Crack Type C1	Detail1	1.029	0.089
	Detail2	1.015	0.067
	Detail3	1.091	0.110
	Detail4	1.054	0.068
Crack Type C2	Detail1	0.998	0.088
	Detail2	1.059	0.079
	Detail3	1.035	0.105
	Detail4	1.039	0.134

However, especially when starting to use the system and for unusual details, the confidence obtained from the measured data will be small and expert judgment needs to be integrated with these values. Step B does this, in such a way that the expert judgment becomes less important as more data is gathered.

8.2.1.2 Step B: dealing with Expert data

Input data from Expert

The data from experts is given in the form of means and associated coefficient of variation for the crack size. For this case study, it is assumed to have the following values:

Table 8-7: Crack data from expert

Expert data		μ	cv
Crack Type C1	Detail1	1.100	0.100
	Detail2	0.900	0.400
	Detail3	0.750	0.200
	Detail4	0.900	0.500
Crack Type C2	Detail1	1.300	0.800
	Detail2	0.900	0.100
	Detail3	0.100	0.800
	Detail4	1.200	0.100

Step1B:

Experts also provide correlation factors for details (Table 8-8) and for crack types (Table 8-9) separately. In this case the partial correlation, as explained in Chapter 7, is used to compute the usefulness factors (Table 8-10).

Table 8-8: Expert correlation factors for details

Expert data	Detail1	Detail2	Detail3	Detail4
Detail1	1.0	0.8	0.7	0.7
Detail2	0.8	1.0	0.6	0.7
Detail3	0.7	0.6	1.0	0.7
Detail4	0.7	0.7	0.7	1.0

Table 8-9: Expert correlation factors for crack types

Expert data	C1	C2
C1	1.0	0.5
C2	0.5	1.0

Table 8-10: Usefulness factors (%) for crack defect based on expert data

Expert data		Crack Type C1				Crack Type C2			
		Detail 1	Detail 2	Detail 3	Detail 4	Detail 1	Detail 2	Detail 3	Detail 4
Crack Type C1	Detail1	100.0	20.3	64.0	56.1	42.3	31.5	49.0	38.9
	Detail2	20.3	100.0	56.1	64.0	31.5	42.3	38.9	49.0
	Detail3	64.0	56.1	100.0	20.3	36.0	24.8	42.3	31.5
	Detail4	56.1	64.0	20.3	100.0	24.8	36.0	31.5	42.3
Crack Type C2	Detail1	42.3	31.5	36.0	24.8	100.0	20.3	49.0	38.9
	Detail2	31.5	42.3	24.8	36.0	20.3	100.0	38.9	49.0
	Detail3	49.0	38.9	42.3	31.5	49.0	38.9	100.0	20.3
	Detail4	38.9	49.0	31.5	42.3	38.9	49.0	20.3	100.0

Step 2B:

The weighted mean (calibration factor) is then computed as above in the case of measurement data. The results are given below.

Table 8-11: Calibration factors based on expert data

Expert data		Calibration factors	Associated *cv*
Crack Type C1	Detail1	0.899	0.148
	Detail2	0.880	0.163
	Detail3	0.868	0.144
	Detail4	0.915	0.168
Crack Type C2	Detail1	0.945	0.326
	Detail2	0.883	0.109
	Detail3	0.762	0.199
	Detail4	0.988	0.137

8.2.1.3 Step C: Combining data sources (measurement and expert)

Step C1:

Once calibration factors from both sources have been computed, the overall calibration factors (Table 8-12) is determined using a weighted sum, where the weights are taken to be the (normalised) inverse of the variance associated to the calibration factors (Section 7.6.5).

Table 8-12: Combined Calibration factors

		Expert		Data	
		Calibration Factors	*cv*	Calibration Factors	*cv*
Crack Type C1	Detail1	1.029	0.089	0.752	0.071
	Detail2	1.015	0.067	0.613	0.071
	Detail3	1.091	0.110	0.797	0.073
	Detail4	1.054	0.068	0.714	0.054
Crack Type C2	Detail1	0.998	0.088	0.841	0.073
	Detail2	1.059	0.079	0.854	0.071
	Detail3	1.035	0.105	0.777	0.066
	Detail4	1.039	0.134	0.820	0.051

Combined		Combined Calibration Factors	*cv*
Crack Type C1	Detail1	0.970	0.081
	Detail2	0.993	0.062
	Detail3	0.992	0.088
	Detail4	1.035	0.063
Crack Type C2	Detail1	0.994	0.085
	Detail2	0.974	0.065
	Detail3	0.878	0.112
	Detail4	1.011	0.096

Step C2:

Confidence intervals for the overall calibration factors and their coefficients of variation are computed (as explained in Section A.4.2.3), assuming that the variables are normally distributed. Results are presented in Table 8-13 and Table 8-14 respectively.

Table 8-13: 95% Confidence interval for the overall calibration factors

Confidence interval		Calibration Factors	Upper bound	Lower bound	Range
Crack Type C1	Detail1	0.970	1.079	0.861	0.218
	Detail2	0.993	1.079	0.908	0.171
	Detail3	0.992	1.112	0.871	0.241
	Detail4	1.035	1.126	0.943	0.183
Crack Type C2	Detail1	0.994	1.112	0.876	0.236
	Detail2	0.974	1.062	0.886	0.176
	Detail3	0.878	1.015	0.741	0.274
	Detail4	1.011	1.146	0.876	0.270

Table 8-14: 95% Confidence interval for the coefficient of variation

Confidence interval		*cv*	Upper bound	Lower bound	Range
Crack Type C1	Detail1	0.081	0.237	0.049	0.188
	Detail2	0.062	0.180	0.037	0.143
	Detail3	0.088	0.257	0.053	0.204
	Detail4	0.063	0.184	0.038	0.146
Crack Type C2	Detail1	0.085	0.250	0.051	0.199
	Detail2	0.065	0.189	0.039	0.150
	Detail3	0.112	0.333	0.067	0.266
	Detail4	0.096	0.283	0.058	0.225

8.2.1.4 Realistic data

Fatigue cracking is subject to a very large natural variability: even in laboratory conditions the fatigue life coefficient of variation is about 30%. When performing laboratory fatigue tests the specimens are subject to cyclic loading until a failure occurs[3], so the overall distribution of fatigue life can be determined. To measure fatigue performance and to determine calibration factors using real ship data, the average fatigue life will usually be higher than the ship life or observation period so only part of the distribution will be observed. It is therefore necessary to infer the mean and standard deviation of the overall distribution of fatigue life from the low-life tail of the distribution of fatigue lives. If the form of distribution is assumed in advance then this can be done by fitting the measured data to the lower tail of the assumed distribution. Usually with tail fitting the requirement is to best define the shape of the tail and to extrapolate further into the tail. In this case it is necessary to define the properties of the underlying parent distribution, so instead of fitting an extreme value distribution it is preferable to fit the data to the estimated parent distribution shape.

8.2.1.5 Remarks

The crack example above was kept intentionally simple in order only to illustrate the step by step application of the calibration process. Although identified, issues such as, those related to errors in observations made over a limited time (up to the age of the structure when inspected or decommissioned), or due to the measurement process, are not discussed in this example.

A more detailed example is presented in the next section where the calibration procedure is applied to general corrosion. Aspects such as effect of sample size are discussed.

[3] Note that, in constant amplitude tests, if stresses are below the endurance limit then the specimen will not fail.

8.2.2 Application to General Corrosion

General corrosion is used in this example to demonstrate the calibration factors computation process as well as the impact of the number of measurements data on the quality of the calibrations factors.

For general corrosion it is assumed that steel plates are uniformly wasted.

As introduced earlier, due to a lack of measurements data for the corrosion, it was decided to use corrosion prediction models to produce “measurements” data.

In modelling the corrosion phenomenon, it is assumed that corrosion does not take place in a coated structure until the coating breaks down (coating is not protecting the steel efficiently anymore). After that, corrosion begins, and wastage increases over time.

Once the corrosion begins, there are three types of models for corrosion progress (Wang et al. 2003) (see Figure 8-2):

- Corrosion wastage linearly increases with time (line a). The most common and most widely used assumption in structural strength analyses.
- Corrosion increases and accelerates over time (line b) (occurs when rust build-up is disturbed).
- The rate of corrosion wastage slows down with time (line c), when the steel is gradually covered by scale and rust, protecting the new steel from contact with corrosive environment.
- As a variation of line c, corrosion wastage eventually approaches a plateau, which remains constant.

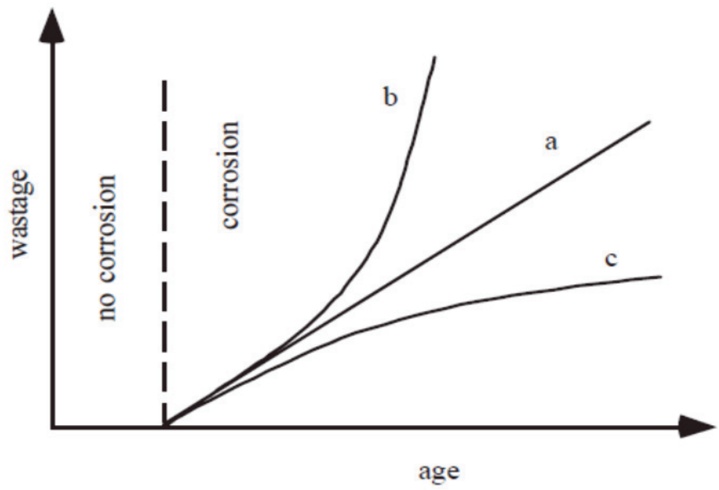


Figure 8-2: Models of corrosion progress (adapted from (Wang et al. 2003))

The model used to produce measurements data is the model proposed by Guedes Soares and Garbatov (1999) which describes the growth of corrosion wastage by a non-linear function of time in three phases (1st phase no corrosion as protection is effective, 2nd phase wastage grows with time in a non-linear manner, 3rd phase growth levels off at a long-term value).

The model is based on the solution to the following differential equation:

$$\tau_t r(t) + d(t) = d_\infty \qquad \text{Eq. 8-1}$$

Where d_∞ is the long term corrosion depth, $d(t)$ is the thickness of the wastage at time t, $r(t)$ is the corrosion rate and τ_t is the transition time during which the corrosion decreases the thickness.

The mean value and standard deviation of corrosion wastage as a function of time are then given by the following equations:

$$\mu[d(t)] = d_\infty \left[1 - \mathrm{e}^{-\frac{t-\tau_c}{\tau_t}}\right] \qquad \textit{Eq. 8-2}$$

$$\sigma[d(t)] = a\,log(t - \tau_c - b) - c \qquad \text{Eq. 8-3}$$

τ_c is the coating life and a, b and c are coefficients.

The long-term probability density function as a function of time is defined as a truncated Normal probability density function.

A total of 14 locations are considered as follows:

bottom (1), inner bottom (2), below top of bilge - hopper tank- face (3), lower slopping (4), lower wing tank - side shell (5), below top of bilge - hopper tank -web (6), between top of bilge, hopper tank, face (7), between top of bilge, hopper tank, web (8), side shell (9), upper than bottom of top side tank, face (10), upper deck (11), upper slopping (12), upper wing tank side shell (13), upper than bottom of top side tank, web (14).

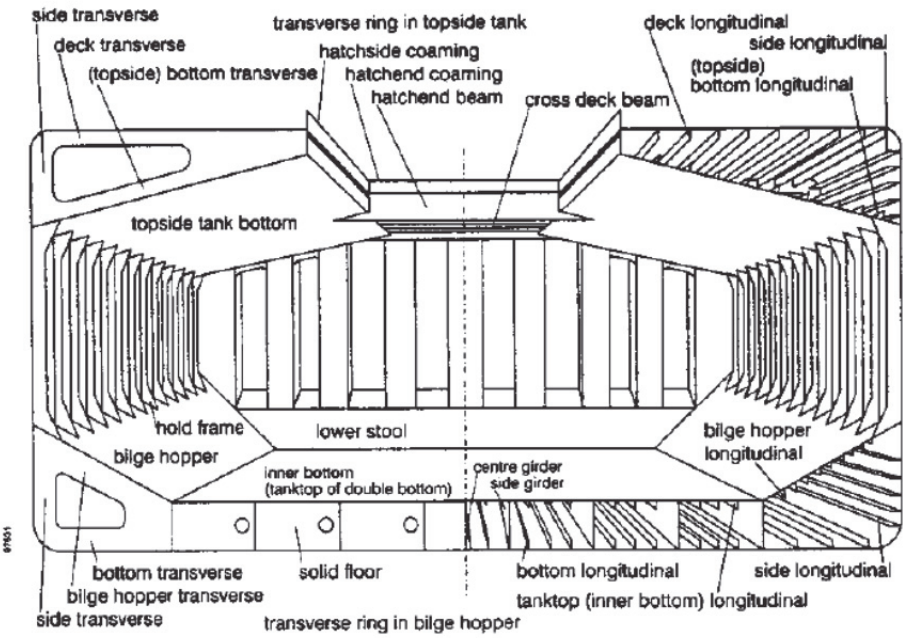


Figure 8-3: Transverse Bulk Carrier (Adapted from(IMO 1997))

The model parameters values for each of the above locations are given in the table below:

Table 8-15: Parameter values of simulation model per location

Location	d_{∞}(mm)	τ_c(years)	τ_t(mm)	a	b	c
1	1.42	14.14	3.17	7.16	-11.60	7.41
2	3.50	18.29	0	1.47	-1.00	-0.23
3	4.68	3,51	9.11	2.08	-1.00	-0.46
4	2.75	19.75	0	16.09	-6.18	12.72
5	1.41	14.72	3.35	13.84	-9.16	13.22
6	3.55	3.17	8.73	11.24	-11.65	11.53
7	4.28	8.54	6.85	7.53	7.53	7.53
8	3.35	5.66	7.26	17.93	-7.75	15.70
9	2.25	25.46	0	1.91	-1.44	0.01
10	2.83	2.92	8.75	1.60	-1.00	-0.42
11	2.50	19.28	0	12.93	-9.83	12.62
12	1.19	15.67	0.69	12.23	12.23	12.23
13	1.58	20.56	0	9.88	-13.24	10.89
14	2.60	5.41	7.25	13.41	-16.42	15.72

The corrosion prediction model used in this case study is as described in (Guo et al. 2008) and follows a Weibull distribution probability density function given by:

$$pdf(C; k, \lambda) = \left(k/_{\lambda}\right)\left(C/_{\lambda}\right)^{k-1} e^{-\left(C/_{\lambda}\right)^{k}} \qquad \text{Eq. 8-4}$$

The shape and scale parameters k and λ are functions of time and are given by:

Cargo oil tanks

$$\begin{cases} k = 0.667 + \dfrac{6.6647}{t} - \dfrac{59.1106}{t^2} \\ \lambda = 0.6665 + 0.0383t - \dfrac{6.322}{t} \end{cases} \qquad \text{Eq. 8-5}$$

Ballast tanks

$$\begin{cases} k = 1.0015 + \dfrac{12.41}{t} - \dfrac{112.7036}{t^2} \\ \lambda = 0.6295 + 0.0388t - \dfrac{5.9015}{t} \end{cases} \qquad \text{Eq. 8-6}$$

For this example 5 locations (number 3, 6, 8, 10 and 14 from Table 8-5) are considered. Similar environment conditions are assumed for all locations.

The computation steps to obtain the calibration factors are the same as the one followed in the crack defect example above.

INPUTS

- A period of 15 years (from10 to 25 years) was assumed.
- The input to represent the measurement data is obtained through simulation using the truncated normal distribution with parameters defined by Eq. 8-2 and Eq. 8-3.
- For each year (year 10 to year 25) and for each location, 10^4 simulations were performed.
- For each year, predicted values for the same locations were also computed using the cargo tank equation of the prediction model (Eq. 8-5).
- Expert data was assumed to come from 100 inputs.

COMPUTATION STEPS

As in the previous example, first the ratios measured/predicted are computed for each location, and then the mean and coefficient of variation of the ratios are calculated.

In the next step, the usefulness (correlation) factors according to the locations have been computed for the measurement data.

For the expert data correlations are given as input.

It is worth noting that when more information is available the correlation should be computed based on more criteria i.e. a particular location such as side shell for example, should be subdivided horizontally to have top middle and bottom parts and vertically to have right, centre and left parts (9 sections) as illustrated in Figure 8-4 below. Also steel grades, coated surfaces, environmental temperature, salinity… should be accounted for in the correlation computation. In other words data should be grouped according to these criteria and the correlations calculated accordingly.

Top left	*Top centre*	*Top right*
Middle left	*Middle centre*	*Middle right*
Bottom left	*Bottom centre*	*Bottom right*

Figure 8-4: Subdivision of location

In this example as no additional data is available a simple correlation (per location) has been considered.

Once the correlations were obtained, four (04) different cases were assumed to compute the calibration factors as follows:

- Case 1; only expert data is available for the 5 locations;
- Case 2: two (locations 3 and 6) of the five locations have, in addition to expert data, measurement data available for each year starting from year 10 to year 25;
- Case 3: four of the five locations have both expert and measurement data available for each year starting from year 10 to year 25, and the remaining location (location 14) has only expert data;
- Case 4: all locations have both expert and measurement data available for each year starting from year 10 to year 25.

Calibration factors and corresponding coefficients of variation of the expert data remain the same for all 4 cases defined above and are given, per year and per location, in Table 8-16 and Table 8-17 below for calibration factors and coefficients of variation respectively.

Table 8-16: Expert data corrosion mean depth per location as function of year (mm)

μ Expert Data	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.655	2.602	2.549	2.496	2.443	2.389	2.336	2.283	2.230	2.177	2.124	2.071	2.018	1.965	1.912	1.858
Location 10	2.875	2.817	2.760	2.702	2.645	2.587	2.530	2.473	2.415	2.358	2.300	2.243	2.185	2.127	2.070	2.012
Location 8	4.364	4.277	4.189	4.102	4.015	3.928	3.840	3.753	3.666	3.578	3.491	3.404	3.317	3.229	3.142	3.055
Location 6	4.152	4.069	3.986	3.903	3.820	3.737	3.654	3.571	3.488	3.405	3.322	3.239	3.156	3.072	2.989	2.906
Location 3	4.332	4.245	4.159	4.072	3.985	3.899	3.812	3.726	3.639	3.552	3.466	3.379	3.292	3.206	3.119	3.032

Table 8-17: Coefficient of variation for expert data per location as function of year

***cv* Expert Data**	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	1.143	1.154	1.166	1.177	1.189	1.200	1.212	1.223	1.234	1.246	1.257	1.269	1.280	1.292	1.303	1.314
Location 10	0.945	0.954	0.964	0.973	0.983	0.992	1.002	1.011	1.021	1.030	1.040	1.049	1.058	1.068	1.077	1.087
Location 8	1.024	1.034	1.044	1.054	1.064	1.075	1.085	1.095	1.105	1.116	1.126	1.136	1.146	1.157	1.167	1.177
Location 6	1.121	1.132	1.143	1.155	1.166	1.177	1.188	1.199	1.211	1.222	1.233	1.244	1.256	1.267	1.278	1.289
Location 3	1.194	1.206	1.218	1.230	1.242	1.254	1.266	1.278	1.290	1.302	1.314	1.326	1.338	1.350	1.362	1.374

GENERAL CORROSION RESULTS

For case 1, only expert data is available so the calibration factors are as given in Table 8-16 above. The corresponding coefficients of variation are as shown in Table 8-17.

Confidence intervals for both the calibration factors and their associated cv are given in Appendix A.5 in Table A.5- 1 to Table A.5- 4.

In case 2, measurements data are available for locations 3 and 6. The calibration factors, their cvs and their confidence intervals bounds are presented in Appendix A.5 in

Table A.5- ***5*** to Table A.5- 10.

The case 3 has measurements data for all but one location (location 14). The calibration factors and their associated cvs as well as the associated confidence intervals bounds are shown in Appendix A.5 in Table A.5- 11 to Table A.5- 16.

The last case, case 4, all the locations have measurements data in addition to the expert data. The calibrations factors, coefficients of variation and the upper and lower bounds of the confidence intervals are shown in Appendix A.5 in Table A.5-17 to Table A.5- 22.

Different sets of measurements and prediction data to those used to compute the calibrations factors were used to demonstrate the calibration process. Graphical representations of the results of the prediction models calibration, per location, over the considered period of time (for 10 to 25 years) are shown in Figure 8-5 to Figure 8-9.

Location 14

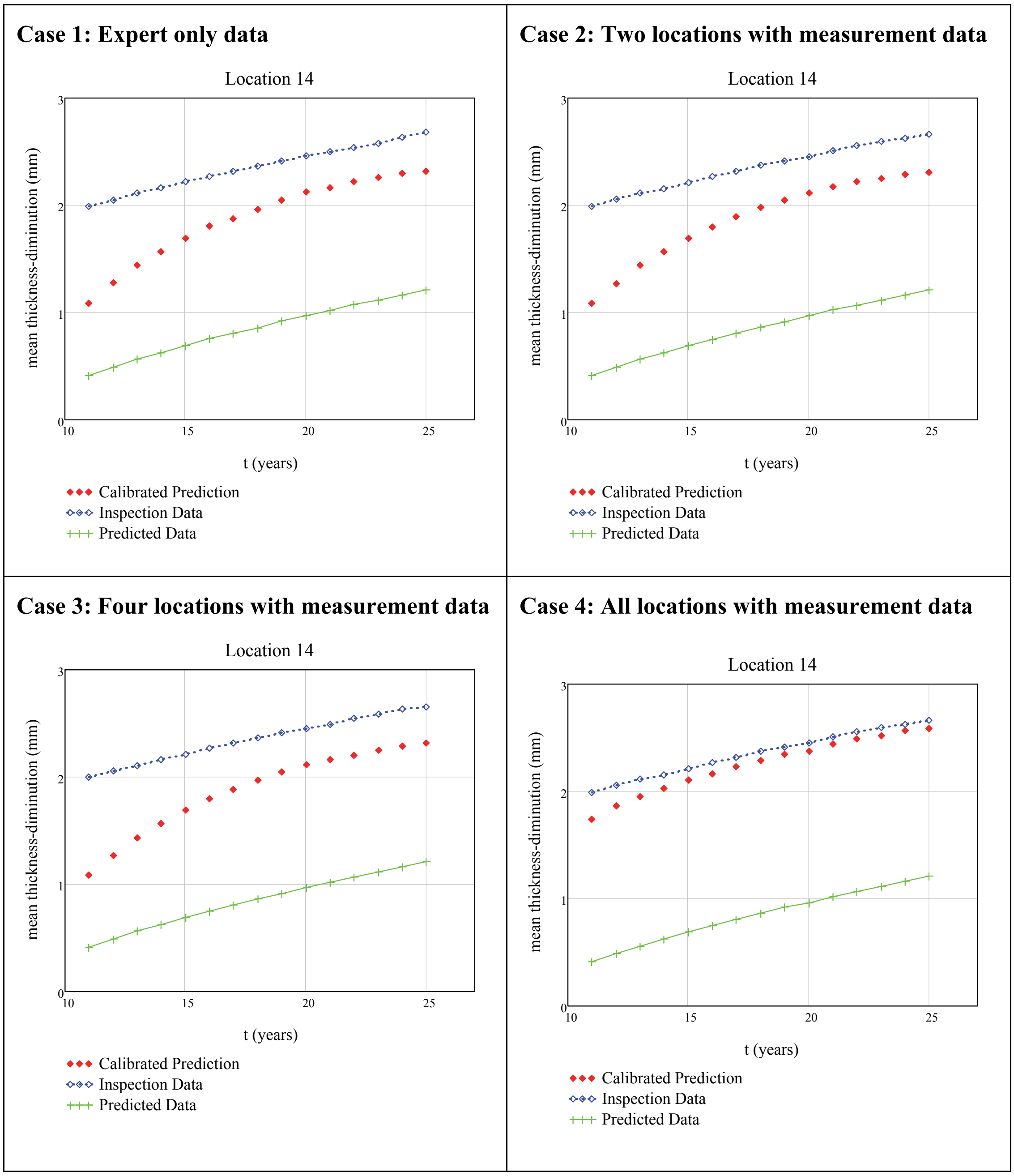
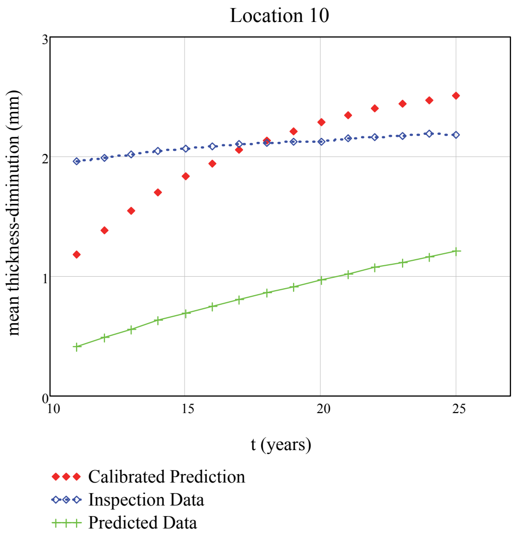


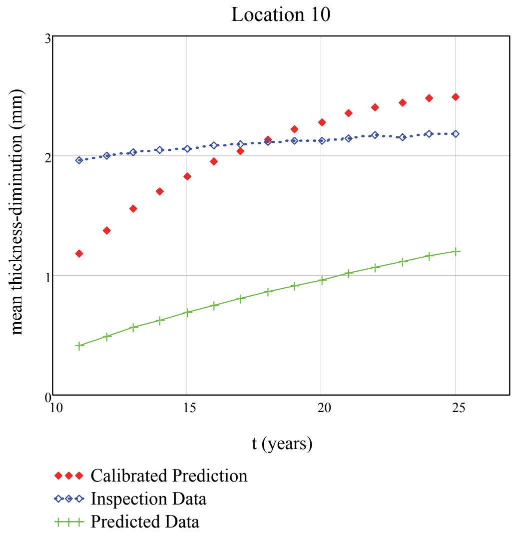
Figure 8-5: Graphs of predicted data, measured data and calibrated data of corrosion depth for location 14

Location 10

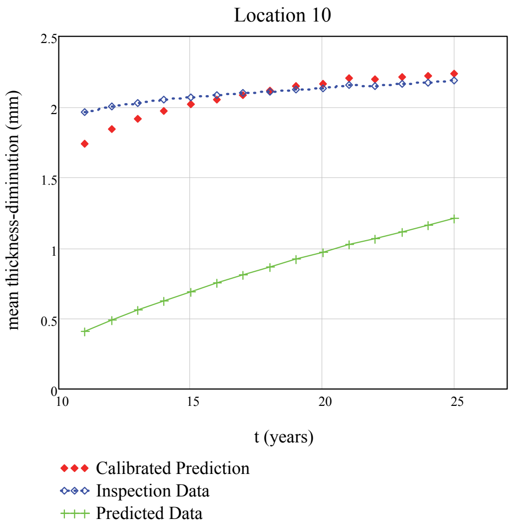
Case 1: Expert only data



Case 2: Two locations with measurement data



Case 3: Four locations with measurement data



Case 4: All locations with measurement data

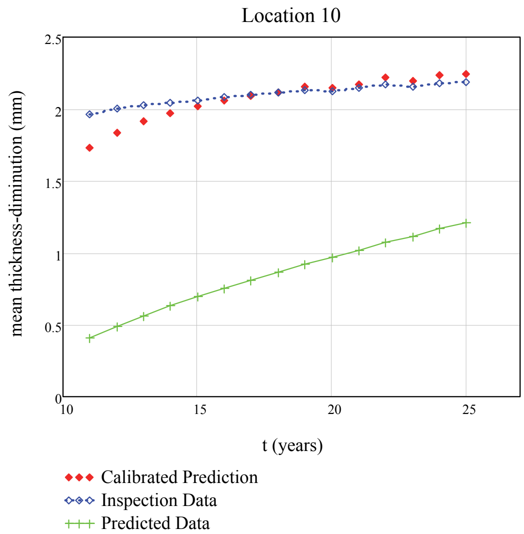
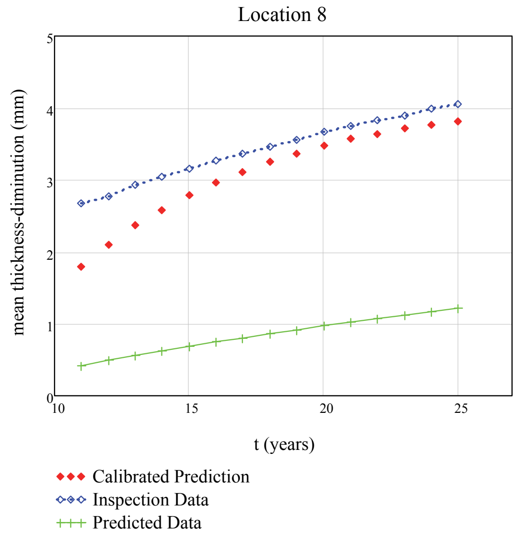


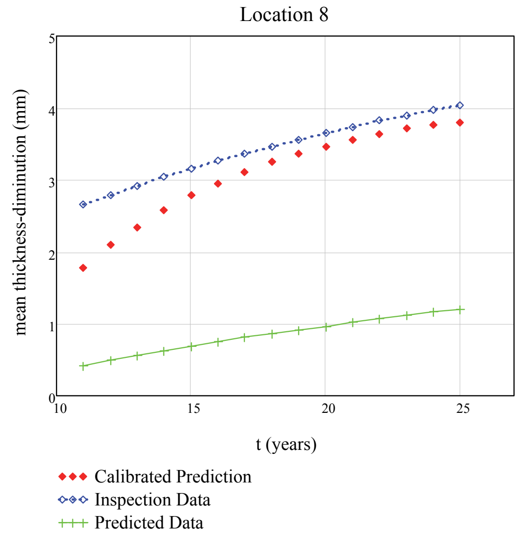
Figure 8-6: Graphs of predicted data, measured data and calibrated data of corrosion depth for location 10

