University of Strathclyde
Department of Naval Architecture and Marine Engineering

A Risk Based Framework for the Analysis of Intact and Damaged Ships

Subin Kelangath K

A thesis presented in fulfilment of the requirements for the Degree of Doctor of Philosophy

Glasgow, United Kingdom
September 2011

Contents

List of Tables

List of Figures

Acknowledgements

I am grateful to Professor Purnendu K. Das for giving me the opportunity to work under his supervision. I benefit a lot from his professional knowledge and experience. I am grateful to him for his countless encouragements, advices and discussions without which this work would not have been possible.

I express my extreme gratitude to Professor John Quigley, Management Science department, University of Strathclyde who not only helped with the Bayesian modelling of the problem but also gave valuable suggestion and recommendations which helped in achieving the overall objective of the work.

I express my sincere gratitude to Dr Sypros Hirdaris, Lloyds Register, London for giving me the necessary data and help in making this work possible. During my PhD studies, I have been funded by Lloyd's Register (London) and MARSTRUCT (EU). My deepest gratitude for these organisations for their financial support. I am thankful to Professor Nigel Barltrop and Professor Attila Incecik (University of Strathclyde) for providing valuable guidance and support for my work. My special thanks are due to Mrs Thelma Will who was always there for any help and guided me with the administrative details of the preparation and submission of my thesis.

I warmly thank all my colleagues and friends for their valuable advice and friendship which made life in Glasgow pleasant and enjoyable to live and work in. I am indebted to my parents for their continuous support, love and encouragement.

Subin Kelangath K

September 2011, Glasgow, United Kingdom

Abstract

Accident to ships, though a rare event, results in very unfavourable consequences to both human life and environment. Continuous efforts are being made by research community to improve methods to mitigate or prevent consequences of accidents from developing into disproportional levels to the original cause. Hence, precise technical information about the ship and its damage condition will be of paramount importance in making decision which could assist in the necessary rescue and salvage operations.

There are no generally accepted accident design standards but, the four main elements which need to be addressed regarding any accident events are:

- How and why accidents occur: navigation, accident scenarios, probability of occurrence of certain types of accidents.
- What happens (structurally) when an accident occurs: such as structural mechanics in grounding and collision.
- What are the consequences of structural damage: property damages, environmental damages, and loss of life.
- What steps to be taken to address the above consequences: salvage and rescue operations

Analysis of past accident data could help to identify the possible explanations behind maritime accidents and their consequences. It helps in making those initiatives meant to reduce the likelihood of similar accidents and associated causalities in future. Bayesian Belief Network (BBN), represents a class of probabilistic models based on statistics, decision theory and graph theory, is a powerful tool to analyse the conditional dependencies and to identify the underlying relationship between various causes and effects related to ship accidents. BBN's can be modelled using database, expert judgement or by a combination of both. The graphical nature of the network makes it easy for

anyone to understand. The probabilistic networks captured by BBN's can be used as a decision making tool under uncertainties.

Ship structures are designed to resist all loads expected to arise in their seagoing environment. In general, the objective in structural design is to ensure that the ship has adequate strength against the loads expected to act on it during its life time. Traditionally, in the design process, practitioners and designers have used fixed deterministic values for loads acting on girder and for its strength assessment. But, in reality these values are not unique but rather have probability distributions that reflect many uncertainties in the load acting on the ship and strength of the hull-girder. Reliability theory deals with the assessment of these uncertainties and the methods to quantify and include them in the design process. It presents the importance of the contributions of different random variables towards the uncertainty of the limit state function. Hence it provides a more rational basis for decision making than is possible with pure deterministic analysis.

Chapter 1. Introduction

1.1 Introduction

The subject topic is introduced in this chapter describing the problems and the motivation behind the work and the chapter concludes with a layout of the thesis in order to provide with a concise framework of the proposed methodology.

1.2 Risk Analysis in Shipping

Shipping or commercial sea borne transport is the backbone of world trade. According to The International Maritime Organisation (2009), more than 90% of global trade is carried out by the sea. The increased demand and dependence on shipping has led to some serious flaws in the management of shipping activities which has resulted in both unregulated and substandard employment practices, resulting in negligence of safety and has led to serious accidents over the years. Accidents occurring in ships could be sufficiently severe enough to cause major structural damage, loss of life or property and may cause environmental pollution. Hence most of the research going in this field aims to assess damages and their associated probability levels, and to minimize the consequences of the accidents and suggest practical ways of improving and developing damage resistant designs

The most famous and severe maritime disaster in human history may be the sinking of *Titanic*, a passenger liner, in 1912. The sinking resulted in the death of 1,517 people. It was speculated that the damage caused by the collision with the iceberg allowed water to flood six of the sixteen major watertight compartments leading to changes in loading condition which lead to initiate hull buckling and eventually collapse. Similarly, the grounding of *Exxon Valdez* in 1989 at Alaska and single hull tanker, Sea Empress in 1996 at southwest Wales resulted in the pouring of more than 40,000 tons of oil into the Sea.

Another incident which resulted in large oil spill is the damage to oil tanker *Prestige in 2002;* she was split in two halves during a storm off Galicia, Northwest Spain. In total, about 20 million gallons of oil were estimated to be spilt into the sea. As seen from these examples, the huge consequences resulting from accidents have led maritime regulatory organisations to make serious efforts to tackle accidents and limit their consequences.

Large number of ship accidents continues to occur regardless of all the improvements in technology, ship traffic management etc. This imposes the need to ensure that there is an acceptable level of safety to the ship under different accidental scenarios such as during grounding or collision accidents and non-accidental structural failure (NASF) during severe weather conditions, fire and explosion etc.

The consequences of accidents could be measured in terms of loss of ships, cargo or loss of life as well as damage to the environment through pollution to name a few. After a ship sustains damage in the most unfavourable condition, a minimum residual strength of hull girder is to be maintained with regard to preventing, or at least substantially reducing the risk of a major oil spill or loss of ship due to post-accident collapse or disintegration of the hull during tow or rescue operation. The residual strength of hull-girder of ships has emerges as an important issue in early design stage, since hull girder failure will generally lead to pollution of environment.

Recognising the importance of the residual strength (i.e. maximum bending moment in the moment-curvature relationship of a damaged ship) of ships, International Maritime Organization (IMO) has proposed an amendment (MARPOL 73/78, Annex I), which states '*All oil tankers of 5000 tonnes dead weight or more shall have prompt access to computerised, shore based damage stability and residual structural strength calculation programmes*'.

Similarly, IMO introduced the International Safety Management Code (ISM Code) in 1993, which aims to achieve an International standard for safety & operation of ships and for pollution prevention. ISM came into force from July 1998 and became mandatory for all vessels after July 2002.

IMO also recognised risk assessment as an important tool for risk management which led to the development of interim guidelines for the application of Formal Safety Assessment (FSA) to the IMO rule making process (IMO, 1997). FSA is a structured and systematic methodology, aimed at enhancing maritime safety, including protection of life, health, the marine environment and property; by using risk analysis and cost benefit assessment.

Risk studies can be classified into risk assessment, risk management and risk communication. The concept of risk is used to assess and evaluate uncertainties associated with an event. Risk can be measured as a pair of probability of occurrence of the event, and the outcomes or consequences associated with the event's occurrence. Risk is commonly evaluated as the product of likelihood of occurrence and the impact of an accident:

$$Risk = Likelihood \times Impact$$
$$Risk = Probability\ of\ failure \times Consequences$$

Equation 1-1

In the above equation, the likelihood can also be expressed as a probability. The reliability of a ship can be defined as its capability to fulfil its design purposes for a specified time period. This ability is commonly measured using probabilities. Reliability is, therefore, the occurrence probability of complementary event to failure;

$$Reliability = 1 - Probability\ of\ failure$$

Equation 1-2

Based on this definition, reliability is one of the components of risk. Safety can be defined as the judgement of risk acceptability for the system. So, in the risk assessment of ship systems, the structural reliability is a key component and it should be studied more rigorously.

1.3 Organisation of the Thesis

The entire thesis has been structured into ten chapters. The thesis structure and corresponding chapter references are presented in Figure 1-1.

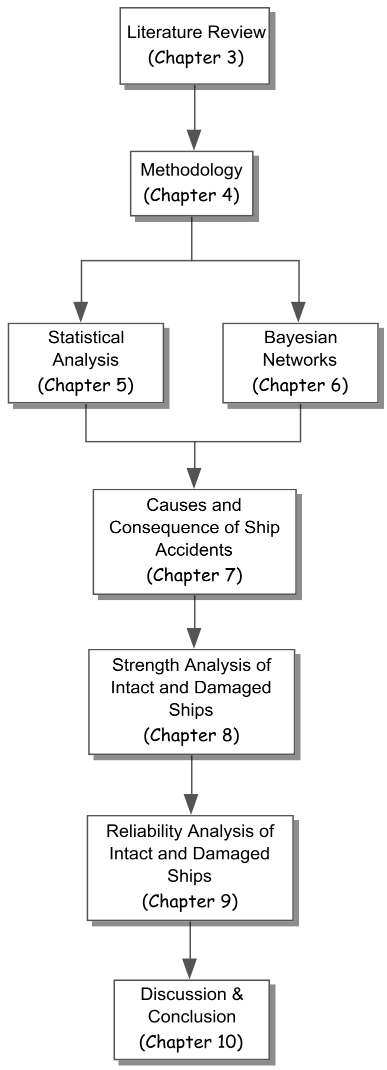


Figure 1-1 Thesis structure and chapter references

A brief description of the content of each chapter is given below;

After a brief introduction in Chapter 1 concerning background and motivation of the work, chapter 2 describes the aims and objectives.

In Chapter 3, a state of the art review on the causes and consequences of ship accidents, followed by in-depth review of literature on the strength and reliability analysis of intact and damaged ships is carried out.

In Chapter 4, the research problem and methodology adopted to address it is described by showing the different elements and their interrelations.

In Chapter 5, statistical and data mining analysis of ship accident database is carried out to determine the underlying factors which acts or are present at the time of an accident.

Chapter 6 gives background and contextual introduction to Bayesian networks and influence diagrams. Different methods available to construct probabilistic networks from a database of cases are shown. Finally, procedure for capturing expert judgement in situation where information on certain variables of interest is either missing or incomplete is described.

In Chapter 7, Bayesian Belief Networks (BBN's) is used to determine the probability of ship accidents and their consequence in terms of structural damage extent and oil spill, for which findings from chapter 5 and 6 are used as input.

In Chapter 8, the ultimate strength analysis of intact and damaged ships are carried out considering different intact and damage scenarios using progressive collapse analysis method.

In chapter 9, the reliability assessment of ships with the focus on hull girder ultimate limits state of intact and damaged ships is carried out. Reliability of damaged ships is studied by considering different load combinations factors for still water and wave bending moment under different damage scenarios.

The conclusion, which the author believes are of relative importance have been presented in Chapter 10.

Chapter 2. Aims and Objectives

2.1 Introduction

The aim and objective of the thesis and the tasks carried out to achieve it are defined in this chapter.

2.2 Objective and Scope of the Work

The analysis of the causes and consequences of accidents and their influence on the strength and reliability of ship is critical in order to make the necessary rescue and recovery operations. The causes of accidents and their consequence are characterised by a large set of interrelated uncertain quantities and alternatives. But, most of the current methods do not consider these conditional dependence or mutual exclusiveness of event and hence fail to capture the true sequence of event leading to an accident and following it. In this regard, Bayesian networks could be considered as a proper risk modelling and analysis tool. Bayesian Belief Networks are graphical representation of uncertain quantities (and decisions) that explicitly reveals the probabilistic dependence between the set of variables and the flow of information in the model. Once the damage extent and its location along the side or bottom are known then the residual strength could be calculated and using this result and the loads acting following accident the reliability index and probability of failure could be determined, which could help limit the consequence of accident from growing into disproportionate levels compared to the initial event.

Hence, the aim of this research is to develop a framework for risk based analysis of ship accidents by integrating information from ship accident database and expert judgement to determine the probability of accidents, the damage extent and oil spill resulting from them and use these results to calculate the residual strength and reliability of ships under different damage scenarios.

These results will be of immense use to design engineers, regulators, insurers etc., and could help in decision making and risk reduction.

In order to meet this aim the following objectives are considered:

- Analyse, ship accident database and other available accident records using statistical and data mining tools to determine the important variables to define causes and consequences of accidents.
- Use Expert judgement to gather information on the causes and consequences of accidents which are either not recorded in the database or include lot of missing data.
- To introduce the use of Bayesian belief networks (BBN) as an ideal risk modelling and analysis tool. The intention is to demonstrate their potential as an intuitive technique, yet rich enough to offer attractive features not always achievable by other means.
- Different methods available for eliciting Bayesian network models from damage database are discussed and compared.
- To elicit probabilistic models using Bayesian Belief Networks by incorporating relevant information's obtained from statistical analysis and expert judgement. These models could be used to determine the probability of realisation of causes and consequences of accidents.
- To determine the residual strength of ships following an accident and its sensitivity to the extent of damage and damage location, a comprehensive study will be carried out by considering different damage sizes and locations along the side and bottom to simulate collision and grounding accidents respectively.
- Simple equations which would be handy in predicting the residual section modulus and ultimate strength will be derived, which is an obvious advantage in cases of emergency or salvage operation.
- The reliability index and probability of failure of ships will be determined under different damage scenarios.

- Sensitivity analysis to identify important design variables and Partial safety factors for codified design to meet the target reliability will be determined.
- Finally, design modification factor will be applied to study its influence on the strength and reliability of damaged ships.

Chapter 3. Literature Review

3.1 Introduction

This chapter make a critical review of existing methods and approaches established to determine the causes and probability of ship accidents and the consequences resulting from it.

3.2 Statistical Analysis of Accidents

Unbiased accident databases can be used as good predictive tools to identify the accident occurrence frequency and their associated consequences. This helps to identify typical and critical incident cases. One of the main problems with accident database is that they are not error free. The source of these errors may be accidental underreporting, information misinterpretation, and incorrect incident categorization regarding ship type, accident type and severity. Furthermore, circumstances related to an incident, such as vessel speed, weather at the time of accident, structural aspects of the vessels (struck and striking vessels) occurrence of pollution, loading condition etc. are not always recorded and are sometimes poorly reported. Another aspect of to be considered while using historic database to predict about the future trends/ frequencies is that, a lot of events will change with time, and these changes would lead to changes in the occurrence frequency of the undesirable events. Friis-Hansen *et al* (2004) listed the changes that will occur which will affect the frequency of wanted events as:

- Traffic composition and a greater number of vessels;
- Improved navigational equipment's;
- Larger and faster vessels;
- The phase out of single hull tankers and the increase of double hull tankers.

Besides, IMO database which maintains marine accidents records, there are several other maritime organizations and agencies which keeps record of such unwanted maritime events. Examples of such organisations are:

- Marine Accident Investigation Bureau (MAIB), under the United Kingdom Ministry of Transport examines and investigates all types of marine accidents to or on board UK ships worldwide, and other ships in UK territorial waters.
- The Australian Transportation Safety Board (ATSB) conducts marine investigations into accidents and serious incidents involving Australian registered ships anywhere in the world, foreign flag ships within Australian waters, or where evidence relating to an accident involving ships is found in Australia.
- The Transportation Safety Board of Canada use an extensive taxonomy to document data from accident/incident investigations.
- The United States Coast Guard (USCG) has documented accident/incident data that date back to the 1960's.
- Japan's Maritime Accident Inquiry Agency (MAIA) collects collision and grounding accidents occurring in Japanese waters.
- Another important course related to maritime accident records is the IHS Fairplay brings the largest maritime database in the world, evolved from the Lloyd's Register of Ships published since 1764, covering ship characteristics, movements, ownership, casualties, ports, news and research. This database provide detailed description of accident in ships, including the type of vessel, its age, years of causality, the operating condition and location at the time of accident, the cargo it was carrying and the consequences such as lives lost and amount of pollution resulting from accidents. But the detailed description of the damage extent is not recorded.

The international Maritime organization (IMO,1995) adopted the Interim Guidelines for Approval of Alternative Methods of Design and Construction of

Oil tankers under Regulation 13F(5) of Annex I of MARPOL 73/78. The guidelines give a probabilistic procedure for assessing the oil outflow performance of an oil tanker design in collision and grounding. The guidelines showed damage density distributions derived from actual damage data of 52 collisions and 63 grounding accident of oil tankers, chemical tankers, Ore/Bulk/Oil carriers of 30,000 tons deadweight and above. Since the publication of the IMO Interim Guidelines, many authors have used them to assess the environmental performance of tankers. According to Sirkar et al. (1997) and Rawson et al. (1998) a major shortcoming of the IMO Guidelines is that they do not consider the effect of the local structural design or the crashworthiness on the damage extent and that all tankers have the same non-dimensional damage distributions.

HARDER - "Harmonization of rules and design rationale" – a project carried out by an association of European industrial, research and academic institutions made a detailed study of the "probabilistic" methods of calculating a vessel's damage stability, in view of the imminent introduction of such approaches to almost all types of ships covered by the SOLAS Convention. Within this work, data on collision and grounding damage were collected, which formed the basis for a accident damage database. New and updated distributions for location, length, penetration, and vertical extent of damage have been drawn from a large database with records of 2,946 casualties, 1,851 collisions, 930 groundings, and 165 other accidents.

The damage data from the HARDER database was processed by Lützen *et al.* (2003), this resulted in various statistical distributions for different types of collision and grounding scenarios. This project and other on-going programs on marine accidents are further described in the 2006 ISSC collision and grounding report.

Other recent comprehensive statistical study on collision and grounding accident data are Zhu *et al* (2002), Skong and Vanem (2004) , Friis-Hansen *et al* (2004) etc.

The Review of Maritime Transport (2010) by United Nations Conference on Trade and Development (UNCTAD) gives a detailed account about the world shipping activities. It provides details regarding the developments in international seaborne trade. It contains details regarding the development of world fleet by millions of dwt, gives overview of world merchant fleet-cargo carrying ship types, the type and quantity of cargo carried.

The International Tanker Owners Pollution Federation Limited (ITOPF) a not-for-profit organisation established on behalf of the world's ship owners to promote an effective response to marine spills of oil, chemicals and other hazardous substances maintains a database of oil spills from tankers, combined carriers and barges. ITOPF report (2009) contains information on Accidental spillages since 1970, except those resulting from acts of war. The data held includes the type of oil spilt, the spill amount, the cause and location of the incident and the vessel involved.

Guedes Soares and Teixeria (2001) studied several databases and made a global assessment of the risk levels and its differentiation in ship types and main type of ship losses and a review was presented on different approaches to quantify the risk in maritime transportation.

Data mining is an important tool for the analysis of databases and to make inferences. It involves discovering new patterns from large data sets and involves methods from statistics and artificial intelligence. Classification tree analysis is one of the important dataming technique. The classification tree is a data mining technique for predicting the membership of cases in classes defined by a dependent variable usually of the categorical type. Each case is measured along a number of predictor variables. The implementation of a classification tree is achieved through a training process (*induction*) in which a specific algorithm is applied to a sample dataset (*a training set*) composed of the predictor variables.

The induction of classification tree works in two phases: the splitting phase and the pruning phase. The splitting phase is an iterative top-down process that expands the tree by defining *nodes* connected by *branches*. The nodes at the end of branches are called *leaves*. The first node at the top of the tree is the *root node*. At every node, the splitting algorithm creates new nodes by selecting a predictor variable so that the resulting nodes are as far as possible from each other. The distance measurement used for the splitting depends primarily on the specific splitting algorithm and is determined by such statistics as gini, entropy, chi-squared, gain ratio, etc. One important feature of the splitting algorithm is the so-called *greedy*. This refers to the ability of the algorithm to look forward in the tree in order to examine if another combination of splitting could produce better overall classification results.

A number of induction algorithms and software tools to implement classification trees appear in the literature. The various algorithms differ mainly in the statistical criteria used for splitting the nodes, in the types of dependent variables they support (scale, ordinal, nominal), in the number of nodes they allow for splitting, and in the elimination of redundancy during the generation of the rules. Among others, Classification and Regression Tree (known as CART or C&RT) (Brieman et al. 1984; Lee et al. 1997), CHAID (Kass 1980) and its extension the Exhaustive CHAID (Biggs et al. 1991), and QUEST (quick unbiased efficient statistical tree) (Loh and Shih 1997) are the most recently developed and more popular induction algorithms. A short description of these algorithms follows:

- **CART** generates only binary trees. It constructs the tree by examining all possible splits at each node for each predictor variable and uses the goodness-of-fit measurement criterion to find the best split. It assumes scale and ordinal or nominal types in the predictor and dependent variables.

- **CHAID** determines the best split at each node by merging pairs of categories of the predictor variable with respect to their distance from the dependent variable. The chi-square test measures this distance. It produces no binary trees and assumes scale and ordinal or nominal types in the predictor variables.