Location 8

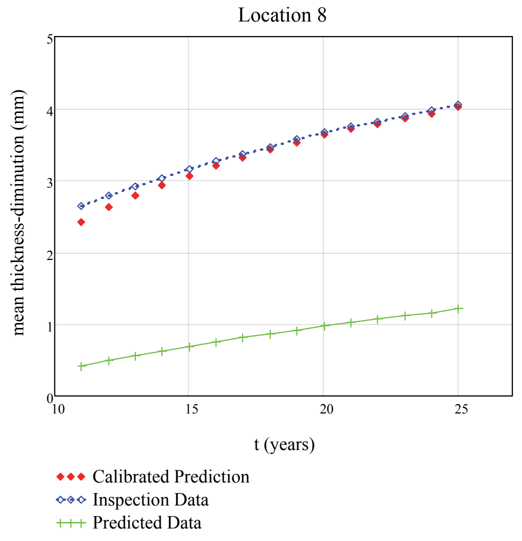
Case 1: Expert only data



Case 2: Two locations with measurement data



Case 3: Four locations with measurement data



Case 4: All locations with measurement data

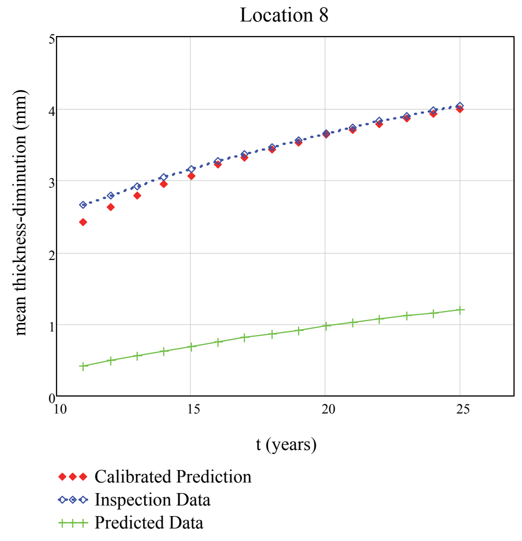


Figure 8-7: Graphs of predicted data, measured data and calibrated data of corrosion depth for location 8

Location 6

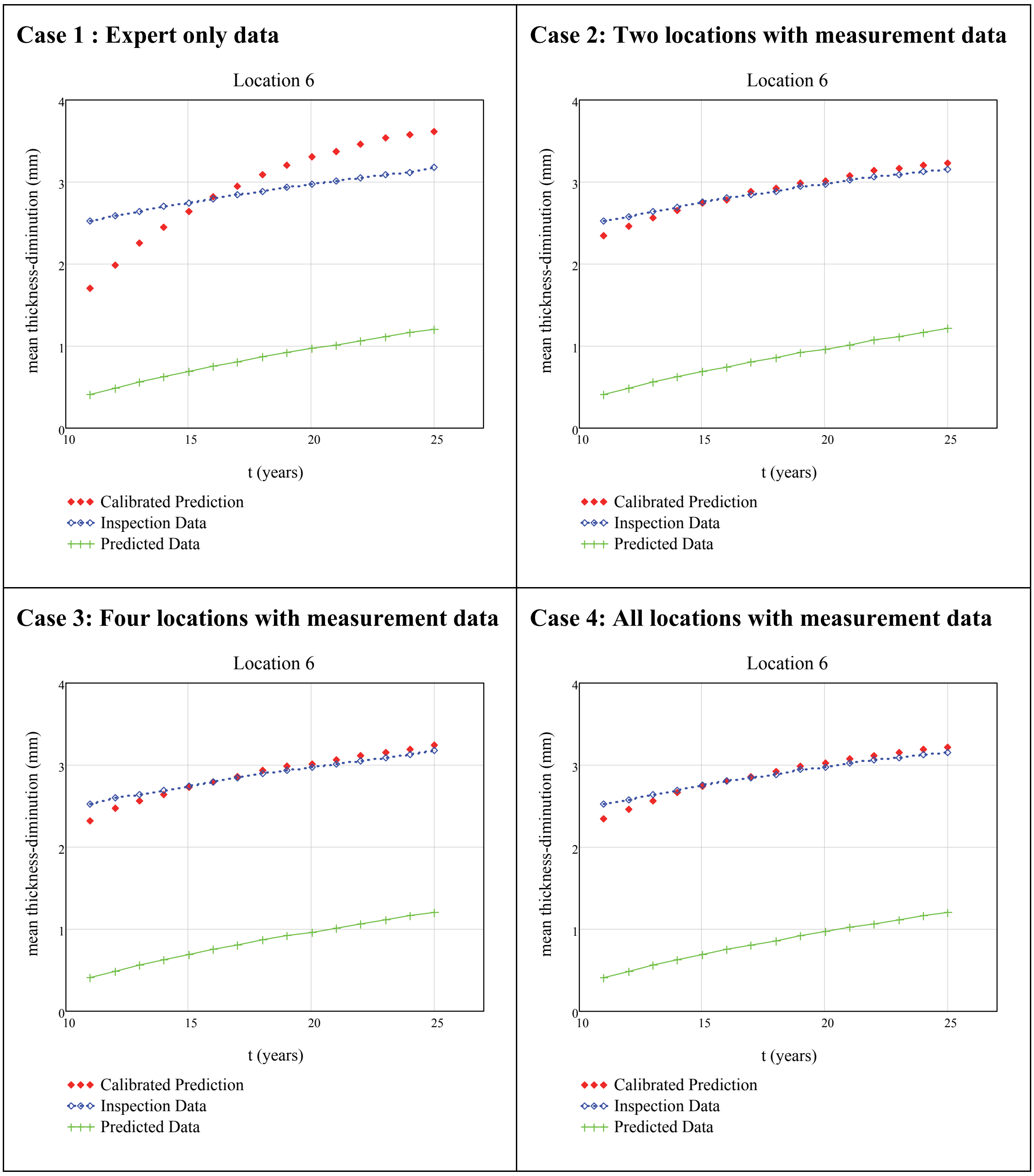


Figure 8-8: Graphs of predicted data, measured data and calibrated data of corrosion depth for location 6

Location 3

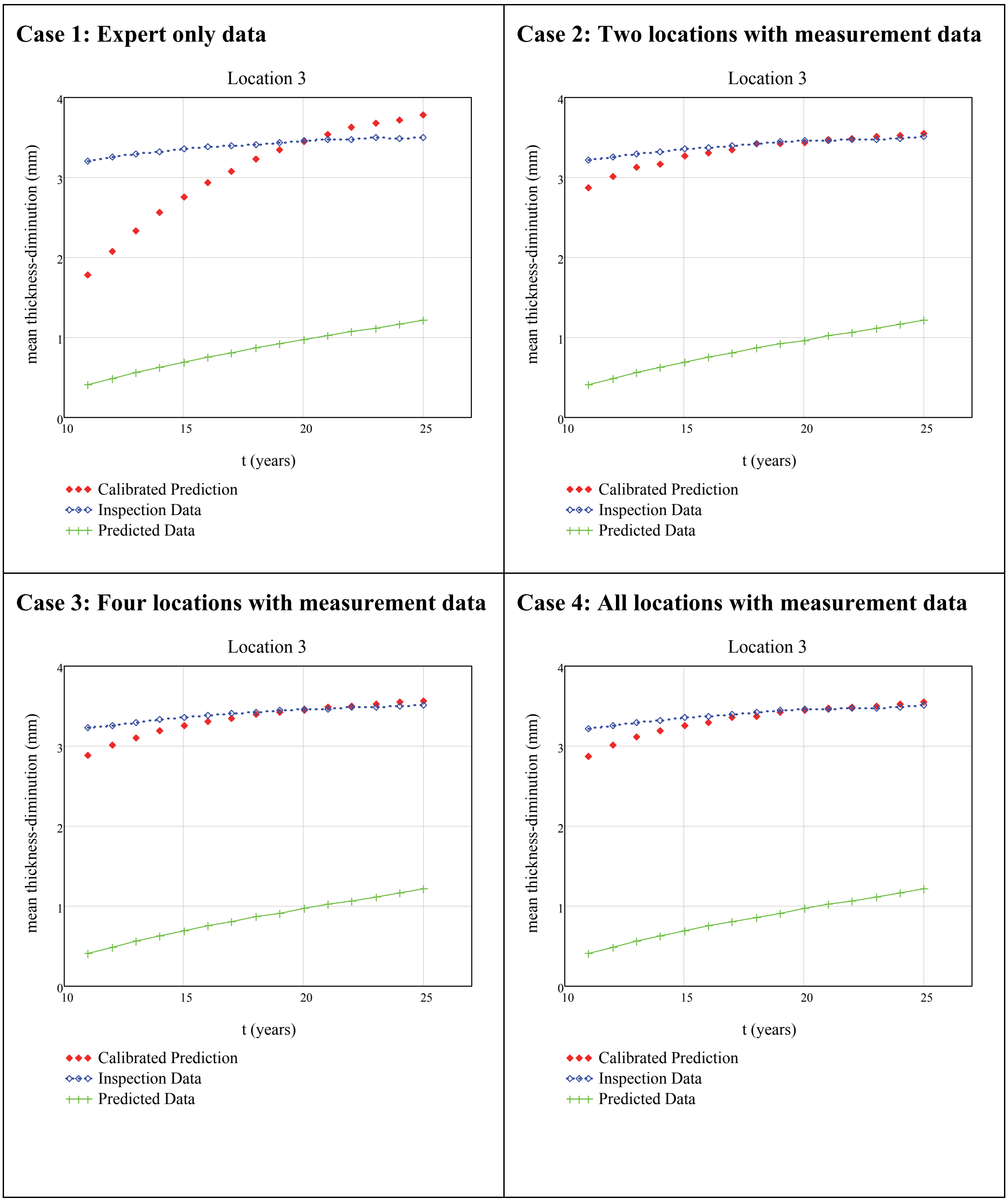


Figure 8-9: Graphs of predicted data, measured (inspection) data and calibrated data of corrosion depth for location 3

8.3 DISCUSSION

When looking at Figure 8-5 to Figure 8-9, it can be noticed that calibration of the prediction models is improved when measurements data are available (case 4) compared to when, only, expert data is available (case 1).

In case 1 the calibrated curve is closer to the inspection data curve when compared to the predicted curve but has a different shape. Whereas in case 4, the calibrated curve is almost superimposed to the measurements curve.

There are few noticeable differences between the locations though.

For location 14, where expert data is the only available data in all cases apart from case 4, the calibrated curve remains practically the same in case 1, 2 and 3. This could be explained by the fact that the usefulness factors of the data from the other locations are very low so they do not influence the calibration factor. In case 4, the measurements data for location 14 is available and its usefulness factor is 100 so its influence on the calibration factor is stronger than the rest of the information coming from the other locations. This explains the improvement in the calibrated curve in case 4 (Figure 8-5).

For location 10, measurements data are available in cases 3 and 4. This is reflected by the calibrated curve which is almost the same for case 1 and case 2, but is improved (gets closer to the inspection curve) when measurements data is available. A slight improvement is also observed in case 4 where measurement data is available in all locations. The same pattern of results is observed for location 8.

Location 6 and 3 share similar patterns too. There is a clear improvement of the calibrated curve between case 1 and case 2. Case 3 and 4 are also quite similar in terms of closeness of the calibrated curve to the measurements curve with a slightly better agreement for case 4 in both locations.

Due to the fact that the data used to demonstrate the calibration process is simulated data, and that the correlation factors (usefulness factors) were computed only based on one criterion, the location, discussion and interpretation of the results are limited.

It is nonetheless enough to demonstrate the methodology and to show how the calibration procedure works.

8.4 SAMPLE SIZE AND CONFIDENCE LEVELS

In addition to the results presented above, an analysis of the relationship between the data sample size and the confidence levels for both the mean and the coefficient of variation was performed:

- First for the mean, the number of data needed to obtain a certain confidence level for a particular error was calculated.
- Second for a specific number of data and a specific error value the confidence level of the mean was computed.

Details of the analysis and the results of the different computations are presented in Appendix A.6.

8.5 SUMMARY

This chapter has presented two different examples of the calibration process. A detailed description of the different steps was demonstrated on a crack example with a small number of data.

The second example involved the corrosion. Due to a lack of real data, two models were used. The first one to simulate the inspection (measurement) data and the second one was used as a prediction model.

The calibration factors were computed and results of the calibrated curves presented.

In addition the relationship between sample size and level of confidence for the value of the mean as well as the upper bound of the coefficient of variation was studied. In the particular example for general corrosion presented above, a high confidence level was achieved with a small sample size when a high error was tolerated (10%). But the same confidence level when error was much smaller (1%) was reached with much higher sample size (almost 8 times the initial size).

CHAPTER 9: CONCLUSIONS AND FUTURE WORK

9.1 CONCLUSIONS AND CONTRIBUTIONS

The thesis demonstrated a new methodology to produce a system to help in the planning of ship risk-based inspections and maintenance. The methodology calibrates model predictions, by bringing together two different methods: risk and reliability methods and experience based methods.

The main contributions are:

1) The conception of the Ship Structural Defect Database which holds ship data, inspection data, output of prediction models and calibration data. The database was conceived to be flexible enough for future additions and to allow for efficient exchanges with external units. The complete architecture of the database was explained in Chapter 6. The concept of the newly developed database in this work is mainly ship structural oriented, but could be developed for any other type of structure or inspection data records.

2) A computational module attached to the database, developed to calibrate the output of prediction models using data from inspections and expert judgment in the form of ratios (actual/predicted) making use of information about the behaviour of a defect/deterioration to inform the likely behaviour of similar defects/deteriorations through the use of usefulness factors. Chapter 8 has presented two different examples of the calibration process. A detailed description of the different computational steps was demonstrated on a cracked example with a small number of data. The second example involved corrosion where two models were used to produce data: the first one to simulate the inspection (measurement) data and the second one was used as a prediction model. In addition, the relationship between sample size and level of confidence for the value of the mean as well as the upper bound of the coefficient of variation was studied. An assessment of the amount of data needed to obtain useful calibration results.

3) A catalogue of structural connections was presented. A different details classification and crack classification system to what is presently used was proposed to provide a general classification system. The classification enables performance of partially similar types of detail to be usefully compared and used for prediction purposes. The proposed classification of the structural details was for Oil Tanker and Bulk Carrier vessels as these two types of ships have been identified in the Rispect project, as being the most affected by structural degradation. However similar details occur in Container Ships and many other vessel types.

4) Analytical model parameters for wave data (height and period) for different sea areas were estimated using data from BMT's (Hogben et al. 1986) Global Wave Statistics document which contains directional scatter diagrams for the 104 "Marsden squares". Using the advance maximum likelihood method, parameters of the mathematical model for the wave height and the wave period for each direction and for the 104 areas have been calculated. Using the estimated distribution parameters for the global wave model, data for the missing sea area for each direction have also been derived. Results obtained from this analysis compared to DNV's results as well as the GWS data show a good agreement and the estimated parameters for the individual directions are a good approximation.

Simulated data has been used to demonstrate the methodologies used in this thesis.

The database was tested with simulated data to check that all the functionalities were working properly as well as the exchanges with the COMOD module.

The system developed and demonstrated in this thesis is not limited to ship structural inspection and maintenance, but can also be adapted and applied to different fields, including machinery, renewable energy devices, bridges, rail….

This work contributed to the development of European Union RISPECT Project (Appendix A.1).

9.2 FUTURE WORK

The lack of real data has hampered the application of the calibration methodology presented in this research and has limited the analysis of the results of the calibration of the prediction models. It is hoped that, when data is available, a complete analysis using the calibration procedure will be performed.

Interesting aspects related to this research which were not covered in this thesis but could be the subject of future research include:

1) In addition to route data, ship voyage data could also be stored in the database. The data consists of data records and events which occurred during ship navigation, e.g.: date and time, ship's position, speed, heading bridge audio, communication audio, radar/ECDIS images, which can be utilized to better understand the immediate consequences of an incident and to assist maritime casualty investigators in identifying the causes. This data when available could be used as base for future reference to further incident prevention.

2) Voyage data that could be recorded automatically and stored in the database:

- Ship draft and trim
- Ship motion (heave, pitch etc.)
- Strain measurements on the deck
- Strain measurements on side shell
- Strain measurements on internal structure
- Water pressure measurements
- Wave data (preferably directional)

This type of data is used to assess the structural loading and response. The availability of this kind of data will be helpful to further improve and calibrate the mathematical models for ship inspection and maintenance planning and will permit more accurate assessment of the reliability instrumented ships, as well as contributing to the reliability assessment of other trading ships and new designs.

In order to achieve this, permanent sensors to measure the required information would need to be added to the ship in addition to a storing device to record the data.

Details of the implementation for the automatically recorded voyage data could be the subject of future development.

3) The analysis of the environmental data presented in Chapter 4 could be extended by developing and incorporating a seasonal analytical model including the directional wave. The outcomes could then be compared with the results of the actual work for validation. The seasonal data could be related to the actual trading history for more accurate assessment of past dynamic loading. It would also be useful for risk assessment in the event that a ship was damaged and was forced to transit in a damaged condition for repair.

4) The connection details presented in Chapter 5 could be used as base and could be extended to include connections from other ship types.

5) It is also important to extend the techniques of model calibration to include the systematic calibration of probability of detection (POD). This has not been discussed in this work and it is not straight forward to infer from inspection data because, for example, an unexpectedly small number of defects found might be a result of poor inspection or a result of the loading being lower than expected.

6) Application of the full concept in other fields (e.g. renewable energy devices, offshore platforms, machinery systems, large structures such as bridges and other transport systems.

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APPENDICES

A.1: CONTRIBUTION TO RISPECT PROJECT

A.1.1 INTRODUCTION

The work reported in this thesis contributed to several tasks of the EU-RISPECT project (2008-2013 - SCP7-GA-2008-218499). To give a better understanding of the significance of this work and its overall contribution, an overview of RISPECT project is given in the following.

A.1.2 RISPECT OVERVIEW AND OBJECTIVES

The RISPECT project aimed to provide a better methodology for the use of Risk-Based Inspection plans in order to have better inspections and more important defects related to primary structure being found and repaired (Barltrop et al. 2010).

The major achievement of the RISPECT Project is the RISPECT inspection planning tool which is intended to be used by the shipping industry. The tool uses standard descriptions of structural components and defects and standardized calculation methods along with experience-based calibration factors and is based on reliability analysis with allowance for corrosion, fatigue cracking and inspection and repair (Hifi et al. 2012a; Hifi et al. 2012b).

A.1.3 RISPECT METHODOLOGY

The Rispect project has set up a data analysis system that allows fully justified decisions on ship structural maintenance of existing ships. The methodology is also useful for the goal-based design of new ships, although the project has concentrated on the use of the methodology for inspection planning.

The system uses detailed structural and survey data for a specific ship, which inspection is to be planned (or which may be at the design stage), in conjunction with structural and survey statistics from other vessels in order to make the best decisions about survey and/or design requirements. The decision making process incorporates the structural component reliability methods, structural system reliability methods, Bayesian updating from target structure, other relevant structures and expert system methods.

The system is designed to meet the needs of different organisations in the shipping industry but be infinitely expandable in order to gather data from the largest possible number of ships in order to perform the most accurate calculations. As well as the analysis methodology, a key outcome of the project is interchange data formats, so that different data bases can share the important statistical information.

It is envisaged that the system could be run as a club where statistical data is shared for mutual benefit. Data transferred, via the Central Statistical Database, between different data bases would be filtered and 'sanitised' in order to avoid sensitive information being released to competitors, whilst making sure that statistical information, which is critically important in the decision making process behind maintenance and design, can be widely distributed.

The system concept is based on a network of databases that store very detailed ship specific information at the Ship, Ship manager, Inspection Company and Classification Society levels, and transmit and receive statistical data (which is necessary for the inspection planning and design tools) to/from the Central Statistical Database (which holds the statistical information).

The inspection planning might be performed optionally at the Ship Manager, Inspection Company or Classification Society level. It is anticipated that the extraction of data for improving new ship design would be at the Classification Society level, but the necessary data would also be available at the Ship & Ship Manager levels. In practice the Ship, Ship Manager and Classification Society Database structures are expected to be very similar but there may be different functionality that is permitted to be used at the different levels. It is important that the system can deal with the interaction of fundamentally different databases, and the project included a demonstration that this can be achieved.

The different databases are explained in section A.1.4

The methods of storing data and passing on statistics from the Ship Manager and Classification society database to the Central Statistical Database (CSD) and then distributing non-attributable statistics back to all users has required careful planning.

At this stage, the system is built to include several ships, one Ship Manager and one Classification Society, shown by the parts included by the solid red curve at the top of Figure A.1- 1, but could handle several ship owners and classification societies.

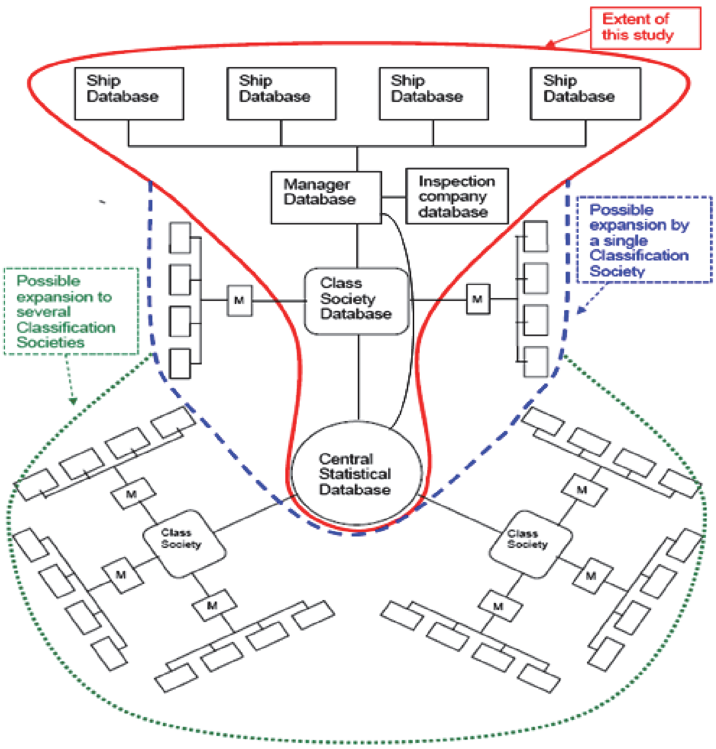


Figure A.1- 1 Overall proposed structure of the network of databases

The major part of the RISPECT project was to develop the tools that appropriately store and extract statistics that are passed on to the CSD, receive statistics for the whole fleet from the CSD and process this data to plan inspections or to set standards for the design of new ships.

The availability of the data is very important to the demonstration of the success of any software. Primarily the data input consists of:

- Design input (this is data that, (except for repairs) is generally fixed from when the ship is first built)
- Ship manager data input
- Ship manager initiation and control

Much of the data is provided in paper form which required a large amount of work to convert it to the electronic form and then upload it on the Ship Database. Increasingly companies and classification societies are starting to store this type of data electronically and an additional important reason for undertaking this study now is to be able to influence the structure of those databases so that the information required for this structural analysis and reliability methodology is stored.

A.1.4 RISPECT SOFTWARE

At early stage of the design of the overall RISPECT system, and to achieve the objectives of the project, it was necessary to demonstrate a good understanding of the expected functionality of the different modules incorporated to define the data requirements for programs, algorithms, and reports.

The following sections describe the system functionality (Figure A.1- 2) and data requirements pertaining to the definition of ships in the context of the RISPECT project.

A.1.4.1 RISPECT Databases

For the purpose of the development of RISPECT Software, more detailed data is required than is often stored at present, so the project needed to produce a suitable database structure. There are several different data bases that contain subsets of data related to individual ships:

- Ship and ship manager database.
- Classification Society database.
- Inspection company database.

In addition a special “Central statistical database” holds information for calibrating the calculated structural degradation by comparing calculated and measured structural and coating degradation.

A.1.4.2 RISPECT Engineering Calculations

This section describes the engineering calculations used within the RISPECT system. The system calibrates models that calculate the structural degradation of ships by using survey results from large numbers of ships. The system then uses these calibrated models to predict the structural reliability and risks of individual ships.

The system is built from multiple programs connected to each other (Figure A.1- 2) and consists of:

- Hydro-Static/Dynamic Pressures & RAOs
- Global and Member Forces
- Extreme and Fatigue Global & Member Forces
- Local Structure & Crack Calculations
- Coating Breakdown Anode Loss & Corrosion
- Structural Strength & Reliability Calculation results
- System Reliability Calculation results
- Risk Calculations
- Strength & Fatigue Check (and other checks on the methodology)
- Fleet Reliability
- Fleet Risk

The links between the different programs and the databases is illustrated in the programs flowchart in Figure A.1- 2.

A.1.5 THE PRESENT STUDY AND ITS RELATION TO THE RISPECT PROJECT

The previous sections have presented the EU-RISPECT project and the RISPECT software.

The developments reported in this thesis have covered several important aspects of the RISPECT software tool, namely:

- The Central Statistical Database and Ship Database architecture, the subject of chapter 6;
- Calibration methods. These methods are presented in chapter 7;
- Environmental data are discussed in chapter 4;
- Ship structural details catalogue which is defined in chapter 5.

In addition, the author of this thesis has had a broad involvement with RISPECT, particularly in the structure of the ship database and the coordination of database activities between the different partners.

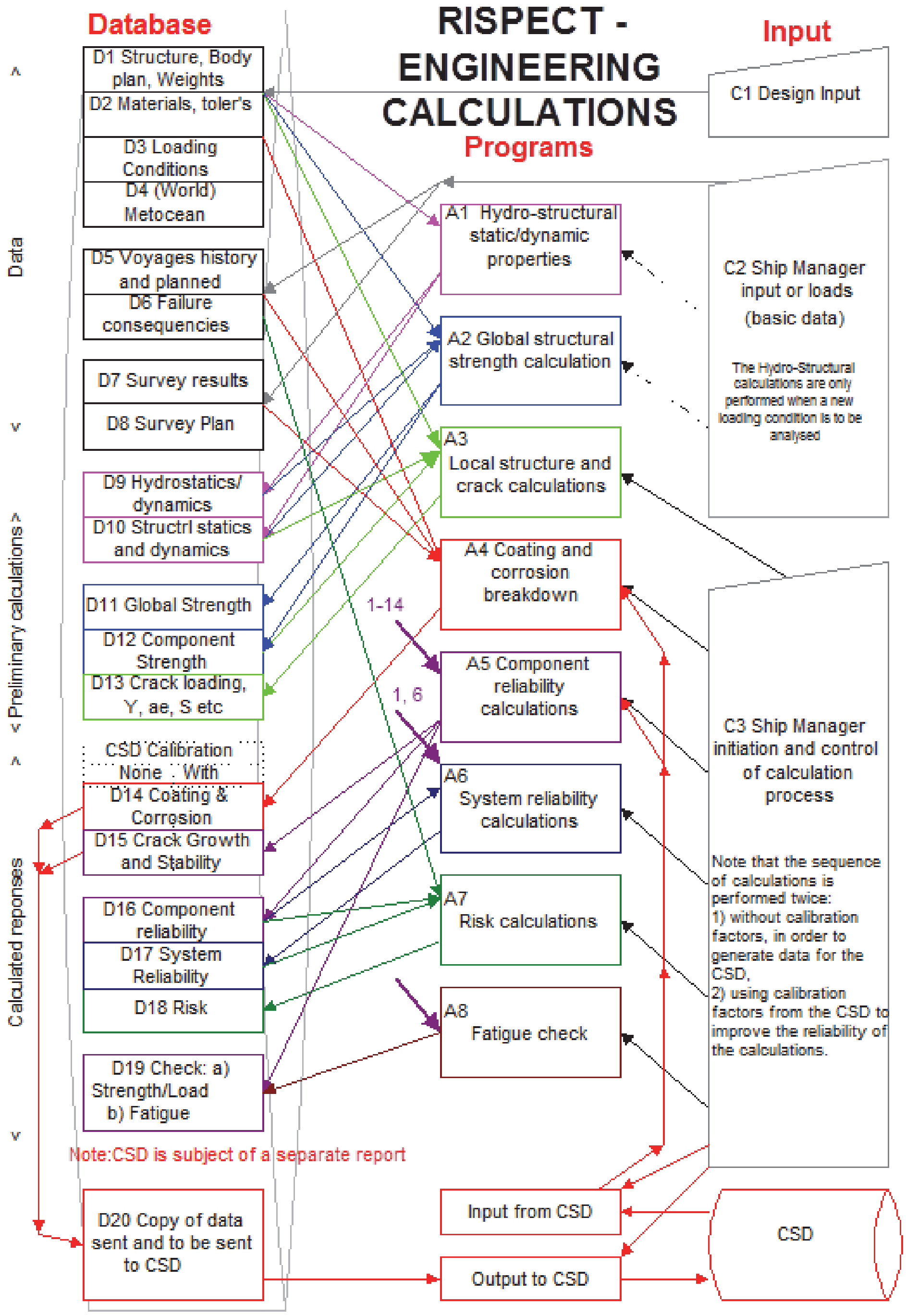


Figure A.1- 2 RISPECT Engineering calculations-flow chart, with beneficiaries associated (Adapted from (Barltrop 2010)

A.2: WAVE PARAMETERS (DATA)

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 1	Omni DNV	2.330	1.330	0.700	0.974	0.205	0.070	0.126	-0.020
	NW	2.358	1.367	0.700	0.967	0.210	0.070	0.115	-0.006
	N	2.220	1.465	0.700	1.002	0.208	0.070	0.120	-0.007
	NE	2.094	1.305	0.700	0.987	0.214	0.070	0.114	-0.007
	E	2.198	1.393	0.700	0.967	0.238	0.070	0.116	-0.007
	SE	2.283	1.215	0.700	0.984	0.214	0.070	0.114	-0.007
	S	2.284	1.324	0.700	1.013	0.114	0.070	0.111	-0.008
	SW	2.550	1.288	0.700	0.914	0.239	0.070	0.114	-0.009
	W	2.483	1.336	0.700	1.019	0.112	0.070	0.126	-0.026
Area 2	Omni DNV	1.960	1.340	0.700	0.994	0.175	0.070	0.141	-0.024
	NW	1.960	1.296	0.700	0.987	0.177	0.070	0.139	-0.017
	N	1.974	1.327	0.700	0.984	0.168	0.070	0.129	-0.007
	NE	1.791	1.287	0.700	0.979	0.154	0.070	0.140	-0.005
	E	2.003	1.308	0.700	1.009	0.245	0.070	0.142	-0.017
	SE	1.849	1.261	0.700	0.876	0.141	0.070	0.124	-0.028
	S	1.751	1.316	0.700	1.088	0.189	0.070	0.182	-0.008
	SW	1.873	1.299	0.700	0.927	0.184	0.070	0.154	-0.027
	W	1.874	1.276	0.700	1.019	0.109	0.070	0.165	-0.016
Area 3	Omni DNV	2.740	1.350	0.700	1.127	0.160	0.070	0.126	-0.091
	NW	2.679	1.368	0.700	1.129	0.141	0.070	0.116	-0.065
	N	2.688	1.340	0.700	1.123	0.113	0.070	0.122	-0.007
	NE	2.764	1.371	0.700	1.137	0.116	0.070	0.125	-0.017
	E	2.659	1.386	0.700	1.137	0.143	0.070	0.116	-0.017
	SE	2.657	1.371	0.700	1.132	0.157	0.070	0.121	-0.020
	S	2.765	1.415	0.700	1.077	0.183	0.070	0.123	-0.007
	SW	2.694	1.361	0.700	1.121	0.157	0.070	0.129	-0.017
	W	2.796	1.392	0.700	1.121	0.161	0.070	0.129	-0.014
Area 4	Omni DNV	2.840	1.530	0.700	1.125	0.150	0.070	0.098	-0.007
	NW	2.717	1.389	0.700	1.139	0.125	0.070	0.095	-0.002
	N	2.733	1.698	0.700	1.128	0.133	0.070	0.097	-0.006
	NE	2.693	1.528	0.700	1.130	0.141	0.070	0.088	-0.008
	E	2.850	1.482	0.700	1.118	0.124	0.070	0.097	-0.015
	SE	2.862	1.432	0.700	1.120	0.183	0.070	0.089	-0.007
	S	2.876	1.563	0.700	1.141	0.118	0.070	0.110	-0.008
	SW	2.826	1.511	0.700	1.110	0.143	0.070	0.092	-0.008
	W	2.836	1.567	0.700	1.099	0.161	0.070	0.105	-0.016

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 5	Omni DNV	1.760	1.590	0.700	0.828	0.167	0.070	0.345	-0.207
	NW	1.644	1.558	0.700	0.787	0.228	0.070	0.230	-0.058
	N	1.751	1.606	0.700	0.864	0.232	0.070	0.126	-0.081
	NE	1.642	1.651	0.700	0.897	0.187	0.070	0.140	-0.079
	E	1.848	1.536	0.700	0.667	0.200	0.070	0.334	-0.148
	SE	1.799	1.502	0.700	0.879	0.118	0.070	0.239	-0.059
	S	1.683	1.524	0.700	0.801	0.103	0.070	0.218	-0.080
	SW	1.752	1.435	0.700	0.779	0.262	0.070	0.131	-0.065
	W	1.816	1.658	0.700	0.781	0.273	0.070	0.235	-0.184
Area 6	Omni DNV	2.760	1.450	0.700	1.128	0.154	0.070	0.096	-0.007
	NW	2.582	1.365	0.700	1.269	0.114	0.070	0.121	-0.058
	N	2.679	1.362	0.700	1.300	0.126	0.070	0.140	-0.081
	NE	2.562	1.342	0.700	1.330	0.135	0.070	0.164	-0.008
	E	2.764	1.435	0.700	1.129	0.139	0.070	0.091	-0.001
	SE	2.805	1.348	0.700	1.103	0.113	0.070	0.071	-0.059
	S	2.763	1.246	0.700	1.023	0.101	0.070	0.052	-0.050
	SW	2.545	1.427	0.700	1.014	0.114	0.070	0.071	-0.065
	W	2.774	1.378	0.700	1.102	0.113	0.070	0.099	-0.018
Area 7	Omni DNV	3.390	1.750	0.700	1.256	0.118	0.070	0.081	-0.007
	NW	3.235	1.876	0.700	1.265	0.127	0.070	0.090	-0.028
	N	2.964	1.731	0.700	1.300	0.148	0.070	0.085	-0.017
	NE	3.374	1.653	0.700	1.299	0.163	0.070	0.090	-0.009
	E	2.913	1.683	0.700	1.191	0.206	0.070	0.094	-0.007
	SE	3.283	1.637	0.700	1.133	0.165	0.070	0.075	-0.019
	S	3.493	1.761	0.700	1.199	0.107	0.070	0.095	-0.076
	SW	3.377	1.799	0.700	1.145	0.159	0.070	0.082	-0.027
	W	3.413	1.781	0.700	1.134	0.191	0.070	0.078	-0.008
Area 8	Omni DNV	3.470	1.570	0.700	1.272	0.114	0.070	0.073	-0.002
	NW	3.719	1.539	0.700	1.166	0.174	0.070	0.068	-0.009
	N	3.277	1.709	0.700	1.174	0.158	0.070	0.071	-0.016
	NE	3.080	1.545	0.700	1.126	0.196	0.070	0.079	-0.069
	E	3.143	1.705	0.700	1.232	0.118	0.070	0.082	-0.053
	SE	2.779	1.651	0.700	1.219	0.137	0.070	0.090	-0.065
	S	3.193	1.507	0.700	1.330	0.104	0.070	0.086	-0.076
	SW	3.445	1.553	0.700	1.261	0.121	0.070	0.080	-0.007
	W	3.951	1.628	0.700	1.249	0.139	0.070	0.092	-0.060

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 9	Omni DNV	3.560	1.610	0.700	1.260	0.119	0.070	0.076	-0.005
	NW	3.495	1.640	0.700	1.234	0.143	0.070	0.072	-0.004
	N	3.222	1.659	0.700	1.305	0.104	0.070	0.082	-0.014
	NE	3.288	1.594	0.700	1.218	0.140	0.070	0.083	-0.026
	E	3.518	1.430	0.700	1.219	0.129	0.070	0.081	-0.036
	SE	3.321	1.434	0.700	1.211	0.109	0.070	0.084	-0.033
	S	3.464	1.488	0.700	1.107	0.186	0.070	0.071	-0.016
	SW	3.637	1.579	0.700	1.251	0.108	0.070	0.074	-0.014
	W	3.673	1.604	0.700	1.247	0.123	0.070	0.085	-0.058
Area 10	Omni DNV	2.450	1.370	0.700	1.036	0.181	0.070	0.117	-0.014
	NW	2.375	1.392	0.700	1.040	0.175	0.070	0.132	-0.018
	N	2.299	1.247	0.700	1.115	0.127	0.070	0.125	-0.017
	NE	2.298	1.254	0.700	1.015	0.182	0.070	0.115	-0.015
	E	2.420	1.428	0.700	1.130	0.141	0.070	0.112	-0.042
	SE	2.330	1.292	0.700	1.020	0.198	0.070	0.115	-0.008
	S	2.309	1.398	0.700	1.113	0.138	0.070	0.121	-0.016
	SW	2.393	1.363	0.700	1.057	0.151	0.070	0.116	-0.007
	W	2.482	1.343	0.700	1.118	0.105	0.070	0.109	-0.015
Area 11	Omni DNV	2.190	1.260	0.700	0.935	0.222	0.070	0.139	-0.021
	NW	2.130	1.213	0.700	0.858	0.280	0.070	0.148	-0.016
	N	2.075	1.246	0.700	0.941	0.242	0.070	0.164	-0.067
	NE	2.020	1.200	0.700	0.860	0.281	0.070	0.164	-0.018
	E	2.194	1.158	0.700	0.883	0.219	0.070	0.193	-0.047
	SE	1.986	1.065	0.700	0.938	0.185	0.070	0.136	-0.027
	S	2.278	1.253	0.700	1.020	0.126	0.070	0.149	-0.067
	SW	2.089	1.242	0.700	0.936	0.163	0.070	0.151	-0.018
	W	2.164	1.197	0.700	0.987	0.125	0.070	0.144	-0.017
Area 12	Omni DNV	3.310	1.560	0.700	1.150	0.150	0.070	0.093	-0.041
	NW	3.273	1.336	0.700	1.012	0.143	0.070	0.095	-0.045
	N	3.196	1.578	0.700	1.138	0.164	0.070	0.088	-0.059
	NE	3.297	1.378	0.700	1.139	0.165	0.070	0.109	-0.044
	E	3.183	1.422	0.700	1.140	0.154	0.070	0.107	-0.039
	SE	3.297	1.345	0.700	1.152	0.153	0.070	0.097	-0.016
	S	3.127	1.499	0.700	1.165	0.155	0.070	0.086	-0.027
	SW	3.206	1.580	0.700	1.126	0.161	0.070	0.096	-0.026
	W	3.317	1.486	0.700	1.119	0.140	0.070	0.085	-0.039

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 13	Omni DNV	3.180	1.640	0.700	1.257	0.111	0.070	0.085	-0.003
	NW	3.192	1.571	0.700	1.260	0.110	0.070	0.087	-0.014
	N	2.968	1.649	0.700	1.149	0.168	0.070	0.092	-0.018
	NE	2.986	1.434	0.700	1.152	0.156	0.070	0.103	-0.014
	E	3.165	1.389	0.700	1.143	0.121	0.070	0.088	-0.005
	SE	2.986	1.365	0.700	1.152	0.110	0.070	0.111	-0.004
	S	3.098	1.703	0.700	1.132	0.150	0.070	0.086	-0.008
	SW	2.963	1.680	0.700	1.259	0.152	0.070	0.090	-0.012
	W	3.280	1.742	0.700	1.257	0.109	0.070	0.094	-0.017
Area 14	Omni DNV	2.620	1.460	0.700	1.215	0.115	0.070	0.098	-0.011
	NW	2.489	1.555	0.700	1.209	0.063	0.070	0.111	-0.007
	N	2.676	1.452	0.700	1.218	0.052	0.070	0.035	-0.050
	NE	2.414	1.394	0.700	1.196	0.113	0.070	0.085	-0.053
	E	2.646	1.418	0.700	1.190	0.152	0.070	0.109	-0.060
	SE	2.423	1.377	0.700	1.240	0.196	0.070	0.098	-0.008
	S	2.585	1.378	0.700	1.134	0.130	0.070	0.095	-0.014
	SW	2.349	1.434	0.700	1.311	0.161	0.070	0.180	-0.027
	W	2.585	1.492	0.700	1.251	0.141	0.070	0.141	-0.057
Area 15	Omni DNV	3.090	1.500	0.700	1.207	0.134	0.070	0.086	-0.012
	NW	3.276	1.655	0.700	1.216	0.129	0.070	0.119	-0.027
	N	2.999	1.646	0.700	1.319	0.130	0.070	0.080	-0.012
	NE	2.657	1.430	0.700	1.238	0.104	0.070	0.093	-0.047
	E	3.082	1.440	0.700	1.073	0.109	0.070	0.086	-0.067
	SE	2.604	1.439	0.700	1.200	0.107	0.070	0.085	-0.016
	S	2.960	1.473	0.700	1.236	0.132	0.070	0.096	-0.035
	SW	2.958	1.470	0.700	1.179	0.146	0.070	0.088	-0.077
	W	3.307	1.548	0.700	1.165	0.173	0.070	0.094	-0.007
Area 16	Omni DNV	3.420	1.560	0.700	1.243	0.126	0.070	0.090	-0.053
	NW	3.402	1.598	0.700	1.176	0.110	0.070	0.103	-0.063
	N	3.130	1.503	0.700	1.316	0.134	0.070	0.090	-0.044
	NE	2.980	1.483	0.700	1.202	0.141	0.070	0.084	-0.017
	E	3.488	1.556	0.700	1.247	0.109	0.070	0.093	-0.133
	SE	3.293	1.593	0.700	1.288	0.071	0.070	0.103	-0.014
	S	3.430	1.499	0.700	1.184	0.142	0.070	0.044	-0.050
	SW	3.197	1.542	0.700	1.227	0.137	0.070	0.085	-0.057
	W	3.625	1.628	0.700	1.297	0.086	0.070	0.092	-0.075

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 17	Omni DNV	2.770	1.410	0.700	1.197	0.135	0.070	0.095	-0.008
	NW	2.707	1.444	0.700	1.158	0.153	0.070	0.102	-0.006
	N	2.710	1.392	0.700	1.198	0.136	0.070	0.106	-0.018
	NE	2.682	1.241	0.700	1.166	0.112	0.070	0.117	-0.017
	E	2.785	1.240	0.700	1.162	0.125	0.070	0.096	-0.018
	SE	2.629	1.394	0.700	1.130	0.134	0.070	0.098	-0.016
	S	2.574	1.357	0.700	1.150	0.143	0.070	0.121	-0.009
	SW	2.658	1.377	0.700	1.143	0.148	0.070	0.109	-0.006
	W	2.774	1.395	0.700	1.162	0.169	0.070	0.110	-0.018
Area 18	Omni DNV	1.660	1.140	0.700	1.310	0.121	0.070	0.401	-0.212
	NW	1.514	1.128	0.700	1.295	0.154	0.070	0.150	-0.077
	N	1.562	1.136	0.700	1.248	0.139	0.070	0.161	-0.043
	NE	1.438	1.109	0.700	1.212	0.143	0.070	0.297	-0.154
	E	1.610	1.143	0.700	1.217	0.177	0.070	0.332	-0.258
	SE	1.452	1.091	0.700	1.321	0.183	0.070	0.165	-0.184
	S	2.119	1.119	0.700	1.233	0.186	0.070	0.263	-0.173
	SW	1.671	1.079	0.700	1.295	0.160	0.070	0.146	-0.176
	W	1.653	1.130	0.700	1.394	0.144	0.070	0.156	-0.183
Area 19	Omni DNV	2.480	1.350	0.700	1.085	0.166	0.070	0.107	-0.010
	NW	2.385	1.382	0.700	1.153	0.144	0.070	0.129	-0.016
	N	2.299	1.328	0.700	0.904	0.289	0.070	0.141	-0.017
	NE	2.364	1.402	0.700	1.162	0.176	0.070	0.114	-0.056
	E	2.466	1.446	0.700	1.165	0.120	0.070	0.133	-0.084
	SE	2.394	1.339	0.700	0.928	0.246	0.070	0.127	-0.090
	S	2.481	1.445	0.700	0.965	0.239	0.070	0.138	-0.075
	SW	2.439	1.320	0.700	0.985	0.260	0.070	0.105	-0.066
	W	2.573	1.358	0.700	1.152	0.149	0.070	0.137	-0.067
Area 20	Omni DNV	3.150	1.480	0.700	1.196	0.139	0.070	0.091	-0.025
	NW	3.145	1.474	0.700	1.161	0.149	0.070	0.083	-0.063
	N	2.743	1.494	0.700	1.194	0.135	0.070	0.093	-0.062
	NE	2.955	1.478	0.700	1.179	0.152	0.070	0.090	-0.046
	E	2.709	1.544	0.700	1.153	0.167	0.070	0.080	-0.044
	SE	3.094	1.435	0.700	1.231	0.143	0.070	0.098	-0.070
	S	2.995	1.375	0.700	1.193	0.139	0.070	0.092	-0.098
	SW	3.197	1.423	0.700	1.178	0.144	0.070	0.111	-0.040
	W	3.442	1.519	0.700	1.181	0.138	0.070	0.103	-0.037

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 21	Omni DNV	2.310	1.380	0.700	0.976	0.197	0.070	0.129	-0.018
	NW	2.219	1.286	0.700	0.951	0.163	0.070	0.124	-0.027
	N	2.198	1.255	0.700	1.020	0.136	0.070	0.117	-0.019
	NE	2.300	1.298	0.700	1.030	0.124	0.070	0.104	-0.014
	E	2.220	1.247	0.700	0.955	0.183	0.070	0.121	-0.023
	SE	2.177	1.248	0.700	0.949	0.198	0.070	0.112	-0.018
	S	2.178	1.193	0.700	0.932	0.178	0.070	0.113	-0.028
	SW	2.317	1.213	0.700	1.013	0.129	0.070	0.126	-0.006
	W	2.295	1.351	0.700	1.001	0.152	0.070	0.124	-0.008
Area 22	Omni DNV	2.290	1.720	0.700	1.139	0.117	0.070	0.116	-0.018
	NW	2.240	1.794	0.700	1.128	0.123	0.070	0.103	-0.006
	N	2.194	1.678	0.700	1.131	0.138	0.070	0.113	-0.028
	NE	2.284	1.626	0.700	1.121	0.129	0.070	0.111	-0.014
	E	2.356	1.655	0.700	1.110	0.113	0.070	0.116	-0.016
	SE	2.269	1.628	0.700	1.095	0.120	0.070	0.106	-0.018
	S	2.192	1.662	0.700	1.060	0.115	0.070	0.108	-0.007
	SW	2.196	1.719	0.700	1.009	0.128	0.070	0.137	-0.024
	W	2.292	1.657	0.700	1.174	0.120	0.070	0.151	-0.025
Area 23	Omni DNV	2.230	1.390	0.700	1.039	0.167	0.070	0.125	-0.013
	NW	2.174	1.305	0.700	1.120	0.124	0.070	0.111	-0.088
	N	2.218	1.468	0.700	1.112	0.117	0.070	0.130	-0.019
	NE	2.080	1.343	0.700	1.119	0.135	0.070	0.132	-0.067
	E	2.099	1.365	0.700	1.059	0.131	0.070	0.131	-0.064
	SE	2.198	1.241	0.700	1.038	0.136	0.070	0.133	-0.017
	S	2.471	1.274	0.700	0.947	0.103	0.070	0.135	-0.016
	SW	1.982	1.332	0.700	0.977	0.101	0.070	0.126	-0.008
	W	2.113	1.253	0.700	1.009	0.153	0.070	0.140	-0.053
Area 24	Omni DNV	2.950	1.480	0.700	1.211	0.131	0.070	0.086	-0.006
	NW	2.944	1.634	0.700	1.300	0.119	0.070	0.085	-0.007
	N	2.758	1.584	0.700	1.327	0.135	0.070	0.092	-0.017
	NE	2.800	1.491	0.700	1.211	0.141	0.070	0.079	-0.006
	E	2.952	1.443	0.700	1.126	0.139	0.070	0.082	-0.007
	SE	2.962	1.441	0.700	1.116	0.115	0.070	0.094	-0.007
	S	2.823	1.402	0.700	0.973	0.297	0.070	0.093	-0.014
	SW	2.875	1.455	0.700	1.119	0.101	0.070	0.094	-0.019
	W	3.035	1.604	0.700	1.275	0.127	0.070	0.091	-0.015

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 25	Omni DNV	2.900	1.610	0.700	1.268	0.096	0.070	0.106	-0.052
	NW	2.731	1.505	0.700	1.206	0.093	0.070	0.124	-0.077
	N	2.845	1.624	0.700	1.230	0.086	0.070	0.118	-0.076
	NE	2.742	1.565	0.700	1.239	0.127	0.070	0.120	-0.062
	E	2.855	1.570	0.700	1.314	0.098	0.070	0.113	-0.056
	SE	2.804	1.570	0.700	1.249	0.128	0.070	0.117	-0.067
	S	2.970	1.468	0.700	1.163	0.093	0.070	0.116	-0.057
	SW	2.758	1.597	0.700	1.192	0.099	0.070	0.113	-0.067
	W	2.987	1.499	0.700	1.182	0.086	0.070	0.123	-0.063
Area 26	Omni DNV	1.810	1.300	0.700	0.858	0.232	0.070	0.196	-0.050
	NW	1.721	1.218	0.700	0.800	0.319	0.070	0.186	-0.046
	N	1.640	1.230	0.700	0.867	0.356	0.070	0.194	-0.036
	NE	1.715	1.222	0.700	0.853	0.266	0.070	0.184	-0.066
	E	1.724	1.186	0.700	0.855	0.220	0.070	0.197	-0.068
	SE	1.810	1.246	0.700	0.960	0.093	0.070	0.214	-0.076
	S	1.724	1.170	0.700	0.831	0.080	0.070	0.190	-0.058
	SW	1.840	1.139	0.700	0.987	0.087	0.070	0.182	-0.088
	W	1.767	1.216	0.700	0.975	0.048	0.070	0.165	-0.052
Area 27	Omni DNV	1.760	1.300	0.700	0.880	0.218	0.070	0.188	-0.042
	NW	1.761	1.287	0.700	0.896	0.225	0.070	0.186	-0.038
	N	1.648	1.214	0.700	0.763	0.256	0.070	0.187	-0.022
	NE	1.542	1.098	0.700	0.654	0.311	0.070	0.153	-0.073
	E	1.541	1.219	0.700	0.795	0.341	0.070	0.187	-0.080
	SE	1.749	1.174	0.700	0.870	0.271	0.070	0.179	-0.076
	S	1.755	1.282	0.700	0.685	0.360	0.070	0.169	-0.066
	SW	1.649	1.235	0.700	0.864	0.283	0.070	0.170	-0.075
	W	1.770	1.286	0.700	1.009	0.122	0.070	0.162	-0.046
Area 28	Omni DNV	1.810	1.280	0.700	0.841	0.241	0.070	0.198	-0.050
	NW	1.764	1.184	0.700	0.695	0.266	0.070	0.192	-0.075
	N	1.840	1.307	0.700	0.872	0.246	0.070	0.182	-0.069
	NE	1.685	1.300	0.700	0.816	0.268	0.070	0.180	-0.077
	E	1.767	1.213	0.700	0.532	0.346	0.070	0.206	-0.069
	SE	1.642	1.212	0.700	1.250	0.157	0.070	0.162	-0.028
	S	1.861	1.285	0.700	0.861	0.310	0.070	0.172	-0.066
	SW	1.643	1.199	0.700	0.875	0.211	0.070	0.204	-0.066
	W	1.743	1.128	0.700	0.752	0.251	0.070	0.190	-0.066

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 29	Omni DNV	2.310	1.380	0.700	0.976	0.197	0.070	0.129	-0.018
	NW	2.219	1.286	0.700	0.951	0.163	0.070	0.124	-0.027
	N	2.198	1.255	0.700	1.020	0.136	0.070	0.117	-0.019
	NE	2.300	1.298	0.700	1.030	0.124	0.070	0.104	-0.014
	E	2.220	1.247	0.700	0.955	0.183	0.070	0.121	-0.023
	SE	2.177	1.248	0.700	0.949	0.198	0.070	0.112	-0.018
	S	2.178	1.193	0.700	0.932	0.178	0.070	0.113	-0.028
	SW	2.317	1.213	0.700	1.013	0.129	0.070	0.126	-0.006
	W	2.295	1.351	0.700	1.001	0.152	0.070	0.124	-0.008
Area 30	Omni DNV	3.140	1.560	0.700	1.243	0.118	0.070	0.086	-0.012
	NW	3.088	1.743	0.700	1.386	0.128	0.070	0.092	-0.008
	N	2.983	1.604	0.700	1.303	0.085	0.070	0.093	-0.016
	NE	2.861	1.497	0.700	1.165	0.135	0.070	0.087	-0.017
	E	2.972	1.668	0.700	1.081	0.135	0.070	0.084	-0.016
	SE	2.865	1.545	0.700	1.083	0.116	0.070	0.085	-0.018
	S	3.180	1.409	0.700	1.231	0.121	0.070	0.085	-0.018
	SW	3.083	1.490	0.700	1.122	0.174	0.070	0.076	-0.018
	W	3.310	1.684	0.700	1.305	0.106	0.070	0.102	-0.018
Area 31	Omni DNV	2.620	1.790	0.700	1.219	0.126	0.070	0.102	-0.012
	NW	2.228	1.825	0.700	1.044	0.145	0.070	0.114	-0.017
	N	2.366	1.735	0.700	1.137	0.166	0.070	0.134	-0.054
	NE	2.597	1.773	0.700	1.215	0.156	0.070	0.085	-0.070
	E	2.651	1.977	0.700	1.238	0.168	0.070	0.093	-0.032
	SE	2.423	1.739	0.700	1.201	0.110	0.070	0.125	-0.080
	S	2.808	1.830	0.700	1.013	0.135	0.070	0.094	-0.024
	SW	2.400	1.796	0.700	1.029	0.128	0.070	0.135	-0.076
	W	3.009	1.964	0.700	1.046	0.120	0.070	0.137	-0.038
Area 32	Omni DNV	1.810	1.470	0.700	0.950	0.158	0.070	0.169	-0.031
	NW	1.696	1.281	0.700	0.913	0.189	0.070	0.137	-0.062
	N	1.797	1.304	0.700	0.846	0.232	0.070	0.130	-0.074
	NE	1.629	1.348	0.700	0.804	0.320	0.070	0.145	-0.054
	E	1.850	1.447	0.700	1.017	0.113	0.070	0.147	-0.061
	SE	1.747	1.429	0.700	1.015	0.128	0.070	0.130	-0.057
	S	1.842	1.359	0.700	0.815	0.270	0.070	0.121	-0.055
	SW	1.794	1.443	0.700	0.937	0.144	0.070	0.117	-0.053
	W	1.696	1.475	0.700	0.894	0.266	0.070	0.194	-0.050

Area	Direction	α	β	a0	a1	a2	b0	b1	b2
Area 33	Omni DNV	2.170	1.660	0.700	1.111	0.135	0.070	0.119	-0.015
	NW	2.166	1.619	0.700	1.101	0.118	0.070	0.116	-0.026
	N	1.993	1.598	0.700	1.020	0.121	0.070	0.129	-0.068
	NE	2.175	1.654	0.700	1.129	0.108	0.070	0.137	-0.067
	E	2.192	1.587	0.700	1.172	0.163	0.070	0.111	-0.088
	SE	1.987	1.534	0.700	1.109	0.125	0.070	0.118	-0.043
	S	2.085	1.582	0.700	0.950	0.159	0.070	0.128	-0.065
	SW	2.099	1.653	0.700	0.987	0.271	0.070	0.129	-0.065
	W	2.102	1.765	0.700	0.981	0.238	0.070	0.110	-0.019
Area 34	Omni DNV	2.460	1.700	0.700	1.189	0.141	0.070	0.106	-0.006
	NW	2.519	1.515	0.700	1.200	0.131	0.070	0.090	-0.059
	N	2.296	1.696	0.700	1.239	0.103	0.070	0.098	-0.046
	NE	2.390	1.566	0.700	1.183	0.063	0.070	0.125	-0.076
	E	2.474	1.710	0.700	1.154	0.131	0.070	0.108	-0.007
	SE	2.296	1.537	0.700	1.216	0.139	0.070	0.109	-0.012
	S	2.399	1.616	0.700	1.263	0.150	0.070	0.111	-0.012
	SW	2.277	1.697	0.700	1.290	0.149	0.070	0.124	-0.005
	W	2.390	1.790	0.700	1.247	0.069	0.070	0.110	-0.016
Area 35	Omni DNV	2.740	2.050	0.700	1.219	0.128	0.070	0.110	-0.010
	NW	2.596	1.869	0.700	1.192	0.140	0.070	0.111	-0.055
	N	2.620	1.853	0.700	1.249	0.107	0.070	0.135	-0.066
	NE	2.653	2.019	0.700	1.129	0.150	0.070	0.140	-0.047
	E	2.697	1.873	0.700	1.240	0.128	0.070	0.117	-0.021
	SE	2.658	1.946	0.700	1.219	0.133	0.070	0.129	-0.042
	S	2.891	1.907	0.700	1.292	0.126	0.070	0.112	-0.044
	SW	2.656	2.083	0.700	1.232	0.127	0.070	0.128	-0.032
	W	2.724	2.362	0.700	1.248	0.136	0.070	0.141	-0.058
Area 36	Omni DNV	2.320	1.820	0.700	1.111	0.143	0.070	0.117	-0.019
	NW	2.175	1.741	0.700	1.015	0.175	0.070	0.119	-0.063
	N	2.284	1.846	0.700	1.109	0.180	0.070	0.126	-0.017
	NE	2.280	1.680	0.700	1.030	0.145	0.070	0.133	-0.029
	E	2.367	1.746	0.700	1.182	0.131	0.070	0.109	-0.014
	SE	2.264	1.724	0.700	1.216	0.142	0.070	0.132	-0.044
	S	2.347	1.715	0.700	1.123	0.138	0.070	0.110	-0.042
	SW	2.186	1.829	0.700	1.105	0.156	0.070	0.119	-0.032
	W	2.092	2.010	0.700	1.124	0.127	0.070	0.116	-0.033

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 37	Omni DNV	1.660	1.530	0.700	0.815	0.199	0.070	0.275	-0.105
	NW	1.640	1.438	0.700	0.825	0.182	0.070	0.269	-0.109
	N	1.675	1.548	0.700	0.792	0.163	0.070	0.240	-0.039
	NE	1.436	1.457	0.700	0.798	0.194	0.070	0.237	-0.076
	E	1.632	1.224	0.700	0.871	0.241	0.070	0.033	-0.075
	SE	1.543	1.309	0.700	0.761	0.171	0.070	0.286	-0.076
	S	1.708	1.474	0.700	0.759	0.128	0.070	0.320	-0.086
	SW	1.575	1.509	0.700	0.789	0.172	0.070	0.259	-0.066
	W	1.533	1.567	0.700	0.796	0.163	0.070	0.240	-0.075
Area 38	Omni DNV	1.230	1.240	0.700	0.616	0.332	0.070	0.320	-0.005
	NW	1.248	1.214	0.700	0.650	0.317	0.070	0.263	-0.070
	N	1.180	1.183	0.700	0.641	0.294	0.070	0.329	-0.018
	NE	1.199	1.198	0.700	1.026	0.143	0.070	0.316	-0.017
	E	1.097	1.235	0.700	0.868	0.243	0.070	0.319	-0.017
	SE	1.095	1.214	0.700	0.879	0.277	0.070	0.274	-0.017
	S	1.215	1.136	0.700	1.108	0.149	0.070	0.247	-0.016
	SW	1.173	1.205	0.700	1.130	0.127	0.070	0.279	-0.022
	W	1.239	1.245	0.700	0.943	0.279	0.070	0.310	-0.079
Area 39	Omni DNV	1.740	1.370	0.700	0.798	0.239	0.070	0.257	-0.091
	NW	1.620	1.258	0.700	0.770	0.218	0.070	0.235	-0.060
	N	1.693	1.319	0.700	0.792	0.263	0.070	0.230	-0.086
	NE	1.730	1.259	0.700	0.744	0.245	0.070	0.248	-0.079
	E	1.829	1.187	0.700	0.877	0.195	0.070	0.238	-0.077
	SE	1.620	1.216	0.700	0.741	0.240	0.070	0.246	-0.086
	S	1.715	1.356	0.700	0.750	0.155	0.070	0.237	-0.077
	SW	1.747	1.397	0.700	0.830	0.152	0.070	0.245	-0.102
	W	1.650	1.269	0.700	0.867	0.166	0.070	0.230	-0.092
Area 40	Omni DNV	2.360	1.420	0.700	0.975	0.195	0.070	0.129	-0.021
	NW	2.152	1.387	0.700	0.936	0.194	0.070	0.150	-0.073
	N	2.191	1.328	0.700	1.052	0.117	0.070	0.145	-0.017
	NE	2.390	1.588	0.700	1.129	0.135	0.070	0.128	-0.028
	E	2.404	1.268	0.700	0.940	0.138	0.070	0.130	-0.020
	SE	2.199	1.203	0.700	0.844	0.173	0.070	0.120	-0.017
	S	2.192	1.387	0.700	0.954	0.175	0.070	0.124	-0.015
	SW	2.190	1.412	0.700	0.921	0.216	0.070	0.105	-0.026
	W	2.296	1.450	0.700	0.969	0.187	0.070	0.140	-0.035