- **Exhaustive CHAID** is an improvement over CHAID as it finds the optimal split by continuously testing all possible category subsets in order to merge related pairs until only one single pair remains.

- **QUEST** constructs the tree by examining the association of each predictor variable to the dependent variable and selecting the predictor with the highest association for splitting. Then Quadratic Discriminant Analysis (QDA) is used to find the best split point for the predictor variable selected. The association of a predictor to the dependent variable is measured by ANOVA F-test, Levene's test, or Pearson's chi-square test if the predictor is of the ordinal, continuous, and nominal type, respectively. QUEST like CART, yields binary trees.

QUEST is generally faster than the other techniques, but cannot be applied to regression type problems, that is, when the dependent variable is continuous. CHAID produces, at each split, a greater number of nodes than the other two algorithms, thus forming wider trees. To date, the literature does not give a recommendation for which algorithm to use to maximize the predictive accuracy of the tree. The practice usually followed is to test the different algorithms in order to find which one minimizes the misclassification costs and at the same time satisfies the restrictions of the dataset, such as the existence of missing values and the handling of ordinal or nominal variables (Witten and Frank 2000). The approach we take in this study is to identify the algorithm that will minimize the total loss accident classification rates.

The present analysis is based on the CHAID (chi-squared Automatic Interaction Detector) algorithm (Kass, 1980). It is a highly efficient statistical technique for segmentation, or tree growing. Since our target variable is a categorical variable, using as a criterion the significance of the chi-squared statistical test, CHAID evaluates all of the values of a potential predictor variable. It merges values that are judged to be statistically homogeneous with respect to the target variable and maintains all other values that are heterogeneous. It then selects the best predictor variable to form the first branch in the decision tree, such that each node is made of a group of homogeneous values of the selected variable. This process continues recursively until the tree is fully grown. As a result of the process, variables that are significant trigger another division of the data while variables that are most significant are discarded for that partition. CHAID is not necessarily binary. Thus, it can produce more than two categories at any particular level in the tree.

Kokotos and Smirlis (2005) used classification trees to predict total ship loss. A set of predictor variables that correspond to a number of factors identified as the most relevant to the total loss of a ship and a sample data generated from a large database of recorded ship accidents worldwide.

Samuelides et al. (2009) studied the probability of occurrence of grounding which is based on a database of accidents involving Greek ships from 1992 to 2005. Parameters influencing the occurrence of grounding are identified and investigated using statistical significant tests.

Kokotaos and Linardatos (2011) used data mining tools for the study of shipping safety in restricted waters. The effectiveness of the enforcement of the International Safety Management Code (ISM-Code) and the examination of its role in the distribution of causes of shipping accidents between human and non-human error was studied. The authors used classification tree and Logistic regression tools for data mining. The results from analysis indicate that influence of human errors in accidents have reduced after the introduction of the ISM-code.

3.3 Causes and Consequences of Accidents

In marine industry the use of formalised methods to compute risk in probabilistic terms has trailed somewhat behind other industries, for example in nuclear and process industries, in which the very high consequence of accidents have encouraged the adaptation of these methods. But, during the last few decades there has been a huge interest in maritime industry to use probabilistic methods to determine the cause and consequences from accidents.

The use of Bayesian Network as a decision support tool in maritime industry is new. There has been very little research in this field. Friis-Hansen (2000) showed the used of Bayesian networks as a decision support tool for maritime application. The accuracy and flexibility of Bayesian networks with other methods were compared with the help of five different examples. It was shown how Bayesian networks may be combined with other methods to use as a good decision support tool. Antão *et al* (2009) showed BBN can be used to model databases. Subin *et al* (2010) showed the different methods available for modelling BBN's from damage database and its application in decision making. Friis-Hansen (2010) used BBN to establish a transparent risk model that describes the relationship between unwanted events and their consequences and how they may materialise.

Bayesian Networks have been successfully applied in other fields such as medical diagnosis (Spiegelhalter *et al.*, 1989), image recognition (Booker & Hota, 1986), language understanding (Charniak & Goldman, 1989a, and 1989b), search algorithms (Hansson & Mayer, 1989), and many others. Heckerman *et al.* (1995b) provides a detailed list of application areas of Bayesian Networks.

Cause of Accident

Reason (1990) proposed the 'Swiss cheese' model, as shown in Figure 3-1, to study Human and Organisational Factors (HOF). This model demonstrates how generic human and organisational errors can be decomposed into logical, mutually exclusive categories, each influencing the next. In the model, each slice of cheese represents a safety barrier relevant to a particular hazard. The holes in the cheese slices represent hidden errors (human error, equipment failure, etc.) waiting to happen. The defensive barriers are like dynamic slices of Swiss cheese against accidents, with the holes constantly subject to changes in size and location. When the holes line up, meaning that all the defences fail and a system's latent susceptibilities are exposed, then an incident occurs. A noteworthy feature of Reason's model is that each of the causative factors is seen as essential but not adequate on its own to cause the occurrence of an accident.

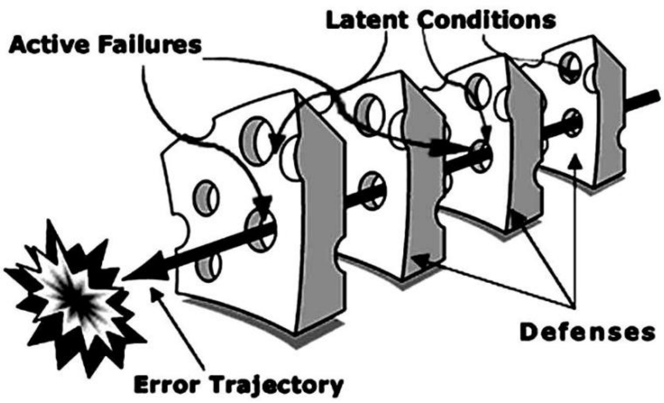


Figure 3-1 Reason's Model

Lützhöft & Decker (2002) studied the effect of automation in shipping and proposed that automation creates new human weaknesses and magnifies existing ones. They use the example of the Royal Majesty (RM) which ran aground when bound to Bermuda as a result of incorrect positioning information, to demonstrate the negative effects of automation.

Parker et al. (2002), made a comparative study of Australian Seafarers and normative data from an onshore population (Australian Maritime Safety Agency-AMSA). Using a self-report questionnaire, respondents were asked to rate how frequently they felt stressed and at what level. Additionally how frequently and to what extent did they engage in health related behaviours (e.g., exercising, drinking, and smoking). The survey had 1,806 respondents comprising; crew, masters, mates, pilots and engineers. Seafarers reported significantly higher levels of stress from source of work pressure than did the normative group, especially on items that assessed relationships with others and the home/work interface. Most seafarers reported occasional to frequent stress at sea (80%). There were inter-departmental differences in stress levels, over 65% of engineers, 60% crew, and over 60% masters report moderate to high stress levels. Frequency and levels of reported stress tended to be lower in the crew that all other groups. Exposure to elevated stress levels for an extended period of time leads to negative mental and physical health outcomes (Quick, Quick, Nelson and Hurrell, 1997). In the AMSA seafaring sample around a third of seafarers (32%) exceeded the National Heart Foundation (NHF-Australia) guidelines for safe limits of Alcohol consumption, 28% of individuals smoked and 81% failed to reach the minimum exercise levels required for good health (as recommended by NHF-Australia) .

In a report by the National Transportation Safety Board (1999) trying to address operator fatigue, seafarers were recognized out of the occupational groups included to have the second highest number of maximum work hours in a 30 day period, behind rail operators.

Psaraftis *et al* (1994) made an in-depth study on accidents involving Greek flagged ships from 1984-1994 and concluded human factors as the major cause of accidents.

Grech, Horberry, and Smith (2002) collected report of 177 maritime accidents from 1987-2007 (from eight countries) to examine human error in maritime.

They observed that 71% of all human error types on ships are situation awareness related problems. Using Endsley's error taxonomy to define three levels of situation awareness, the most commonly occurring SA based errors were at level one 59%, 33% at level 2 and 9% at level 3.

Baker *et al* (2004) made an in-depth study on the role of human factors in ship accidents. The finding of the study shows that human errors is the most dominant factor in maritime accidents and that among all human error types classified in numerous databases and libraries of accident reports, failures of situation awareness and situation assessment overwhelmingly predominate.

A lot research work has been carried out in estimating the dependency of shipping accidents from various factors (Celik *et al.,* 2010; Grech *et al.,* 2008; Tzannatos, 2005; Tzannatos, 2002) as well as in assessing the effectiveness of the measure of the enforcement of the ISM-Code. It could be concluded from these studies that post ISM implementation, there is significant improvement in safety standards in shipping.

Consequence of an Accident

According to ISSC (2009), the damages to hull structures after grounding can be classified into five fundamental damage modes, which are: (a) the stretching mode of shell plating and local large deformation, (b) plate perforating model for ruptured plating, (c) plate denting mode for main supporting members, (d) axial crushing mode for intersection of main supporting member and (e) plate tearing mode for plate in plane compressed by sharp body.

A grounding accident represents ships hitting the seabed or shore. The coastal zones, shoals, rocks and islands are basically stationary objects relative to the vessel. Thus a Probabilistic collision scenario data includes:

- Speed and mass of the vessel
- Depth (or elevation) of the obstruction or bottom

- Description of the obstruction or bottom
- Bottom-vessel interaction (lifting of vessel)

Except for ship speed, very little grounding scenario data has been collected or published. The 'standard rock' remains a submerged mystery. Tikka (2001) collected grounding data from four US high tanker-traffic locations. Data included ship speed, tidal conditions and obstruction depth. Rawson *et al.* (1998) proposed a set of grounding scenario pdfs developed using expert opinion, and these pdfs were used with MIT's DAMAGE program to calculate grounding damage pdfs. These pdfs showed reasonable agreement with the IMO grounding damage pdfs, but results are not conclusive.

Many researchers have been carried out to find the consequence resulting from accidents. Sirkar *et al.* (1997), Rawson *et al.* (1998) and Simonsen (1998) performed theoretical grounding analyses and established damage density distributions given a grounding event for a specific ship. These calculations are based upon many assumptions, such as the distribution of grounding speeds and the distributions of rock shapes and rock elevations. Therefore the validity of the damage density distributions obtained by such theoretical calculations needs further verification.

Previous analyses of bottom damage due to grounding on plane, sloping sand or rock bottoms have shown that larger ships suffer considerably larger bottom damages than smaller ships. In addition, larger ships are exposed to larger hull girder sectional force due to grounding (Pedersen, 1994).

Zhang *et al.* (2000) studied analytical methods for assessing the effect of structural design and size of ships in accidental grounding and collisions. Analytical equations for calculating the approximate ratio between the relative damage lengths of two ships were derived. From the results it is seen that for similar conditions the relative damage length of a 240m tanker is two times that of a 100m tanker. This shows that the tanker size has a significant influence on the relative damage length in accidental grounding. Zhang (2002) developed a semi-empirical formula based on a parametric study to determine the grounding force in the event of a ship running into rock in a high-energy grounding. The bottom strength of single hull structures and double hull structures in ship-grounding incidents are compared. Simple expressions for estimating damage resistance and damage extent in oil tankers grounded on a rock were proposed. These formulae are considered valid for oil tankers of 190m and above, in high-energy grounding scenario since the derivation are based on the analyses of oil tankers.

Naar *et al* (2002) examined the performance of several double bottom arrangements in stranding damage scenarios. The ship bottom was loaded with a conical indenter with a rounded tip, which is forced laterally into the structures at different positions. The resistance forces, energy absorption and penetration with fracture for four different structures were equated, which were:

- type I, a conventional double bottom,
- type II a structure with hat-profiles stiffened bottom plating,
- type III, a structure with steel sandwich panel in outer bottom and
- type IV, a structure with hat-profiles in both inner and bottom.

The results showed that the penetration where the tank top fractures is almost the same for the four structures; moreover, the energy absorption at this point of puncture of the inner bottom was quite high for structures II and IV, whereas the weights of those structures are not much higher than for the conventional structure. Structure IV, for example, is 4% heavier than the conventional structure (structure I) but the average energy absorption at the point of tank top fracture is 33% larger than for the conventional structure. Sandwich panels are locally weak due to the small thickness, when a sharp local contact takes place. On the contrary, for a wider shape of contact the double bottom construction will be stronger than conventional stiffened plate bottom.

Friis-Hansen et al (2002) at Technical University of Denmark developed Grounding and Collision Analysis Toolbox (GRACAT) a software which allows a multitude of analyses related to collision and grounding accidents. The software consists of three basic analysis modules and one risk mitigation module: (1) frequency, (2) damage, and (2) consequence. These modules can be used individually or in series and the analyses can be performed in deterministic or probabilistic mode. Finally, in the mitigation module risk profiles for the calculated consequences can be calculated and compared to alternative solutions by assignment of a cost function to the consequences. The use of Bayesian networks for predicting the causation factor is also included in the software.

Simonsen *et al* (2004) developed a probabilistic framework for the damage stability requirements, also taking into account the crashworthiness of the ships. They reported a length of damage, counting from the fore end of the vessel, which is less than or equal to the ship length and not less than

$$L_{dR} = 1.12\, L.GDI^{0.7}P^{1.45}\ [m]$$

where P is the probability of survival and is suggested to be set to P=0.6, and the Grounding Damage Index (GDI), which is the ration of kinetic energy to raking resistance is calculated as

$$GDI = \frac{0.5MV_s^2}{LF_H}$$

where , L [m] is vessel length, M [kg] is vessel mass, V_S [m/s] is vessel service speed, F_H [N] is the horizontal raking force.

Zhu *et al* (2002) did a comprehensive damage data survey also derived theoretical models and semi-empirical formulae based on parametric studies to study the damage extents of grounding ships resulting from single rock and multi rock grounding scenarios. Simonsen *et al*. (2009) developed a simplified yet rather accurate expression for the raking force based on raking tests, large scale grounding tests and large-scale FEM analysis.

Alsos *et al.* (2007) using finite element simulations calculated the effect of locations and different sea bottom topologies in the resistance of penetration of the ship bottom in grounding accidents. Three indenter topologies with four different locations as shown in Figure 3-2 were examined: (1) ‘Rock’: Indenters are much smaller than the ship itself, with a paraboloid bottom diameter of 0.2 ship beam; (2) ‘Shoal’: The ‘shoal’ dimension is about half the ship hull width; (3) ‘Reef’: An intermediate indenter. It was found from the study that traditional pinnacle indenter punctures the skin easily with local structural damage, large shoals or dish type indenters may deform large parts of the hull structure.

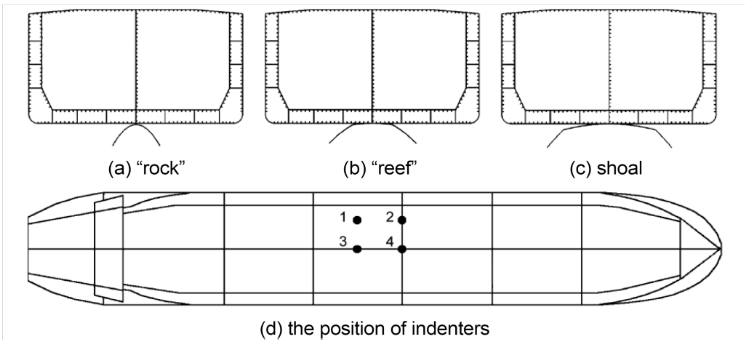


Figure 3-2 Three indenter topologies and position Alsos *et al* (2007)

Other comprehensive studies include statistical collision and grounding accident data and analysis. These studies are: Zhu et al (2002), Skjong and Vanem (2004), Friis-Hansen et al (2004), Wu and Liu (2004), and Liu and Wu (2004).

A collision accident represents an impact between two moving objects. A collision may also vary in terms of how the vessels approach each other: head-on, crossing or overtaking. Thus a probabilistic collision scenario data includes:

- Description of the striking ship
- Struck and striking ship collision speeds
- Collision angle

- Impact location.

Ship speed, collision angle and strike locations probability distribution functions (pdfs) are less sensitive to particular ship design characteristics and are more common in their applicability. Hence, it is desirable to use historical data for these pdfs. Specific trade routes may also be used in collision and grounding simulations to predict ship speeds and collision angles, such a prediction becomes very tenuous when two ships are manoeuvring to avoid a collision. .

Details of damage location in ship accidents are limited. It is only possible to infer these from the damage description. The current IMO pdf for longitudinal impact location specifies a constant value over the entire length of the stuck ship. Sandia (1998) data indicates a somewhat higher probability of midship and forward strikes compared to the IMO data. HARDER project data indicates a gradual and slight bias towards the bow when uncertain bow striking cases are removed. This is probably the best collection of data for impact location available at this time.

Ship heading and speed prior to a collision are often included in accident reports, but collision angle and ship speed at the moment of collision are frequently not included or only estimated and described imprecisely. These parameters, particularly striking ship speed are extremely important in determining absorbed energy. The striking ship speed, at the moment of collision, is not strongly related to service speed, or even ship speed prior to the collision event. It depends primarily on actions taken just prior to the collision. Striking ship speeds reported by the HARDER Project are somewhat higher than speeds reported by Brown (2002) and this difference is significant. Additional data is required for this parameter and the data should be updated over time.

The pdf for struck-ship collision speed tend to be very different from service speed. Struck ships are frequently moored or at anchor end this greatly skews their pdfs towards zero speed. Again, the HARDER data represents somewhat higher speeds than the data collected by Brown (2002) but the trends are consistent.

Samuelides *et al* (2008) investigated ship-ship collision scenarios that are included in existing rules and regulations or have been applied in the design process of a ship, and present data concerning the distributions of the kinetic energies of ships travelling worldwide. The authors further include quantitative examples of the 'loading' according to rules and regulations or derived from the energy distributions, which is to be used in the design process of a ship.

The information paper on Formal Safety Assessment on crude oil tankers, submitted to IMO by Denmark, (IMO 2008) specified typical damage penetrations and their associated probability of occurrence.

The DNV rules for Compressed Natural Gas (CNG) carriers (Dnv, 2004) include a special section for collision damage analysis.

3.4 Strength Analysis of Ships

The ultimate strength of ship plates is very important from the design and safety point of view because the collapse loads of plates can often act as an indicator of the ultimate strength of the whole stiffened panel in ship structures (Guedes Soares, 1992). The problem has been addressed for centuries for the general plated structures and for several decades even with regard to ship structures (Mansour, 1971).

Caldwell (1965) was the first to make attempts to evaluate the ultimate strength hull-girder strength of a ship structure. He applied *Rigid Plastic Mechanism Analysis* to evaluate the ultimate hull girder strength. The influence of buckling was considered by reducing the yielding stress of the material at the buckled part.

Smith et al (1977, 1986) and Dow et al (1981) developed an incremental curvature procedure to determine the strength of ship, which allows the derivation of a moment-curvature relationship for a complete hull. It is a hybrid method based mainly on a finite-element formulation but where the plate element strength is obtained from a set of empirical curves.

Billingsley (1980) used an engineering approach which considered a very simplified model for each individual beam column element. The strength of the hull girder was obtained from the summation of the individual contributions of each element.

While the early attempts were based on the collapse strength of an individual plate, more recent ones have considered the sequence of collapsing plates. Adamchak (1984) has developed a simplified method, together with a computer program which implements it, where the ultimate strength of each panel includes a flexural-torsional buckling formulation. Curves of moment-curvature are built from a set of discrete points corresponding to the buckling of each panel.

Lin (1985) described a similar method but he considered a different approach to assess the plate strength and used a dynamic relaxation method for the stiffened panel strength. Several comparisons were made with experimental results, from which two simplified expressions for ultimate moment prediction were presented.

In addition to these simplified methods, a fully nonlinear finite-element analysis has been performed, for example, by Kutt et al (1985), but this was shown to be a very time consuming task both in modelling the structure and in computing time.

Rutherford & Caldwell (1990) presented a comparison between the ultimate bending moment experienced by a very large crude carrier (VLCC) and the results of retrospective strength calculations in which a simplified approach to stiffened plates collapse was used, but without considering the post-buckling behaviour. Also, the importance of lateral pressure, initial deformations, and corrosion rates was investigated. The validity of the model and method was confirmed by a nonlinear finite-element program. Later Gordo *et al* (1996) calculated the ultimate Energy Concentration using simplified formula considering the effects of corrosion and initial imperfections on flexural buckling. Khan *et al* (2006) studied the ultimate strength of Energy Concentration considering the tripping, flexural buckling and post buckling behaviour of local elements, taking into account of corrosion, welding induced residual stresses and imperfection.