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 41	Omni DNV	2.470	1.500	0.700	1.044	0.161	0.070	0.117	-0.016
	NW	2.348	1.490	0.700	1.018	0.180	0.070	0.120	-0.018
	N	2.420	1.514	0.700	1.060	0.128	0.070	0.117	-0.028
	NE	2.469	1.539	0.700	1.082	0.121	0.070	0.120	-0.014
	E	2.389	1.449	0.700	1.019	0.139	0.070	0.139	-0.025
	SE	2.297	1.350	0.700	1.017	0.138	0.070	0.135	-0.038
	S	2.295	1.371	0.700	1.107	0.140	0.070	0.191	-0.027
	SW	2.384	1.297	0.700	1.114	0.128	0.070	0.128	-0.016
	W	2.418	1.450	0.700	1.038	0.134	0.070	0.138	-0.048
Area 42	Omni DNV	2.320	1.410	0.700	1.121	0.128	0.070	0.116	-0.012
	NW	2.298	1.439	0.700	1.083	0.129	0.070	0.132	-0.015
	N	2.199	1.416	0.700	1.139	0.136	0.070	0.119	-0.028
	NE	2.197	1.368	0.700	1.127	0.121	0.070	0.129	-0.028
	E	2.380	1.543	0.700	1.129	0.139	0.070	0.119	-0.025
	SE	2.220	1.219	0.700	1.019	0.123	0.070	0.130	-0.028
	S	2.196	1.259	0.700	1.092	0.175	0.070	0.120	-0.017
	SW	2.081	1.404	0.700	1.038	0.119	0.070	0.118	-0.028
	W	2.210	1.255	0.700	1.130	0.103	0.070	0.120	-0.027
Area 43	Omni DNV	2.780	1.780	0.700	1.222	0.124	0.070	0.103	-0.008
	NW	2.529	1.665	0.700	1.159	0.137	0.070	0.104	-0.015
	N	2.577	1.675	0.700	1.147	0.145	0.070	0.116	-0.027
	NE	2.694	1.565	0.700	1.124	0.124	0.070	0.105	-0.017
	E	2.810	1.710	0.700	1.212	0.147	0.070	0.111	-0.007
	SE	2.499	1.574	0.700	1.187	0.133	0.070	0.105	-0.017
	S	2.498	1.682	0.700	1.149	0.142	0.070	0.105	-0.009
	SW	2.608	1.785	0.700	1.200	0.131	0.070	0.109	-0.018
	W	2.856	1.900	0.700	1.148	0.142	0.070	0.113	-0.012
Area 44	Omni DNV	2.830	2.170	0.700	1.181	0.149	0.070	0.101	-0.012
	NW	2.584	1.815	0.700	1.239	0.119	0.070	0.104	-0.028
	N	2.535	1.886	0.700	1.257	0.150	0.070	0.092	-0.013
	NE	2.655	2.104	0.700	1.220	0.143	0.070	0.105	-0.024
	E	2.856	2.135	0.700	1.163	0.129	0.070	0.120	-0.028
	SE	2.484	1.811	0.700	1.006	0.139	0.070	0.105	-0.027
	S	2.798	2.007	0.700	1.187	0.140	0.070	0.111	-0.036
	SW	2.674	2.215	0.700	1.214	0.125	0.070	0.096	-0.037
	W	2.778	2.145	0.700	1.248	0.176	0.070	0.145	-0.043

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 45	Omni DNV	2.600	2.070	0.700	1.177	0.173	0.070	0.102	-0.026
	NW	2.255	1.878	0.700	1.160	0.137	0.070	0.107	-0.058
	N	2.325	1.885	0.700	1.164	0.118	0.070	0.125	-0.076
	NE	2.698	1.966	0.700	1.227	0.137	0.070	0.135	-0.112
	E	2.578	1.988	0.700	1.213	0.142	0.070	0.120	-0.075
	SE	2.123	1.965	0.700	1.135	0.142	0.070	0.112	-0.011
	S	2.199	1.924	0.700	1.165	0.162	0.070	0.110	-0.049
	SW	2.371	2.105	0.700	1.194	0.161	0.070	0.107	-0.051
	W	2.685	2.065	0.700	1.158	0.176	0.070	0.097	-0.027
Area 46	Omni DNV	1.760	1.440	0.700	1.070	0.139	0.070	0.137	-0.031
	NW	1.739	1.418	0.700	1.088	0.147	0.070	0.131	-0.018
	N	1.680	1.350	0.700	1.078	0.129	0.070	0.153	-0.075
	NE	1.685	1.273	0.700	1.108	0.139	0.070	0.136	-0.076
	E	1.651	1.430	0.700	1.069	0.123	0.070	0.143	-0.064
	SE	1.648	1.425	0.700	1.039	0.140	0.070	0.121	-0.027
	S	1.660	1.414	0.700	1.013	0.153	0.070	0.111	-0.036
	SW	1.680	1.454	0.700	1.020	0.132	0.070	0.100	-0.035
	W	1.754	1.332	0.700	1.029	0.149	0.070	0.160	-0.069
Area 47	Omni DNV	2.300	1.780	0.700	1.058	0.149	0.070	0.130	-0.025
	NW	2.082	1.713	0.700	0.922	0.280	0.070	0.134	-0.016
	N	2.197	1.750	0.700	0.710	0.466	0.070	0.144	-0.019
	NE	2.285	1.690	0.700	1.020	0.124	0.070	0.137	-0.027
	E	2.278	1.782	0.700	1.107	0.126	0.070	0.129	-0.032
	SE	2.193	1.685	0.700	0.739	0.447	0.070	0.119	-0.018
	S	2.006	1.682	0.700	0.785	0.426	0.070	0.119	-0.019
	SW	2.100	1.785	0.700	0.781	0.421	0.070	0.129	-0.036
	W	2.086	1.949	0.700	0.836	0.323	0.070	0.130	-0.031
Area 48	Omni DNV	2.550	2.200	0.700	1.160	0.172	0.070	0.105	-0.023
	NW	2.430	1.923	0.700	1.182	0.125	0.070	0.125	-0.077
	N	2.352	1.860	0.700	1.075	0.142	0.070	0.110	-0.036
	NE	2.517	2.068	0.700	1.193	0.162	0.070	0.108	-0.062
	E	2.540	2.099	0.700	1.194	0.134	0.070	0.104	-0.045
	SE	2.374	1.903	0.700	1.019	0.113	0.070	0.118	-0.043
	S	2.497	2.032	0.700	1.056	0.237	0.070	0.127	-0.032
	SW	2.305	2.125	0.700	1.026	0.254	0.070	0.125	-0.113
	W	2.412	2.159	0.700	1.057	0.206	0.070	0.099	-0.047

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 49	Omni DNV	2.500	2.130	0.700	1.141	0.149	0.070	0.122	-0.012
	NW	2.385	1.901	0.700	1.125	0.141	0.070	0.129	-0.015
	N	2.411	1.897	0.700	1.114	0.125	0.070	0.145	-0.041
	NE	2.465	2.093	0.700	1.132	0.152	0.070	0.137	-0.037
	E	2.381	1.819	0.700	1.114	0.134	0.070	0.116	-0.023
	SE	2.245	2.023	0.700	1.156	0.130	0.070	0.124	-0.049
	S	2.320	1.974	0.700	1.016	0.137	0.070	0.121	-0.037
	SW	2.584	2.171	0.700	1.169	0.144	0.070	0.126	-0.040
	W	2.347	2.484	0.700	1.143	0.152	0.070	0.128	-0.029
Area 50	Omni DNV	2.050	1.280	0.700	0.879	0.237	0.070	0.165	-0.034
	NW	1.914	1.262	0.700	0.852	0.239	0.070	0.174	-0.069
	N	1.835	1.342	0.700	0.820	0.226	0.070	0.159	-0.066
	NE	2.038	1.234	0.700	0.877	0.245	0.070	0.173	-0.066
	E	2.117	1.269	0.700	1.028	0.112	0.070	0.159	-0.043
	SE	1.873	1.227	0.700	0.854	0.254	0.070	0.160	-0.059
	S	2.147	1.385	0.700	0.897	0.237	0.070	0.145	-0.009
	SW	1.946	1.233	0.700	0.861	0.240	0.070	0.152	-0.006
	W	2.182	1.331	0.700	0.874	0.270	0.070	0.167	-0.067
Area 51	Omni DNV	1.780	1.440	0.700	0.952	0.159	0.070	0.176	-0.054
	NW	1.669	1.408	0.700	0.888	0.264	0.070	0.155	-0.065
	N	1.622	1.249	0.700	0.907	0.161	0.070	0.170	-0.077
	NE	1.796	1.331	0.700	0.871	0.186	0.070	0.167	-0.058
	E	1.627	1.311	0.700	0.869	0.187	0.070	0.152	-0.059
	SE	1.652	1.358	0.700	0.899	0.254	0.070	0.170	-0.077
	S	1.783	1.398	0.700	0.958	0.154	0.070	0.150	-0.067
	SW	1.729	1.410	0.700	0.937	0.141	0.070	0.167	-0.057
	W	1.651	1.283	0.700	0.886	0.218	0.070	0.172	-0.028
Area 52	Omni DNV	2.140	1.500	0.700	1.072	0.133	0.070	0.127	-0.025
	NW	1.877	1.361	0.700	0.998	0.122	0.070	0.137	-0.017
	N	2.080	1.404	0.700	0.937	0.209	0.070	0.120	-0.017
	NE	2.072	1.553	0.700	1.038	0.243	0.070	0.117	-0.057
	E	2.160	1.568	0.700	1.095	0.128	0.070	0.121	-0.059
	SE	1.974	1.280	0.700	0.897	0.212	0.070	0.128	-0.018
	S	2.194	1.449	0.700	0.951	0.219	0.070	0.090	-0.020
	SW	2.018	1.397	0.700	0.974	0.137	0.070	0.119	-0.018
	W	1.954	1.360	0.700	1.023	0.133	0.070	0.125	-0.016

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 53	Omni DNV	2.560	1.930	0.700	1.188	0.129	0.070	0.104	-0.009
	NW	2.265	1.833	0.700	1.138	0.162	0.070	0.099	-0.021
	N	2.291	1.822	0.700	1.140	0.176	0.070	0.113	-0.022
	NE	2.465	1.841	0.700	1.124	0.190	0.070	0.103	-0.014
	E	2.578	1.942	0.700	1.158	0.144	0.070	0.109	-0.030
	SE	2.283	1.830	0.700	1.086	0.177	0.070	0.107	-0.014
	S	2.688	1.807	0.700	1.103	0.132	0.070	0.113	-0.017
	SW	2.467	1.951	0.700	1.134	0.171	0.070	0.115	-0.018
	W	2.305	1.918	0.700	1.124	0.154	0.070	0.115	-0.025
Area 54	Omni DNV	2.450	2.190	0.700	1.176	0.168	0.070	0.110	-0.009
	NW	2.349	1.921	0.700	1.119	0.178	0.070	0.110	-0.057
	N	2.284	1.811	0.700	1.142	0.188	0.070	0.110	-0.040
	NE	2.386	1.902	0.700	1.123	0.182	0.070	0.108	-0.015
	E	2.380	2.024	0.700	1.155	0.143	0.070	0.107	-0.026
	SE	2.400	2.047	0.700	1.123	0.184	0.070	0.093	-0.008
	S	2.509	1.953	0.700	1.250	0.183	0.070	0.132	-0.030
	SW	2.273	2.238	0.700	1.223	0.143	0.070	0.120	-0.013
	W	2.282	2.276	0.700	1.199	0.163	0.070	0.123	-0.046
Area 55	Omni DNV	1.830	1.960	0.700	1.046	0.143	0.070	0.154	-0.019
	NW	1.732	1.826	0.700	1.026	0.161	0.070	0.146	-0.068
	N	1.642	1.832	0.700	1.019	0.256	0.070	0.150	-0.066
	NE	1.590	1.840	0.700	1.017	0.172	0.070	0.157	-0.025
	E	1.655	1.874	0.700	1.024	0.124	0.070	0.139	-0.017
	SE	1.721	1.859	0.700	1.018	0.153	0.070	0.148	-0.017
	S	1.924	1.832	0.700	1.108	0.125	0.070	0.139	-0.015
	SW	1.818	1.984	0.700	0.918	0.173	0.070	0.146	-0.016
	W	1.753	2.224	0.700	1.008	0.168	0.070	0.154	-0.018
Area 56	Omni DNV	2.400	2.180	0.700	1.157	0.157	0.070	0.107	-0.017
	NW	1.985	1.918	0.700	1.128	0.173	0.070	0.104	-0.046
	N	2.205	1.977	0.700	1.217	0.186	0.070	0.117	-0.027
	NE	2.396	2.079	0.700	1.116	0.122	0.070	0.110	-0.014
	E	2.286	1.986	0.700	1.122	0.160	0.070	0.120	-0.012
	SE	2.195	1.867	0.700	1.120	0.168	0.070	0.122	-0.047
	S	2.244	2.015	0.700	1.296	0.182	0.070	0.120	-0.031
	SW	2.207	2.226	0.700	1.199	0.183	0.070	0.123	-0.015
	W	2.216	2.560	0.700	1.247	0.162	0.070	0.112	-0.014

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 57	Omni DNV	2.170	2.190	0.700	1.083	0.214	0.070	0.120	-0.017
	NW	1.954	1.921	0.700	0.995	0.322	0.070	0.128	-0.018
	N	2.073	1.819	0.700	1.051	0.183	0.070	0.122	-0.015
	NE	2.110	2.045	0.700	1.125	0.173	0.070	0.118	-0.026
	E	1.980	2.084	0.700	1.115	0.210	0.070	0.102	-0.005
	SE	2.088	1.924	0.700	1.115	0.141	0.070	0.142	-0.068
	S	2.289	1.924	0.700	1.009	0.143	0.070	0.124	-0.015
	SW	1.980	2.238	0.700	1.130	0.189	0.070	0.107	-0.048
	W	2.080	2.158	0.700	1.138	0.140	0.070	0.115	-0.019
Area 58	Omni DNV	1.850	2.080	0.700	1.013	0.165	0.070	0.158	-0.025
	NW	1.761	1.882	0.700	1.094	0.150	0.070	0.139	-0.035
	N	1.880	1.858	0.700	1.071	0.160	0.070	0.178	-0.049
	NE	1.900	1.947	0.700	1.071	0.140	0.070	0.171	-0.048
	E	1.613	1.984	0.700	1.107	0.163	0.070	0.154	-0.046
	SE	1.764	1.975	0.700	1.031	0.158	0.070	0.170	-0.029
	S	1.830	2.109	0.700	1.020	0.145	0.070	0.164	-0.039
	SW	1.644	2.116	0.700	1.001	0.130	0.070	0.149	-0.036
	W	1.796	2.074	0.700	1.027	0.140	0.070	0.153	-0.015
Area 59	Omni DNV	2.020	1.760	0.700	1.025	0.159	0.070	0.143	-0.025
	NW	2.190	1.698	0.700	1.020	0.136	0.070	0.160	-0.017
	N	1.720	1.737	0.700	1.018	0.154	0.070	0.150	-0.035
	NE	1.829	1.662	0.700	1.018	0.145	0.070	0.143	-0.038
	E	1.970	1.692	0.700	1.037	0.135	0.070	0.162	-0.026
	SE	1.974	1.666	0.700	1.029	0.131	0.070	0.122	-0.005
	S	2.140	1.666	0.700	1.020	0.137	0.070	0.156	-0.062
	SW	1.961	1.648	0.700	1.029	0.133	0.070	0.142	-0.048
	W	1.835	1.718	0.700	1.017	0.144	0.070	0.140	-0.040
Area 60	Omni DNV	1.930	1.390	0.700	1.057	0.145	0.070	0.135	-0.022
	NW	1.820	1.332	0.700	1.098	0.144	0.070	0.142	-0.086
	N	1.864	1.380	0.700	1.083	0.151	0.070	0.138	-0.072
	NE	1.753	1.346	0.700	1.038	0.147	0.070	0.142	-0.058
	E	1.655	1.345	0.700	1.026	0.168	0.070	0.137	-0.036
	SE	1.743	1.309	0.700	1.029	0.131	0.070	0.142	-0.055
	S	1.943	1.357	0.700	1.017	0.140	0.070	0.168	-0.060
	SW	1.879	1.355	0.700	1.084	0.152	0.070	0.160	-0.026
	W	1.989	1.360	0.700	1.046	0.149	0.070	0.138	-0.010

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 61	Omni DNV	2.100	1.820	0.700	1.080	0.132	0.070	0.130	-0.026
	NW	1.595	1.741	0.700	1.009	0.277	0.070	0.162	-0.126
	N	1.375	1.773	0.700	0.965	0.381	0.070	0.123	-0.087
	NE	1.470	1.715	0.700	1.097	0.139	0.070	0.136	-0.104
	E	2.163	1.746	0.700	1.171	0.113	0.070	0.109	-0.105
	SE	1.582	1.724	0.700	0.792	0.476	0.070	0.123	-0.063
	S	2.178	1.629	0.700	1.016	0.151	0.070	0.106	-0.014
	SW	2.205	1.719	0.700	1.039	0.195	0.070	0.128	-0.069
	W	1.960	1.569	0.700	1.012	0.161	0.070	0.163	-0.135
Area 62	Omni DNV	1.730	1.390	0.700	0.871	0.214	0.070	0.194	-0.027
	NW	1.670	1.285	0.700	0.877	0.214	0.070	0.127	-0.031
	N	1.740	1.205	0.700	0.837	0.162	0.070	0.078	-0.007
	NE	1.639	1.425	0.700	0.878	0.152	0.070	0.187	-0.026
	E	1.820	1.229	0.700	0.840	0.154	0.070	0.081	-0.069
	SE	1.439	1.233	0.700	0.869	0.249	0.070	0.159	-0.064
	S	1.895	1.220	0.700	0.803	0.162	0.070	0.108	-0.001
	SW	1.639	1.322	0.700	0.813	0.158	0.070	0.109	-0.030
	W	1.637	1.286	0.700	0.862	0.224	0.070	0.170	-0.042
Area 63	Omni DNV	1.880	1.700	0.700	1.026	0.155	0.070	0.148	-0.022
	NW	1.865	1.652	0.700	1.012	0.096	0.070	0.177	-0.124
	N	1.865	1.696	0.700	0.956	0.155	0.070	0.217	-0.164
	NE	1.796	1.683	0.700	1.084	0.121	0.070	0.141	-0.017
	E	1.893	1.659	0.700	0.969	0.245	0.070	0.139	-0.096
	SE	1.868	1.608	0.700	0.933	0.258	0.070	0.189	-0.197
	S	1.921	1.616	0.700	1.016	0.151	0.070	0.086	-0.014
	SW	1.765	1.697	0.700	1.012	0.161	0.070	0.163	-0.135
	W	1.781	1.827	0.700	0.877	0.239	0.070	0.170	-0.012
Area 64	Omni DNV	2.340	2.160	0.700	1.138	0.186	0.070	0.113	-0.006
	NW	1.987	1.911	0.700	1.078	0.202	0.070	0.079	-0.086
	N	2.160	1.862	0.700	1.005	0.275	0.070	0.120	-0.040
	NE	1.887	2.018	0.700	0.986	0.255	0.070	0.034	-0.033
	E	1.943	2.057	0.700	0.985	0.382	0.070	0.044	-0.013
	SE	2.422	2.115	0.700	1.006	0.295	0.070	0.075	-0.012
	S	2.255	2.000	0.700	1.020	0.213	0.070	0.125	-0.120
	SW	2.170	2.204	0.700	1.100	0.226	0.070	0.052	-0.020
	W	2.138	2.530	0.700	1.011	0.321	0.070	0.122	-0.110

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 65	Omni DNV	2.020	1.900	0.700	1.132	0.169	0.070	0.119	-0.013
	NW	1.972	1.792	0.700	1.100	0.034	0.070	0.122	-0.016
	N	1.859	1.810	0.700	1.098	0.190	0.070	0.122	-0.140
	NE	1.828	1.786	0.700	0.961	0.276	0.070	0.120	-0.012
	E	2.089	1.820	0.700	1.179	0.064	0.070	0.105	-0.001
	SE	1.867	1.801	0.700	1.128	0.177	0.070	0.105	-0.015
	S	2.126	1.793	0.700	1.117	0.126	0.070	0.103	-0.014
	SW	1.765	1.917	0.700	1.194	0.114	0.070	0.105	-0.015
	W	1.920	2.132	0.700	1.081	0.106	0.070	0.127	-0.109
Area 66	Omni DNV	2.330	2.150	0.700	1.115	0.183	0.070	0.119	-0.020
	NW	2.060	1.908	0.700	1.108	0.138	0.070	0.132	-0.014
	N	1.987	1.862	0.700	1.081	0.184	0.070	0.121	-0.018
	NE	2.139	2.109	0.700	1.026	0.229	0.070	0.107	-0.022
	E	2.228	2.081	0.700	1.100	0.190	0.070	0.102	-0.019
	SE	2.296	2.184	0.700	1.102	0.185	0.070	0.127	-0.018
	S	2.333	1.990	0.700	1.129	0.170	0.070	0.120	-0.074
	SW	2.015	2.193	0.700	0.956	0.272	0.070	0.127	-0.026
	W	2.125	2.514	0.700	1.032	0.213	0.070	0.142	-0.110
Area 67	Omni DNV	2.170	2.190	0.700	1.083	0.214	0.070	0.120	-0.017
	NW	1.864	1.921	0.700	1.134	0.198	0.070	0.118	-0.019
	N	1.973	1.819	0.700	1.081	0.219	0.070	0.107	-0.013
	NE	2.011	2.045	0.700	1.049	0.196	0.070	0.114	-0.019
	E	1.990	2.084	0.700	0.957	0.312	0.070	0.119	-0.195
	SE	2.199	1.924	0.700	1.099	0.198	0.070	0.140	-0.141
	S	2.185	1.924	0.700	1.120	0.132	0.070	0.136	-0.177
	SW	1.958	2.124	0.700	1.069	0.194	0.070	0.108	-0.173
	W	2.081	2.076	0.700	1.031	0.172	0.070	0.120	-0.012
Area 68	Omni DNV	2.420	2.160	0.700	1.121	0.155	0.070	0.124	-0.015
	NW	1.998	1.911	0.700	0.842	0.322	0.070	0.115	-0.057
	N	1.964	1.862	0.700	0.739	0.397	0.070	0.133	-0.072
	NE	1.952	2.018	0.700	0.967	0.261	0.070	0.095	-0.018
	E	2.292	2.057	0.700	1.113	0.156	0.070	0.161	-0.023
	SE	2.318	1.992	0.700	1.079	0.170	0.070	0.104	-0.046
	S	2.456	1.999	0.700	0.874	0.340	0.070	0.130	-0.049
	SW	2.086	2.204	0.700	1.094	0.142	0.070	0.109	-0.031
	W	2.242	2.123	0.700	1.022	0.265	0.070	0.104	-0.078

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 69	Omni DNV	2.230	1.890	0.700	1.177	0.124	0.070	0.118	-0.010
	NW	2.162	1.786	0.700	1.125	0.135	0.070	0.128	-0.025
	N	1.964	1.806	0.700	1.155	0.171	0.070	0.130	-0.025
	NE	2.012	1.777	0.700	1.125	0.133	0.070	0.125	-0.132
	E	1.981	1.710	0.700	1.103	0.184	0.070	0.107	-0.024
	SE	2.196	1.796	0.700	1.110	0.138	0.070	0.133	-0.110
	S	2.286	1.775	0.700	1.144	0.149	0.070	0.129	-0.026
	SW	2.088	1.906	0.700	1.185	0.121	0.070	0.106	-0.014
	W	2.195	1.721	0.700	1.035	0.191	0.070	0.114	-0.036
Area 70	Omni DNV	2.320	1.840	0.700	1.170	0.167	0.070	0.166	-0.209
	NW	2.177	1.754	0.700	1.095	0.207	0.070	0.146	-0.138
	N	1.980	1.583	0.700	1.199	0.108	0.070	0.146	-0.179
	NE	1.987	1.673	0.700	1.140	0.187	0.070	0.170	-0.185
	E	2.088	1.765	0.700	1.229	0.150	0.070	0.182	-0.197
	SE	2.395	1.645	0.700	1.033	0.167	0.070	0.126	-0.147
	S	2.289	1.694	0.700	1.091	0.175	0.070	0.121	-0.125
	SW	2.185	1.751	0.700	1.037	0.229	0.070	0.146	-0.180
	W	2.200	1.792	0.700	1.029	0.267	0.070	0.129	-0.199
Area 71	Omni DNV	1.790	1.690	0.700	1.005	0.147	0.070	0.160	-0.031
	NW	1.560	1.402	0.700	1.001	0.102	0.070	0.143	-0.009
	N	1.528	1.389	0.700	1.011	0.109	0.070	0.125	-0.012
	NE	1.680	1.460	0.700	1.012	0.097	0.070	0.168	-0.004
	E	1.663	1.512	0.700	1.025	0.098	0.070	0.172	-0.059
	SE	1.784	1.616	0.700	1.008	0.091	0.070	0.147	-0.019
	S	1.851	1.445	0.700	0.894	0.129	0.070	0.165	-0.040
	SW	1.670	1.457	0.700	0.961	0.141	0.070	0.151	-0.029
	W	1.698	1.427	0.700	0.950	0.150	0.070	0.152	-0.026
Area 72	Omni DNV	2.440	1.930	0.700	1.158	0.187	0.070	0.107	-0.011
	NW	2.063	1.809	0.700	1.105	0.247	0.070	0.108	-0.028
	N	2.219	1.982	0.700	1.053	0.294	0.070	0.099	-0.056
	NE	2.197	1.813	0.700	1.032	0.272	0.070	0.104	-0.063
	E	2.480	1.894	0.700	1.239	0.127	0.070	0.103	-0.011
	SE	2.388	1.894	0.700	1.090	0.242	0.070	0.111	-0.025
	S	2.306	1.893	0.700	1.110	0.227	0.070	0.107	-0.018
	SW	2.273	1.928	0.700	0.994	0.307	0.070	0.098	-0.014
	W	2.198	1.722	0.700	1.092	0.171	0.070	0.109	-0.037

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 73	Omni DNV	2.800	2.260	0.700	1.174	0.182	0.070	0.105	-0.049
	NW	2.455	1.939	0.700	0.967	0.262	0.070	0.099	-0.023
	N	2.416	1.852	0.700	1.024	0.179	0.070	0.109	-0.021
	NE	2.591	2.330	0.700	1.020	0.245	0.070	0.106	-0.022
	E	2.810	2.253	0.700	1.211	0.185	0.070	0.102	-0.027
	SE	2.638	2.107	0.700	1.142	0.176	0.070	0.111	-0.106
	S	2.635	2.061	0.700	1.153	0.141	0.070	0.149	-0.163
	SW	2.635	2.148	0.700	0.978	0.264	0.070	0.124	-0.109
	W	2.739	2.268	0.700	1.147	0.159	0.070	0.125	-0.028
Area 74	Omni DNV	2.230	1.690	0.700	1.143	0.148	0.070	0.115	-0.009
	NW	2.150	1.544	0.700	1.028	0.256	0.070	0.199	-0.289
	N	2.198	1.689	0.700	1.123	0.194	0.070	0.120	-0.054
	NE	1.978	1.627	0.700	1.155	0.146	0.070	0.112	-0.066
	E	2.198	1.624	0.700	1.126	0.167	0.070	0.146	-0.140
	SE	2.190	1.578	0.700	1.032	0.263	0.070	0.109	-0.059
	S	2.165	1.723	0.700	1.018	0.262	0.070	0.132	-0.103
	SW	2.395	1.524	0.700	0.947	0.257	0.070	0.136	-0.078
	W	2.352	1.668	0.700	0.996	0.260	0.070	0.162	-0.173
Area 75	Omni DNV	2.690	1.670	0.700	1.216	0.118	0.070	0.099	-0.010
	NW	2.594	1.628	0.700	1.139	0.146	0.070	0.110	-0.136
	N	2.491	1.636	0.700	1.172	0.170	0.070	0.124	-0.038
	NE	2.704	1.398	0.700	1.018	0.164	0.070	0.160	-0.159
	E	2.483	1.577	0.700	1.126	0.181	0.070	0.170	-0.166
	SE	2.528	1.628	0.700	1.240	0.119	0.070	0.095	-0.038
	S	2.655	1.650	0.700	1.214	0.145	0.070	0.123	-0.046
	SW	2.787	1.518	0.700	1.146	0.167	0.070	0.120	-0.021
	W	2.693	1.568	0.700	1.182	0.116	0.070	0.119	-0.015
Area 76	Omni DNV	2.860	1.770	0.700	1.218	0.143	0.070	0.102	-0.025
	NW	2.772	1.706	0.700	1.154	0.148	0.070	0.090	-0.027
	N	2.597	1.644	0.700	1.251	0.157	0.070	0.104	-0.057
	NE	2.654	1.627	0.700	1.219	0.160	0.070	0.109	-0.063
	E	2.695	1.601	0.700	1.124	0.145	0.070	0.094	-0.017
	SE	2.799	1.676	0.700	1.219	0.142	0.070	0.107	-0.060
	S	2.870	1.674	0.700	1.151	0.173	0.070	0.120	-0.052
	SW	2.854	1.700	0.700	1.220	0.146	0.070	0.106	-0.096
	W	2.696	1.634	0.700	1.241	0.109	0.070	0.082	-0.011