Kozlyakov and Egorov (1991) carried out to determine the strength of ships with side damage on either port or starboard side. It was noted that the hull girder section modulus was reduced by 25% and could be as high as 47% in container carriers. In addition, the damaged hulls were exposed to additional stresses for losing symmetry in its cross section. The combined action of vertical bending and torsion could cause up to 50-80% reduction of the ship's longitudinal strength.

Yao (1993) proposed an analytical methods to derive average stress-strain relationship for the element composed of a stiffener and attached plating by combining the elastic large deflection analysis and the rigid-plastic mechanism analysis in analytical forms form the work performed by Yao and Nikolov (1991, 1992). Then by taking into account of the equilibrium condition of forces and bending moments acting on the element, the relationships are derived. When the stiffener is in elastic region, a sinusoidal deflection mode is assumed, whereas after the yielding has started, a plastic-deflection component is introduced which gives constant curvature at the yielding mid span region.

Wang *et al* (2002) presented some simple equations for a quick evaluation of the residual section modulus of typical commercial ships. Different degrees of damage caused by either a collision or grounding is assumed, and the formulae were derived form a n extensive study of 67 ships (double hull tankers, single hull tankers, bulk carriers, container carriers). These formulae provide handy tools for predicting the residual strength of a ship's hull in an accident, without performing step-by-step detailed calculations.

The application of FEM to predict the ultimate strength of hull girders is very few due to their time complication. A ship's hull girder is, perhaps, too large for such a kind of analysis to get accurate results easy, a number of significant works have, nevertheless, been published. Chen *et al* (1983) and kutt *et al* (1985) performed static and dynamic FEM analyses modelling a part of a ship hull with plate and beam-column elements and orthotropic plate elements representing stiffened plates and discusses the sensitivities of the ultimate hull-girder strength with respect to yield stress, plate thickness and initial imperfections. Valsgaard *et al* (1991) analysed the progressive collapse behaviour of the hull-girder models tested by Mansour *et al* (1995), Ozguc *et al* (2006) compared hull girder ultimate strength of a single hull and a double hull bulk carrier with collision damages. Damage to side structures was derived from FEM analyses of various collision scenarios. Amlashi *et al* (2007) carried out the ultimate strength analysis of a bulk carrier hull girder under alternate hold loading condition to establish rational ultimate longitudinal strength criteria for the hull girder under combined loading. But unfortunately the results of FEM analysis to evaluate the hull girder strength are not so many at the moment because the number of elements and nodal points become very huge if rational results are required.

Luis et al. (2007) investigated the residual longitudinal strength of double Suezmax tankers after groundings or collision. The calculations were performed using a computer code based on the Smith method. The damage was simulated by removing the damaged elements from the midship section. Luis et al (2006) presented a reliability assessment of a damaged hull in which they account for the reduced strength and also for the changes in loading in a damaged state.

Fujii, Kawabe and Yao (2007) investigated a series of progressive collapse analysis applying the Smith's method for evaluation of ultimate hull girder strength and its sensitivities with respect to design parameters and suggested from the numerical results, that the ultimate hull girder strength might be sensitive to the progress of corrosion.

Rim et al. (2008) conducted the a series of collapse test using box-girder model of 720mm×720mm in section and 900mm in length to investigate the effect of stranding damage size on the ultimate strength of ship structures. From the experimental results, they found that the ultimate strength is reduced as the damage size increased, and the ultimate strength is reduced by about 20% than that of no damaged one when the damaged size is 30% of the breadth of the specimen.

Ren et al. (2008) calculated the ultimate bending moment of damaged warships based on Smith method. They showed the statistic characteristic values of residual capability are most evidently influenced by the variability of yield stress and secondary influenced by the variability of broken hole and plate thickness.

Guedes Soares *et al* (2008) evaluated the ability of simplified structural analysis methods, based on Smith's formulation to predict the ultimate strength of a damaged ship. The simplified methods used in the study compare well with each other for the ultimate strength calculation. The results compare well with FEM results also. It is possible to say that simplified methods compare well among each other for the calculation of the ultimate bending moment of damaged ships.

There exist design standards to obtain the required strength following an accident. Germanischer Lloyd (GL) has a class notation COLL that ranks the collision resistance of ships (GL 2004), under which the collision resistance of a vessel's strengthened side is compared to another vessel's non-strengthened single hull. ABS has a class notation RES for Safe Hull vessels that demonstrate adequate hull girder strength after a collision or grounding accident. This notation requires a ship to maintain a minimum hull girder residual strength after sustaining structural damages in the prescribed most un-favourable condition. This minimum strength will help to prevent or substantially reduce the risk of a major oil spill, ship loss due to a post-accident collapse or disintegration of the hull during a tow or rescue operation. The International Association of Classification Societies (IACS) has developed a series of unified requirements for bulk carriers that directly require adequate structural strength in flooded conditions.

3.5 Load Effects on Ships

The hull of ship at sea is subjected to the most complex and varying load. The prediction of loads and load effects is a fundamental task in the design of ship structures. In general this consists of the following three major aspects:

- Prediction of still-water loads
- Prediction of wave loads
- Prediction of combined loads

Still-water loads are forces that result from the action of the ship-self weight, the cargo or dead-weight and the buoyancy. They include bending moment, shear force and lateral pressure. Still-water loads remain constant under a specific load condition. Still-water bending moment changes from one loading condition to another and hence need to be treated as a stochastic process in long term.

Wave loads are the forces that result from wave action. Wave bending moment is considered as a stochastic process in long and short term due to the varying nature of it. Wave bending moment include vertical moment, horizontal moment, torsional moment, shear forces, hydrodynamic pressure, and transient loads such as springing and slamming.

The prediction of ship motions and dynamic wave induced loads acting on a ship has been a main topic in the field of ship hydrodynamics. The development of a two-dimensional harmonic flow solution was accomplished by Ursell (1949). Korvin-Kroukovsky (1955) introduced the heuristically-derived strip theory to ship motions as the first strip theory. This theory was modified by his sequel paper (Korvin- Kroukovsky and Jacobs, 1957) and Jacobs (1958), and the theory restricted on heaving and pitching only. Jacobs et al. (1960) carried out correlation works with the analytical calculation of ship bending moments and the results of model tests in regular waves. The validity of the strip theory on a high-speed destroyer hull was shown by Gerritsma and Beukelman (1967). Salvesen et al. (1970) expanded the original theory for more general modes of motions and wave headings. Further a number of improved strip theories have been developed. Among them there are rational strip theory (Ogilvie and Tuck, 1969) and unified strip theory (Newman, 1978). Good agreement between strip theory predictions and experimental data has been found for many classes of mono-hull forms (Kim et al., 1980) and twin-hull ships (Lee and Curphey, 1977). Fully three-dimensional numerical solutions of the slender ship motion problem at forward speed have been attempted by Chang (1977), Inglis (1980) and Chan (1992, 1993 and 1995). In spite of practical success of these linear two-dimensional and three-dimensional theories, their applications are limited to small amplitude motions.

However, large amplitude motions and resulting structural responses, which cannot be accurately predicted by linear theory, are key issues for assessments of ultimate hull girder strength of intact ship and residual strength of damaged ship in extreme wave conditions. There is a need to use techniques being capable to take into account these non-linear effects. Although non-linear boundary element technique is applicable to solving full non-linear ship motion problem, its computational cost is prohibitively expensive in practical applications. On the other hand, alternative practical approaches to solving non-linear problem have been attempted. For the past decades, practical tools have been developed based on the calculations of the hydrodynamic and hydrostatic forces at the instantaneous positions of the ship body sections for intact vessels motions with or without forward speed. In these practical, so called quasi-non-linear, time domain methods the hydrodynamic forces are obtained from the solution of linear frequency domain. These time dependent hydrodynamic coefficients, wave exciting forces and hydrostatic forces are employed in the coupled equations of motion. Various applications of the quasi-non-linear time domain method to the prediction of mono and multi-hull ship motions and loads can be found in Yamamato et al. (1978), Borresen & Tellsgard (1980), Chiu & Fujino (1989), Fang & Her (1995), Fang et al. (1997) and Tao & Incecik (1996). No oblique waves were considered in these studies. On the other hand, Fujino & Yoo (1985) investigated wave loads acting on a ship in large amplitude oblique waves. The predicted peak values of the wave loads and their non-linear behaviour are in good agreement with experimental measurements. Although large amplitude motions have been investigated in the above studies, the equations of motion were solved in a linear sense where Euler angles are implicitly assumed to be small.

The still water bending moment (SWBM) may be modelled by a Poisson rectangular pulse processor in the time domain. This is because the SWBM at a given section of the ship is constant under specific load condition but varies from one load condition to another, and the duration of each load condition is also a random variable.

The space variation of still water loads largely depends on the amount of cargo and its distribution along the ship. Measures are taken to ensure that the maximum specified still water loads are not exceeded during ship operation. Captains are encouraged to load their ships in a way not dramatically different from those reference conditions given in a load manual, in the hope that maximum values are not exceeded. However, application of computerised load distribution procedure gives captains as much freedom to load the ship as they want, as long as the maximum loads are within the specific limits. The consequence is that the load manual is less likely to be followed, and a larger variation of load conditions is due to the human decision involved.

Statistical analysis of SWBM has been addressed since 1970's. The idea that any ship has a probability distribution of SWBM was first supported by Lewis et al. (1973) based on limited data of several cargo ships and one bulk carrier. Ivanov&Madjarov (1975) fitted the normalised maximum SWBM by a normal distribution according to full or partial cargo load conditions from eight cargo ships for periods of two to seven years. Mano et al. (1977) studied the nature of still water conditions by surveying log-books of 10 container ships and 13 tankers, and concluded that their distribution is approximately normal as shown in Figure 3-3. Dalzell et al. (1979) examined the service and full-scale stress data of a large, fast container ship, a VLCC and a bulk carrier. They concluded that the still water bending stress variations appear to be random and subject to the control of their extremes by operators.

In early 1980's, some still water bending stresses of different ships were reported by Akita (1982) as a result of work carried out in Japan. This information was presented separately for a group of 10 container ships as well as for a group of 8 tankers. Based on this, Kaplan et al. (1984) found that the coefficient of variation (cov) of still water bending moment (SWBM) for container ships is 0.29, and for tankers it is 0.99 for ballast condition and 0.52 for full load condition.

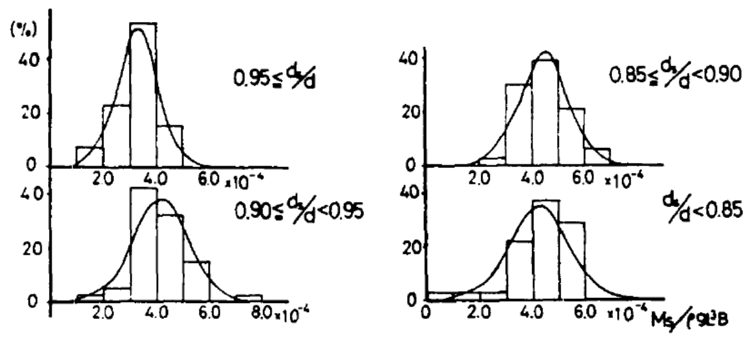


Figure 3-3 Distribution of still water bending moment of container ships (Mano et al., 1977)

Guedes Soares& Moan (1988) analysed SWBM resulting from about 2000 voyages of 100 ships belonging to 39 ship owners in 14 countries. Still water load effects were assumed to vary from voyage to voyage for a particular, from one ship to another in a particular class of ships and also from one class of ships to another. The analysis was centred on the mean value and standard deviations of the loads in the critical midship region. The still water loads were treated as ordinary random variables. The authors reported a very large variability for tankers.

Due to the random nature of the ocean, the wave induced vertical bending moment is a stochastic process. It may be described by either short-term or long term statistics or probabilistic estimates. The short term WVBM corresponds to a steady (random) sea state which is considered as stationary with duration of several hours. Within one sea state, the WVBM follows a Gaussian process. The maxima of WVBM thus follow a Rice distribution. For a narrow banded Gaussian process, the Rice distribution reduces to the simple Rayleigh distribution.

The evaluation of the wave induced load effects that occur during long-term operation of the ships in a seaway was carried out for sea areas in the North Atlantic given by Global Wave Statistics (Hogbenet al., 1986). ATLN refers to the wave induced bending moment in the North Atlantic calculated based on the world sea areas 8, 9, 11, 15 and 16. (Figure 3-4). This scatter diagram was considered representative of a North Atlantic crossing although other assumptions about the route could obviously be made. The effect of choosing alternative routes was dealt for example by GuedesSoares and Moan (1988). To standardize the procedure for computation of long-term distributions, IACS (2000) has issued Recommendation note No. 3 suggesting that the IACS North Atlantic scatter diagram covering areas 8, 9, 15, 16 should be used.

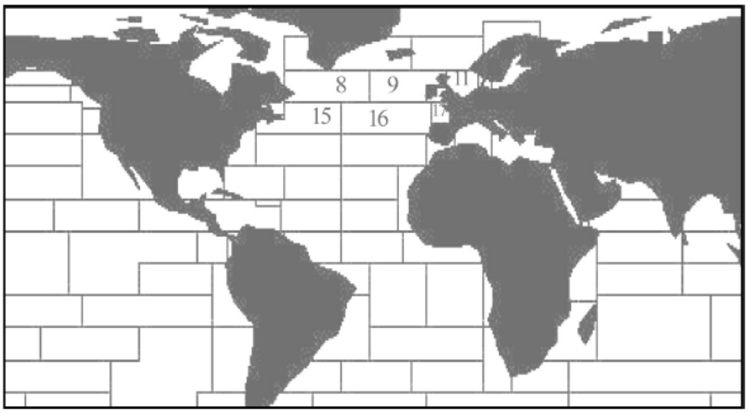


Figure 3-4 Global wave statistics of ocean areas

The long-term statistics are based on weighted short-term statistics over the reference period of concern. Typically, design wave loads in classification society rules are of specifically based on long term statistics. The long term prediction of wave loads is usually based on a linear analysis, which is then corrected to account for nonlinear effects, based on experiments and/or full-scale measurements. It is generally accepted that long-term WVBM may be modelled as a Poisson process. The peak of each individual WVBM, M_{wv} canbe well approximated by a two parameter Weibull distribution, as shown in Figure 3-5 after Frieze et al. (1991). Denoting $M_{wv,0}$ as the maximum WVBM in the reference design period T_0, the cumulative distribution function of each individual $M_{wv}$is then expressed as:

$$F_{M_{wv}}(M_{wv}) = 1 - exp\left[-ln\,(v_w T_0)\left[\frac{M_{wv}}{M_{wv,0}}\right]^{h_w}\right] \qquad \text{Equation 3-1}$$

where$h_w$is the shape parameter and $v_w$is the mean arrival rate of one wave cycle.

It should be noted that Equation 3-1 does not account for the dependence between the individual peaks, while in reality they are correlated with in a single sea state. Alternatively, M_{wv} in Equation 3-1 may be considered to refer to the individual maximum bending moment of each sea-state, in which $v_w$then becomes the mean arrival rate of one sea-state, so that mutual dependence of individual moments can be neglected.

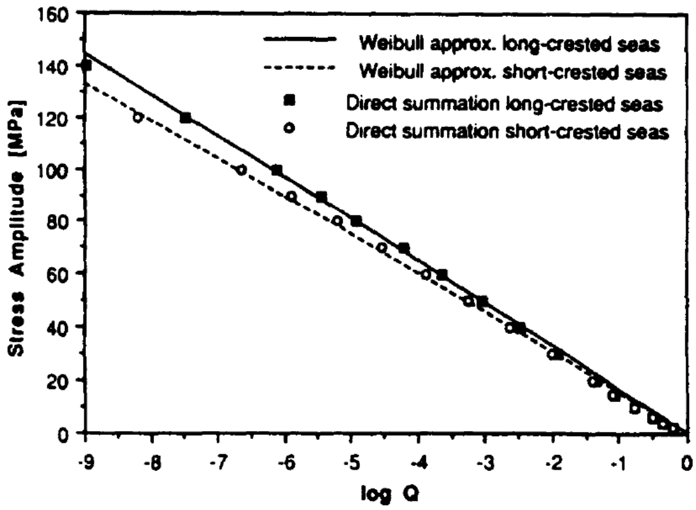


Figure 3-5 Long term distribution of deck stresses resulting from WVBM (Frieze et al., 1991)

3.6 Reliability Analysis of Ships

The determination of Probability of failure is the most researched part in the theory of reliability. Before the sixties a variety of studies on second moment were carried out, a milestone in this direction was laid by Freudenthal (1956) who used complete probability models. However, it is the work by Cornell (1967) which gave second moment concept a wide acceptance. To date, second moment concept have become so popular that it has a significant place in any text books concerning structural safety. Typical of them are those by Ang and Tang (1984), Madsen, Krenk and Lind (1986), Ditlevsen and Madsen (1996), Zhao (1996), and Melchers (1998). The first order and second order moment theories (FOSM and SOSM) are now increasingly used in a variety of engineering fields. In these theories the tedious part of integrating of the joint probability density functions (JPDF) of the design variables are circumvented by transforming the actual problem into a least distance problem in a standard normalised space. Orthogonal transform is used to uncouple the correlated design variables which essentially show that the problem is in its core an optimization procedure.

Monte Carlo Simulation (MCS) plays a very important role in reliability analysis. MCS is not affected by the number and distribution type of the basic variables.

The method solves highly non-linear problems and problems where the limit state function is not known explicitly. A number of variation reduction techniques have been proposed such as the Importance Sampling Method but as always the computation cost in large complex structural systems is still significantly high (Bucher, 1988).

The latest development in the field of structural reliability analysis is the Response Surface Method (RSM). It is very suitable in cases where the limit state function is known only point-wisely by such numerical methods as the FEM rather that in closed form. In short, RSM is a system identification procedure, in which a transfer function relates the input parameters (loading and system conditions) to the output (response in terms of displacements or stresses). The observations required for the identification of the most suitable way to relate those two are usually taken from systematic numerical experiments with the dull mechanical model and the transfer function obtained approximately defined as the response surface (RS). It was in the early 1950s that the basis concept of RSM first developed in experimental fields, but only recently, it has been introduced into the field of reliability analysis. It combines the deterministic structural analysis software and the basic reliability ideas aforementioned. In addition to this, even for those problems that other approximate methods seem to be susceptible to, the RSM is shown to be superior in both accuracy and efficiency with its only drawback being the experiment design and the identification of unknown parameters in the RS which influence the whole algorithm. Work by Bucher (1990) and Rajashekahar *et al.* (1993) have led the ways of future research. Advanced algorithm based on that work can be found in work published by Kim *et al.* (1997), Zheng *et al* (2000, 2001) and Yu *et al* (2001).

The first work on ship structural reliability was reported by Nordenstron (1971). He calculated the failure probability by integrating the failure domain assuming a normal distribution for both ultimate strength and still water bending moment and Weibull distribution for wave bending moment. Mansour

(1972) and Mansour & Faulkner (1973) presented the level three formulations to provide the first complete reliability analysis of a ship structure. They adopted Nordenstrom's model for wave induced loads and developed a probabilistic model for the ship strength for various modes of failure.

Mansour adopted the distribution of the wave-induced vertical bending moment at a random point in time to calculate the reliability index of 19 merchant ships using the second order reliability method. Faulker & Sadden (1979) considered the most probable maximum load given by Poisson distribution whose mean value is the most probable maximum calculated at the 10^{-8} probability level. Using this approach, they obtained a reliability index of 2 for warships, while the one calculated by Mansour for merchant ships were in the range of 7.

Mansour (1990) presented an introduction to structural reliability theory in the form of ship structural committee report (SSC-351). The author presented a state-of-the-art report in structural reliability theory directly specifically for marine industry.

Lee (1992) presented reliability based limit state design format of ship structures. The author presented the reliability analysis of local and global structures of bulk carriers and oil tankers and derived the target reliability indices.

Mansour & Wirsching (1994) studied the sensitivity factor and their application to marine structures. They considered four different ships for their study and presented the potential of using sensitivity factors in decision making and trade-off studies.

Zheng & Das (2000) proposed an improved response surface method for reliability analysis of stiffened plate structures. The response surface function is formed in a cumulative manner in order to account properly for the second order effects in the response surface with acceptable computational effort involved in the evaluation of the state function.

Guedes Soares & Teixeira (2000) performed structural reliability analysis of two bulk carriers. They considered the time dependent degrading effect of corrosion on the capacity of structure. First-order reliability method was used for calculating the probability of failure. It was shown that the loss in ultimate strength in sagging is equivalent to the reduction in total area of the section, but the ultimate moment in hogging exhibits a larger reduction. Comparison of reliability indices for single and double skin tankers were performed and it was observed that the single skin tankers exhibits lower reliability index.

Das *et al.* (2003) presented modelling uncertainty evaluations of strength predictions of ring stiffened shells and ring and stringer stiffened shells for various modes of buckling and various radius to thickness ratio values (range used in offshore structures). Comparisons are made for API BUL 2U and DNV buckling strength of shell models.