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 77	Omni DNV	3.040	1.830	0.700	1.213	0.152	0.070	0.084	0.000
	NW	2.976	1.748	0.700	1.141	0.149	0.070	0.092	-0.002
	N	3.128	1.778	0.700	0.942	0.318	0.070	0.103	-0.023
	NE	2.854	1.535	0.700	1.273	0.140	0.070	0.104	-0.012
	E	2.960	1.820	0.700	1.154	0.149	0.070	0.113	-0.023
	SE	2.982	1.792	0.700	1.146	0.180	0.070	0.104	-0.009
	S	2.725	1.724	0.700	1.212	0.169	0.070	0.125	-0.191
	SW	2.952	1.781	0.700	1.263	0.135	0.070	0.086	-0.028
	W	3.029	1.621	0.700	1.220	0.156	0.070	0.102	-0.069
Area 78	Omni DNV	2.600	1.700	0.700	1.244	0.073	0.070	0.106	-0.006
	NW	2.303	1.652	0.700	1.248	0.121	0.070	0.135	-0.129
	N	2.308	1.696	0.700	1.268	0.122	0.070	0.126	-0.070
	NE	2.098	1.338	0.700	1.214	0.112	0.070	0.127	-0.107
	E	2.486	1.637	0.700	1.218	0.119	0.070	0.113	-0.117
	SE	2.540	1.464	0.700	1.123	0.065	0.070	0.100	-0.025
	S	2.681	1.616	0.700	1.225	0.082	0.070	0.121	-0.087
	SW	2.404	1.628	0.700	1.199	0.099	0.070	0.103	-0.017
	W	2.465	1.827	0.700	1.276	0.096	0.070	0.110	-0.016
Area 79	Omni DNV	2.180	1.530	0.700	1.069	0.131	0.070	0.129	-0.017
	NW	1.966	1.501	0.700	1.045	0.108	0.070	0.127	-0.020
	N	1.974	1.548	0.700	1.166	0.145	0.070	0.120	-0.072
	NE	2.174	1.436	0.700	0.979	0.274	0.070	0.136	-0.109
	E	1.905	1.446	0.700	1.083	0.157	0.070	0.128	-0.059
	SE	2.269	1.486	0.700	0.990	0.160	0.070	0.103	-0.011
	S	2.153	1.448	0.700	1.059	0.175	0.070	0.109	-0.038
	SW	1.974	1.409	0.700	1.074	0.122	0.070	0.110	-0.023
	W	2.099	1.550	0.700	0.948	0.128	0.070	0.124	-0.011
Area 80	Omni DNV	2.540	1.700	0.700	1.201	0.131	0.070	0.102	-0.010
	NW	2.496	1.565	0.700	1.130	0.144	0.070	0.109	-0.029
	N	2.422	1.696	0.700	1.215	0.135	0.070	0.112	-0.019
	NE	2.191	1.450	0.700	1.212	0.127	0.070	0.106	-0.020
	E	2.489	1.660	0.700	1.153	0.151	0.070	0.108	-0.021
	SE	2.531	1.608	0.700	1.138	0.142	0.070	0.104	-0.014
	S	2.375	1.564	0.700	1.160	0.150	0.070	0.091	-0.020
	SW	2.491	1.641	0.700	1.147	0.156	0.070	0.099	-0.017
	W	2.550	1.563	0.700	1.157	0.161	0.070	0.108	-0.011

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 81	Omni DNV	2.540	1.700	0.700	1.201	0.131	0.070	0.102	-0.010
	NW	2.496	1.652	0.700	1.197	0.126	0.070	0.096	-0.019
	N	2.398	1.663	0.700	1.152	0.250	0.070	0.113	-0.019
	NE	2.212	1.504	0.700	1.151	0.149	0.070	0.116	-0.020
	E	2.489	1.596	0.700	1.053	0.202	0.070	0.095	-0.006
	SE	2.591	1.683	0.700	1.217	0.140	0.070	0.093	-0.038
	S	2.317	1.564	0.700	1.156	0.180	0.070	0.118	-0.099
	SW	2.491	1.641	0.700	1.130	0.188	0.070	0.110	-0.075
	W	2.550	1.727	0.700	1.138	0.167	0.070	0.110	-0.063
Area 82	Omni DNV	2.840	1.940	0.700	1.209	0.246	0.070	0.091	0.000
	NW	2.482	1.815	0.700	1.169	0.262	0.070	0.100	-0.011
	N	2.682	1.740	0.700	1.220	0.248	0.070	0.097	-0.049
	NE	2.750	1.913	0.700	1.156	0.295	0.070	0.104	-0.014
	E	2.940	1.914	0.700	1.157	0.280	0.070	0.102	-0.031
	SE	2.793	1.931	0.700	1.198	0.258	0.070	0.098	-0.016
	S	2.497	1.815	0.700	1.180	0.269	0.070	0.098	-0.016
	SW	2.850	1.881	0.700	1.105	0.272	0.070	0.093	-0.013
	W	2.673	1.834	0.700	1.181	0.249	0.070	0.088	-0.017
Area 83	Omni DNV	2.600	1.830	0.700	1.214	0.132	0.070	0.108	-0.008
	NW	2.520	1.748	0.700	1.110	0.165	0.070	0.103	-0.023
	N	2.313	1.778	0.700	1.167	0.137	0.070	0.103	-0.032
	NE	2.098	1.724	0.700	1.015	0.101	0.070	0.116	-0.005
	E	2.627	1.756	0.700	1.131	0.109	0.070	0.126	-0.012
	SE	2.226	1.734	0.700	1.147	0.148	0.070	0.127	-0.013
	S	2.684	1.824	0.700	1.213	0.148	0.070	0.108	-0.018
	SW	2.330	1.860	0.700	1.120	0.161	0.070	0.101	-0.019
	W	2.478	2.025	0.700	1.134	0.162	0.070	0.102	-0.001
Area 84	Omni DNV	2.920	2.100	0.700	1.190	0.170	0.070	0.102	-0.097
	NW	2.658	1.890	0.700	1.055	0.218	0.070	0.112	-0.158
	N	2.791	1.860	0.700	1.070	0.218	0.070	0.105	-0.157
	NE	2.567	1.965	0.700	1.034	0.214	0.070	0.115	-0.152
	E	2.785	2.022	0.700	1.198	0.185	0.070	0.112	-0.164
	SE	2.898	1.993	0.700	1.198	0.172	0.070	0.105	-0.104
	S	2.909	2.196	0.700	1.216	0.187	0.070	0.090	-0.091
	SW	2.768	2.138	0.700	1.071	0.193	0.070	0.093	-0.039
	W	2.683	2.438	0.700	1.128	0.189	0.070	0.113	-0.098

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 85	Omni DNV	3.320	1.940	0.700	1.226	0.145	0.070	0.095	-0.051
	NW	3.110	1.815	0.700	1.164	0.154	0.070	0.109	-0.091
	N	2.994	1.825	0.700	1.154	0.177	0.070	0.155	-0.139
	NE	2.968	1.822	0.700	1.218	0.172	0.070	0.115	-0.091
	E	3.085	1.856	0.700	1.199	0.162	0.070	0.134	-0.133
	SE	3.244	1.920	0.700	1.245	0.138	0.070	0.112	-0.060
	S	3.300	1.815	0.700	1.202	0.134	0.070	0.113	-0.043
	SW	3.199	1.962	0.700	1.197	0.138	0.070	0.101	-0.077
	W	3.180	1.934	0.700	1.174	0.181	0.070	0.100	-0.090
Area 86	Omni DNV	2.910	1.540	0.700	1.261	0.111	0.070	0.087	-0.003
	NW	2.781	1.482	0.700	1.260	0.124	0.070	0.096	-0.103
	N	2.874	1.531	0.700	1.149	0.181	0.070	0.110	-0.098
	NE	2.725	1.527	0.700	1.234	0.139	0.070	0.093	-0.020
	E	2.794	1.491	0.700	1.250	0.120	0.070	0.091	-0.035
	SE	2.643	1.454	0.700	1.247	0.125	0.070	0.081	-0.009
	S	2.822	1.482	0.700	1.123	0.182	0.070	0.090	-0.025
	SW	2.935	1.492	0.700	1.261	0.125	0.070	0.103	-0.055
	W	2.894	1.482	0.700	1.198	0.138	0.070	0.089	-0.015
Area 87	Omni	2.430	1.400	0.700	1.203	0.129	0.070	0.101	-0.007
	NW	2.399	1.478	0.700	1.192	0.126	0.070	0.107	-0.005
	N	2.340	1.403	0.700	1.220	0.139	0.070	0.126	-0.032
	NE	2.381	1.341	0.700	1.209	0.133	0.070	0.092	-0.025
	E	2.346	1.421	0.700	1.126	0.156	0.070	0.111	-0.024
	SE	2.153	1.319	0.700	1.150	0.125	0.070	0.104	-0.044
	S	2.520	1.466	0.700	1.185	0.144	0.070	0.103	-0.043
	SW	2.470	1.366	0.700	1.140	0.141	0.070	0.114	-0.006
	W	2.564	1.231	0.700	1.205	0.124	0.070	0.114	-0.020
Area 88	Omni	3.350	1.750	0.700	1.248	0.128	0.070	0.084	-0.019
	NW	3.286	1.740	0.700	1.114	0.167	0.070	0.105	-0.017
	N	3.264	1.802	0.700	1.167	0.162	0.070	0.108	-0.097
	NE	2.971	1.653	0.700	1.230	0.149	0.070	0.105	-0.016
	E	3.393	1.683	0.700	1.220	0.136	0.070	0.083	-0.004
	SE	3.099	1.657	0.700	1.245	0.135	0.070	0.094	-0.061
	S	3.279	1.753	0.700	1.238	0.133	0.070	0.103	-0.004
	SW	3.385	1.814	0.700	1.245	0.127	0.070	0.106	-0.043
	W	3.348	1.784	0.700	1.241	0.136	0.070	0.101	-0.065

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 89	Omni DNV	3.020	1.450	0.700	1.249	0.124	0.070	0.094	-0.044
	NW	2.740	1.419	0.700	1.199	0.158	0.070	0.113	-0.077
	N	3.265	1.596	0.700	1.246	0.133	0.070	0.101	-0.048
	NE	2.644	1.585	0.700	1.198	0.130	0.070	0.101	-0.063
	E	3.017	1.409	0.700	1.167	0.127	0.070	0.113	-0.070
	SE	2.586	1.658	0.700	1.210	0.129	0.070	0.097	-0.011
	S	3.161	1.407	0.700	1.209	0.136	0.070	0.099	-0.009
	SW	3.460	1.421	0.700	1.218	0.120	0.070	0.102	-0.005
	W	3.036	1.444	0.700	1.197	0.139	0.070	0.092	-0.019
Area 90	Omni DNV	3.350	1.590	0.700	1.266	0.116	0.070	0.077	-0.005
	NW	3.148	1.532	0.700	1.149	0.175	0.070	0.104	-0.051
	N	2.809	1.728	0.700	1.210	0.128	0.070	0.127	-0.098
	NE	2.976	1.510	0.700	1.090	0.282	0.070	0.103	-0.071
	E	3.323	1.676	0.700	1.042	0.233	0.070	0.073	-0.007
	SE	3.155	1.649	0.700	1.296	0.127	0.070	0.112	-0.057
	S	3.378	1.564	0.700	1.196	0.158	0.070	0.087	-0.035
	SW	3.856	1.575	0.700	1.231	0.124	0.070	0.075	-0.024
	W	3.395	1.636	0.700	1.249	0.122	0.070	0.103	-0.041
Area 91	Omni DNV	3.540	1.680	0.700	1.281	0.110	0.070	0.083	-0.040
	NW	3.439	1.651	0.700	1.300	0.103	0.070	0.080	-0.037
	N	3.204	1.628	0.700	1.260	0.126	0.070	0.087	-0.033
	NE	3.299	1.728	0.700	1.144	0.143	0.070	0.083	-0.014
	E	3.499	1.731	0.700	1.193	0.138	0.070	0.080	-0.041
	SE	3.299	1.717	0.700	1.280	0.121	0.070	0.091	-0.012
	S	3.295	1.599	0.700	1.262	0.123	0.070	0.078	-0.042
	SW	3.872	1.705	0.700	1.234	0.138	0.070	0.081	-0.019
	W	3.692	1.805	0.700	1.292	0.128	0.070	0.085	-0.017
Area 92	Omni DNV	3.420	1.710	0.700	1.283	0.105	0.070	0.083	-0.023
	NW	3.273	1.618	0.700	1.161	0.158	0.070	0.083	-0.014
	N	2.992	1.704	0.700	1.239	0.113	0.070	0.093	-0.019
	NE	2.762	1.694	0.700	1.149	0.143	0.070	0.099	-0.013
	E	3.388	1.668	0.700	1.163	0.149	0.070	0.082	-0.035
	SE	2.928	1.797	0.700	1.270	0.127	0.070	0.079	-0.009
	S	3.533	1.670	0.700	1.237	0.113	0.070	0.076	-0.005
	SW	3.702	1.967	0.700	1.251	0.127	0.070	0.090	-0.049
	W	3.708	1.888	0.700	1.269	0.123	0.070	0.072	-0.008

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 93	Omni DNV	2.660	1.450	0.700	1.233	0.119	0.070	0.101	-0.020
	NW	2.411	1.412	0.700	1.165	0.161	0.070	0.102	-0.010
	N	2.541	1.357	0.700	1.264	0.117	0.070	0.124	-0.090
	NE	2.472	1.385	0.700	1.141	0.180	0.070	0.096	-0.008
	E	2.499	1.381	0.700	1.137	0.177	0.070	0.097	-0.015
	SE	2.582	1.459	0.700	1.168	0.139	0.070	0.110	-0.038
	S	2.664	1.407	0.700	1.237	0.143	0.070	0.097	-0.019
	SW	2.582	1.377	0.700	1.110	0.172	0.070	0.094	-0.020
	W	2.664	1.422	0.700	1.247	0.124	0.070	0.098	-0.018
Area 94	Omni DNV	3.890	1.690	0.700	1.296	0.112	0.070	0.063	0.000
	NW	3.828	1.644	0.700	1.120	0.217	0.070	0.073	-0.019
	N	3.329	1.689	0.700	1.124	0.215	0.070	0.069	-0.009
	NE	3.424	1.599	0.700	1.213	0.101	0.070	0.070	-0.009
	E	3.824	1.628	0.700	1.300	0.116	0.070	0.081	-0.015
	SE	3.389	1.599	0.700	1.125	0.160	0.070	0.068	-0.012
	S	3.457	1.607	0.700	1.231	0.193	0.070	0.071	-0.009
	SW	4.072	1.686	0.700	1.298	0.112	0.070	0.062	-0.005
	W	4.164	1.811	0.700	1.297	0.126	0.070	0.081	-0.018
Area 95	Omni DNV	3.710	1.930	0.700	1.256	0.131	0.070	0.073	-0.002
	NW	3.601	1.809	0.700	1.144	0.146	0.070	0.094	-0.018
	N	3.362	1.822	0.700	1.283	0.132	0.070	0.094	-0.019
	NE	2.997	1.813	0.700	1.267	0.127	0.070	0.075	-0.007
	E	3.657	1.847	0.700	1.251	0.122	0.070	0.079	-0.012
	SE	3.212	1.830	0.700	1.193	0.139	0.070	0.088	-0.002
	S	3.523	1.807	0.700	1.152	0.161	0.070	0.088	-0.011
	SW	3.834	1.951	0.700	1.296	0.125	0.070	0.081	-0.017
	W	3.928	2.178	0.700	1.211	0.142	0.070	0.076	-0.002
Area 96	Omni DNV	2.650	1.470	0.700	1.200	0.110	0.070	0.099	-0.010
	NW	2.553	1.440	0.700	1.271	0.107	0.070	0.114	-0.020
	N	2.562	1.448	0.700	1.200	0.126	0.070	0.128	-0.050
	NE	2.491	1.384	0.700	1.127	0.109	0.070	0.114	-0.026
	E	2.673	1.427	0.700	1.213	0.123	0.070	0.103	-0.010
	SE	2.372	1.387	0.700	1.215	0.122	0.070	0.092	-0.025
	S	2.643	1.424	0.700	1.068	0.163	0.070	0.090	-0.011
	SW	2.437	1.394	0.700	1.048	0.167	0.070	0.080	-0.023
	W	2.630	1.431	0.700	1.076	0.178	0.070	0.093	-0.004

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 97	Omni DNV	3.610	1.630	0.700	1.279	0.114	0.070	0.073	-0.003
	NW	3.475	1.593	0.700	1.318	0.082	0.070	0.066	-0.028
	N	3.069	1.641	0.700	1.267	0.164	0.070	0.086	-0.003
	NE	3.292	1.655	0.700	1.059	0.193	0.070	0.098	-0.042
	E	3.564	1.573	0.700	1.068	0.125	0.070	0.091	-0.007
	SE	3.114	1.541	0.700	1.264	0.065	0.070	0.091	-0.010
	S	3.661	1.557	0.700	1.168	0.174	0.070	0.067	-0.017
	SW	3.703	1.619	0.700	1.240	0.122	0.070	0.083	-0.017
	W	3.766	1.768	0.700	1.267	0.130	0.070	0.077	-0.012
Area 98	Omni DNV	3.530	1.700	0.700	1.248	0.135	0.070	0.074	-0.003
	NW	3.375	1.652	0.700	1.250	0.185	0.070	0.064	-0.020
	N	3.299	1.696	0.700	1.146	0.135	0.070	0.091	-0.004
	NE	2.851	1.608	0.700	1.079	0.153	0.070	0.089	-0.038
	E	3.490	1.637	0.700	1.021	0.180	0.070	0.081	-0.005
	SE	3.036	1.608	0.700	1.174	0.192	0.070	0.081	-0.006
	S	3.475	1.616	0.700	1.317	0.063	0.070	0.093	-0.017
	SW	4.114	1.876	0.700	1.168	0.145	0.070	0.091	-0.023
	W	3.863	1.900	0.700	1.259	0.142	0.070	0.074	-0.004
Area 99	Omni DNV	4.070	1.770	0.700	1.305	0.106	0.070	0.061	-0.001
	NW	3.755	1.651	0.700	1.256	0.107	0.070	0.073	-0.025
	N	3.655	1.674	0.700	1.262	0.156	0.070	0.075	-0.015
	NE	3.882	1.670	0.700	1.165	0.120	0.070	0.100	-0.002
	E	3.991	1.701	0.700	1.205	0.162	0.070	0.081	-0.006
	SE	3.957	1.676	0.700	1.234	0.126	0.070	0.077	-0.002
	S	3.767	1.674	0.700	1.212	0.147	0.070	0.076	-0.014
	SW	4.115	1.790	0.700	1.308	0.104	0.070	0.091	-0.014
	W	4.134	1.802	0.700	1.322	0.104	0.070	0.071	-0.012
Area 100	Omni DNV	3.760	1.540	0.700	1.279	0.120	0.070	0.064	-0.001
	NW	3.664	1.510	0.700	1.240	0.110	0.070	0.104	-0.029
	N	3.651	1.558	0.700	1.187	0.130	0.070	0.082	-0.028
	NE	3.371	1.466	0.700	1.249	0.134	0.070	0.086	-0.026
	E	3.703	1.649	0.700	1.199	0.141	0.070	0.092	-0.014
	SE	3.261	1.454	0.700	1.159	0.129	0.070	0.082	-0.030
	S	3.489	1.482	0.700	1.245	0.108	0.070	0.065	-0.034
	SW	3.743	1.520	0.700	1.274	0.162	0.070	0.066	-0.007
	W	3.776	1.615	0.700	1.257	0.141	0.070	0.085	-0.021

Area	Direction	α	β	a_0	a_1	a_2	b_0	b_1	b_2
Area 101	Omni DNV	3.210	1.570	0.700	1.261	0.116	0.070	0.093	-0.005
	NW	3.281	1.637	0.700	1.151	0.169	0.070	0.087	-0.018
	N	2.982	1.522	0.700	1.266	0.129	0.070	0.088	-0.011
	NE	2.959	1.492	0.700	1.257	0.122	0.070	0.102	-0.046
	E	2.953	1.504	0.700	1.135	0.140	0.070	0.097	-0.072
	SE	2.930	1.683	0.700	1.200	0.125	0.070	0.088	-0.055
	S	3.247	1.656	0.700	1.289	0.113	0.070	0.131	-0.136
	SW	3.214	1.553	0.700	1.252	0.132	0.070	0.110	-0.014
	W	3.206	1.561	0.700	1.251	0.127	0.070	0.106	-0.013
Area 102	Omni DNV	3.080	1.600	0.700	1.243	0.130	0.070	0.083	-0.005
	NW	2.956	1.566	0.700	1.261	0.135	0.070	0.091	-0.020
	N	2.965	1.578	0.700	1.168	0.168	0.070	0.098	-0.014
	NE	2.964	1.655	0.700	1.248	0.124	0.070	0.085	-0.017
	E	2.970	1.610	0.700	1.176	0.157	0.070	0.085	-0.003
	SE	3.069	1.595	0.700	1.149	0.156	0.070	0.086	-0.007
	S	2.953	1.532	0.700	1.137	0.162	0.070	0.085	-0.003
	SW	3.139	1.547	0.700	1.187	0.167	0.070	0.084	-0.013
	W	3.191	1.639	0.700	1.294	0.129	0.070	0.087	-0.016
Area 103	Omni DNV	3.520	1.580	0.700	1.253	0.122	0.070	0.076	-0.006
	NW	3.362	1.548	0.700	1.175	0.117	0.070	0.091	-0.022
	N	3.399	1.697	0.700	1.078	0.143	0.070	0.093	-0.020
	NE	3.130	1.501	0.700	1.113	0.132	0.070	0.089	-0.001
	E	3.481	1.527	0.700	1.159	0.148	0.070	0.079	-0.001
	SE	3.026	1.493	0.700	1.283	0.123	0.070	0.079	-0.004
	S	3.278	1.516	0.700	1.253	0.135	0.070	0.064	-0.012
	SW	3.584	1.564	0.700	1.280	0.165	0.070	0.082	-0.001
	W	3.747	1.673	0.700	1.276	0.154	0.070	0.082	-0.026
Area 104	Omni DNV	2.970	1.570	0.700	1.267	0.108	0.070	0.085	-0.005
	NW	2.888	1.539	0.700	1.252	0.113	0.070	0.086	0.028
	N	2.764	1.487	0.700	1.165	0.134	0.070	0.092	-0.006
	NE	2.697	1.492	0.700	1.137	0.135	0.070	0.096	-0.057
	E	2.970	1.518	0.700	1.269	0.105	0.070	0.087	-0.039
	SE	2.858	1.483	0.700	1.157	0.121	0.070	0.095	-0.002
	S	2.792	1.507	0.700	1.186	0.160	0.070	0.098	-0.052
	SW	2.889	1.553	0.700	1.238	0.121	0.070	0.102	-0.007
	W	2.986	1.527	0.700	1.272	0.116	0.070	0.094	-0.003

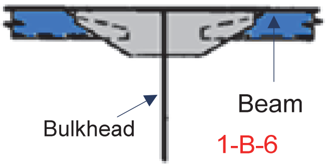
A.3: STRUCTURAL DETAILS

BEAM BRACKET DETAILS-FAMILY N°. 1

<u>FUNCTION-PROVIDES:</u> "END CONSTRAINT FOR FRAMING"

STRUCTURALLY CONTINUOUS – PHYSICAL INTERCOSTAL BEAMS

Plate Bracket without Bulkhead Stiffener



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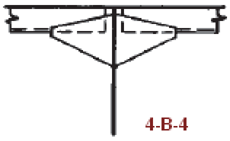

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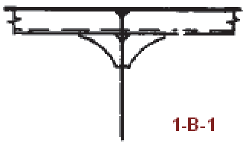

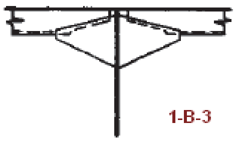

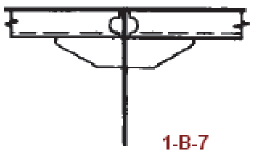

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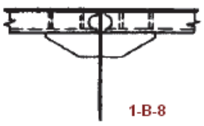

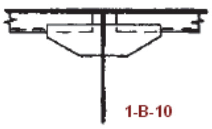

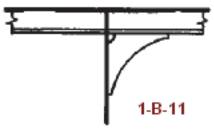

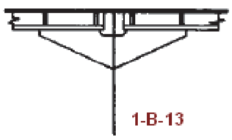

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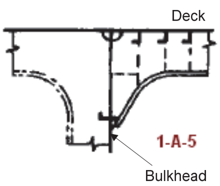
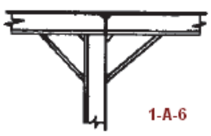
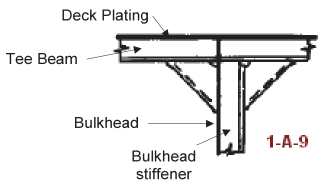
Built-Up Bracket in Way of Bulkhead Stiffener







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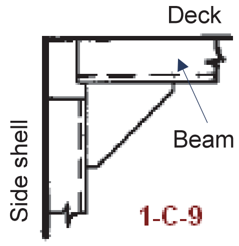
CORNER

Straight Corner Brackets

Plate



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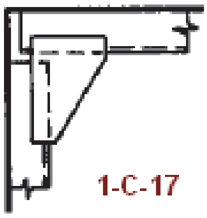
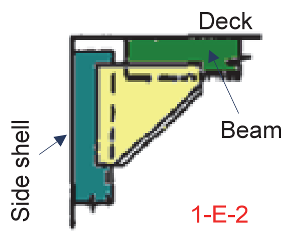


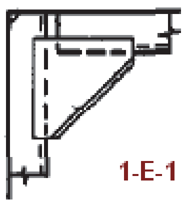
BULK CARRIER

Flanged

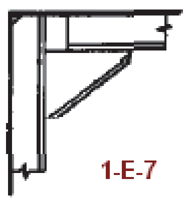


BULK CARRIER

TANKER



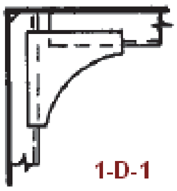
TANKER



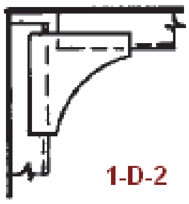
TANKER

Curved Corner Brackets

Plate

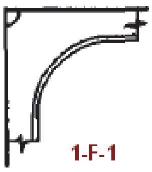


BULK CARRIER



BULK CARRIER

Built-Up



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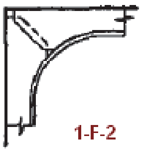

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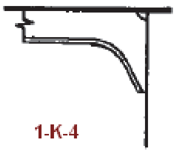

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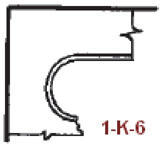
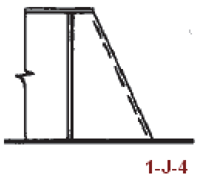


TANKER

END

Hatch Girder End Brackets



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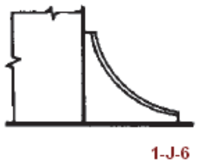

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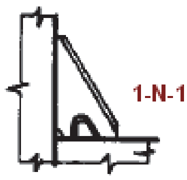
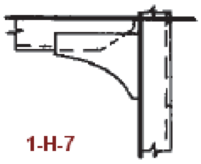


BULK CARRIER

Beam End Brackets

At "Soft" Plating



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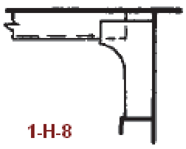

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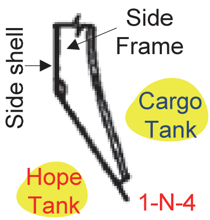
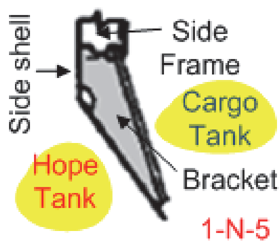
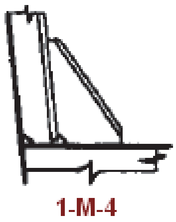


BULK CARRIER



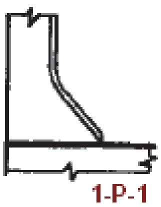
BULK CARRIER

Flanged at Rigid Structure



TANKER

Built-up at Rigid Structure



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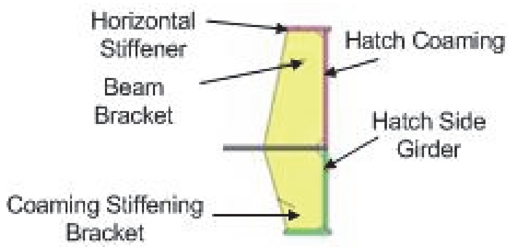
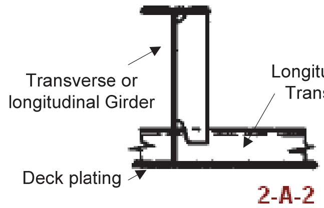


BULK CARRIER

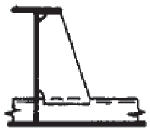
TRIPPING BRACKETS FAMILY N°2

<u>FUNCTION-PROVIDES:</u> "LATERAL SUPPORT"

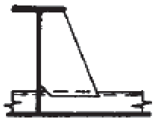


2-A-2

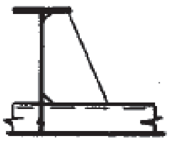
TANKER



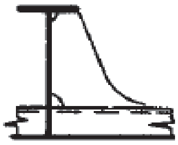
2-A-4



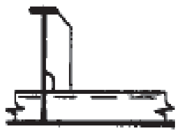
2-A-5



2-A-6

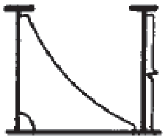


2-A-7



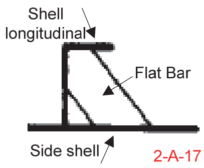
2-A-10

TANKER — TANKER — BULK CARRIER / TANKER — TANKER — TANKER



2-A-9

2-A-14



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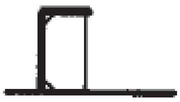
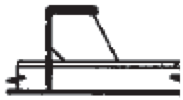
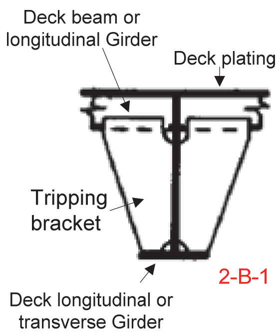


2-A-19



2-A-27

TANKER — TANKER — BULK CARRIER / TANKER — TANKER — TANKER

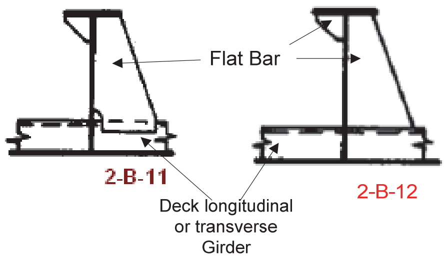


2-B-1

2-B-2

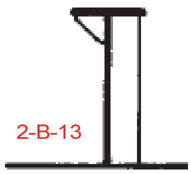
2-B-3

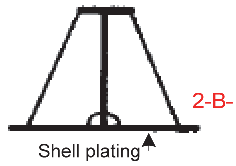
BULK CARRIER — TANKER — BULK CARRIER / TANKER



TANKER

BULK CARRIER
TANKER

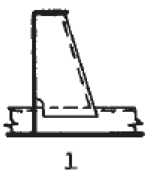


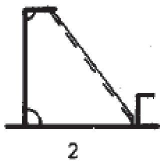


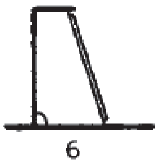
TANKER

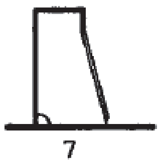
TANKER

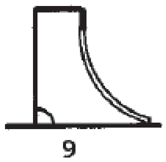
C











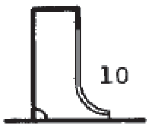
TANKER

TANKER

TANKER

BULK CARRIER

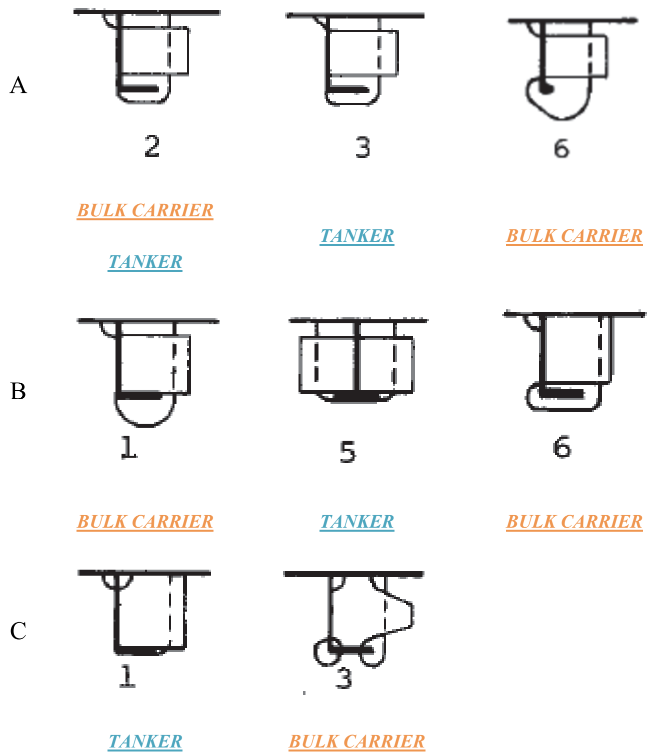
BULK CARRIER



BULK CARRIER

Non-TIGHT COLLARS DETAILS FAMILY N°3

FUNCTION-PROVIDES: "SHEAR CONNECTION FOR CONTINUOUS FRAMING"



TIGHT COLLARS DETAILS FAMILY N°4

<u>FUNCTION-PROVIDES:</u> "SAME AS #3 AND A TIGHT PENETRATED PLATE"

A

1

BULK CARRIER

5

TANKER

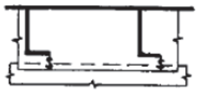
6

BULK CARRIER

7

BULK CARRIER

C



6

BULK CARRIER

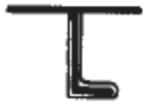
D

1

TANKER

2

TANKER



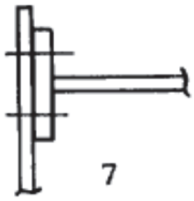
4

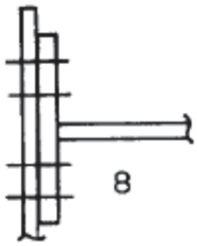
TANKER

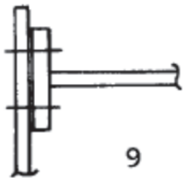
GUNWALE CONNECTIONS DETAILS FAMILY N°5

<u>FUNCTION-PROVIDES:</u> "CONNECTION OF STRENGTH DECK TO SIDE SHELL"

A







TANKER

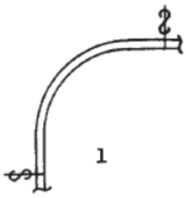
BULK CARRIER

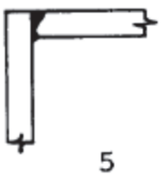
TANKER

BULK CARRIER

TANKER

B





BULK CARRIER

TANKER

TANKER

BULK CARRIER

TANKER

MISCELLANEOUS CUTOUTS DETAILS FAMILY N°7

FUNCTION-PROVIDES: "HOLES FOR ACCESS, DRAINAGE, EASE OF FABRICATION, CABLEWAYS, PIPES, AIR HOLES, ETC."

A


1
BULK CARRIER
TANKER


3
BULK CARRIER
TANKER


6
BULK CARRIER


7
BULK CARRIER
TANKER


8
BULK CARRIER
TANKER

B


1
TANKER


2
BULK CARRIER
TANKER


3
BULK CARRIER
TANKER

C

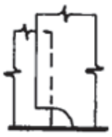

1
BULK CARRIER
TANKER

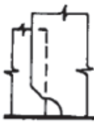

3
TANKER

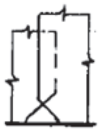

9
BULK CARRIER
TANKER

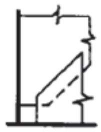

15
TANKER

D


1
TANKER


2
BULK CARRIER


4
BULK CARRIER


5
TANKER

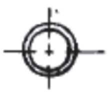
E


1
BULK CARRIER


2
BULK CARRIER
TANKER

F


1


2


3

BULK CARRIER	BULK CARRIER	BULK CARRIER
TANKER	TANKER	TANKER

G

1	2	3	5
BULK CARRIER	BULK CARRIER	BULK CARRIER	BULK CARRIER
TANKER	TANKER	TANKER	TANKER

H

1	3	4	5	6
BULK CARRIER			BULK CARRIER	
TANKER	TANKER	TANKER	TANKER	TANKER

7	8	9	10
		BULK CARRIER	BULK CARRIER
TANKER	TANKER	TANKER	TANKER

CLEARANCE CUTOUTS DETAILS FAMILY N°8

FUNCTION-PROVIDES: "FOR PASSING ONE MEMBER THROUGH ANOTHER AND A SHEAR CONNECTION"

B

1

3

BULK CARRIER *TANKER*

C

2

6

7

TANKER *BULK CARRIER* *BULK CARRIER*

D

2

5

6

7

8

TANKER *TANKER* *TANKER* *TANKER* *TANKER*

E

2

3

4

5

6

BULK CARRIER

TANKER

TANKER *BULK CARRIER* *TANKER* *TANKER*

11

. 12

TANKER *TANKER* *TANKER*

STRUCTURAL DECK CUTS DETAILS FAMILY N°9

<u>FUNCTION-PROVIDES:</u> "PASSAGE THROUGH DECKS FOR ACCESS, TANK CLEANING, PIPING, CABLES, ETC."

(A)

Not Reinforced

1 — BULK CARRIER, TANKER

3 — BULK CARRIER

6 — TANKER

7 — BULK CARRIER

8 — TANKER

9 — TANKER

(B)

Reinforced

1 — BULK CARRIER, TANKER

2 — TANKER

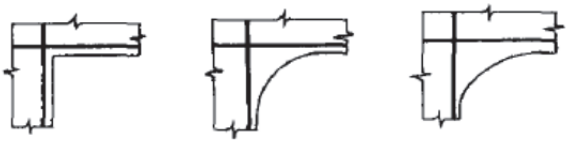
4 — BULK CARRIER

5 — BULK CARRIER, TANKER

6 — TANKER

(C)

Hatch Corners



1 — BULK CARRIER

4 — BULK CARRIER

6 — BULK CARRIER

STANCHION ENDS DETAILS FAMILY N°10

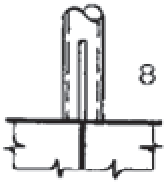
FUNCTION-PROVIDES: “LOAD PATH BETWEEN STANCHION AND DECK”

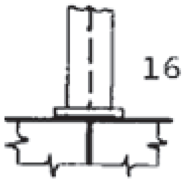
Top of Circular Stanchions

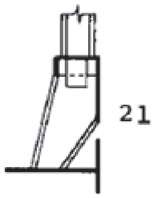
TANKER *TANKER*

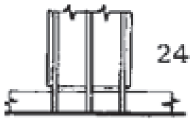
Bottom of Circular Stanchions

(B)

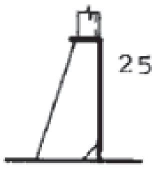








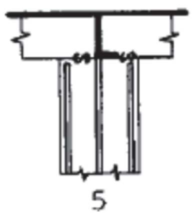
BULK CARRIER *TANKER* *TANKER* *TANKER* *BULK CARRIER*

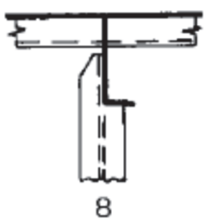


TANKER

Top of ‘H” Stanchions

(C)





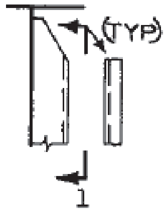
TANKER *TANKER* *BULK CARRIER* *TANKER*

STANCHION ENDS DETAILS FAMILY N°11

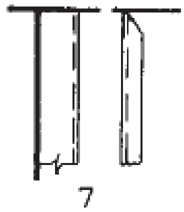
<u>FUNCTION-PROVIDES:</u> “DESIGNED END RESTRAINT LOAD CARRYING MEMBERS”

(A)

Full Connection



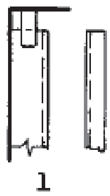
TANKER



BULK CARRIER
TANKER

(B)

Padded



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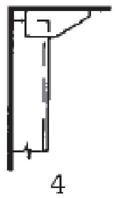

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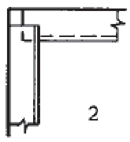
(D)

With End

Chocks



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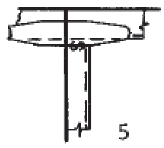


TANKER

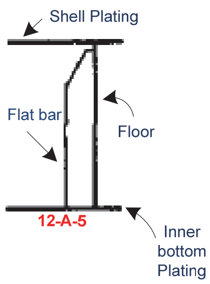
(E)

Sniped

TANKER

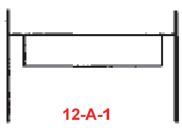
PANEL STIFFENERS DETAILS FAMILY N°12

FUNCTION-PROVIDES: "STABILITY TO PLATING"



TANKER

A



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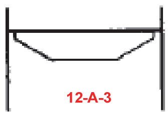
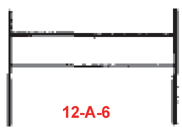


BULK CARRIER

TANKER



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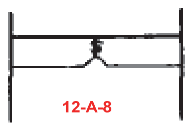

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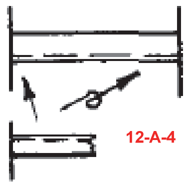
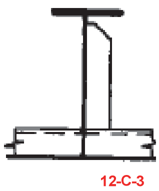


BULK CARRIER

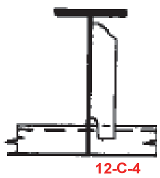
TANKER

C



BULK CARRIER

TANKER



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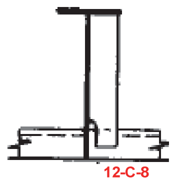
BULK CARRIER



BULK CARRIER

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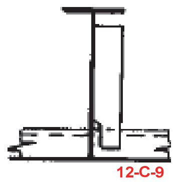

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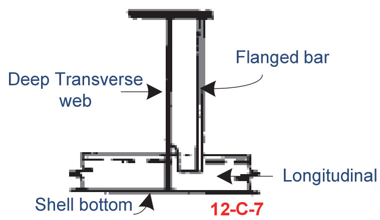

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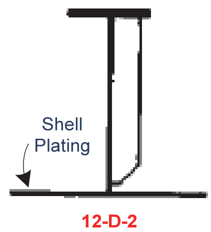

TANKER

The following group of details is an extension for the <u>Flat Bars on Girder Webs in Way of Longitudinal</u>, where brackets have been added.

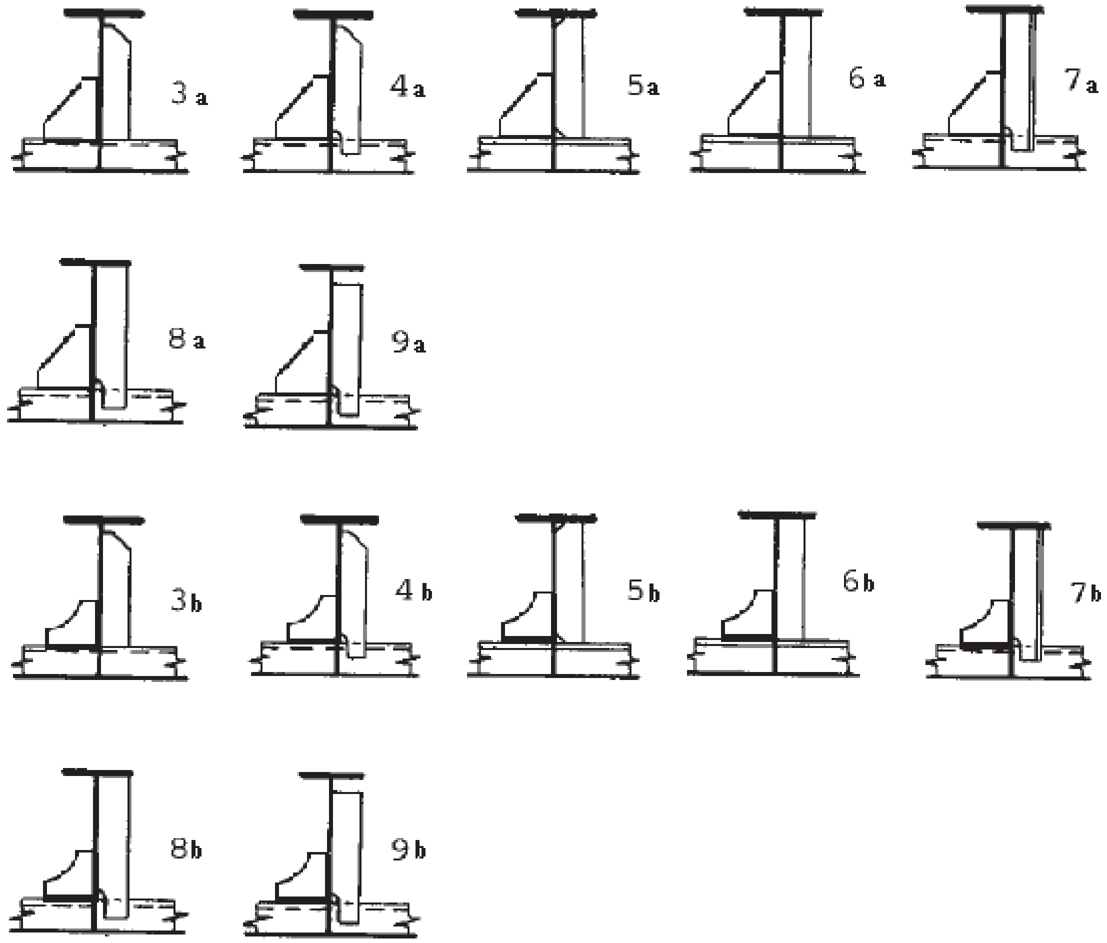

Table A.3-1 Detail Family 2: Tripping Brackets

Detail Family number	Ship Type	Location on Ship		
2-A-2	Tanker	Fwd	Mid	Aft
2-A-4	Tanker		Mid	
2-A-5	Tanker		Mid	
2-A-6	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
2-A-7	Tanker		Mid	
2-A-9	Bulk Carrier		Mid	
2-A-10	Tanker	Fwd	Mid	Aft
2-A-14	Tanker	Fwd	Mid	Aft
2-A-15	Tanker	Fwd		Aft
2-A-17	Bulk Carrier		Mid	
	Tanker	Fwd	Mid	
2-A-19	Tanker	Fwd	Mid	Aft
2-A-27	Tanker		Mid	
2-B-1	Bulk Carrier	Fwd	Mid	Aft
2-B-2	Tanker	Fwd	Mid	Aft
2-B-3	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
2-B-11	Tanker	Fwd	Mid	Aft
2-B-12	Bulk Carrier		Mid	Aft
	Tanker		Mid	Aft
2-B-13	Tanker		Mid	
2-B-15	Tanker	Fwd	Mid	Aft
2-C-1	Tanker		Mid	
2-C-2	Tanker		Mid	
2-C-6	Tanker		Mid	
2-C-7	Bulk Carrier		Mid	
2-C-9	Bulk Carrier		Mid	
2-C-10	Bulk Carrier		Mid	

Table A.3-2 Detail Family 3: Non-Tight Collars

Detail Family number	Ship Type	Location on Ship		
3-A-2	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
3-A-3	Tanker	Fwd	Mid	
3-B-1	Bulk Carrier	Fwd	Mid	Aft
3-B-5	Tanker	Fwd	Mid	Aft
3-B-6	Bulk Carrier	Fwd	Mid	Aft
3-C-1	Tanker		Mid	
3-C-3	Bulk Carrier	Fwd	Mid	Aft

Table A.3-3 Detail Family 4: Tight Collars

Detail Family number	Ship Type	Location on Ship		
4-A-1	Bulk Carrier	Fwd	Mid	Aft
4-A-5	Tanker	Fwd	Mid	Aft
4-A-6	Bulk Carrier	Fwd	Mid	Aft
4-A-7	Bulk Carrier		Mid	
4-C-6	Bulk Carrier	Fwd	Mid	Aft
4-D-1	Tanker	Fwd	Mid	Aft
4-D-2	Tanker	Fwd	Mid	Aft
4-D-4	Tanker		Mid	Aft

Table A.3-4 Detail Family 5: Gunwale Connections

Detail Family number	Ship Type	Location on Ship		
5-A-1	Tanker		Mid	
5-A-7	Bulk Carrier		Mid	
	Tanker		Mid	
5-A-8	Bulk Carrier		Mid	
5-A-9	Tanker		Mid	
5-B-1	Bulk Carrier		Mid	
	Tanker		Mid	
5-B-5	Tanker		Mid	
5-B-8	Bulk Carrier		Mid	
	Tanker		Mid	

Table A.3-5 Detail Family 7: Miscellaneous Cut-outs

Detail Family number	Ship Type	Location on Ship		
7-A-1	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-A-3	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-A-6	Bulk Carrier	Fwd	Mid	Aft
7-A-8	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-B-1	Tanker	Fwd	Mid	Aft
7-B-2	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-B-3	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-C-1	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-C-3	Tanker	Fwd	Mid	Aft
7-C-9	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-C-15	Tanker	Fwd	Mid	Aft
7-D-1	Tanker	Fwd	Mid	Aft
7-D-2	Bulk Carrier	Fwd	Mid	Aft
7-D-4	Bulk Carrier	Fwd	Mid	Aft
7-D-5	Tanker	Fwd	Mid	Aft
7-E-1	Bulk Carrier	Fwd	Mid	Aft
7-E-2	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft

Detail Family number	Ship Type	Location on Ship		
7-F-1	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-F-2	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-F-3	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-G-1	Bulk Carrier		Mid	Aft
	Tanker		Mid	Aft
7-G-2	Bulk Carrier		Mid	Aft
	Tanker		Mid	Aft
7-G-3	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-G-5	Bulk Carrier	Fwd	Mid	Aft
7-H-1	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-H-3	Tanker	Fwd	Mid	Aft
7-H-4	Tanker		Mid	
7-H-5	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-H-6	Tanker	Fwd	Mid	Aft
7-H-7	Tanker		Mid	Aft
7-H-8	Tanker	Fwd	Mid	Aft
7-H-9	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
7-H-10	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft

Table A.3-6 Detail Family 8: Clearance Cutouts

Detail Family number	Ship Type	Location on Ship		
8-B-1	Bulk Carrier	Fwd	Mid	
8-B-3	Tanker		Mid	Aft
8-C-2	Tanker	Fwd	Mid	Aft
8-C-6	Bulk Carrier	Fwd	Mid	Aft
8-C-7	Bulk Carrier	Fwd	Mid	Aft
8-D-2	Tanker	Fwd	Mid	Aft
8-D-5	Tanker	Fwd	Mid	Aft
8-D-6	Tanker	Fwd	Mid	Aft
8-D-7	Tanker	Fwd	Mid	Aft
8-D-8	Tanker		Mid	
8-E-2	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
8-E-3	Tanker	Fwd	Mid	Aft
8-E-4	Bulk Carrier		Mid	
8-E-5	Tanker	Fwd	Mid	Aft
8-E-6	Tanker	Fwd	Mid	Aft
8-E-10	Tanker		Mid	
8-E-11	Tanker		Mid	
8-E-12	Tanker		Mid	

Table A.3-7 Detail Family 9: Structural Deck Cuts

Detail Family number	Ship Type	Location on Ship		
9-A-1	Bulk Carrier		Mid	
	Tanker		Mid	Aft
9-A-3	Bulk Carrier	Fwd	Mid	Aft
9-A-6	Tanker		Mid	
9-A-7	Bulk Carrier	Fwd	Mid	
9-A-8	Tanker		Mid	
9-A-9	Tanker		Mid	
9-B-1	Bulk Carrier	Fwd	Mid	Aft
9-B-2	Tanker	Fwd	Mid	Aft
9-B-4	Bulk Carrier		Mid	
9-B-5	Bulk Carrier		Mid	Aft
	Tanker		Mid	
9-B-6	Tanker		Mid	
9-C-1	Bulk Carrier		Mid	
9-C-4	Bulk Carrier		Mid	
9-C-6	Bulk Carrier		Mid	

Table A.3-8 Detail Family10: Stanchion Ends

Detail Family number	Ship Type	Location on Ship		
10-A-2	Tanker	Fwd	Mid	Aft
10-A-14	Tanker		Mid	
10-B-2	Tanker	Fwd	Mid	Aft
10-B-8	Tanker		Mid	Aft
10-B-16	Tanker		Mid	Aft
10-B-21	Tanker		Mid	
10-B-24	Bulk Carrier		Mid	
10-B-25	Tanker		Mid	
10-C-2	Tanker		Mid	
10-C-3	Tanker		Mid	
10-C-5	Bulk Carrier		Mid	
10-C-8	Tanker		Mid	

Table A.3-9 Detail Family 11: Stiffener Ends

Detail Family number	Ship Type	Location on Ship		
11-A-1	Tanker	Fwd	Mid	Aft
11-A-7	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
11-B-1	Tanker	Fwd	Mid	Aft
11-B-4	Tanker		Mid	
11-D-2	Tanker		Mid	Aft
11-D-5	Tanker		Mid	Aft
11-E-2	Tanker	Fwd	Mid	

Table A.3-10 Detail Family 12: Panel Stiffeners

Detail Family number	Ship Type	Location on Ship		
12-A-1	Tanker	Fwd	Mid	Aft
12-A-3	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
12-A-5	Tanker	Fwd	Mid	Aft
12-A-6	Bulk Carrier	Fwd	Mid	Aft
12-A-8	Tanker	Fwd	Mid	Aft
	Bulk Carrier		Mid	Aft
12-B-4	Tanker	Fwd	Mid	Aft
	Bulk Carrier	Fwd	Mid	Aft
12-C-3	Bulk Carrier	Fwd	Mid	Aft
	Tanker	Fwd	Mid	Aft
12-C-4	Tanker	Fwd	Mid	Aft
12-C-5	Tanker	Fwd	Mid	Aft
12-C-6	Bulk Carrier	Fwd	Mid	Aft
12-C-7	Tanker		Mid	Aft
12-C-8	Tanker	Fwd	Mid	Aft
12-C-9	Tanker	Fwd	Mid	Aft
12-D-2	Tanker	Fwd	Mid	Aft

A.4: STATISTICAL DEFINITIONSAND CORRECTION OF MODEL PREDICTIONS

A.4.1 INTRODUCTION

This appendix covers the statistical notions and methods used in this thesis. The purpose is to give a brief self-contained presentation of some statistical concepts relevant to the present work.

First a reminder of basic statistical notions is presented. Then uncertainties and methods of models calibration are discussed.

Finally a section about data from expert judgment closes this appendix.

A.4.2 BASIC STATISTICAL NOTIONS

This section gives a reminder of basic statistical notions used in the computational work of the present thesis. The notes have been adapted from different publications such as (Rice 1995; Bury 1999; Soong 2004).

A.4.2.1 Measure of central value

One of the most important objectives of statistical analysis is to get one single value that describes the characteristic of the entire data. Such a value is called central value or an ‘average’. There are different types of average: arithmetic mean (simple and weighted), geometric mean, harmonic mean, mode and median (Croxton 1959).

The ***arithmetic mean*** is the most popular and widely used and is a mathematical representation of the typical value of a series of numbers, computed as the sum of all the numbers in the series divided by the size of the series. Arithmetic mean is commonly referred to as "average" or simply as "mean" (Ouellet 1985).

It is important to distinguish between the population mean and the sample mean (Geller 1979).

The population mean μ is:

$$\mu = \frac{x_1 + x_2 + x_3 + \cdots + x_N}{N} \qquad \text{Eq. A.4-1}$$

Using a more compact notation:

$$\mu = \frac{1}{N}\sum x_i \qquad \text{Eq. A.4-2}$$

where $\sum x_i$ represents the sum of all values in the population and *N* represents the population size. The s***ample mean*** $\bar{X}$ is given by**:**

$$\bar{X} = \frac{x_1 + x_2 + x_3 + \cdots + x_n}{n} \qquad \text{Eq. A.4-3}$$

In more succinct notation,

$$\bar{X} = \frac{1}{n}\sum x_i \qquad \text{Eq. A.4-4}$$

The formulas for population mean μ and sample mean $\bar{X}$ are [almost] identical. Calculating a population mean or sample mean is based on whether data represent the entire population or a sample. In practice, it is assumed that the estimation is based on a sample and not the entire population (Lohr 2010).

The mean represents the gravitational centre of a distribution. This is where the distribution would balance. It is a reflection of:

1. An individual value drawn at random from the sample.
2. An individual value drawn at random from the population.
3. The population mean.

There is a generalisation of the sample mean that turns out to be important for some purposes called a *weighted mean (Wilcox 2010)*. The weighted mean is computed when the relative importance of the different items is not the same. The weighted mean M_ω of a set of N values ($x_1, x_2, ..., x_N$) is computed according to the following formula:

$$M_\omega\left(x_1, x_2, ..., x_N\right) = \frac{\sum_{i=1}^{N} \omega_i \times x_i}{\sum_{j=1}^{N} \omega_j} \quad ; \quad \omega_i \geq 0 \qquad \text{Eq. A.4-5}$$

where $\omega_1, \omega_2, ..., \omega_N$ are non-negative coefficients, called "weights", that are ascribed to the corresponding values $x_1, x_2, ..., x_N$.

A.4.2.2 Measures of Spread

Various measures of spread or dispersion of a given sample are defined hereafter. One simple way to measure spread is to provide the smallest (minimum) and largest (maximum) values in the data set. The difference of these values is the ***sample range*** and is given by:

$$\boldsymbol{R}ange = \boldsymbol{M}aximum - \boldsymbol{M}inimum \qquad \text{Eq. A.4-6}$$

Inter-Quartile Range (IQR) is another measure of dispersion. The IQR is the value obtained when the lower quartile is subtracted from the upper quartile:

$$\boldsymbol{IQR} = \boldsymbol{Q_3} - \boldsymbol{Q_1} \qquad \text{Eq. A.4-7}$$

In some cases, the Semi Inter-Quartile Range (SIQR) is used where

$$SIQR = \frac{1}{2}(Q3 - Q1) \qquad \text{Eq. A.4-8}$$

They are based on central 50% of the data and thus not influenced by the extreme values and are often used when date contains extreme values, or has open ended classes or is not symmetrical. Mostly, The IQR is used in conjunction with a box plot, especially when the set (sample) of data contain one or more extreme values, known as outliers (Attwood et al. 2000).

Another measure of spread and the most common one is the ***standard deviation*** (Falk et al. 2002).

A deviation is defined as the difference between a value and the mean: $(x_i - \overline{x})$. Each deviation is squared $(x_i - \bar{x})^2$ (the negative or positive sign associated with the deviation is unimportant) and the sum of squares (SS) is then computed as follows:

$$SS = \sum (x_i - \bar{x})^2 \qquad \text{Eq. A.4-9}$$

The ***population variance*** is the average sum of squares:

$$\sigma^2 = \frac{SS}{N} \qquad \text{Eq. A.4-10}$$

The ***sample variance*** is given by:

$$s^2 = \frac{SS}{n-1} \qquad \text{Eq. A.4-11}$$

The sample variance divides the sum of squares by (n - 1) instead of n. When n is large, (n – 1) ≈ n, so the numerical results from the two formulas will be similar. However, when n is small, the sample variance formula will give a bigger result than the population variance formula. This is necessary to derive an unbiased estimate of the population variance. The number (n – 1) is called the ***degree of freedom*** of the variance. One degree of freedom is lost when using $\bar{x}$ to estimate μ.

Standard deviation is a measure of the dispersion of a set of data from its mean. The more spread apart the data, the higher the deviation. Standard deviation is calculated as the square root of variance. The ***sample standard deviation*** is the square root of the variance:

$$s = \sqrt{s^2} \qquad \text{Eq. A.4-12}$$

Or:

$$s = \sqrt{\frac{1}{n-1}\sum(x_i - \bar{x})^2} \qquad \text{Eq. A.4-13}$$

The ***coefficient of variation*** denoted 'c.o.v' (or 'cv') is a statistical measure of the dispersion of data points in a data series around the mean. The coefficient of variation eliminates the unit of measurement from the standard deviation of a series of number by dividing it by the mean of this series. The '*c.o.v'* is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other.