Fang and Das (2005) used Monte Carlo simulation to predict hull-girder collapse reliability for intact and damaged ships. The strength predictions were based on Smith's method which was presented in Fang and Das (2004). Paik *et al.* (2003) carried out time-dependent reliability model on a bulk carrier, a double hull tanker and a FPSO. The reliability model accounts for the effects of fatigue-induced cracking and corrosion. Timelines are presented for each vessel relating the probability of hull-girder failure to ship age. Each timeline is heavily dependent upon the modelling assumptions such as severity and location of corrosion or cracking. Qin and Cui (2003) presented a discussion on current corrosion models and propose a new model that uses three piece-wise continuous stage to represent the corrosion process.

Guedes Soares *et al.* (2006) studied the reliability of a suezmax double hull tanker accidently grounded using First-order reliability method. The wave induced loads were calculated from the long-term distribution related to the

'Global wave statistics' and still water load from the loading manual. Different damage sizes were considered and a relationship established with reliability index and ultimate strength.

Das and Fang (2007) studied the residual strength and survivability of a single side skin bulk carrier and a double side skin bulk carrier after collision and grounding. The authors studied the residual strength after collision and grounding, as well as the residual torsional constant and shear strength, based on the advanced analysis methods developed by the authors. The authors observed that the probability of failure of the double side skin bulk carriers is less than that of the single side skin bulk carriers in hogging and sagging for same damage scenario. Khan and Das (2007) presented the reliability analysis of tankers and bulk carriers during grounding and collision accidents. They considered the combined effect of vertical and horizontal bending, and used the limit state function derived from the interaction equation in combined bending in different scenarios.

Khan and Das (2008) carried out a sensitivity analysis to determine the most important random variable responsible for the failure of ship structures. This he study shows the importance of the contribution of the design variables towards the uncertainty of the limit state function and the advantages for using the sensitivity factors for safety assessment of ship structures.

Guedes Soares and Hussein (2009) studied the residual strength and reliability of three double hull tanker designed according to the new IACS common structural rule (CSR). Different damage sizes at side and bottom were considered and the reliability analysis was carried out considering the worst scenario. Reliability of damaged ships is calculated considering the increase in still water bending moment due to damage and the loss in ultimate strength.

Zhi Shu and Moan (2010) used an interaction equation based on ultimate hull girder strength assessment obtained by nonlinear finite element analysis as the basis for the failure function. The annual probability of failure was obtained by

FORM analysis considering tow typical load cases, namely, pure longitudinal hogging bending moment and local lateral pressure loads. The results show that the local lateral pressure has a significant influence on the annual probability of failure of bulk carrier in the hogging and alternative hold loading.

Chapter 4. Research Methodology

4.1 Introduction

In this chapter a detailed description about the research problem and the procedure adopted to address it is shown. The interrelation between the different elements/steps used in the procedure to achieve the overall objective of the thesis is also discussed.

4.2 Risk Based Analysis of Ships

Ship accidents are low frequency events with high consequences, especially when tankers or passenger ship are involved. Hence, it becomes necessary to determine the causes and consequences of accidents so as to make efforts to reduce the number of accidents and limit the extent of consequences in the future. In this regard, risk assessment is considered as an ideal tool to determine the causes and consequences of accidents , and a tool to aid in future planning and decision making. Risk assessment is the process of gathering data and processing information to develop an understanding of the risk of a particular enterprise. In general, the elements of Risk Assessment are shown in Figure 4-1.

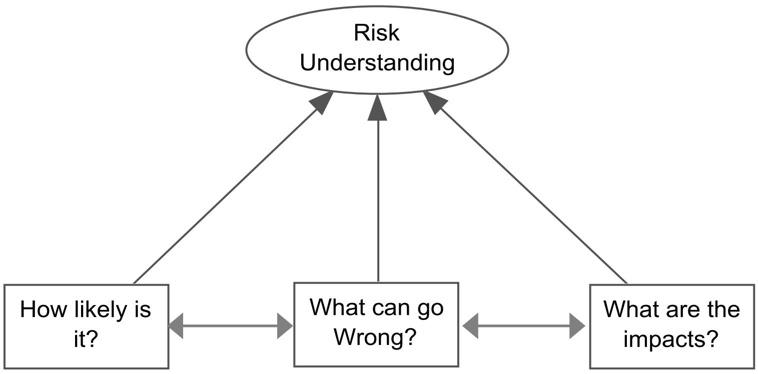


Figure 4-1 Elements of Risk Assessment

So, in order to gain an understanding of the risk of an operation, the following questions needs to be answered

- What can go wrong?
- How likely is it?
- What are the impacts?

Risk assessment process is a systematic method applied to answer the above questions. Figure 4-2 shows the different steps in risk assessment process.

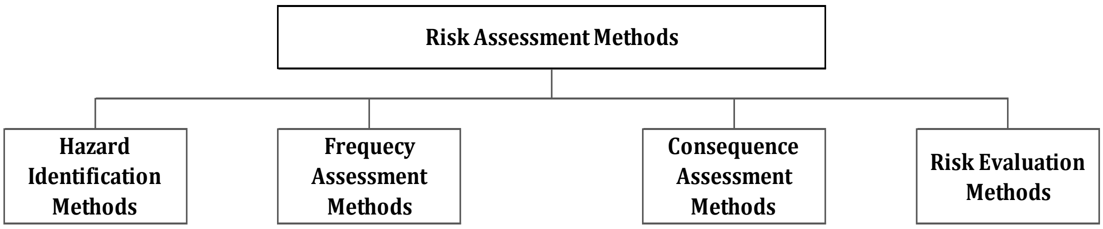


Figure 4-2 Stages in risk assessment

- **Hazard identification –** to identify the hazards and associated events that have the potential to result in a significant consequence.
- **Frequency assessment –** to estimate the frequency at which the hazardous events may occur.
- **Consequence assessment –** to predict the effect of a particular event of concern.
- **Risk evaluation –**used to determine the relative risk associated with the events.

Once the hazards are identified, then the frequency and consequence assessment can be carried out. The consequences from a ship accident could be loss of life, environmental pollution, structural damage, ship loss, financial losses etc.

The main components in the IMO guidelines (IMO, 1995) for probabilistic evaluation of tanker subdivision to calculate the pollution prevention index are to determine the probability of accident, the conditional probability of damage location and size and the conditional probability of the ship floating after the damage. The probability of accident depends on the area in which the ships are sailing, the weather condition and other related factors which affects the operation. The location and size of the resulting damage is related to the type and size of the vessels involved their speed and aspects such as obstruction (in case of grounding) and the type and size of striking ships (in case of collision). Again, the traffic in different areas has different proportion of ships and thus those probabilities will be area dependent. Design features may also limit the damage extent.

This thesis focuses on determining causes of accidents, the resulting damage extent & oil outflow and to use damage extent to calculate the residual strength and probability of failure considering different damage scenarios. Figure 4-3 shows the three main elements considered in this thesis. The results from each stage are used as input in the next which could finally be used in planning and decision making.

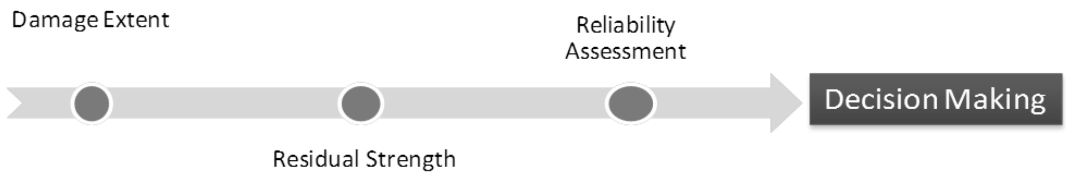


Figure 4-3 Inputs for risk based decision making

The procedure adopted to achieve the objective of the thesis is shown in Figure 4-4.

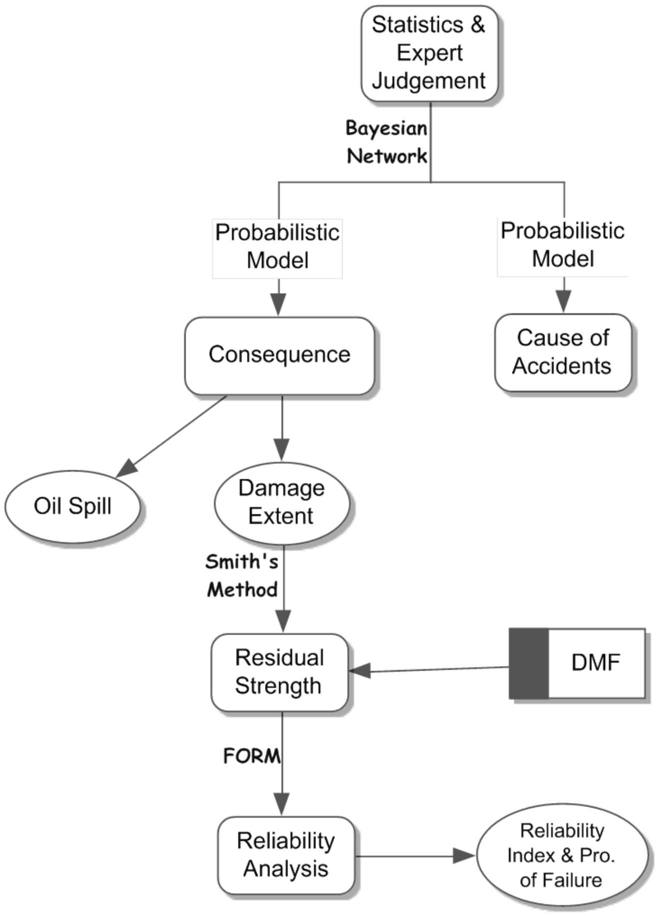


Figure 4-4 Flowchart of the procedure adopted in this thesis

In the first stage using Statistics and data mining tools the damage database is analysed to determine the underlying relationship, between different variables, which are hidden in the database.

The database do not include information about all the variables necessary to determine the causes and consequences of accidents. Hence, information about the necessary variables are gathered by consulting experts working in this field.

The causes and consequence of accidents are associated with large sets of interrelated uncertain quantities, conditional dependencies and mutual exclusive event. Currently, there are different risk analysis techniques and methods available to aid in determining the frequency and consequence of accident, but they fail to incorporate the conditional dependencies and mutual exclusiveness of events. In this thesis Bayesian networks, because of their ability to incorporate conditional dependencies and mutual exclusiveness, are used for model elicitation. The network elicitation is carried out using information from both database analysis and expert judgement. The network so developed will be used to determine the probability of accident and its consequence in terms of damage extent and oil spill.

Once the damage extent is known then the residual strength analysis could be carried out using smith's methods. The intact ship ultimate strength is calculated to define the pre-damage strength of ships. To determine the sensitivity of residual strength to the location and damage extent, studies are carried out considering different damage sizes and location along the side and bottom of the ship to simulate grounding and collision accidents respectively.

Once the damage extent, the residual strength and the loading condition is known the reliability analysis could be carried out which could help in determining the reliability index and probability of failure. Reliability analysis also helps to determine the most sensitive design variables and its effect on the reliability index. Another important application of the structural reliability methods is that it can be used as a tool for codified design and in particular to derive probabilistically based partial safety factors.

Finally, to determine the effect of different designs on the residual strength and reliability of ships following accidents, design modification factors will be applied to the structure. The results of which shows the minimum design modification factor which should be considered at the design stage to meet both the residual strength requirement and target reliability following any damage scenario.

4.3 Short Introduction to different elements considered

The different elements considered in the above procedure and their interrelation between each other is discussed in this section.

4.3.1 Statistical Analysis

Statistical analysis is long considered as the best and the most reliable source to determine the causes and circumstances leading to accidents (that is weather at the time of accident, location of accident etc.) and in determining the structural damage & pollution resulting from them. There are different data mining tools available which could determine the underlying phenomena's surrounding accidents and could be used as aid in decision making.

In this thesis data analysis is carried out using IHS Fairplay ship accident database from 1980-2009. This database is used in Chapter 5 for data analysis and data mining and in chapter 6 and 7 this database is used as input in the data driven modelling and also used as background information to elicit the grounding and collision consequence models also. The detailed information about which could be found in the respective chapters.

4.3.2 Expert Judgement

There are certain limitations in the database such as in many cases it will be incomplete or data not properly recorded. Also, data analysis could not be used for long term prediction since there will be lot of change in the factors leading to an accidents mainly due to changes in traffic density, emergence of new technology etc. which cannot be considered by the database. Hence, in situation where the data is missing or not properly recorded expert judgements could be used to fill in the gap, also expert judgement could help to take into account the anticipated changes and in this way could help in building better decision making model. But for any expert judgement the knowledge about the past accidents and the circumstances leading to it need to be known in this way both database learning and expert judgement modelling are interrelated.

4.3.3 Bayesian Network

The causes and consequences resulting from accidents have events which are interrelated to one another and are conditionally dependent on the presence or absence of other events. But most of the current methods could not consider this interrelation and dependence of variables and in this regards Bayesian networks analysis could be considered as an ideal tool for risk modelling and analysis. A Bayesian network is a graphical representation of uncertain quantities (and decisions) that explicitly reveals the probabilistic dependence between the set of variables and the flow of information in the model. Since they are graphical in nature they are easy to understand for both experts and non-experts, also they could be modelled using database of cases, expert judgement or using a combination of both. In short, a Bayesian network is designed as a knowledge representation of the considered problem and may therefore be considered as the proper vehicle to bridge the gap between the analysis and formulations.

In this thesis the Bayesian network models to determine the probability of ship accidents, their causes and consequences are elicited using the information obtained from database analysis and expert judgement.

4.3.4 Strength Analysis of Intact and Damaged Ships

Ultimate strength of structural members and systems is a real measure in strength assessment in a sense that the ultimate strength is the maximum capacity that they can have. No additional load can be carried beyond the ultimate strength. A ship in intact condition will sustain applied loads smaller than the design loads, and in normal seagoing and approved cargo loading conditions it will not suffer any structural damage such as buckling and collapse. However, the loads acting on the ship hull are uncertain both because of the nature of rough seas and because of possibly unusual loading/unloading of cargo. Also following an accident the structural members in the damage zone will be ineffective in their contribution to strength. Hence, it become important to determine the strength of ships in both intact and damaged conditions to properly assess in seagoing and load carrying capacity. There are different methods available for strength calculation, which will be discussed further in Chapter 8. In this thesis progressive collapse analysis proposed by Smith *et al* (1977) is used. This method considers the progressive loss of stiffness of a cross section due to buckling and yielding of structural components under longitudinal bending.

In order to take into account the effect of age related degradation analysis are carried out considering two scantling viz gross scantling (to simulate new build ships) and net scantling (to consider the corrosion deduction) and the results compared. Finally, simplified equations to calculate the residual strength are derived which depends only on the damage extent, Hence, once the damage extent is known the residual strength could be calculated.

4.3.5 Reliability Analysis of Intact and Damage Ships

Limit state design is an integral part of structural design and is currently widely used in the design of ships and offshore structures compared to allowable stress design. In allowable stress design the focus is on keeping the stresses resulting from design loads to be below a certain working stress level which is usually obtained from previous experience on similar structures and expert judgement. In contrast to allowable stress design, limit state design considers the various conditions under which a system or a structure fail to perform its function and the capacity or loads corresponding to this is taken during the design phase.

The steps in reliability assessment are shown in Figure 4-5. The limit state function corresponds to the state of the system when it fails to perform its intended function and reliability analysis is used to calculate or predict the probability of limit state violation The design variables with their uncertainties are used as input in the limit state function which is fed into the reliability assessment program, which gives the reliability index and probability of failure. These results are compared with the target reliability to check whether the structure have adequate reliability to fulfil its intended functions properly under any operating condition. In the design stage this process could be continued until the structure meets the target reliability level.

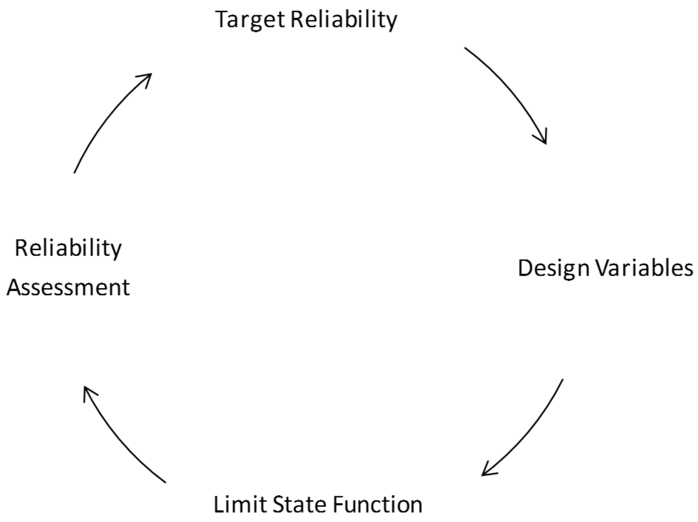


Figure 4-5 Steps in Reliability Analysis

In this thesis, the limit state equation considered corresponds to the hull girder failure under vertical bending. The input for which include the residual strength and the loads acting on the structure following accident. Since, the loads acting on a structure following an accident could be very different from its intact condition; a comprehensive study is carried out by changing still water and wave bending moment.

4.4 Summary

This chapter describes the research methodology and the procedure adopted to fulfil the overall objective of the thesis. The different elements/ steps considered in the study and their logical relation with each other is described.

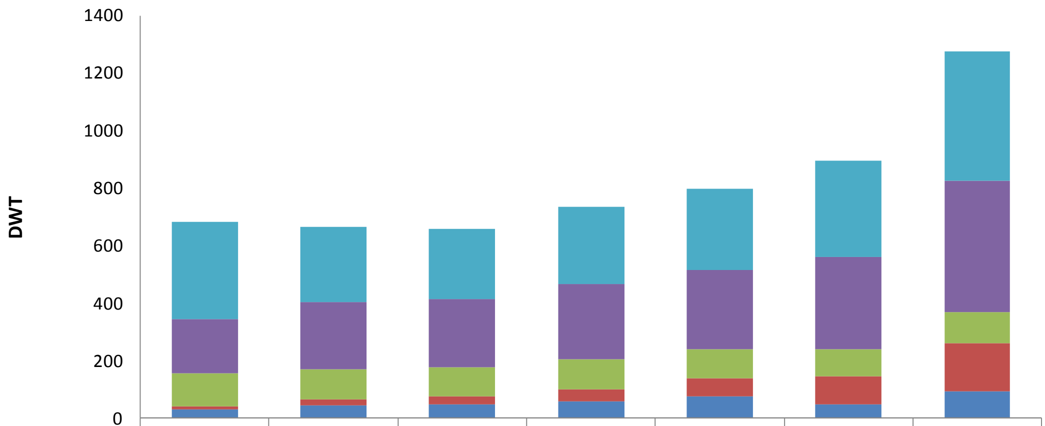
Chapter 5. Statistical Analysis of Ship Accidents

5.1 Introduction

In this chapter statistical analysis of ship accidents using IHS Fairplay database of ship accidents from 1980 to 2009 is carried out to determine the underlying factors which acts or are present at the time of an accident. Finally, data giving the consequences of ship accidents, such as damage extent, pollution and human casualties, are collected and presented.

5.2 World Ship Statistics

Today's world fleet of propelled sea-going merchant ships of no less than 100 GT comprises 99,741 ships of 830.7 million GT with an average age of 22 years (LRF/Fairplay World Fleet Statistics 2008); they are registered in over 150 nations and manned by over a million seafarers of virtually every nationality.



	1980	1985	1990	1995	2000	2005	2010
Oil Tanker	339	261	246	268	282	336	450
Dry Bulk	186	232	235	262	276	321	457
General Cargo	116	106	103	104	101	92	108
Container	11	20	26	44	64	98	169
Other	31	45	49	58	75	49	92

Figure 5-1 Development of world fleet by millions of dwt (cargo carrying vessels of 100GT and above, Source: UNCTAD Review of Maritime Transport 2010)

From Figure 5-1 it can be seen that, as of 2010, oil tankers and dry bulk carrier tonnage together account for more than 71% of the world fleet.

5.2.1 Overview of Ship Types

From Table 5-1 it can be seen that world's cargo carrying fleet, as of 2010, is 52,944 ships of 1,156.7 million dwt (791.1 million GT) and average age of 21 years.