For a series of numbers, with standard deviation σ and mean μ, the coefficient of variation is computed by the following formula:

$$cv = \frac{\sigma}{\mu} \qquad \text{Eq. A.4-14}$$

Often the coefficient of variation is expressed as a percentage which corresponds to the following formula for the coefficient of variation

$$cv = \frac{\sigma}{\mu} \times 100 \qquad \text{Eq. A.4-15}$$

If the standard deviation increases as the average increases, the '*c.o.v'* is the best way to summarize the variation. In contrary if the standard deviation does not change with the average, the standard deviation is the best way to summarize the variation.

A.4.2.3 Confidence intervals

A.4.2.3.1 Confidence interval of the population parameter

A confidence interval (CI) is an interval estimate of a population parameter. It is used to indicate the reliability of an estimate. Given a distribution of samples, the confidence interval indicates the probability that the confidence range would capture the true population parameter. This is expressed by a percentage such as 99% confidence interval, or 95% confidence interval. Or in a more formal way $(1-\alpha)\%$ confidence interval where α, the significance level, is a small positive number ususally closed to 0.

For a normal distribution the confidence interval of the population mean is given by:

$$\bar{X} \mp z\frac{s}{\sqrt{n}} \qquad \text{Eq. A.4-16}$$

Where s is the sample standard deviation, n the sample size and z a constant related to α. For a 95% confidence interval, $z = 1.96$.

A.4.2.3.2 Confidence interval for the coefficient of variation

It is assumed that the coefficient of variation follows a normal distribution. There exist exact and approximate methods to compute the cv confidence interval (Iglewicz et al. 1970).

In this research McKay's modified approximate method (Panichkitkosolkul 2010) has been used to compute the confidence interval.

The sample estimate of the coefficient of variation of a population is given by:

$$\widehat{cv} = \frac{S}{\bar{X}} \qquad \text{Eq. A.4-17}$$

For a $(1-\alpha)\%$ confidence interval the approximate confidence interval is given by:

$$CI_{lower} = \widehat{cv}\left[\left(\frac{\chi^2_{\nu,1-\alpha/2} + 2}{\nu + 1} - 1\right)\widehat{cv}^2 + \frac{\chi^2_{\nu,1-\alpha/2}}{\nu}\right]^{-1/2}$$ Eq. A.4-18

$$CI_{Upper} = \widehat{cv}\left[\left(\frac{\chi^2_{\nu,\alpha/2} + 2}{\nu + 1} - 1\right)\widehat{cv}^2 + \frac{\chi^2_{\nu,\alpha/2}}{\nu}\right]^{-1/2}$$ Eq. A.4-19

Where, $\nu = n - 1$, the degrees of freedom of the χ^2 distribution.

A.4.2.4 Stratified random sampling

In stratified random sampling, the population is partitioned into subpopulations, or strata, which are then independently sampled. The results from the strata are combined to estimate population parameters, such as the mean (Rice 1995; Rice).

Following are some examples that suggest the range of situations in which stratification is natural:

- In a sample of corrosion data, the compartment, location and area often form strata.
- In samples of human populations, geographical areas often form natural strata.
- In a study of records of shipments of household goods by motor carriers, the carriers can be grouped into three strata: large carriers, medium carriers, and small carriers.

Stratified samples are used for a variety of reasons. The use of a stratified random sample guarantees a prescribed number of observations from each subpopulation, whereas the use of a simple random sample can result in underrepresentation of some subpopulations. A second reason for using stratification is that the stratified sample mean can be considerably more precise than the mean of a simple random sample, especially if the population members within each stratum are relatively homogeneous and if there is considerable variation between strata.

Properties of Stratified Estimates

If we consider L strata, and denote by $N_l, l = 1, \cdots L$, the population sizes in the L strata; then $N_1 + N_2 + \cdots + N_{L-1} + N_L = N$ is the total population size.

The population mean and variance of the l^{th} stratum are denoted by μ_l and σ_l^2 .

The overall population mean can be expressed in terms of the μ_l as follows:

let x_{il} denote the i^{th} population value in the l^{th} stratum and let $W_l = {}^{N_l}/_{N}$ denote the fraction of the population in the l^{th} stratum (the l^{th} stratum weight), then:

$$\mu = \frac{1}{N}\sum_{l=1}^{L}\sum_{i=1}^{N_l} X_{il}$$

$$= \frac{1}{N}\sum_{l=1}^{L} N_l\mu_l \qquad \text{Eq. A.4-20}$$

$$= \sum_{l=1}^{n_l} W_l\mu_l$$

Within each stratum, a simple random sample of size n_l is taken. The sample mean in stratum l is denoted by

$$\bar{X}_l = \frac{1}{n_l}\sum_{i=1}^{n_l} X_{il} \qquad \text{Eq. A.4-21}$$

Here X_{il} denotes the i^{th} observation in the l^{th} stratum.

Note that, $\bar{X}_l$ is the mean of a simple random sample from the population consisting of the l^{th} stratum, $E(\bar{X}_l) = \mu_l$ (Rice 2007). By analogy with the preceding relationship between the overall population mean and the population means of the various strata, the obvious estimate of μ, is

$$\bar{X} = \sum_{l=1}^{L} \frac{N_l \bar{X}_l}{N} = \sum_{l=1}^{L} W_l \bar{X}_l \qquad \text{Eq. A.4-22}$$

The variance is given by:

$$Var(\bar{X}) = \sum_{l=1}^{L} W_l^2 \left(\frac{N_l - n_l}{N_l - 1}\right) \frac{\sigma_l^2}{n_l} \qquad \text{Eq. A.4-23}$$

A.4.2.5 Covariance of Random Variables

Suppose that X_1 and X_2 are random variables with expected (mean) values $E(X_1) = \mu_1$, $E(X_2) = \mu_2$ and variances $Var(X_1) = \sigma_1^2$ and $Var(X_2) = \sigma_2^2$.

The covariance of X_1 and X_2 is defined as:

$$Cov(X_1, X_2) = E[(X_1 - \mu_1)(X_2 - \mu_2)] = E(X_1, X_2) - E(X_1)E(X_2) \qquad \text{Eq. A.4-24}$$

Some properties of the covariance:

$$Cov(X_1, X_2) = Cov(X_2, X_1) \qquad \text{Eq. A.4-25}$$

$$Cov(X, X) = Var(X) \qquad \text{Eq. A.4-26}$$

The covariance matrix is given by:

$$C = \begin{pmatrix} Var(X_1) & \dots & Cov(X_1, X_n) \\ \vdots & \cdots & \vdots \\ Cov(X_n, X_1) & \cdots & Var(X_n) \end{pmatrix} \qquad \text{Eq. A.4-27}$$

If the random variables are statistically independent then $Cov(X_i, X_j) = 0$ for all $i = j$ but the converse is not necessarily true. The random variables may not be correlated and still be statistically dependent.

$$Var\left(\sum_{i=1}^{n} X_i\right) = \sum_{i=1}^{n} Var(X_i) + 2\sum_{i<j}\sum Cov(X_i, X_j) \quad \text{Eq. A.4-28}$$

For statistically independent random variables (Polianin et al. 2007):

$$Var\left(\sum_{i=1}^{n} X_i\right) = \sum_{i=1}^{n} Var(X_i) \quad \text{Eq. A.4-29}$$

If all the variables have the same variance σ^2 then

$$Var(\bar{X}) = Var\left(\frac{1}{n}\sum_{i=1}^{n} X_i\right) = \frac{1}{n^2}\sum_{i=1}^{n} Var(X_i) = \frac{\sigma^2}{n} \quad \text{Eq. A.4-30}$$

The wighted sum of multiple random variables is given by:

$$Var\left(\sum_{i} a_i X_i\right) = \sum_{i} a_i^2\, Var(X_i) + \sum_{i}\sum_{j\neq i} a_i a_j Cov(X_i, X_j) \quad \text{Eq. A.4-31}$$

A.4.2.6 Other useful properties of random variables

Variance of the product of independent variables

If two variables X_1 and $X_2$are independent, the variance of their product is given by:

$$Var(X_1X_2) = [E(X_1)]^2Var(X_2) + [E(X_2)]^2Var(X_1) + Var(X_1)Var(X_2) \quad \text{Eq. A.4-32}$$

Decomposition

If X_1 and X_2 are two random variables and the variance of X_1 exists, then

$$Var(X_1) = Var\big(E(X_1|X_2)\big) + E(Var(X_1|X_2)) \quad \text{Eq. A.4-33}$$

Where $E(X_1|X_2)$ is the conditional expectation of X_1 given X_2 and $Var(X_1|X_2)$ is the conditional variance of X_1 given X_2

Computational formula

The computational formula for the variance (often used to calculate the variance in practice) is given by:

$$\begin{aligned} Var(X) &= E\left(X^2 - 2XE(X) + \big(E(X)\big)^2\right) \\ &= E(X^2) - 2\big(E(X)\big)^2 + \big(E(X)\big)^2 \quad \text{Eq. A.4-34} \\ &= E(X^2) - \big(E(X)\big)^2 \end{aligned}$$

A.4.2.7 Correlation coefficient

The correlation coefficient concept is a form of statistical modelling that attempts to summarise how one dataset will vary in response to another. It is also a measure of how well the predicted values from a forecast model "fit" with the real-life or available data.

There are different ways to compute the correlation factors:

- Pearson's (product moment) or linear correlation
- Spearman
- Kendall

Spearman and Kendal methods use the ranking technique for the data.

The most common correlation coefficient, which is the one used in this research, is the product-moment correlation or Pearson correlation. It is used for assessing the strength of the linear relation between two (or more) variables.

Let X_1 and X_2 be two random variables, the correlation coefficient $\rho_{1,2}$ characterising X_1 and X_2 measures the degree of linear association between X_1 and X_2 and is defined as:

$$\rho_{1,2} = \frac{Cov(X_1, X_2)}{\sigma_1 \sigma_2} \qquad -1 \leq \rho_{1,2} \leq 1 \qquad \text{Eq. A.4-35}$$

A correlation coefficient of +1.0 means that where there are high values in one set there will be high values in the other, while a correlation coefficient of -1.0 means that where there are high values in one set there will be low values in the other. A correlation coefficient of 0.0 means that there is no discernible relationship between the two sets.

As the strength of the relationship between the predicted values and actual values increases so does the correlation coefficient.

Note that a change of scale will alter the correlation coefficient and that a nonlinear relation will result in a low correlation even if the two variables are strongly associated. In such circumstances, use of the correlation of ranks may be more appropriate (Spearman, Kendall).

Correlation Test

Once the correlation coefficient ρ has been computed for a sample, it is needed to determine what is likelihood that the ρ-value found occurred by chance. The likelihood of occurrence can be assessed using critical value or hypotheses test methods (Figure A.4- 1).

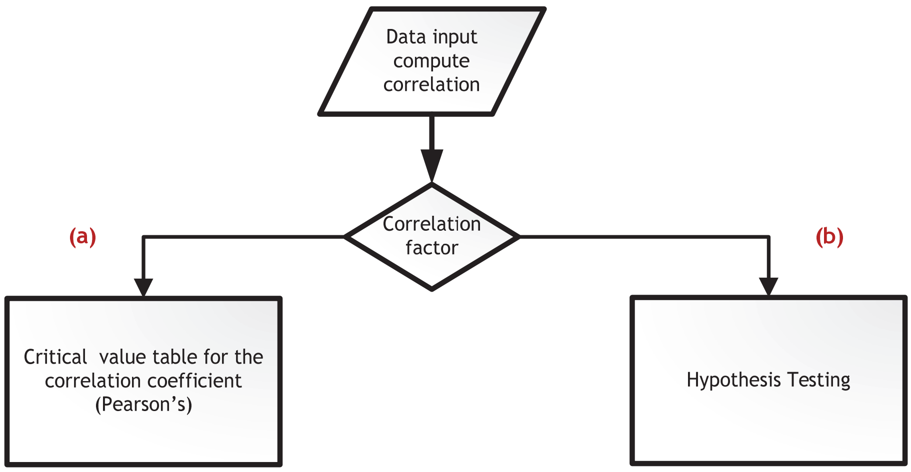

Figure A.4- 1: Correlation test

Hypothesis testing

The usual hypothesis test is that the correlation is zero; however, in some cases, it may be appropriate to test whether the correlation differs from some other defined value.

Conducting a hypothesis test of correlation is similar to the methods of hypothesis testing with a few noticeable differences:

The relevant distribution is the t-distribution, with $\rho = 0$ at the centre (mean).

The rejection region is determined through degrees of freedom and significance level. The difference is the change in the method for determining the Degrees of Freedom:

Degrees of Freedom = n - 2

The distribution is entered by converting the ρ -value with the following equation (Anderson 1980; Rice 1995):

$$t = \frac{\rho}{\sqrt{1-\rho^2/_{n-2}}} \qquad \text{Eq. A.4-36}$$

Where $\sqrt{\frac{1-\rho^2}{n-2}}$ is taken to be approximately the standard error SE_ρ of the correlation coefficient.

Critical Value Table

If the value of ρ to be tested is greater than the critical value for the number of XY pairs at the required level of significance, it can be accepted that there is a significant relationship between X and Y and that the correlation is not due to chance.

Example

The table shows the results of two tests:

Test	*No of XY Pairs*	*Correlation Coefficient*	*Significance Level*	*Critical Value*	*Significant*
A	15	0.910	0.05	0.514	***Yes***
B	15	0.170	0.05	0.514	***No***

Confidence interval for the population correlation coefficient

Although the hypothesis test indicates whether there is a linear relationship, it gives no indication of the strength of that relationship. This additional information can be obtained from a confidence interval for the population correlation coefficient.

To calculate a confidence interval, ρ must be transformed to give a Normal distribution making use of Fisher's z transformation. The purpose of the test is to see if ρ would still be different from 0 if there was infinite data.

$$Z_\rho = \frac{1}{2} ln\left(\frac{1+\rho}{1-\rho}\right) \qquad \text{Eq. A.4-37}$$

The standard error of Z_ρ is approximately:

$$\frac{1}{\sqrt{n-3}} \qquad \text{Eq. A.4-38}$$

and hence a 95% confidence interval for the true population value for the transformed correlation coefficient Z_ρ is given by Z_ρ - (1.96 × standard error) to Z_ρ + (1.96 × standard error). Because Z_ρ is normally distributed, 1.96 deviations from the statistic will give a 95% confidence interval.

A.4.2.8 Partial correlation

Partial correlation is computed when there is a need to measure the degree of the relationship between the random variable Y and one of the X variables taking into account the effect on Y of all other Xs. Partial correlation can be expressed in terms of the simple correlation coefficients as follows (Hickman 1971; Kirkwood 2003).

Let Y, X_2 and X_3 be three random variables, the partial correlation between Y and X_2 is given by:

$$\rho_{2Y.3} = \frac{\rho_{2Y} - \rho_{3Y}\,\rho_{23}}{\sqrt{(1-\rho_{3Y}^2)(1-\rho_{23}^2)}} \qquad \text{Eq. A.4-39}$$

The partial correlation relating Y and X_3 is then:

$$\rho_{3Y.2} = \frac{\rho_{3Y} - \rho_{2Y}\,\rho_{32}}{\sqrt{(1-\rho_{2Y}^2)(1-\rho_{32}^2)}} \qquad \text{Eq. A.4-40}$$

These coefficients are called the first order coefficients (only one variable held constant).

A.4.2.9 Interpreting the Correlation Factor: Usefulness Factor

One estimate commonly employed for the communality measure is the squared multiple correlation coefficient (SMC) of one variable with all the others. The SMC multiplied by 100 measures the percent of variation that can be produced (predicted, accounted for, generated, or explained) for one variable from all the others.

The squared correlation describes the proportion of variance in common between the two variables and can be a measure of usefulness. If we multiply this by 100, we then get the percent of variance in common between two variables. That is:

$$\rho_{ij}^2 \times 100 = Percent\ of\ variance\ in\ common\ between\ X_i\ and\ X_j \qquad \text{Eq. A.4-41}$$

A.4.3 UNCERTAINTIES AND CALIBRATION METHODS

Uncertainties in engineering may be associated with physical phenomena that are inherently random (variability of the physical process) or with predictions and estimations of reality (i.e., state of nature) performed under conditions of incomplete or inadequate information (imperfection in the modelling of physical process).

Uncertainty is naturally associated with random phenomena because the exact realisation of a phenomenon cannot be determined with certainty. The possible realisations may be described in terms of range of possibilities, with their respective relative likelihoods of occurrence (e.g. with a probability density function). In other words, if the state of nature is random, it cannot be described with a deterministic model. Its description must include a measure of its inherent variability and thus uncertainty. For practical purposes, the required description may have to be limited to the main descriptors of interest, which are the central value (e.g. mean or median) and its measure of dispersion (e.g. standard deviation or coefficient of variation). Available observational data are normally used to estimate the central value and degree of dispersion of the possible realisations.

Prediction or modelling error may contain two components: the *Systematic component* and the *random component*.

In measurement theory, these are known as the “systematic error” and “random error”, respectively. Inherent variability is essentially a state of nature and the resulting uncertainty may not be controlled or reduced. The uncertainty associated with prediction or modelling error may be reduced using more accurate models or the acquisition of additional data.

Model calibration refers to the process of adjusting parameter values or output of a (computer) model so that model predictions accurately reflect observations (Neter et al. 1996; Fox 2002). Model calibration targets to enhance the reliability of a predictive model by estimating unknown model parameters by means of field data corresponding to model outcomes, or the model output when parameters are not explicitly known. In cases where the model output is far from the true recorded value, a correction factor could be applied to adjust the prediction by either adding or subtracting or multiply the correction value (also called bias) to the actual value (Anderson 1980; Hunter et al. 1990).

Model calibration can also be used to adapt one model derived from one setting to another setting (Martens 1989). Depending on the situation, different calibration methods can be used:

- Calibration based on manual intervention

  This approach heuristically test different calibration parameter values based on expert's knowledge and experience until the discrepancy between model predictions and monitored data is satisfactorily small.

- Calibration based on graphical comparison

  This approach uses graphical representation of data that compares predicted against monitored data in order to identify which model parameters cause the discrepancy.

- Calibration based on mathematical methods

  This approach employs sensitivity analysis (SA) methods to select calibration parameters and optimization algorithms to obtain calibration results in order to reduce experts' involvements in the calibration process.

For this study, the latest method is the most relevant. In a statistical meaning, there are two main uses of the term calibration that denote special types of statistical inference problems:

- A reverse process to regression, where instead of a future dependent variable being predicted from known explanatory variables, a known observation of the dependent variables is used to predict a corresponding explanatory variable.

- Procedures in statistical classification to determine class membership probabilities which assess the uncertainty of a given new observation belonging to each of the already established classes.

In addition, "calibration" is used in statistics with the usual general meaning of calibration. For example, model calibration can be also used to refer to Bayesian inference about the value of a model's parameters, given some data set, or more generally to any type of fitting of a statistical model (Upton et al. 2008).

The objective of model calibration is to reduce uncertainty in the model. Sources of uncertainty in the model calibration are as follows:

- ***Parameter uncertainty:*** this uncertainty comes from not assigning true values to model parameters.
- ***Model inadequacy:*** this uncertainty arises from the inability of the model to perfectly represent the reality.
- ***Code uncertainty:*** this uncertainty is due to numerical errors in the model implementation.
- ***Observation error:*** this uncertainty refers to errors in measured data used for calibration.

Two approaches could be considered to effectively reduce these biases, with simple statistical correction and the bias-correction, model can have a more realistic internal variability as well as an improved prediction performance.

The first approach for model calibration is to modify or update the individual model parameters using data until the output from the model matches an observed set of data. This technique requires a lot of data about the specific parameters that is often not available and implies access to the parameters.

The second approach (used in this work) is to consider the model as a black box (Figure A.4- 2) to calibrate the model as a whole, as discussed in the next section.

In this work the idea is to estimate the error generated by the prediction model outputs based on the real data collected from inspections as discussed in C*hapter 7.*

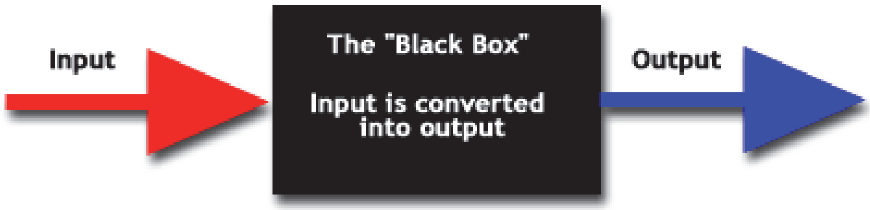

Figure A.4- 2: Black box model

A.4.4 CALIBRATION FACTORS (SIMPLE BIAS)

An error can be defined as a difference between a computed or estimated result and the actual or real result. Modelling error (as described in section A.4.3 above) can be:

1) Systematic: A systematic error is where the bulk of observed data lies above or below some predicted value, often described by term "bias".

2) Random: Random errors have a distribution which might be described by a probability density function.

The bias factor γ is defined as:

$$\gamma_i = \frac{Measured\ value\ _i}{Calculated\ value\ _i} \qquad \text{Eq. A.4-42}$$

The bias contains systematic and random errors and it could be treated as a random variable for which the following are specified:

a) The median (or mean)

b) The standard deviation (or coefficient of variation)

c) The distribution

The mean bias factor is given by:

$$\gamma = \frac{1}{n}\sum_{i=1}^{n}\gamma_i \qquad \text{Eq. A.4-43}$$

The upper and lower bands of the bias factor are given by:

$$LowerBand = min(\gamma_i) \qquad \text{Eq. A.4-44}$$

$$UpperBand = max(\gamma_i) \qquad \text{Eq. A.4-45}$$

The standard deviation and coefficient of variation of γ are calculated as given by equations Eq. A.4-13 and Eq. A.4-14 respectively.

Analytically speaking, if (bias > 1), the model underestimates the correct value, and if (bias < 1), then there is an over-estimation.

In both cases, the data predicted will need to be corrected using the appropriate factor.

A.4.5 WEIGHTED CALIBRATION FACTOR (WEIGHTED BIAS)

When data do not have the same influence, the arithmetic mean is no longer a good representative measure for the dataset. In this case the weighted mean is computed. This is also true when dealing with calibration factors.

The weighted bias factor γ_ω of a set of n values $(\gamma_1, \gamma_2, \dots, \gamma_n)$ is computed according to the following formula:

$$\gamma_\omega(\gamma_1, \gamma_2, \dots, \gamma_n) = \frac{\sum_{i=1}^{n} \omega_i \times \gamma_i}{\sum_{j=1}^{n} \omega_j} \quad \text{Eq. A.4-46}$$

where; $(\omega_1, \omega_2, \dots, \omega_n)$ are non-negative coefficients, called "weights", that are ascribed to the corresponding values $(\gamma_1, \gamma_2, \dots, \gamma_n)$, and:

$$\sum_{i=1}^{n} \frac{\omega_i}{\sum_{j=1}^{n} \omega_j} = 1 \quad \text{Eq. A.4-47}$$

In this work, weights are calculated differently depending on the computation that is performed. In the case for example, of defect assessment in a connection detail, weights ω_i are computed by normalising the weight value based on usefulness factor (UF) values as follows:

$$\omega_i = \frac{UF_i}{\sum_{j=1}^{n} UF_j} \quad \text{Eq. A.4-48}$$

A.4.6 CONFIDENCE FACTOR (CF)

To manage the uncertainty in the data and models, the use of confidence factors (CF) is important. The CF (also called confidence level or certainty factor) is an index of certainty. It is a numerical measure of the confidence one has in the validity of a given evidence or rule.

It varies from 0 (no confidence at all) to 100 (complete confidence).

Confidence factors are also used to measure the degree of uncertainty in rules.

There are several approaches to compute a Confidence Factor; this could be for example a subjective probability (guesstimate) or a correlation analysis combined with a confidence level obtained from a t-test (Hotelling et al. 1953; Ghosh 1966).

CF can be computed using the Z-test (*that the distribution is normal*). The confidence factor is given by:

$$CF = p\_value * 100 \qquad \text{Eq. A.4-49}$$

When more than one evidence is available for a hypothesis h and the information sources for the evidence are independent, confidence factors can be combined.

Lets CF_1 and CF_2 be confidence factors of evidence e_1 and e_2 respectively. The combined confidence factor CF_{Comb} is calculated as follows:

$$CF_{Comb} = CF_1 + CF_2 - (CF_1 \times CF_2)/100 \qquad \textit{Eq. 4-50}$$

When another evidence $e_3$for the same hypothesis h becomes available with a confidence factor CF_3, then the confidence factor of the hypothesis can be recalculated as follows:

$$CF_{New\_Comb} = CF_{Comb} - (CF_3 \times CF_{Comb})/100 \qquad \textit{Eq. 4-51}$$

The process is continued for every new evidence that becomes available (Zadeh 1965; Rodionov et al. 2003; Wu et al. 2004).

A.4.7 EXPERT JUDGMENT

Expert judgments are informed opinions that experts make based on their experience and knowledge of particular problems. Experts are recognised to be qualified to address the problems.

Expert judgment is used in all sort of technical fields from engineering to medicine and can be used either to structure a technical problem for example, the assumptions used in developing a prediction model or, which data sets to include in an analysis or, to provide estimates such as probability of occurrence of an event or, determine weighting factors for combining data sources.

Expert judgment is typically prompted when data are sparse, difficult or costly to obtain.

Expert judgment can be provided in a qualitative or quantitative form (Meyer et al. 1991). When the expert judgment is in the form of quantitative estimates, it can be considered to be data which can be handled statistically (i.e. aggregating differing experts' responses, quantifying the accuracy of experts' predictions, combining different types and sources of data). In this research only quantitative data is of interest.

Expert judgment can be obtained informally where experts are asked for their best guess which is then used in the analysis or it can be elicited through a formal process where experts are selected using specific procedures, and methods of eliciting and analysing their response are chosen.

Data coming from expert judgment have inherent uncertainties and formal elicitation can counter common biases arising from human cognition and behaviour as additional information such as expert's source of information and assumptions are documented as part of their judgment (Booker et al. 2002).

A.5: CASE STUDY RESULT TABLES

Case 1- Upper bound of confidence interval for calibration factors

Table A.5- 1: Upper bound of the confidence interval for the calibration factors in Case 1

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.922	2.866	2.810	2.754	2.698	2.641	2.585	2.529	2.472	2.415	2.359	2.302	2.245	2.188	2.130	2.073
Location 10	3.114	3.054	2.994	2.934	2.873	2.813	2.753	2.692	2.632	2.571	2.510	2.449	2.388	2.327	2.266	2.205
Location 8	4.756	4.665	4.574	4.482	4.390	4.298	4.206	4.114	4.022	3.929	3.837	3.744	3.651	3.558	3.464	3.371
Location 6	4.561	4.474	4.386	4.299	4.211	4.123	4.035	3.947	3.859	3.770	3.681	3.593	3.504	3.414	3.325	3.236
Location 3	4.787	4.695	4.604	4.512	4.420	4.328	4.236	4.144	4.051	3.959	3.866	3.773	3.679	3.586	3.492	3.398

Case 1- Lower bound of confidence interval for calibration factors

Table A.5- 2: Lower bound of the confidence interval for the calibration factors in Case 1

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.388	2.338	2.288	2.238	2.187	2.138	2.088	2.038	1.988	1.939	1.889	1.840	1.791	1.742	1.693	1.644
Location 10	2.636	2.581	2.526	2.471	2.417	2.362	2.307	2.253	2.198	2.144	2.090	2.036	1.982	1.928	1.874	1.820
Location 8	3.972	3.888	3.805	3.722	3.639	3.557	3.474	3.392	3.310	3.228	3.146	3.064	2.983	2.901	2.820	2.739
Location 6	0.818	0.810	0.801	0.792	0.783	0.773	0.763	0.753	0.742	0.731	0.720	0.708	0.696	0.684	0.671	0.658
Location 3	3.877	3.795	3.714	3.632	3.550	3.469	3.388	3.307	3.226	3.146	3.065	2.985	2.905	2.825	2.746	2.666

Case 1-Upper bound of confidence interval for cv

*Table A.5- 3: Upper bound of the confidence interval for the **cv** in Case 1*

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	1.817	1.851	1.887	1.923	1.961	1.999	2.039	2.080	2.123	2.167	2.212	2.259	2.308	2.358	2.411	2.466
Location 10	1.329	1.349	1.369	1.389	1.410	1.430	1.452	1.473	1.495	1.517	1.540	1.563	1.586	1.610	1.634	1.659
Location 8	1.502	1.526	1.551	1.576	1.601	1.628	1.654	1.681	1.709	1.738	1.767	1.796	1.827	1.858	1.890	1.922
Location 6	1.753	1.785	1.818	1.852	1.887	1.922	1.959	1.997	2.036	2.076	2.118	2.160	2.205	2.251	2.298	2.347
Location 3	1.980	2.021	2.063	2.107	2.153	2.200	2.248	2.299	2.351	2.406	2.463	2.523	2.586	2.651	2.720	2.793

Case 1-Lower bound of confidence interval for cv

*Table A.5- 4: Lower bound of the confidence interval for the **cv** in Case 1*

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	0.886	0.893	0.899	0.906	0.913	0.920	0.926	0.933	0.939	0.946	0.952	0.959	0.965	0.972	0.978	0.984
Location 10	0.759	0.766	0.772	0.778	0.785	0.791	0.797	0.803	0.809	0.815	0.821	0.828	0.834	0.839	0.845	0.851
Location 8	0.811	0.818	0.824	0.831	0.837	0.844	0.850	0.857	0.863	0.869	0.875	0.882	0.888	0.894	0.900	0.906
Location 6	0.872	0.879	0.886	0.893	0.899	0.906	0.913	0.919	0.926	0.932	0.939	0.945	0.951	0.958	0.964	0.970
Location 3	0.916	0.923	0.930	0.937	0.944	0.951	0.957	0.964	0.971	0.977	0.984	0.990	0.997	1.003	1.009	1.016

Case 2- Calibration factors

Table A.5- 5: Calibration factors. Case 2

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.655	2.602	2.549	2.496	2.443	2.389	2.336	2.283	2.230	2.177	2.124	2.071	2.018	1.965	1.912	1.858
Location 10	4.235	3.790	3.471	3.147	2.908	2.766	2.612	2.448	2.328	2.232	2.186	2.099	2.007	1.936	1.883	1.783
Location 8	5.984	5.347	5.005	4.673	4.450	4.246	4.117	3.968	3.898	3.741	3.695	3.484	3.446	3.413	3.318	3.201
Location 6	5.653	5.063	4.602	4.214	3.920	3.719	3.599	3.385	3.212	3.119	3.037	2.942	2.841	2.720	2.629	2.574
Location 3	6.940	6.189	5.516	5.099	4.676	4.388	4.138	3.888	3.791	3.574	3.393	3.258	3.149	3.026	2.890	2.849

Case 2- Upper bound of confidence interval for calibration factors

Table A.5- 6: Upper bound of the confidence interval for the calibration factors in Case 2

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.922	2.866	2.810	2.754	2.698	2.641	2.585	2.529	2.472	2.415	2.359	2.302	2.245	2.188	2.130	2.073
Location 10	4.336	3.876	3.550	3.220	2.977	2.829	2.672	2.506	2.382	2.284	2.238	2.147	2.054	1.981	1.928	1.826
Location 8	6.127	5.486	5.130	4.791	4.563	4.356	4.217	4.071	4.000	3.836	3.786	3.579	3.539	3.500	3.405	3.286
Location 6	5.795	5.189	4.714	4.321	4.017	3.813	3.689	3.470	3.293	3.199	3.114	3.017	2.914	2.792	2.698	2.645
Location 3	7.093	6.323	5.643	5.213	4.779	4.486	4.236	3.979	3.876	3.658	3.470	3.334	3.222	3.097	2.959	2.917

Case 2- Lower bound of confidence interval for calibration factors

Table A.5- 7: Lower bound of the confidence interval for the calibration factors in Case 2

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.388	2.338	2.288	2.238	2.187	2.138	2.088	2.038	1.988	1.939	1.889	1.840	1.791	1.742	1.693	1.644
Location 10	4.134	3.705	3.392	3.073	2.840	2.702	2.551	2.389	2.273	2.181	2.134	2.052	1.961	1.892	1.838	1.740
Location 8	5.840	5.208	4.880	4.556	4.338	4.137	4.017	3.865	3.796	3.646	3.605	3.389	3.354	3.327	3.231	3.116
Location 6	5.511	4.937	4.490	4.108	3.823	3.625	3.508	3.300	3.131	3.038	2.960	2.867	2.768	2.649	2.560	2.504
Location 3	6.787	6.054	5.390	4.985	4.573	4.291	4.041	3.797	3.706	3.491	3.315	3.183	3.076	2.955	2.821	2.782

Case 2- cv

Table A.5- 8: Coefficient of variation for Case 2.

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	1.143	1.154	1.166	1.177	1.189	1.200	1.212	1.223	1.234	1.246	1.257	1.269	1.280	1.292	1.303	1.314
Location 10	0.271	0.256	0.259	0.266	0.267	0.261	0.263	0.272	0.267	0.263	0.270	0.256	0.264	0.263	0.273	0.275
Location 8	0.273	0.296	0.284	0.286	0.288	0.293	0.276	0.295	0.297	0.288	0.279	0.310	0.305	0.289	0.298	0.304
Location 6	0.286	0.283	0.276	0.288	0.282	0.288	0.286	0.287	0.288	0.293	0.288	0.289	0.292	0.299	0.298	0.313
Location 3	0.251	0.248	0.260	0.255	0.251	0.252	0.268	0.268	0.254	0.266	0.259	0.264	0.263	0.267	0.271	0.270

Case 2-Upper bound of confidence interval for cv

Table A.5- 9: Upper bound of the confidence interval for the $\boldsymbol{cv}$ *in Case 2*

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	1.817	1.851	1.887	1.923	1.961	1.999	2.039	2.080	2.123	2.167	2.212	2.259	2.308	2.358	2.411	2.466
Location 10	0.301	0.284	0.287	0.296	0.296	0.290	0.292	0.303	0.297	0.292	0.301	0.283	0.293	0.292	0.304	0.306
Location 8	0.304	0.332	0.318	0.319	0.322	0.329	0.307	0.331	0.334	0.323	0.311	0.351	0.344	0.323	0.335	0.342
Location 6	0.320	0.317	0.308	0.322	0.315	0.322	0.321	0.321	0.322	0.329	0.322	0.324	0.328	0.336	0.335	0.353
Location 3	0.278	0.274	0.289	0.282	0.277	0.279	0.298	0.297	0.282	0.295	0.287	0.293	0.292	0.297	0.301	0.300

Case 2-Lower bound of confidence interval for cv

Table A.5- 10: Lower bound of the confidence interval for the $\boldsymbol{cv}$ *in Case 2*

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	0.886	0.893	0.899	0.906	0.913	0.920	0.926	0.933	0.939	0.946	0.952	0.959	0.965	0.972	0.978	0.984
Location 10	0.263	0.249	0.252	0.259	0.259	0.254	0.255	0.265	0.260	0.255	0.263	0.248	0.257	0.255	0.266	0.268
Location 8	0.266	0.290	0.277	0.279	0.282	0.287	0.269	0.289	0.292	0.282	0.272	0.306	0.300	0.282	0.293	0.298
Location 6	0.280	0.277	0.269	0.282	0.275	0.282	0.280	0.281	0.281	0.287	0.281	0.283	0.286	0.293	0.293	0.308
Location 3	0.243	0.240	0.253	0.247	0.243	0.244	0.261	0.260	0.247	0.258	0.252	0.257	0.256	0.260	0.264	0.263

Case 3- Calibration factors

Table A.5- 11: Calibration factors. Case 3

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.655	2.602	2.549	2.496	2.443	2.389	2.336	2.283	2.230	2.177	2.124	2.071	2.018	1.965	1.912	1.858
Location 10	2.875	2.817	2.760	2.702	2.645	2.587	2.530	2.473	2.415	2.358	2.300	2.243	2.185	2.127	2.070	2.012
Location 8	4.364	4.277	4.189	4.102	4.015	3.928	3.840	3.753	3.666	3.578	3.491	3.404	3.317	3.229	3.142	3.055
Location 6	5.653	5.063	4.602	4.214	3.920	3.719	3.599	3.385	3.212	3.119	3.037	2.942	2.841	2.720	2.630	2.574
Location 3	6.940	6.189	5.516	5.099	4.676	4.388	4.138	3.888	3.791	3.574	3.393	3.258	3.149	3.026	2.890	2.849

Case 3- Upper bound of confidence interval for calibration factors

Table A.5- 12: Upper bound of the confidence interval for the calibration factors in Case 3

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.922	2.866	2.810	2.754	2.698	2.641	2.585	2.529	2.472	2.415	2.359	2.302	2.245	2.188	2.130	2.073
Location 10	3.114	3.054	2.994	2.934	2.873	2.813	2.753	2.692	2.632	2.571	2.510	2.449	2.388	2.327	2.266	2.205
Location 8	4.756	4.665	4.574	4.482	4.390	4.298	4.206	4.114	4.022	3.929	3.837	3.744	3.651	3.558	3.464	3.371
Location 6	5.795	5.189	4.714	4.321	4.017	3.813	3.689	3.470	3.293	3.199	3.114	3.017	2.914	2.792	2.699	2.645
Location 3	7.093	6.323	5.643	5.213	4.779	4.486	4.236	3.979	3.876	3.658	3.470	3.334	3.222	3.097	2.959	2.917

Case 3- Lower bound of confidence interval for calibration factors

Table A.5- 13: Lower bound of the confidence interval for the calibration factors in Case 3

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	2.388	2.338	2.288	2.238	2.187	2.138	2.088	2.038	1.988	1.939	1.889	1.840	1.791	1.742	1.693	1.644
Location 10	2.636	2.581	2.526	2.471	2.417	2.362	2.307	2.253	2.198	2.144	2.090	2.036	1.982	1.928	1.874	1.820
Location 8	3.972	3.888	3.805	3.722	3.639	3.557	3.474	3.392	3.310	3.228	3.146	3.064	2.983	2.901	2.820	2.739
Location 6	5.511	4.937	4.490	4.108	3.823	3.625	3.508	3.300	3.131	3.038	2.960	2.867	2.768	2.649	2.561	2.504
Location 3	6.787	6.054	5.390	4.985	4.573	4.291	4.041	3.797	3.706	3.491	3.315	3.183	3.076	2.955	2.821	2.782

Case 3- cv

Table A.5- 14: Coefficient of variation for Case 3

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	1.143	1.154	1.166	1.177	1.189	1.200	1.212	1.223	1.234	1.246	1.257	1.269	1.280	1.292	1.303	1.314
Location 10	0.945	0.954	0.964	0.973	0.983	0.992	1.002	1.011	1.021	1.030	1.040	1.049	1.058	1.068	1.077	1.087
Location 8	1.024	1.034	1.044	1.054	1.064	1.075	1.085	1.095	1.105	1.116	1.126	1.136	1.146	1.157	1.167	1.177
Location 6	0.286	0.283	0.276	0.288	0.282	0.288	0.286	0.287	0.288	0.293	0.288	0.289	0.292	0.299	0.298	0.313
Location 3	0.251	0.248	0.260	0.255	0.251	0.252	0.268	0.268	0.254	0.266	0.259	0.264	0.263	0.267	0.271	0.270

Case 3-Upper bound of confidence interval for cv

Table A.5- 15: Upper bound of the confidence interval for the $\boldsymbol{cv}$ *in Case 3*

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	1.817	1.851	1.887	1.923	1.961	1.999	2.039	2.080	2.123	2.167	2.212	2.259	2.308	2.358	2.411	2.466
Location 10	1.329	1.349	1.369	1.389	1.410	1.430	1.452	1.473	1.495	1.517	1.540	1.563	1.586	1.610	1.634	1.659
Location 8	1.502	1.526	1.551	1.576	1.601	1.628	1.654	1.681	1.709	1.738	1.767	1.796	1.827	1.858	1.890	1.922
Location 6	0.320	0.317	0.308	0.322	0.315	0.322	0.321	0.321	0.322	0.329	0.322	0.324	0.328	0.336	0.335	0.353
Location 3	0.278	0.274	0.289	0.282	0.277	0.279	0.298	0.297	0.282	0.295	0.287	0.293	0.292	0.297	0.301	0.300

Case 3-Lower bound of confidence interval for cv

Table A.5- 16: Lower bound of the confidence interval for the $\boldsymbol{cv}$ *in Case 3*

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	0.886	0.893	0.899	0.906	0.913	0.920	0.926	0.933	0.939	0.946	0.952	0.959	0.965	0.972	0.978	0.984
Location 10	0.759	0.766	0.772	0.778	0.785	0.791	0.797	0.803	0.809	0.815	0.821	0.828	0.834	0.839	0.845	0.851
Location 8	0.811	0.818	0.824	0.831	0.837	0.844	0.850	0.857	0.863	0.869	0.875	0.882	0.888	0.894	0.900	0.906
Location 6	0.280	0.277	0.269	0.282	0.275	0.282	0.280	0.281	0.281	0.287	0.281	0.283	0.286	0.293	0.293	0.308
Location 3	0.243	0.240	0.253	0.247	0.243	0.244	0.261	0.260	0.247	0.258	0.252	0.257	0.256	0.260	0.264	0.263

Case 4- Calibration factors

Table A.5- 17: Calibration factors. Case 4

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	4.919	4.243	3.754	3.461	3.316	3.066	2.869	2.699	2.662	2.500	2.498	2.406	2.362	2.281	2.172	2.148
Location 10	4.813	4.124	3.695	3.276	2.979	2.810	2.631	2.442	2.309	2.206	2.162	2.072	1.973	1.900	1.847	1.740
Location 8	6.548	5.710	5.249	4.833	4.567	4.330	4.183	4.022	3.957	3.779	3.742	3.504	3.478	3.455	3.359	3.236
Location 6	6.142	5.343	4.753	4.288	3.941	3.715	3.588	3.350	3.162	3.066	2.987	2.890	2.786	2.659	2.569	2.515
Location 3	7.755	6.711	5.857	5.330	4.815	4.482	4.202	3.918	3.817	3.578	3.381	3.240	3.127	2.999	2.856	2.822

Case 4- Upper bound of confidence interval for calibration factors

Table A.5- 18: Upper bound of the confidence interval for the calibration factors in Case 4

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	4.379	3.918	3.561	3.330	3.208	2.999	2.834	2.685	2.645	2.503	2.490	2.404	2.357	2.281	2.180	2.150
Location 10	4.336	3.876	3.550	3.220	2.977	2.829	2.672	2.506	2.382	2.284	2.238	2.147	2.054	1.981	1.928	1.826
Location 8	6.127	5.486	5.130	4.791	4.563	4.356	4.217	4.071	4.000	3.836	3.786	3.579	3.539	3.500	3.405	3.286
Location 6	5.795	5.189	4.714	4.321	4.017	3.813	3.689	3.470	3.293	3.199	3.114	3.017	2.914	2.792	2.699	2.645
Location 3	7.093	6.323	5.643	5.213	4.779	4.486	4.236	3.979	3.876	3.658	3.470	3.334	3.222	3.097	2.959	2.917

Case 4- Lower bound of confidence interval for calibration factors

Table A.5- 19: Lower bound of the confidence interval for the calibration factors in Case 4

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	4.163	3.727	3.390	3.171	3.055	2.850	2.698	2.546	2.512	2.372	2.364	2.284	2.238	2.167	2.072	2.041
Location 10	4.134	3.705	3.392	3.073	2.840	2.702	2.551	2.389	2.273	2.181	2.134	2.052	1.961	1.892	1.838	1.740
Location 8	5.840	5.208	4.880	4.556	4.338	4.137	4.017	3.865	3.796	3.646	3.605	3.389	3.354	3.327	3.231	3.116
Location 6	5.511	4.937	4.490	4.108	3.823	3.625	3.508	3.300	3.131	3.038	2.960	2.867	2.768	2.649	2.561	2.504
Location 3	6.787	6.054	5.390	4.985	4.573	4.291	4.041	3.797	3.706	3.491	3.315	3.183	3.076	2.955	2.821	2.782

Case 4- cv

Table A.5- 20: Coefficient of variation for Case 4

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	0.288	0.284	0.279	0.279	0.277	0.289	0.279	0.303	0.294	0.306	0.297	0.291	0.295	0.292	0.291	0.297
Location 10	0.271	0.256	0.259	0.266	0.267	0.261	0.263	0.272	0.267	0.263	0.270	0.256	0.264	0.263	0.273	0.275
Location 8	0.273	0.296	0.284	0.286	0.288	0.293	0.276	0.295	0.297	0.288	0.279	0.310	0.305	0.289	0.298	0.304
Location 6	0.286	0.283	0.276	0.288	0.282	0.288	0.286	0.287	0.288	0.293	0.288	0.289	0.292	0.299	0.298	0.313
Location 3	0.251	0.248	0.260	0.255	0.251	0.252	0.268	0.268	0.254	0.266	0.259	0.264	0.263	0.267	0.271	0.270

Case 4-Upper bound of confidence interval for cv

*Table A.5- 21: Upper bound of the confidence interval for the **cv** in Case 4*

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	0.339	0.335	0.329	0.328	0.326	0.341	0.329	0.358	0.347	0.361	0.350	0.343	0.348	0.344	0.343	0.351
Location 10	0.301	0.284	0.287	0.296	0.296	0.290	0.292	0.303	0.297	0.292	0.301	0.283	0.293	0.292	0.304	0.306
Location 8	0.304	0.332	0.318	0.319	0.322	0.329	0.307	0.331	0.334	0.323	0.311	0.351	0.344	0.323	0.335	0.342
Location 6	0.320	0.317	0.308	0.322	0.315	0.322	0.321	0.321	0.322	0.329	0.322	0.324	0.328	0.336	0.335	0.353
Location 3	0.278	0.274	0.289	0.282	0.277	0.279	0.298	0.297	0.282	0.295	0.287	0.293	0.292	0.297	0.301	0.300

Case 4-Lower bound of confidence interval for cv

*Table A.5- 22: Lower bound of the confidence interval for the **cv** in Case 4*

	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Location 14	0.250	0.248	0.243	0.243	0.242	0.252	0.243	0.264	0.256	0.266	0.258	0.253	0.257	0.254	0.253	0.259
Location 10	0.263	0.249	0.252	0.259	0.259	0.254	0.255	0.265	0.260	0.255	0.263	0.248	0.257	0.255	0.266	0.268
Location 8	0.266	0.290	0.277	0.279	0.282	0.287	0.269	0.289	0.292	0.282	0.272	0.306	0.300	0.282	0.293	0.298
Location 6	0.280	0.277	0.269	0.282	0.275	0.282	0.280	0.281	0.281	0.287	0.281	0.283	0.286	0.293	0.293	0.308
Location 3	0.243	0.240	0.253	0.247	0.243	0.244	0.261	0.260	0.247	0.258	0.252	0.257	0.256	0.260	0.264	0.263

A.6: SAMPLE SIZE AND CONFIDENCE LEVELS

In addition to the results presented in Chapter 8, an analysis of the relationship between the data sample size and the confidence levels for both the mean and the coefficient of variation was performed.

First for the mean, the number of data needed to obtain a certain confidence level for a particular error was calculated. The formula given in the Appendix A.4 (Section A.4.2.3.1) was used to obtain the sample size as follows:

Recall that the confidence level of the mean (for normal distribution) is given by:

$$\bar{X} \mp z\frac{s}{\sqrt{n}} \qquad \text{Eq. A.6-1}$$

$$error = z\frac{s}{\sqrt{n}} \qquad \text{Eq. A.6-2}$$

Then the size of the sample data is given by:

$$n = \left(\frac{z \times s}{error}\right)^2 \qquad \text{Eq. A.6-3}$$

This is illustrated for location 14, year 10 of Table A.5- 17, where $\mu = 4.92$ and $\sigma = 1.42$.

The following levels of confidence are assumed 30, 40, 50, 60, 70, 80, 90, 95 and 99 per cent and 0.01, 0.02, 0.03, 0.04 and 0.05 for the error values.

The sample sizes are summarised in Table A.6- 1 below. The variations of the sample size as a function of the confidence level for each error are shown in Figure A.6- 1.

Table A.6- 1 : Sample size for different confidence levels of the mean and error values

Confidence level	30	40	50	60	70	80	90	95	99
Error/sample size									
0.01	2994	5545	9173	14283	21660	33117	54555	77459	133786
0.02	748	1386	2293	3571	5415	8279	13639	19365	33447
0.03	333	616	1019	1587	2407	3680	6062	8607	14865
0.04	187	347	573	893	1354	2070	3410	4841	8362
0.05	120	222	367	571	866	1325	2182	3098	5351

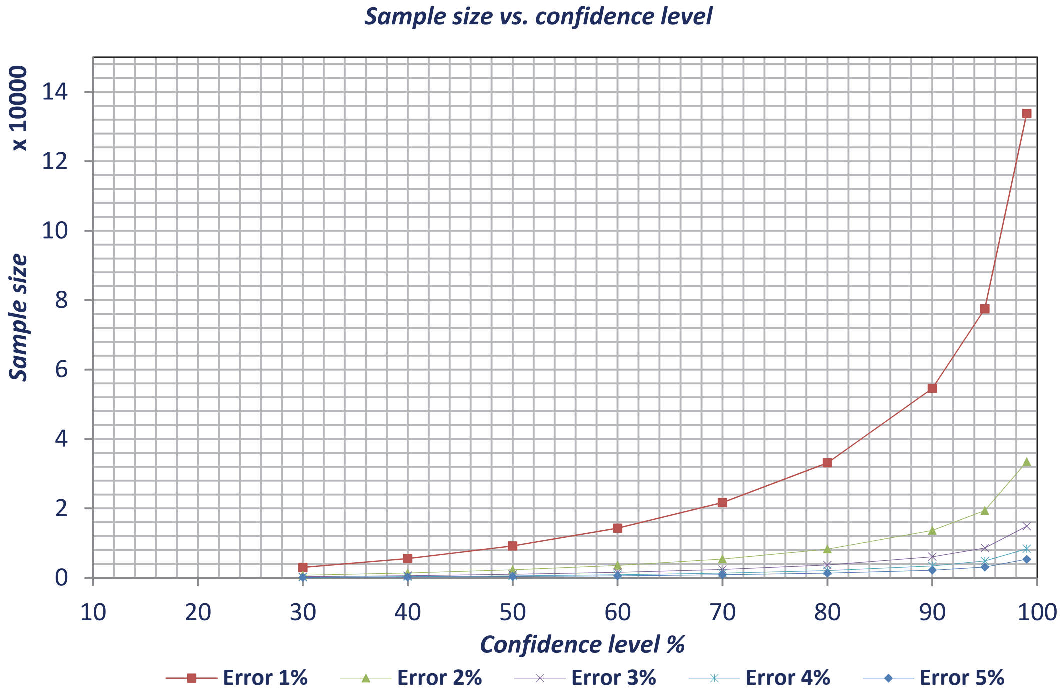

Figure A.6- 1: Sample size variation as a function of confidence level of the mean
(Corrosion at location 14, year 10 of Table A.5- 17, where $\mu = 4.92$ and $\sigma = 1.42$)

As can be seen in the figure above, the sample size increases with the confidence level for all error values but the increase rate is significantly higher for the smallest error value (1% error).

Second for a specific number of data and a specific error values the confidence level of the mean was computed. In this case the z score of equation Eq. A.6-1 above is computed and the corresponding confidence level is determined.

The same location as above is used to illustrate this. Table A.6- 2 below summarised the results for the sample sizes and errors considered.

The variation of the confidence level as a function of the samples size for specific error values is illustrated in Figure A.6- 2.

Table A.6- 2: Confidence level % of the mean for specific size sample and error values.

Simple size	50	100	150	250	400	650	1050	1700	2750	4450	7200
Error											
0.000001	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
0.00001	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
0.0001	50.0	50.0	50.0	50.0	50.1	50.1	50.1	50.1	50.1	50.2	50.2
0.001	50.2	50.3	50.3	50.4	50.6	50.7	50.9	51.2	51.5	51.9	52.4
0.01	52.0	52.8	53.4	54.4	55.6	57.1	59.0	61.4	64.4	68.1	72.5
0.1	69.1	75.9	80.6	86.7	92.1	96.4	98.9	99.8	100.0	100.0	100.0
0.2	84.0	92.1	95.8	98.7	99.8	100.0	100.0	100.0	100.0	100.0	100.0
0.3	93.2	98.3	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

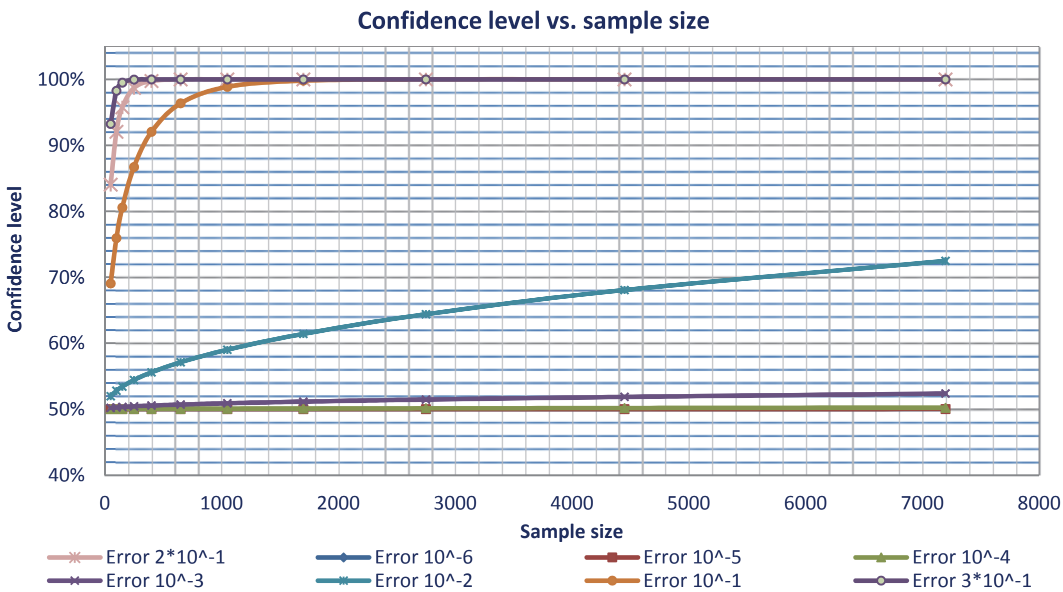

Figure A.6- 2: Variation of confidence level for the mean as a function of the sample size for specific error values.

(Corrosion at location 14, year 10 of Table A.5- 17, where $\mu = 4.92$ and $\sigma = 1.42$)

For this particular example when the error is very small (from 10^{-6} to 10^{-3}), the confidence level stays at 50% even when the sample size increases by two orders of magnitude. When the error value is higher (from 0.1 to 0.3), the confidence levels are higher and increase at a higher rate.

For the coefficient of variation, the formulas to compute the approximate confidence interval ($(1-\alpha)\%$) upper and lower bounds as explained in Appendix A.4 sectionA.4.2.3.2, are as follows:

$$CI_{lower} = \widehat{cv}\left[\left(\frac{\chi^2_{v,1-\alpha/2}+2}{v+1}-1\right)\widehat{cv}^2+\frac{\chi^2_{v,1-\alpha/2}}{v}\right]^{-1/2} \quad \text{Eq. A.6-4}$$

$$CI_{Upper} = \widehat{cv}\left[\left(\frac{\chi^2_{v,\alpha/2}+2}{v+1}-1\right)\widehat{cv}^2+\frac{\chi^2_{v,\alpha/2}}{v}\right]^{-1/2} \quad \text{Eq. A.6-5}$$

Where, $v = n-1$, the degrees of freedom of the χ^2 distribution.

Contrary to the mean the confidence interval for the cv is not symmetric. In this case the confidence level obtained from the number of data (sample size) is only investigated for one side of the interval. In this situation the choice was to consider the upper limit of the approximated confidence interval.

The results using data for location 10 at year 10 of Table A.5- 20 are shown in Table A.6- 3.

The variation of the confidence level for the upper bound for specific sample sizes and error values is shown in Figure A.6- 3.

The figure shows that when the error is small, there is a need for a high number of data to reach a high level of confidence, whereas for a higher value of error, the confidence level is already high even with a small sample size. In the particular example chosen here, for an error of 1% the highest sample size (7200 values) provides a confidence level of 73%. When the error is 10%, this level is reached with a much smaller sample size (only 100 values). The results presented above show that from a specific sample size and for a particular error value "e", the confidence level for the mean μ to be within the range defined by $\mu \mp e$ can be determined.

As could be expected a high number of available data provides high confidence level for small error values.

The same applies to the coefficient of variation.

Table A.6- 3: Confidence level % for upper bound for specific sample sizes and error values

Sample size	50	100	150	250	400	650	1050	1700	2750	4450	7200
Error											
1%	1.4	6.2	9.3	13.7	18.6	24.5	31.6	40.1	50.0	61.2	73.0
2%	8.5	16.3	21.5	29.3	37.7	47.7	58.9	70.8	82.2	91.4	97.2
3%	15.5	25.9	33.1	43.4	54.3	66.3	78.2	88.5	95.5	99.0	99.9
4%	22.2	35.0	43.7	55.9	67.8	79.8	89.7	96.3	99.2	99.9	100.0
5%	28.7	43.5	53.3	66.4	78.3	88.8	95.7	99.0	99.9	100.0	100.0
10%	56.1	75.1	84.9	94.0	98.3	99.8	100.0	100.0	100.0	100.0	100.0
13%	66.5	84.6	92.3	97.9	99.7	100.0	100.0	100.0	100.0	100.0	100.0
15%	99.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

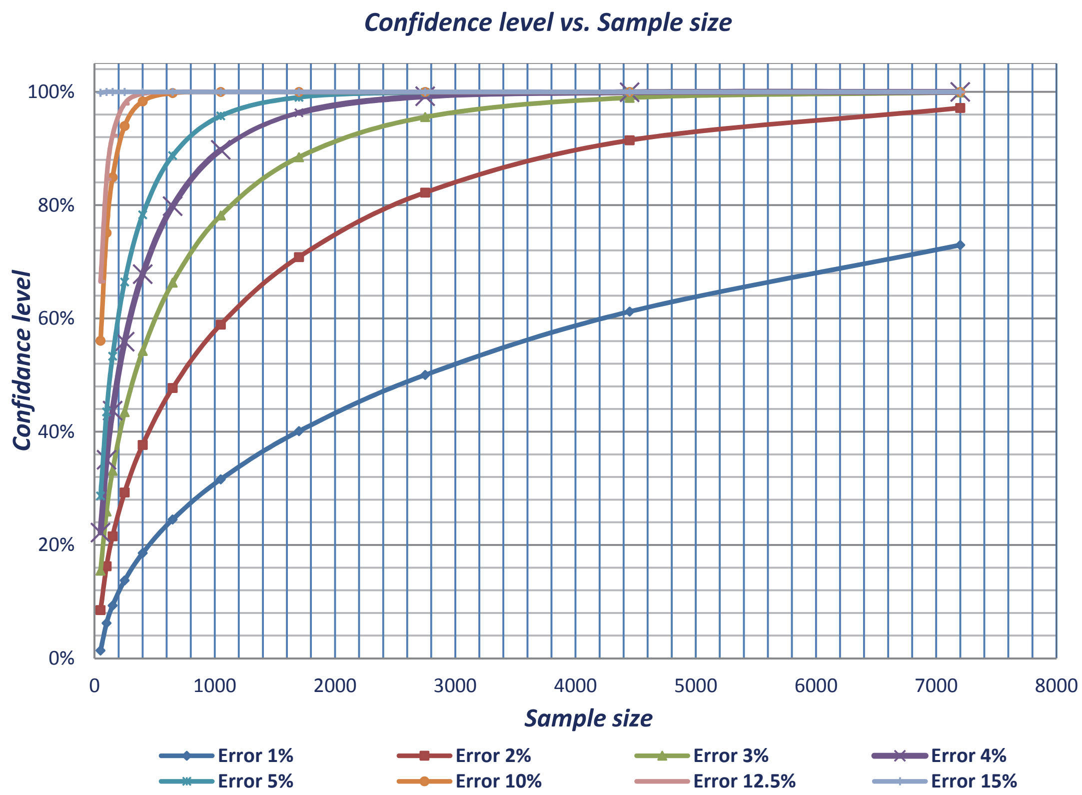

Figure A.6- 3 : Variation of the confidence level for the upper bound of the $\boldsymbol{cv}$ as a function of the sample size for specific error values

(Corrosion at location 14, year 10 of Table A.5- 17, where $\boldsymbol{\mu = 4.92}$ and $\boldsymbol{\sigma = 1.42}$)