Table 5-1 Overview of world merchant fleet-cargo carrying ship types (Source: UNCTAD Review of Maritime Transport 2010)

Ship Type Category	No.	DWT	GT	Age
Bulk Dry	6306	394968275	216749258	15
Crude Oil Tanker	2105	303734893	163691586	10
Container	4641	161921733	139563042	10
General Cargo	17002	80417587	56433536	24
Chemical	4212	68891467	42900705	12
Oil Products Tanker	4954	52908628	31667027	23
LNG Tanker	301	22269871	29047680	10
RO-RO Tanker	2489	18459423	41634505	17
LPG Tanker	1154	14071706	11996216	16
Other Bulk Dry	1165	11744287	8947465	22
Refrigerated Cargo	1210	6454779	5989059	23
Self-Discharging Bulk Dry	175	6415716	3808636	32
Passenger/RO-RO Cargo	2868	4408950	16794304	24
Bulk Dry/Oil	98	4149162	2458800	23
Other Dry Cargo	226	3120984	2881528	26
Passenger (Cruise)	506	1740055	14405871	22
Passenger Ship	3035	598334	1498867	24
Passenger/General Cargo	335	274324	536112	33
Other Liquids	162	121972	82404	32
Total Cargo Carrying	52,944	1,156,672,146	791,086,601	20.9474

General cargo ships forms the highest number of ships in the world fleet with 17002 ships with a total of 56 million GT, while dry bulk carriers with 6306 ships accounts for 27% (216 million GT) of the total GT.

Tankers make up the second largest category. There are many different types of tankers, ranging from those carrying crude oil, through those built to transport various refined hydrocarbon products, to highly specialized ships that carry liquefied petroleum gas and natural gas. There are even tankers designed to carry cargoes such as fresh water, wine or orange juice.

Bulk carriers are often called the workhorses of the international fleet. They can be thought as relatively simple but however highly efficient vessels that usually carry commodities such as grain, coal and mineral ores. If tankers provide the fuel that powers the modern economy, bulk carriers are responsible for moving the raw materials that are its lifeblood.

Passenger ship comes next in the world fleet league table. There are two basic categories- which can be summed up as ‘fun’ and ‘function’. The latter category are those which are designed to transport people and, often, vehicles or itineraries from one place to another as quickly and cheaply as possible and, in the former, those which the passengers see as a leisure destination in their own right.

Container ships are cargo ships that transport their complete load in truck-size intermodal containers, in a technique called containerization. They form a common means of commercial intermodal freight transport. Container ships are comparitvely new addition and are relatively unheard of before the 1960s, the container is now abundant and is the standard unit of cargo for just every form of manufactured item on the planet.

5.2.2 Seaborne trade by cargo type

It can be seen from Table 5-2 that, as of 2009, 39% of cargo transport has been other dry cargo, 34% oil and the remaining 27% is main bulk.

Table 5-2 Development of world seaborne Trade (selected years in millions of tonnes)

Year	Oil	Main Bulks[a]	Other dry Cargo	Total (all cargos)
1970	1442	448	676	2566
1980	1871	796	1037	3704
1990	1755	968	1285	4008
2000	2163	1288	2533	5984
2006	2698	1849	3135	7682
2007	2747	1972	3265	7983
2008	2732	2079	3399	8210
2009[b]	2649	2113	3081	7843

Source: *Compiled by the UNCTAD secretariat on the basis of data supplied by reporting countries as published on the relevant government and port industry websites, and by specialist sources. The* *data for 2006 onwards have been revised and updated to reflect improved reporting, including more recent figures and better information regarding the breakdown by cargo type.*

[a] *Iron ore, grain, coal, bauxite/alumina and phosphate.*

[b] *Preliminary.*

The data for 2006 onwards are based on Dry Bulk Trade Outlook produced by Clarkson Research Services Limited.

5.3 Accident database

In this thesis IHS Fairplay database of ship accidents from 1980-2009 is used. This database contains details about 9143 accidents during this period, falling under 8 ship types and 9 incident types. In this section an overview of the database stating the different variables and its distribution is given.

5.3.1 Ship Type

The database records details of accidents on 8 ship types as show in Table 5-3. It can be seen from Figure 5-2 that Bulk carriers and Tankers together constitute 67% of all accidents during this period followed by chemical and container ships with 12% each.

Table 5-3 Number of accidents in each ship type

Ship Type	Number of Accidents
Bulk Carrier	3634
Tanker	2484
Chemical	1123
Container	1075
Cruise	239
LNG	29
LPG	307
PCC	252
Grand Total	**9143**

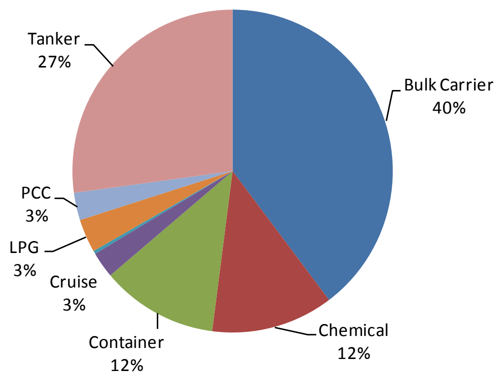


Figure 5-2 Percentage of Accidents under each ship

5.3.2 Incident Type

The database contains 9 types of accident as shown in Table 5-4. From Figure 5-3 it can be seen that Hull/Machinery damage account for 33% of all the accident recorded in the database followed by collision and grounding, which together constitute 41% of all accidents during this period.

Table 5-4 Number of accident classified by incident type

Incident Type	Number of Accidents
Collision	1731
Contact	686
Fire/explosion	1046
Foundered	262
Hull/Machinery Damage	2997
Miscellaneous	27
Missing	18
War loss/hostilities	334
Wrecked/stranded	2041
(blank)	1
Grand Total	**9143**

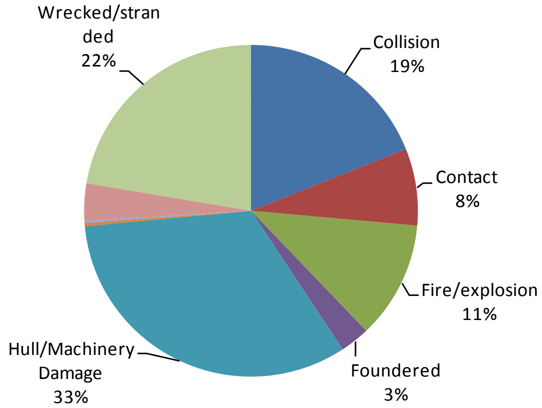


Figure 5-3 Percentage of accidents under each incident type

5.3.3 Weather at the time of accident

The database records details about the weather at the time of accident as shown in Table 5-5.

Table 5-5 Number of accident by weather at the time of incident

Weather Type	Number of Accidents
Calm weather/seas	41
Fog etc. & calm weather/seas	4
Fog etc. & heavy weather etc.	3
Fog/mist/poor visibility	259
Freak seas	6
Freezing & good weather	1
Freezing & heavy weather etc.	2
Freezing conditions	48
Good vis & calm weather/seas	2
Good vis & good weather	8
Good vis & heavy weather etc.	1
Good visibility	17
Good weather	162
Heavy swell	36
Heavy weather etc.	957
Hurricane etc.	128
Lightning	6
N/a (not relevant)	18
Snow	10
Snow & heavy weather etc.	3
Snow & hurricane etc.	4
Unknown/not reported	7427
Grand Total	**9143**

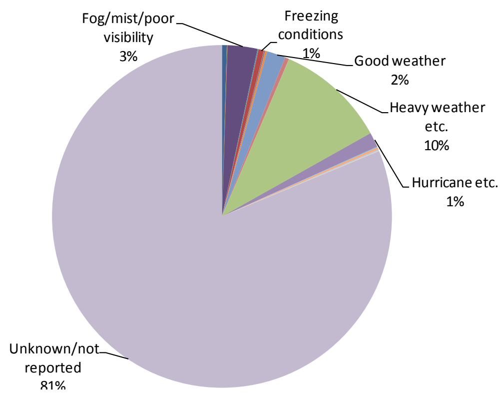


Figure 5-4 Weather type at the time of

Weather at the time of accident is categorised into 20 different categories. But, for almost 81% of accident, as shown in Figure 5-4 , there is no record of the weather at the time of accident and is shown as either unknown or unreported in the database which makes it hard to find a relation between the effect weather has on incident type.

Out of the known cases, it was heavy weather (75%) at the time of accident. Since a large number of weather variables have very few numbers, a careful data reprocessing by grouping similar data was done to reduce the number of categories as shown Table 5-6.

Table 5-6 Reprocessed weather data categories

Reprocessed weather data
Fog/mist/poor visibility
Good weather
Heavy weather etc.
Unknown/not reported

5.3.4 Ship's Operating Conditions at the time of Accident

The detailed ship status (DSS) at the time of accident has 16 different categories as shown in Table 5-7. From Figure 5-5 it can be seen that 76% of accident occurred while the ship was on voyage. For 4% of accidents data on DSS was not recorded in the database.

Table 5-7 DSS at the time of accident

Detail Ship Status	Number of Accidents
Alongside shore facility	356
Being towed	22
Bunkering	10
In attendance/assisting	4
In dry/floating dock	12
Manoeuvring	32
Manoeuvring with assistance	105
Manoeuvring without assistance	772
Moored/anchored	599
On station	2
On trials	14
On voyage	6918
Pushed	1
Towing	1
Unknown	49
Unknown/not applicable	246
Grand Total	**9143**

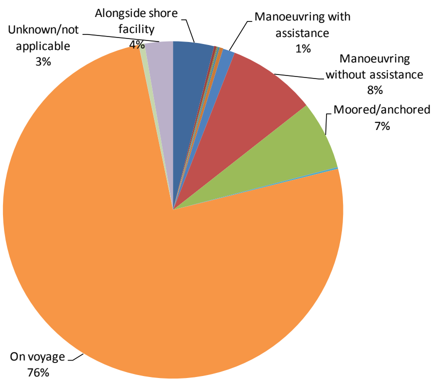


Figure 5-5 DSS at the time of accident

The number of DSS types was reduced by regrouping similar categories of data as shown in Table 5-8.

Table 5-8 Reprocessed DSS data categories

Reprocessed DSS data
On Voyage
Manoeuvring with or without assistance
Other
Unknown

5.3.5 Accident Location

The nine locations at which accident occurred, as recorded in the database, is given in Table 5-9. It can be seen that Majority of accident have occurred while the ship was at sea (60%) followed by accidents in ports/harbour/dock etc.

Table 5-9 Location at the time of accident

Location of Accident	**Number of Accidents**
At sea	5490
Canal	234
Estuary/river	744
Fjord	4
Great lakes/caspian sea etc.	91
In port/harbour/dock/at...	2006
Offshore terminal	2
Restricted waters	546
Shipyard/dry dock	26
Grand Total	**9143**

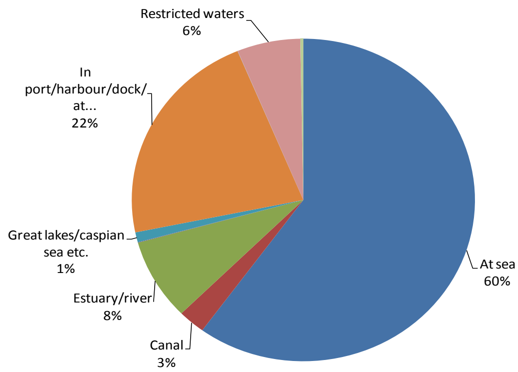


Figure 5-6 Location of ship at the time of accident

The data reprocessing was done as shown in Table 5-10, which include three categories namely At sea, restricted waters (ports, canals, straits, anchorages, coast waters etc) and other which include the rest.

Table 5-10 Reprocessed location data categories

Reprocessed Location data
At Sea
Restricted waters
Other

From Figure 5-5 and Figure 5-6, it could be said that more than 60% accidents during this period occured while the ship was on voyage at the sea.

5.3.6 Cargo Status at the time of accident

The cargo status at the time of accident is given in Table 5-11. From Figure 5-7, it can be seen that almost half the accidents occurred while the cargo status was loaded, for 34% cases the cargo status is not recorded in the database and the remaining constituted by other categories such as ballast, part loaded etc.

Table 5-11 Cargo status at the time of accident

Cagro status	Number of accidents
Ballast	971
Ballasting	14
Cars	1
Containers	6
Discharging	144
Empty	132
Gas freeing	5
Loaded	4465
Loading	108
Not applicable	14
Part loaded	177
Tank cleaning	16
Unknown	3090
Grand Total	**9143**

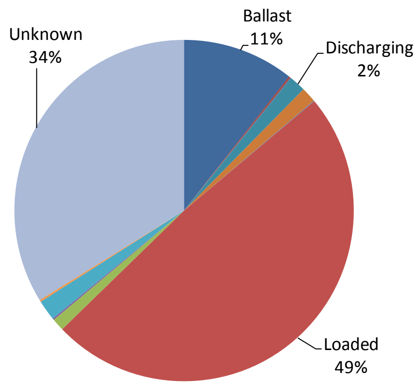


Figure 5-7 Cargo status at the time of

The regrouping of the data was done by arranging them into 4 categories as shown in Table 5-12.

Table 5-12 Reprocessed cargo data categories

Reprocessed Cargo data
Ballast
Loaded
Part loaded
Unknown

5.3.7 Lives lost due to accidents

The ratio of lives lost to the number of lives transported for the period 2004-2008 is as shown in Table 5-13. From this table it is clear that there is a gradual increase in the number of lives transported by ships. It should also be noted that even with the improvements in technology there is still risks to life in maritime transport.

Table 5-13 Ratio of lives lost to lives transported (2004-2008) (Source: Lloyd's Register Fairplay for loss of lives & Statistics shippax (statistics & Outlook 2006) for number of passengers)

	2004	2005	2006	2007	2008
LRF lives lost all ships	664	470	1825	525	1160
Estimated amount of seafarers		1187000	1232000	1277000	1246200
Estimated total number of ferry passengers	1321228835	1395306149	1629573558	1681931684	n/a
Estimated total number of cruise passengers	15402793	16719322	16927718	17857711	n/a
Estimated total number of passengers	1336631628	1412025471	1646501276	1699789395	1913962859
Total amount of passengers and crew		**1413212471**	**1647733276**	**1701066395**	**1915209059**
Ratio best estimate	**4.9677E-07**	**3.3258E-07**	**1.1076E-06**	**3.0863E-07**	**6.0568E-07**

From the analysis of the database, as shown in Figure 5-8, it can be seen that 71% of human casualties occurred in accidents involving Passenger ships, followed by general cargo ship, whereas accidents in bulk carriers and tankers resulted in a total of 7% deaths. The higher percentage of death in passenger ships compared to other ships is owing to the number of passenger carried by them, in this regard since bulk carriers and tankers carry few passenger/crew the number of lives lost due to an accident is less.

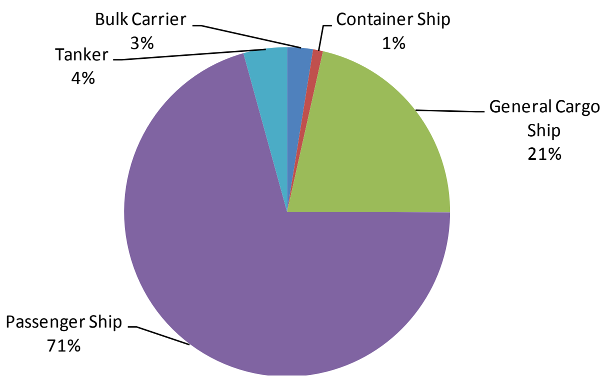


Figure 5-8 Distribution of human causality based on ship types

5.3.8 Pollution due to accidents

The database records the occurrence of pollution following accidents. But in 40% of cases the details regarding pollution is missing, out of the remaining 60% cases, 5% of accidents resulted in pollution. Table 5-14 shows the amount of oil carried and the amount of oil spilt following accident. It is clear from this table that the energy needs are on the increase and hence safer shipping practices are necessary to avoid oil spills resulting from accidents.

Table 5-14 Ratio of oil discharged into the sea to total carried by sea (2003-2008) (Source:ITOPF annual statistics and clarksons shipping intelligence network)

Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Annual quantitiy of oil spilt (million tonnes)	0.042	0.015	0.017	0.013	0.018	0.002
Annual quantity of oil carried by sea (million toonnes)	2345	247	2556	2644	2719	2798
Ratio	1.8E-05	6.1E-06	6.7E-06	4.9E-06	6.6E-06	7.1E-07

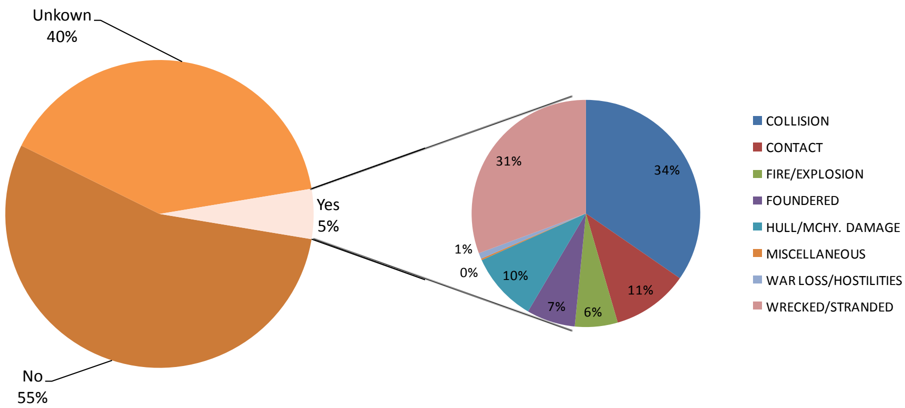


Figure 5-9 Distribution of incidence of Pollution based on Incident Type

It can be seen from Figure 5-9 that in 65% of cases when there was pollution the incident type had been Collision or grounding.

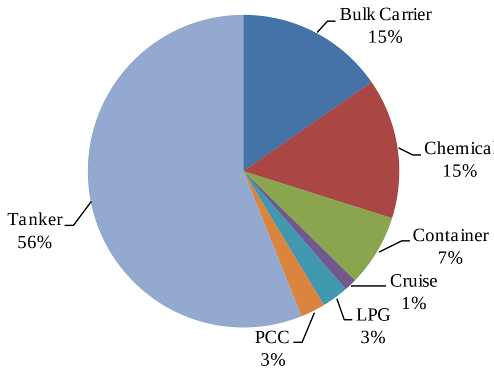


Figure 5-10 Distribution of incidence of Pollution based on ship Type

From Figure 5-10 it can be seen that in 56% of accident when pollution occurred the ship was tanker, 15% each for bulk carriers chemical carriers and the remaining on the other categories of ships.

5.3.9 Ship Particulars

The ship particulars such as, length, breath, depth, dead weight tonnage, gross weight tonnage and age of ship are also recorded in the database.

From Figure 5-11 it could be seen that length of the ships which met with accident have an approximate normal distribution (mean length = 168m) with more number of accidents occurring in ships between the lengths of 170 to 240 m. Another important finding is that most of the collision accident involve ships of similar size, this may be due to the fact that ships of particular size use the same route.

Figure 5-12 shows the distribution of length of ships which met with accident to their breadth, depth and deadweight tonnage. The variation of breadth and depth is linear whereas DWT shows a nonlinear relation with length. These relationship between the ship particular variables will be captured in the consequence model to be elicited in the chapter 7.

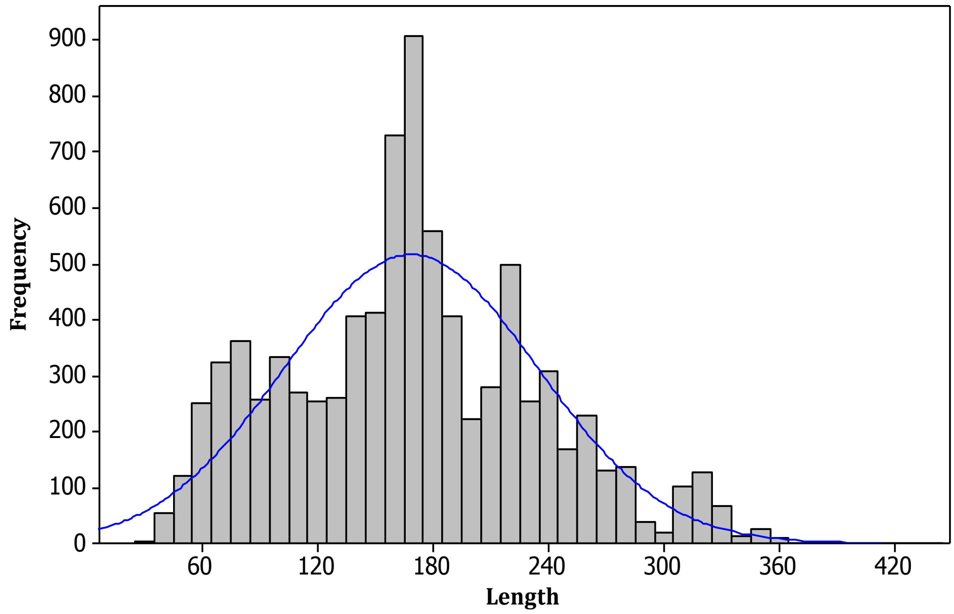


Figure 5-11 Histogram of Length of ship met with accidents

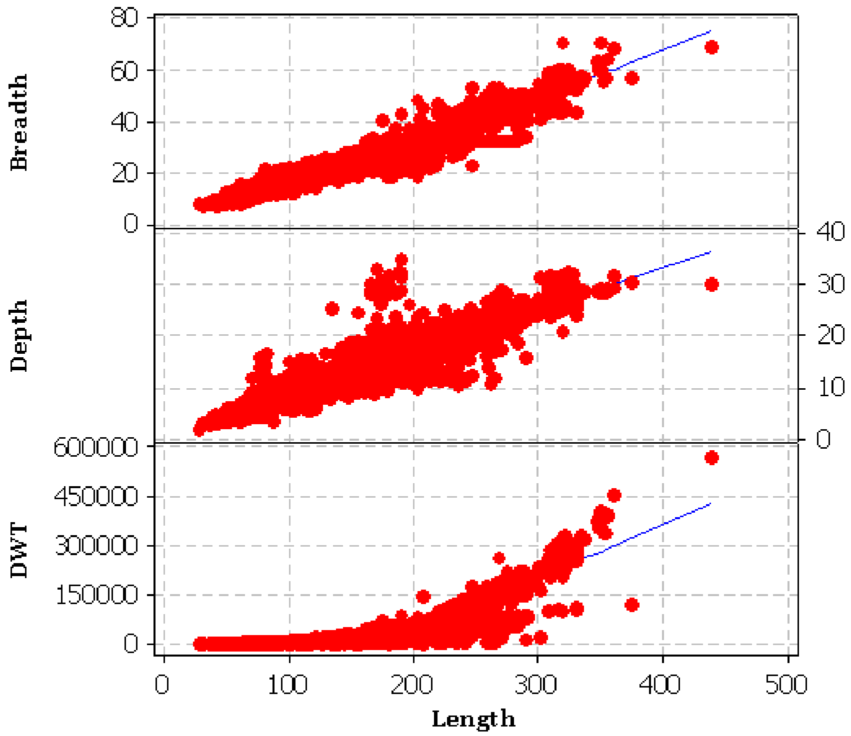


Figure 5-12 Distribution of Length of ships vs. (a) Displacement (b) Depth (C) Breadth

The relation between accident frequency and age of ship at the time of accident is shown in Figure 5-13. Till the age of 22 years all the ships have almost same frequency of being involved in accidents with the peak being around the age of 14 to 20 years. Ship over the age of 30 years are involved in less number of accident, the reason for this could be that there are less number of ships of age above 30 in operation. The average age at the time of accident for the whole database is 14.39 years. For tankers the average age of ships involved in collision accidents is 14.21 whereas the average age in case of grounding accidents are 15.91 years.

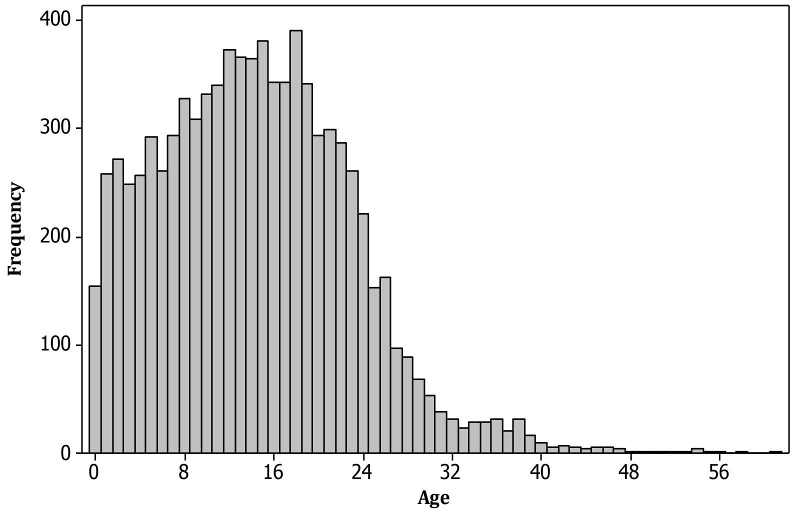


Figure 5-13 Age of ship at the time of accident

5.4 Data Analysis

From section 5.3 it could be seen that accident in bulk carriers and tankers constitute a major portion of maritime causalities and the consequence of a collision or grounding accident have severe impact with respect to financial and environmental losses. Hence, in this section data analysis of collision and grounding accidents in bulk carriers and tankers of 500GRT or more is carried out. A total of 2538 collision and grounding accident have been reported in bulk carriers and tankers during this period. Statistical analysis of data based on different variables is as follows:

5.4.1 Incident Type

During this period, 57% accidents were grounding accidents and 43% collision. Incident type studied against different variable are as follows;

Ship Type: A breakdown of number of collision and grounding accident in bulk carriers and tankers is shown in Figure 5-14.

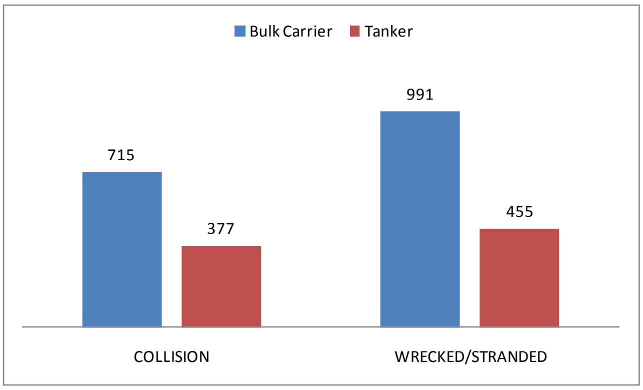


Figure 5-14 Distribution of Incident type for different ship types

- Collision: 65% accident occurred on bulk carriers and 34% on tankers.
- Grounding: 68% accident occurred on bulk carriers and 31% on tankers.

Weather type: During 78% of accidents the weather was not recorded, hence in this analysis the unknown weather was removed and based on the remaining 22% data the analysis was carried out.

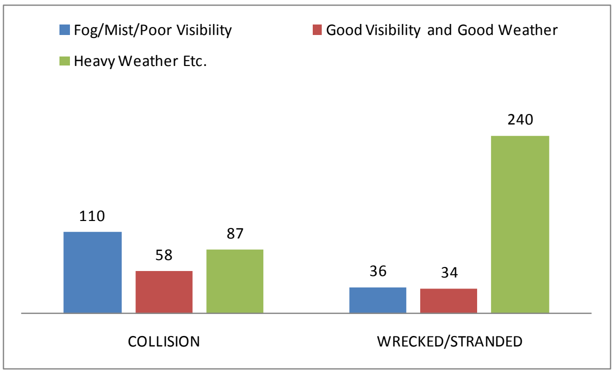


Figure 5-15 Distribution of Incident type for different weather types

- Collision: 43% of collision accident happened due to Fog/Mist/Poor visibility, 34% due to heavy weather etc and the remaining 23% of accident occurred during Good weather and good visibility.
- Grounding: 77% of accidents happened when the weather was heavy, 12% happened due to Fog/Mist/Poor visibility and the remaining 11% of accident occurred during Good weather and good visibility.

Ship Operating condition at the time of accident: The distribution of ship operating condition at the time of accident is given in Figure 5-16.

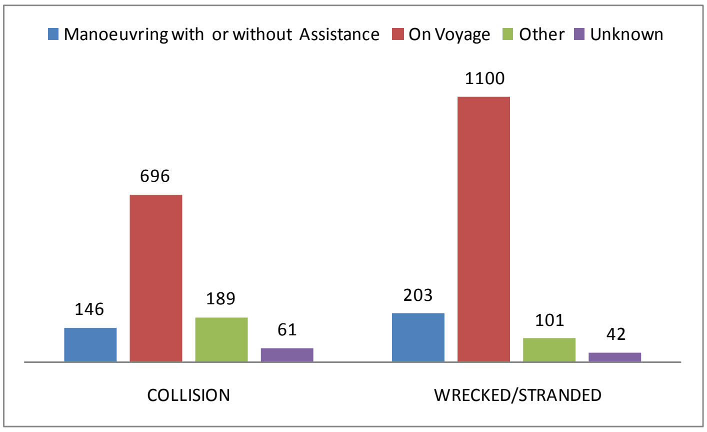


Figure 5-16 Distribution of Ship operating condition at the time of accident

- Collision: 64% of collision accident happened while the ship was on voyage, 17% during other operating conditions, 13% while the ship was manoeuvring with/without assistance and the remaining 6% was not recorded.
- Grounding: 76% of accident happened while the ship was on voyage, 14% while the ship was manoeuvring with/without assistance, 7% during other operating conditions, and the reaming 3% was not recorded.

Cargo Status at the time of Accident: The distribution of cargo status at the time of accident is given in Figure 5-17. For 28% of accidents the cargo status was not recorded, hence this data was removed and the analysis was carried out. The results are as follows:

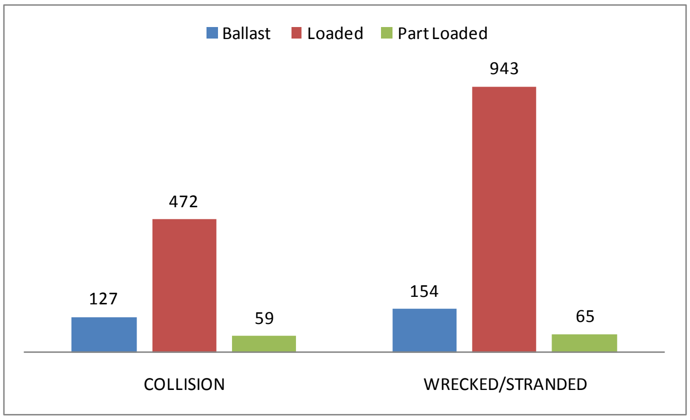


Figure 5-17 Distribution of Cargo statuses at the time of different accident types

- Collision: In 72% of accidents the ships was loaded, 19% it was in ballast condition and 9% of cases it was part loaded.
- Grounding: In 81% of accidents the ships was loaded, 13% it was in ballast condition and 6% of cases it was part loaded.

Location of ship at the time of accidents: The location distribution ship at the time of incident is given in Figure 5-18.

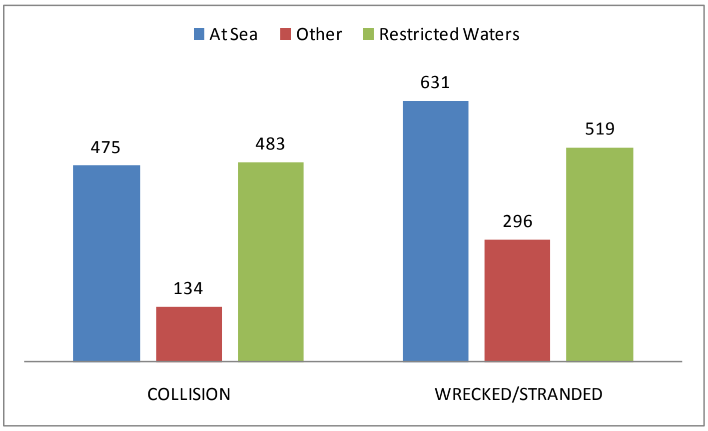


Figure 5-18 Distribution of Incident type at different locations

- Collision: In 44% of accidents ship was sailing at sea, in 44% cases ship was in restricted water and in the remaining 12% of cases it ship was sailing in OTHER locations.

- Grounding: In 44% of accidents ship was sailing at sea, in 36% of cases the ship was in restricted water and in the remaining 20% of cases it ship was sailing in OTHER locations.

5.4.2 Ship Type

During this period 67% accidents happened on Bulk Carriers and 33% accidents on tankers.

Weather at the time of accident: The accident on different ship types based on weather at the time of accident is given in Figure 5-19.

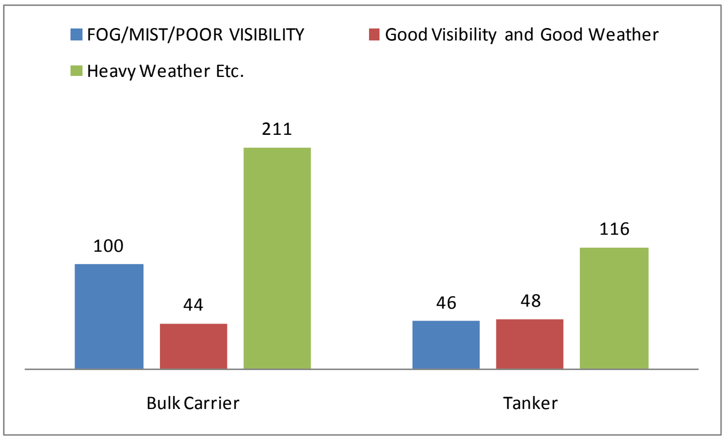


Figure 5-19 Distribution of accident on Ship type under different weather conditions

- Bulk carrier: For 60% of accidents in Bulk carriers the weather at the time of accident was Heavy weather, in 28% cases it was Fog/Mist/Poor visibility and in the remaining cases the weather was Good weather/Good Visibility.
- Tanker: For 55% of accidents in Bulk carriers the weather at the time of accident was Heavy weather, in 22% cases it was Fog/Mist/Poor visibility and in the remaining cases the weather was Good weather/Good Visibility.

Ship operating condition at the time of accident (Figure 5-20):

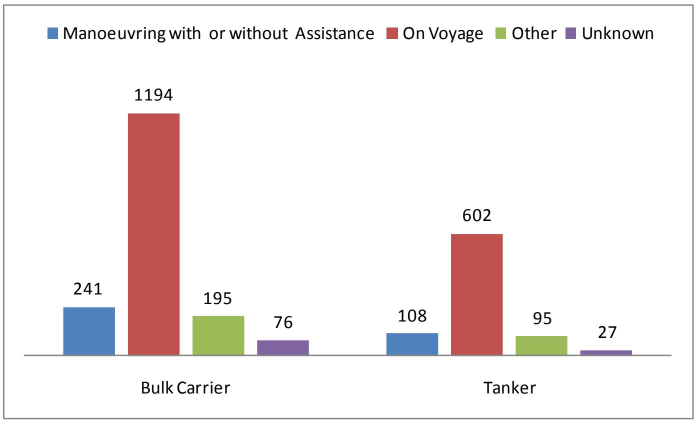


Figure 5-20 Distribution of Ship type under different operating conditions

- Bulk Carrier: In 70% of cases the ship was on voyage at the time of accident, in 14% cases it was manoeuvring with or without assistance, in 11% cases the operating condition was recorded OTHER and the remaining 4% data was not recorded.
- Tanker: In 72% of cases the ship was on voyage at the time of accident, in 13% cases it was manoeuvring with or without assistance, in 11% cases the operating condition was recorded other and the remaining 3% data was not recorded.

Cargo status at the time of accident (Figure 5-21): The data on cargo status had around 28% of the data unrecorded, hence this was removed and analysis on the remaining 72% was carried out.

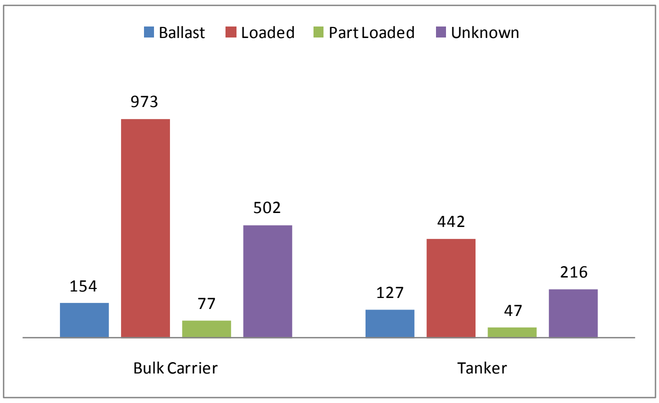


Figure 5-21 Distribution of Cargo statuses of ships at the time of accident

- Bulk Carrier: In 81% cases the ship was loaded at the time of accident, in 13% of cases the ship was in ballast condition and in the remaining 6% cases it was part loaded.
- Tanker: In 72% cases the ship was loaded at the time of accident, in 21% of cases the ship was in ballast condition and in the remaining 8% cases it was part loaded.

Location of ship at the time of accident (Figure 5-22):

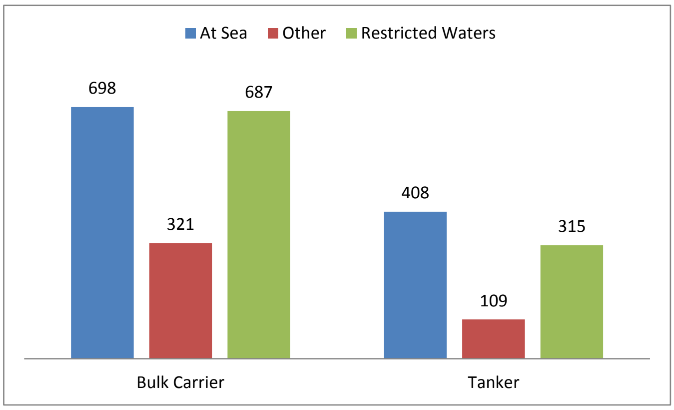


Figure 5-22 Distribution of accidents on different ship types at various locations

- Bulk Carrier: In 41% cases the ship was at sea when the accident happened, in 40% of cases it was travelling through restricted waters and the remaining 19% cases occurred at other locations.

- Tanker: In 49% cases the ship was at sea at the time of accident, in 38% of cases it was travelling through restricted waters and the remaining 13% cases happened at other locations.

5.4.3 Ship operating condition at the time of accident

In 76% of cases accident happened while the ship was on voyage, 11% on Other Operating condition, 10% while the ship was taking manoeuvring with or without assistance and 3% of data was unrecorded/unknown.

Weather at the time of accident (Figure 5-23): For large number of accidents the weather was not recorded, hence in this analysis the unknown weather was removed and based on the remaining data the analysis was carried out.

- On Voyage: 47% accident happened when the weather was heavy, 34% when there was fog, mist or poor visibility, 20% when the weather is good and there is good visibility
- Manoeuvring with or without assistance: 51% of accidents happened when the weather was heavy, 25% when there was fog, mist or poor visibility and 25% when the weather is good or good visibility.
- Other Operating condition: 91% of accidents happened when the weather was heavy, 4% when there was fog, mist or poor visibility and 5% when the weather is good or good visibility.

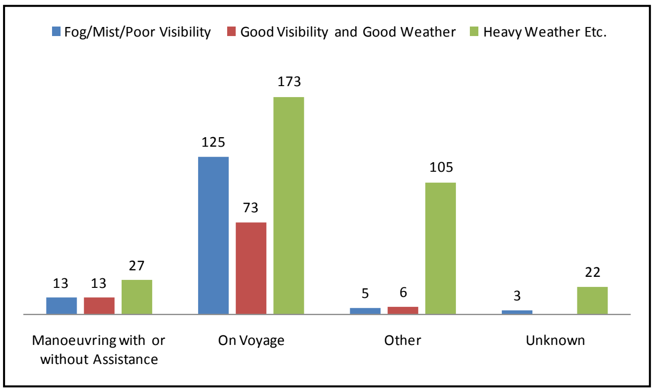


Figure 5-23 Distribution of operating condition of ship and weather at the time of accident

Cargo status at the time of accident (Figure 5-24): The data on cargo status had around 28% of the data unrecorded, hence this was removed and analysis on the remaining 72% was carried out.

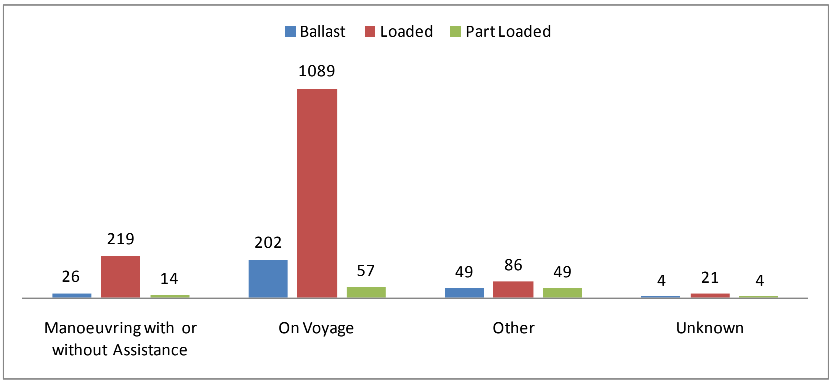


Figure 5-24 Distribution of operating condition of ship and cargo status at the time of accident

- On Voyage: During 81% of accidents the ship was loaded, in 15% cases it was running on ballast and for the remaining cases it was part loaded.
- Manoeuvring with or without assistance: During 85% of accidents the ship was loaded, in 10% cases it was running at ballast and for the remaining cases it was part loaded.
- Other Operating condition: During 47% of accident the ship was loaded, in 27% cases it was in ballast condition and for 27% accident it ship was part loaded.

Location of Accident (Figure 5-25):

- On Voyage: 58% accident occurred while the ship was at sea, 23% in restricted waters and for 19% accident it was in Other locations.
- Manoeuvring with or without assistance: In 81% accident the ship was moving through restricted waters, 14% in other locations and for 5% accident it was when the ship was at sea.
- Other Operating condition: In 77% accident the ship was moving through restricted waters, 13% when ship was at sea and for 9% accident it was in Other locations.

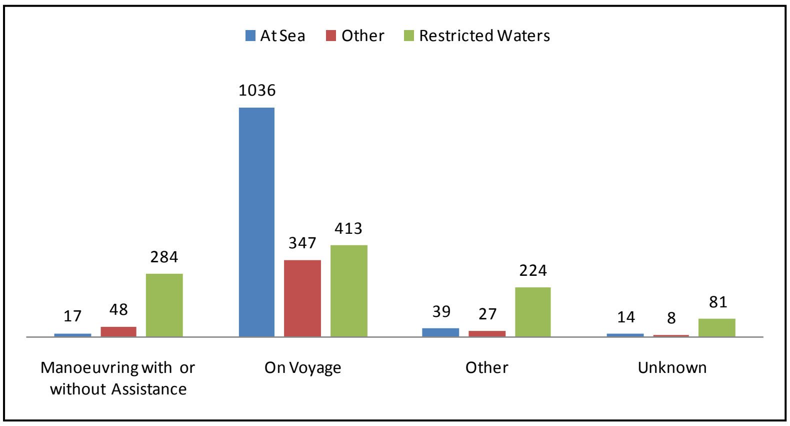


Figure 5-25 Distribution of operating condition of ship and location of accident

5.4.4 Location of accident

The location of accident in 44% of cases has been at sea, 39% at restricted waters and remaining 17% accidents at Other locations.

Weather at the time of accident (Figure 5-26): For large number of accidents the weather was not recorded, hence in this analysis the unknown weather was removed and based on the remaining data the analysis was carried out

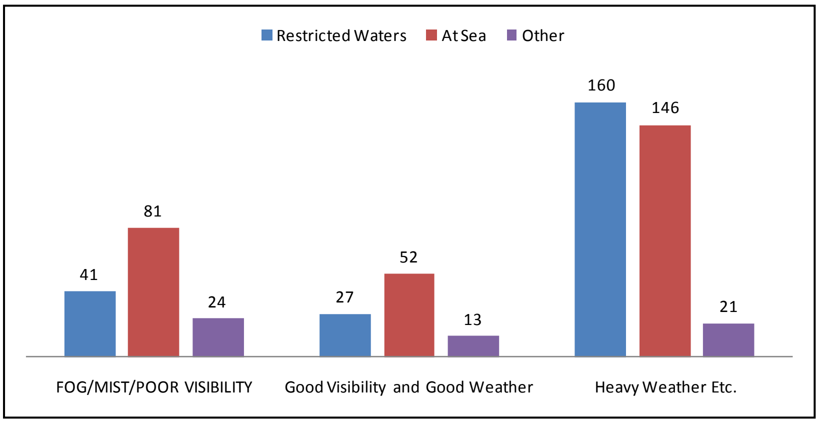


Figure 5-26 Distribution of location of ship at the time of accident and the weather condition

- At sea: In 52% cases of accidents at sea the weather has been heavy, 29% there was fog/mist or poor visibility and the remaining 19% of accident occurred when the weather and visibility was good.

- Restricted waters: In 70% cases of accidents in restricted waters the weather has been heavy, 18% there was fog/mist or poor visibility and in the remaining 12% of accident occurred when the weather and visibility was good.
- Other Location: In 36% cases of accidents in restricted waters the weather has been heavy, 41% there was fog/mist or poor visibility and in the remaining 22% of accident occurred when the weather and visibility was good.

Cargo Status at the time of accident (Figure 5-27)

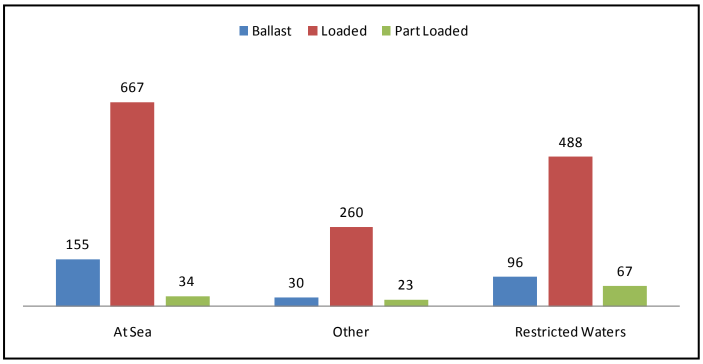


Figure 5-27 Distribution of location of ship at the time of accident and its cargo status

- At sea: In 78% cases of accidents at sea the ship was loaded, for 18% cases it was in ballast condition and in the remaining 4% cases ship was part loaded.
- Restricted waters: In 75% cases of accidents in restricted waters the ship was loaded, for 15% cases it was in ballast condition and in the remaining 10% cases ship was part loaded.
- Other Location: In 83% cases of accidents at other locations the ship was loaded, for 10% it was ballast condition and in the remaining 7% cases ship was part loaded.

5.5 Classification Tree Analysis on Damage Database

In this study the relation of three dependent (target) variable viz Incident type, pollution and lives lost in an accident are studied separately for a given set of independent (predictive) variables. The variables used are shown in Table 5-15.

Table 5-15 Variables used for classification tree

Variable	Dependency
Incident Type	Dependent and/or Independent Variable
Pollution	Dependent and/or Independent Variable
Killed	Dependent and/or Independent Variable
ShipType	Independent Variabble
Length of Ship	Independent Variabble
Year of Casualty	Independent Variabble
Dead weight of Ship	Independent Variabble
Cargo Status	Independent Variabble
Detail Ship Status	Independent Variabble
Location of Ship	Independent Variabble

In the first case 'Incident Type' is taken as the dependent variable and the independent variables are ship type, killed, pollution index, detailed ship status(DSS), cargo status, year of casualties, DWT, length of ship, age of the ship and the weather decode. The tree representation of the given dataset for Incident type as dependent variables is shown in Figure 5-28.

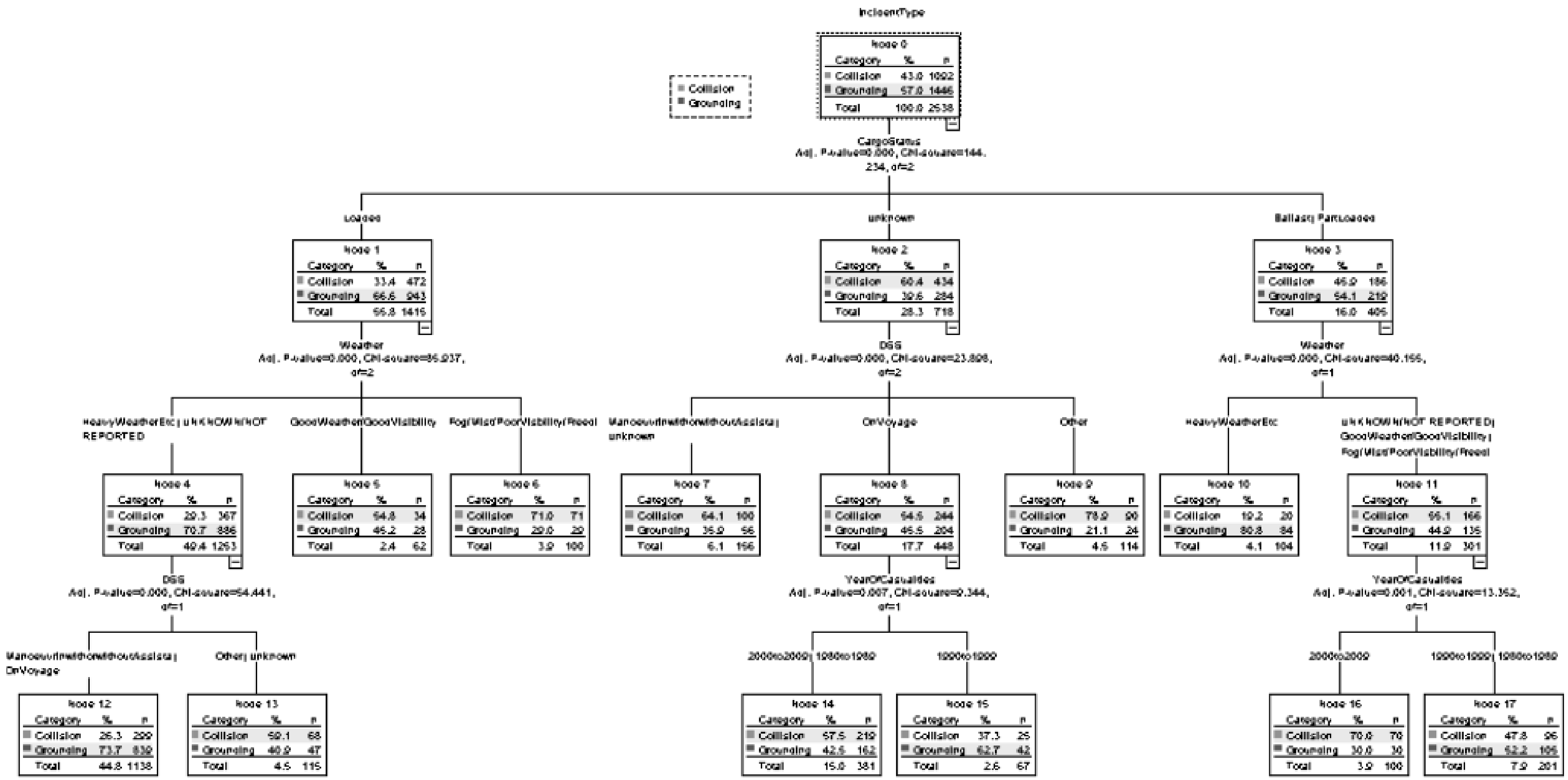


Figure 5-28 Classification tree considering Incident Type as dependent variable

Since, our target variable is a categorical type; the significance of the chi-square test was employed by CHAID to evaluate all the values of potential predictor variable. It merges values that are judged to be statistically homogenous with respect to the target variable and maintains all other values that are heterogeneous. The best predictor variable forms the first branch of the tree such that each node is made of homogenous values of the selected variable. This process continues recursively until the tree is fully grown. As a result of the process, variables that are significant trigger another division of the data while variables that are not significant are discarded for that partition.

The tree obtained has a depth 3 with 18 nodes and 11 leaves. Here the root node is the target variable (incident type) divided into 'Collision' and 'Grounding' by 43% and 57%. The hierarchy of the tree shows that the cargo status is the best predictor variable for the root and it gives the first split of the tree in level 1 into three branches having node1, node2 and node 3 representing loaded, unknown and ballast/part loaded condition. The obtained p value is 0.00<0.05, chi-square value 144.234 and df 2. Node 1 which represents loaded consists of 55.8% of both the incident types. Within the domain of the cargo status 'loaded' the predictor variable 'weather decode' gives the next level split into three branches with node4 representing heavy weather and leaves node5 and node6 representing good weather/good visibility and fog/mist/poor visibility/Freezing. Again the predictor variable DSS gives the next split to node 4 into two leaves namely node 12 that contains 'manoeuvring with or without assistance' and node 13 with DSS 'unknown'. The p value is 0.00<0.05 and chi-square 54.441. The node 2 of predictor variable cargo status in level 1 representing 'unknown' is further uses DSS as the predictor variable to split into leaf nodes node7 and node9 showing manoeuvring with or without assistance and 'others' respectively, and node8 for DSS 'on voyage'. The p value is 0.00<0.05 and chi-square 23.898 with degree of freedom (DF) =2. The node 8 is again divided under the predictor variable year of casualties into two leaf nodes node14 and node15. Node 14 represents years of casualties b/w 2000-2009; 1980-1989 and node15 includes year's b/w 1990-1999. Again the third split of node1 at level 0 is the cargo status showing ballast/part loaded condition at node3 consisting of 16% of the total incident cases. Within the domain of node3, the predictor variable weather condition at level 1 produces the next division into heavy weather represented by a leaf node (node 10) and an internal node (node 11) comprising of unknown/not reported; fog/mist/poor visibility/freezing; good weather/good visibility conditions. Finally at the level 2 of the left portion of the tree again the predictor variable gives a fresh split into the leaves node16 and node17 representing years of casualties b/w 2000-2009 and 1980-1989; 1990-1999 respectively. The tree also reveals that the variables ship type, killed, age of ship, length, DWT, environment and pollution were found insignificant and were hence not a part of the tree obtained. The significant predictor variables influencing the target variable incident type were cargo status, DSS, year of casualties and weather.

In the second case, dependency of the 'pollution' upon the independent variables like ship type, killed, incident type, detailed ship status(DSS), cargo status, year of casualties, DWT, length, age of the ship and the weather decode is determined as shown in Figure 5-29.

The tree obtained has a depth 3 with 21 nodes and 12 leaves. Here the root node is the target variable (pollution index) divided into three categories yes, no and unknown each with probability 8.1%, 59.1% and 32.7% respectively. The hierarchy of the tree shows that the year of casualties is the best predictor variable for the root and it gives the first split of the tree in level 1 into three branches having node1, node 2 and node 3 representing the years b/w 2000-2009, 1990-1999 and 1980-1989. The obtained p value is $0.00<0.05$, chi-square value 592 and df = 4. Node 1 represents incidents in the period 2000-2009 and shows that 8.3% of the accidents in this period caused pollution. Within the domain of the year of casualties 2000-2009 the predictor variable 'weather decode' gives the next level split into two branches with node4 representing heavy weather and leaves node5 representing good weather/good visibility; fog/mist/poor visibility/Freezing. Again the two predictor variables environment and ship type produce two splits each to node4 and node5 to give two pairs of leaf nodes at level 3 to produce node10 and node11 representing environment conditions of in port/harbour/dock, at sea; restricted waters respectively and mode12 and node13 representing ship types of bulk carrier and tanker. The node2 of predictor variable showing year of casualties b/w 1990-1999 is split by ship types with a p value 0.00<0.05 with chi-square 49 and df = 2 into bulk carriers(node6 being a leaf) and tankers(node7). The third level split of node7 by the predictor variable cargo status produces the leaf nodes node14 and node15 to represent loaded and unknown; ballast; part loaded condition. Again the third split of node0 by the year of casualties b/w 1980-1989(node3) consisting of 37.9% of total accidents is further split into bulk carrier and tankers by the predictor variable ship types as node 8 and node9. Node8 is further split by the by the predictor variable weather with p-value 0.002<0.05 and Chi-square 21 and df = 4 to give nodes node16, node17 and node18 representing the heavy weather, unknown/ not reported and good weather, good visibility; fog, mist, poor visibility, freezing conditions. Also the node 9 is split into the leaves node19 and node20 by the predictor variable cargo status to loaded, part loaded and unknown; ballast.

The tree also reveals that the variables incident type, killed, age of ship, length, DWT and DSS were found insignificant and were hence not a part of the tree obtained. The significant predictor variables influencing the target variable pollution index were cargo status, environment, ship types, year of casualties and weather.

It is particularly interesting to note that year of accident is a significant factor in pollution. During 1980-1989 and 1990-1999 the number of unknown cases were around 50 percentage and of the known cases 11% and 6% respectively resulted in pollution, whereas during the period from 2000 to 2009 the number of unknowns cases about pollution is only 5% and only 8% of accidents resulted in pollution, which clearly indicated the an improvement in data recording and a positive effect of the introduction of ISM code in 1998.

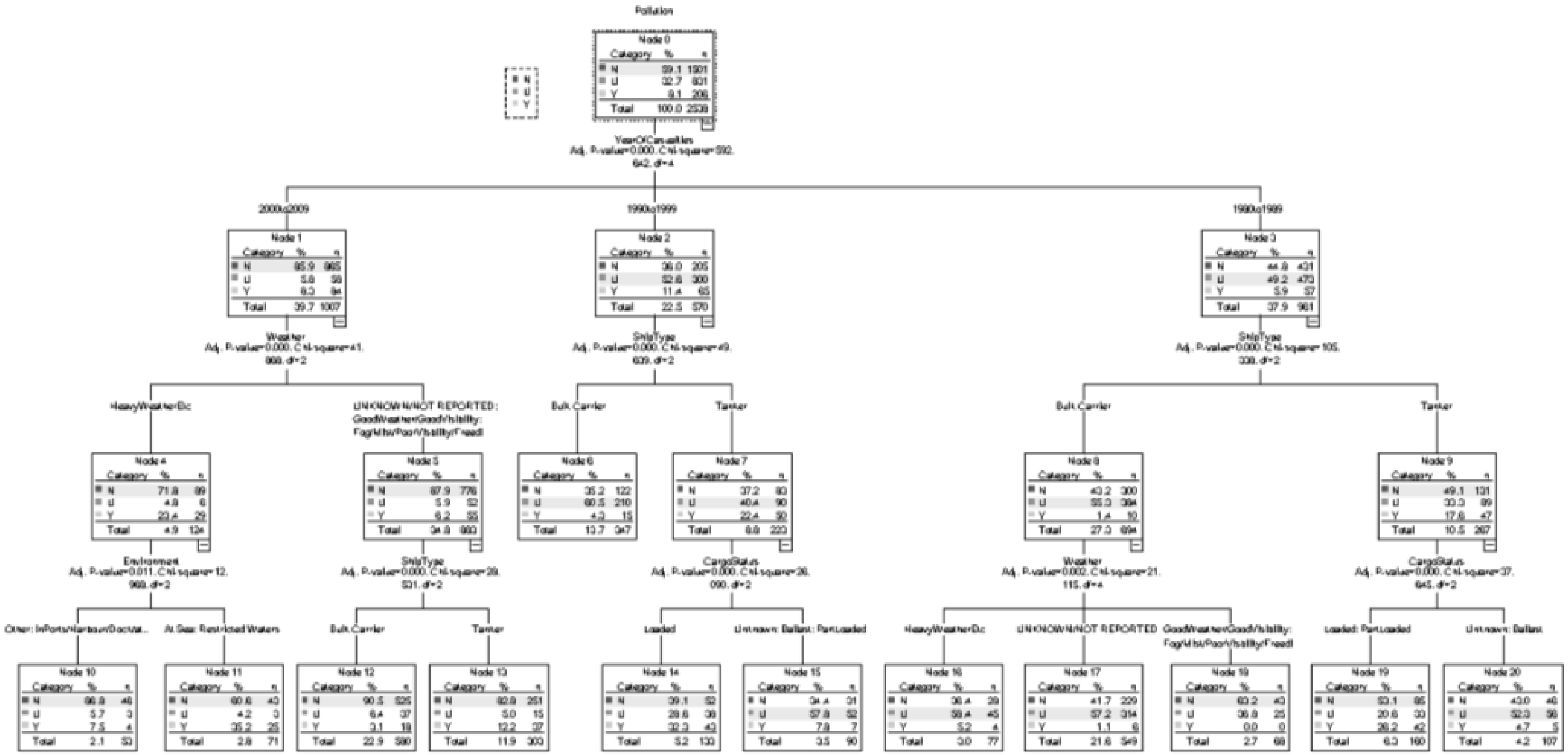


Figure 5-29 Classification tree considering Pollution Indicator as dependent variable

In the third case, dependency of the 'killed indicator' upon the independent variables like ship type, pollution, incident type, detailed ship status(DSS), cargo status, year of casualties, DWT, length, age of the ship and the weather decode is determined as shown in Figure 5-30

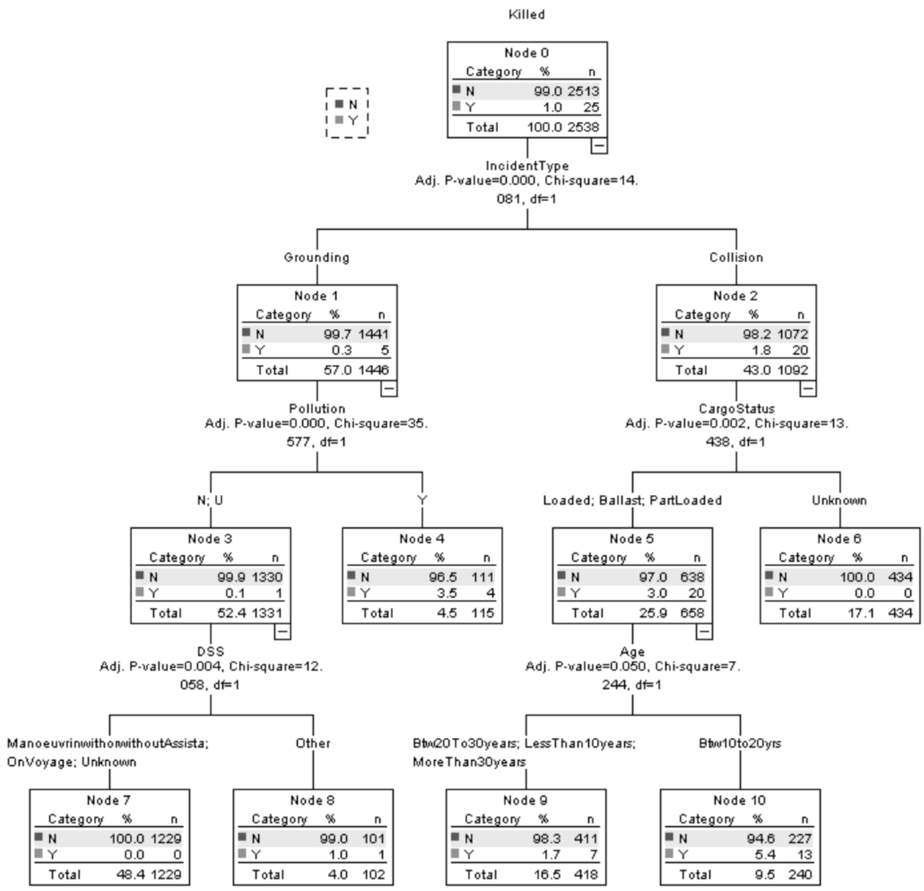


Figure 5-30 Classification tree considering Human casualty as dependent variable

It is clearly seen from the tree that incident type is most significant factor which affects human casualty, with collision accidents being the more dangerous. The tree obtained has a depth 3 with 11 nodes and 6 leaves. Here the root node0 is the target variable (killed) divided into two categories by the predictor variable incident type into collision and grounding accidents under node1 and node2 with 43% and 57% of the total accidents respectively. The p-value is 0.00<0.05 and chi-square 14 and df 1. Node2 is split by the predictor variable pollution into node3 and node4 (leaf) representing pollution index no; unknown and yes.

The third level split of node3 by the predictor variable DSS includes node7 and node8 representing manoeuvring with or without assistance; on voyage; unknown and other. Node2 which includes collision accidents is split by the predictor cargo status into ballast; loaded; part loaded (node5) and unknown (node6) which is a leaf at level 2. The p-value is 0.002<0.05 with chi-square 13 and df 1.The predictor age produces the final branch of the right which includes node9 and node10 representing b/w 20-30; less than 10; greater than 30 and b/w 10-20 years. The p value is 0.05 with chi-square 7 and df 1.

The tree also reveals that the variables ship type, year of casualties, length, weather and DWT were found insignificant and were hence not a part of the tree obtained. The significant predictor variables influencing the target variable killed were cargo status, incident type, DSS, pollution and age of the ship.

5.6 Consequence of Accidents

Accidents of any form are undesirable in shipping owing to the large financial, environmental and human losses resulting from it. The consequence resulting from accidents are many and in some cases the impact of it may be permanent (Human loss) or have a long term effect (environmental pollution). The main consequences resulting from ship accident can be broadly classified as;

- Environmental Pollution
- Human loss
- Damage to the ship
- Financial losses

In this section a statistical analysis is carried out to determine the oil pollution and damage to the ship structure caused by accidents. Since accident database do not include detailed information about these consequences other sources of information such as organisation reports like IMO (1995, 2004. 2008), ITOPF (2009), HARDER Project (2001) etc. along with the accident database are used.

5.6.1 Oil Pollution

The types of cargo carried by ships varies from oil, chemical, grains to containers etc. When an accident occurs there is higher probability of discharge of cargo to the water. It was seen in section 5.3.8, that in 56% of recorded cases pollution happened in tankers and 15% each for bulk carriers and chemical carriers. Hence, in this section pollution caused by tankers will only be considered

The outcome from oil spill depends on a large number of factors, such as the quanitity of oil spilled; its initial physical and chemical characteristics; the weather and sea conditions at the time of accident; and whether the oil remains at sea or moves ashore and most notably the clean-up and response strategy used. Typical environmental impacts range from toxicity to smothering effects.

The effect of oil spills can be far reaching, it can pose both environmental and economic threats. Recreational activities, local industry, fisheries, and marine life are among the resources that can be badly disturbed by oil spills.

5.6.1.1 Causes of Spills

Most oil spill incidents are as a consequence of a combination of actions and circumstances, all of which contribute in varying degrees to the final outcome. The following analysis explores the incidence of spills of different sizes in terms of the event or operation in progress at the time of the spill. These "causes" for oil spill are grouped into three categories during Operations and following Accidents. Spills for which the adequate information is not presented or not clear are listed under "Other/unknown".

It is apparent from the Table 5-16 and Figure 5-31 that:

- most spills from tankers result from routine operations such as loading, discharging and bunkering which normally occur in ports or at oil terminals;

- the majority of these operational spills are small, with some 90% involving quantities of less than 7 tonnes;
- accidents such as collisions and groundings generally give rise to much larger spills, with at least 84% of these incidents involving quantities in excess of 700 tonnes.

Table 5-16 Incidence of Spills by Cause (<7 Tonnes 1974-'09, 7-700 & >700 Tonnes 1970-'09) (ITOPF, 2009)

	Type of Incident	Number of accidents based on spill volume			
		<7 Tonnes	7-700 Tonnes	>700 Tonnes	Total
Operations	Loading/Discharging	3155	383	36	3574
	Bunkering	560	32	0	592
	Other Operations	1221	62	5	1288
Accidents	Collisions	176	334	129	639
	Groundings	236	265	161	662
	Hull Failures	205	57	55	317
	Equipment Failures	206	39	4	249
	Fire & Explosions	87	33	32	152
	Other/Unknown	1983	44	22	2049
	Total	7829	1249	444	9522

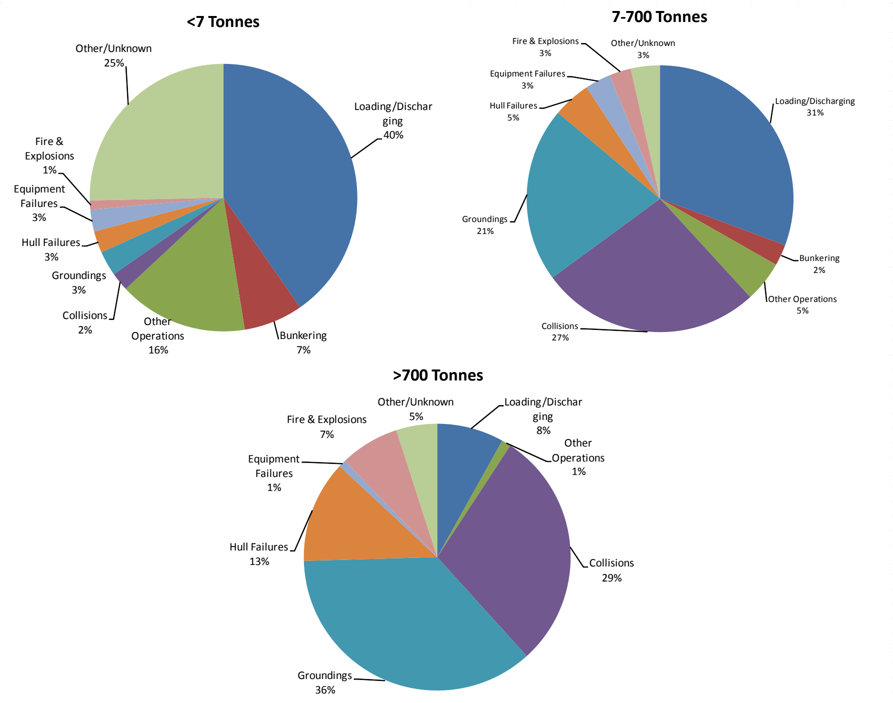


Figure 5-31 Incidence of Spills by Cause (<7 Tonnes 1974-'09, 7-700 & >700 Tonnes 1970-'09) (ITOPF, 2009)

5.6.1.2 Number of oil spills

The number of incidences resulting in large amount of oil spills are relatively low and detailed statistical analysis is rarely possible, hence more emphasis is given on identifying trends. Thus, it is apparent from the Table 5-17 and Figure 5-32 that the number of large spill incidences (>700 tonnes) have decreased noticeably during the last 40 years, such that the average number of major spills for the decade (2000- 2009) is about three. The average for the 2000s is less than half of the average for the 1990s and just an eighth of the average for the 1970s. The same is true for medium sized spills from tankers (7-700 tonnes) where the average number of spills occurring in the last decade was 14, half of that experienced during the previous decade.

It is notable that the number of large spills in the 1970s is more than a half of all the spills recorded in the 40 years between 1970 and 2009. Furthermore, the average number of large spills per year during the 1990s was less than a third of that witnessed during the 1970s. This downward trend continued during the 2000s during which only 7% of all recorded spills occurred

Table 5-17 Number of spills classified according the spill volume (ITOPF, 2009)

Year	7-700 Tonnes	>700 Tonnes
1970	7	29
1971	18	14
1972	48	27
1973	28	32
1974	89	28
1975	96	23
1976	67	27
1977	68	17
1978	59	21
1979	60	35
1980	52	13
1981	54	7
1982	45	4
1983	52	13
1984	26	8
1985	31	8
1986	28	7
1987	27	10
1988	11	10
1989	33	13

Year	7-700 Tonnes	>700 Tonnes
1990	50	14
1991	30	7
1992	31	10
1993	31	11
1994	26	9
1995	20	3
1996	20	3
1997	28	10
1998	26	6
1999	20	6
2000	20	4
2001	17	3
2002	13	3
2003	15	4
2004	16	5
2005	22	4
2006	13	5
2007	13	4
2008	8	1
2009	3	0

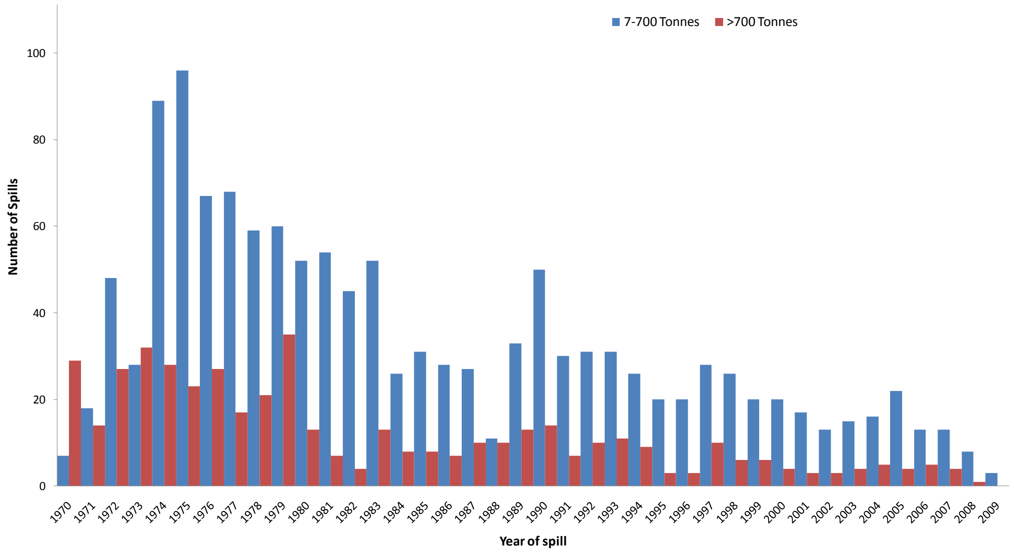


Figure 5-32 Number of spill between 7-700 Tonnes and over 700 Tonnes

Figure 5-33 shows the number of spill at different geographical location as recorded in the damage database. This would be useful to determine the zone in which accidents have higher probability of leading to pollution and based on which actions could be taken to prevent similar incidents in the future.

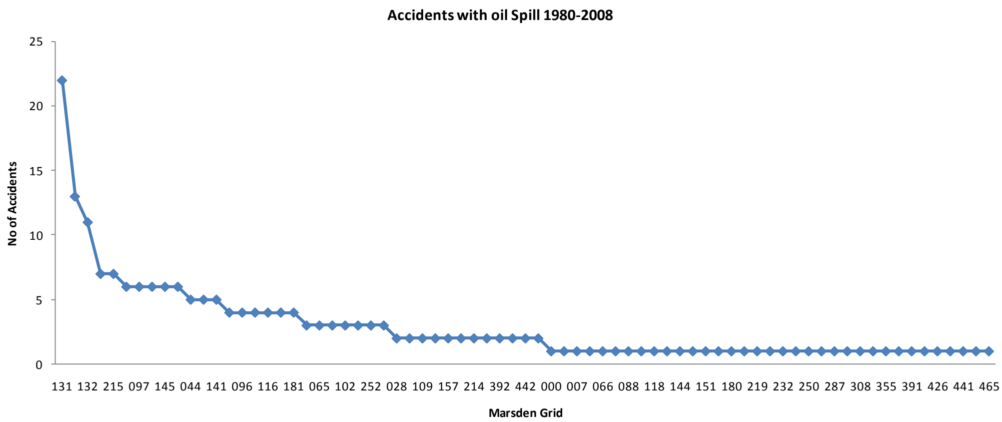


Figure 5-33 Number of spill based on Location

The marsden grid is given in Appendix A.

5.6.1.3 Quantities of Oil Spilt

The vast majority of oil spills fall into the small spill category (i.e. less than 7 tonnes) and data on their numbers and amounts is incomplete due to the inconsistent reporting of smaller incidents worldwide. Reports on spills of 7 tonnes and above tend to be more reliable and information from these is included in the database (ITOPF, 2009) to give a series of annual estimates of the total quantity spilled for the years 1970-2009. Figure 5-34 shows the annual quantity of oil spilt during the period from 1970-2009.

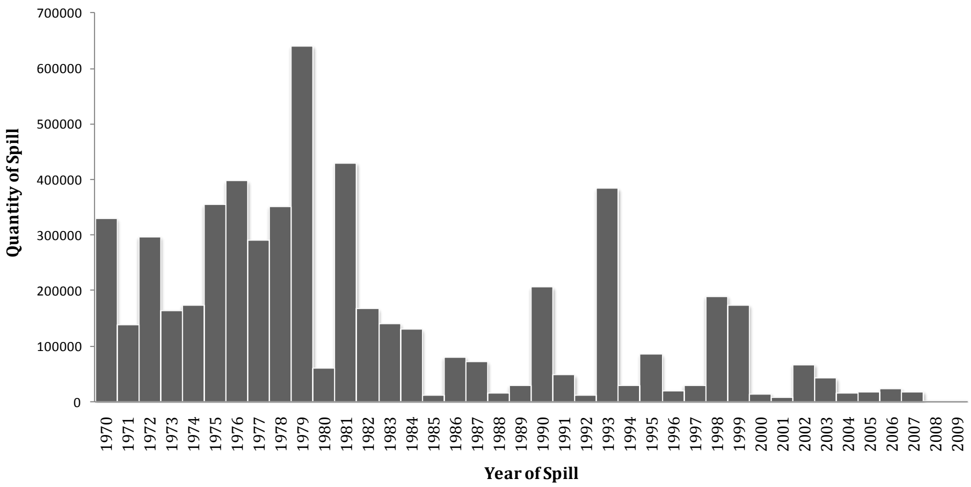


Figure 5-34 Annual Quantity of Oil Spilt (1970-2009)

Approximately 5.65 million tonnes of oil were lost as a result of tanker incidents from 1970 to 2009 (ITOPF, 2009). Consistent with the reduction in the number of oil spills from tankers, the volume of oil spilt also shows a marked reduction. In some cases, the total quantity of oil spilt in the last decade was less than had been spilt previously in a single year. It is notable that a few very large spills are responsible for a high percentage of the oil spilt.

5.6.1.4 Major Oil Spill

Table 5-18 (a) and (b) gives a brief summary of 13 major oil spills as given in the IHS Fairplay database.. It shows the details regarding the incident type which lead to the pollution, the year of casualty, the age of the vessel, the amount of spill , the weather at the time of incident and the location of the accident.

Table 5-18 (a) 13 Major Oil Spills

Position	Name	Incident Type	Year of casualties	Age	Spill Size (Tonnes)
1	ABT SUMMER	FIRE/EXPLOSION	1991	17	260,000
2	CASTILLO DE BELLVER	FIRE/EXPLOSION	1983	5	252,000
3	HAVEN	FIRE/EXPLOSION	1991	18	144,000
4	ODYSSEY	FIRE/EXPLOSION	1988	17	132,000
5	IRENES SERENADE	FIRE/EXPLOSION	1980	15	100,000
6	BRAER	WRECKED/STRANDED	1993	18	85,000
7	KHARK 5	FIRE/EXPLOSION	1989	14	80,000
8	AEGEAN SEA	WRECKED/STRANDED	1992	19	74,000
9	SEA EMPRESS	WRECKED/STRANDED	1996	3	72,000
10	NOVA	COLLISION	1985	10	70,000
11	KATINA P	FOUNDERED	1992	26	66,700
12	PRESTIGE	FOUNDERED	2002	26	63,000
13	EXXON VALDEZ	WRECKED/STRANDED	1989	3	37,000

Table 5-18 (b) 13 Major Oil Spills

Position	Name	WeatherDecode	Detailed Ship Status Decode	EnvironmentDecode
1	ABT SUMMER	UNKNOWN/NOT REPORTED	ON VOYAGE	AT SEA
2	CASTILLO DE BELLVER	HEAVY SWELL	ON VOYAGE	AT SEA
3	HAVEN	UNKNOWN/NOT REPORTED	MOORED/ANCHORED	RESTRICTED WATERS
4	ODYSSEY	HEAVY WEATHER ETC.	ON VOYAGE	AT SEA
5	IRENES SERENADE	UNKNOWN/NOT REPORTED	MANOEUVRING WITHOUT ASSISTANCE	AT SEA
6	BRAER	HEAVY WEATHER ETC.	ON VOYAGE	AT SEA
7	KHARK 5	HEAVY WEATHER ETC.	ON VOYAGE	AT SEA
8	AEGEAN SEA	HEAVY WEATHER ETC.	MANOEUVRING WITHOUT ASSISTANCE	AT SEA
9	SEA EMPRESS	UNKNOWN/NOT REPORTED	MANOEUVRING WITHOUT ASSISTANCE	RESTRICTED WATERS
10	NOVA	UNKNOWN/NOT REPORTED	ON VOYAGE	AT SEA
11	KATINA P	HEAVY WEATHER ETC.	ON VOYAGE	AT SEA
12	PRESTIGE	HEAVY WEATHER ETC.	ON VOYAGE	AT SEA
13	EXXON VALDEZ	UNKNOWN/NOT REPORTED	ON VOYAGE	AT SEA

5.6.1.5 Oil Spill Frequencies

Table 5-19 shows the frequency and spill rate of oil under different accident types. It can be seen that collision, grounding and structural failure accounts for the highest frequency of oil spill and the average amount of oil spilled after a grounding accident is more than any other type of accident.

Table 5-19 Oil tanker oil spill frequencies

Accident Type	Oil Spill Frequency (Spills per ship year)	Oil Spill rate (Tonnes per ship year)	Average oil spill size (Tonnes)
Collision	1.50E-03	4.49	2922
Grounding	5.60E-04	5.2	9227
Contact	7.20E-04	0.11	148
Fire/Explosion	5.10E-04	1.52	2973
War Loss	5.10E-05	0.001	27
Structural Failure	1.30E-03	5.68	4435
Transfer Spill	1.70E-03	0.23	133
Unauthorised discharge	5.10E-04	0.21	408
Total	6.85E-03	17.441	

5.6.2 Damage Extent

IHS Fairplay ship accident database (2009) does not record the extent of damage on the ship structure resulting from accident. But it has records regarding the damage component of the ship as shown in Table 5-20. It gives the number of accidents in which a particular component, such as bow, rudder, tanks etc., has suffered damage. As expected with collision accident the bow and the side structure is damaged in most of the cases, whereas with grounding the bottom structure is damaged.

Table 5-20 Damage location after accident on tankers (a) Collision (b) Grounding

(a) Collision

Event Component Decode	Number of cases
HULL/SHIP UNK/UNSPEC.	79
WHOLE HULL/SHIP	66
HULL/SHIP CMPTMT SPEC. IN TEXT	45
BOW	40
TANK(S) SPEC. IN TEXT	34
HULL STRUCTRE SIDE SPEC IN TXT	25
TANK(S) UNK/UNSPEC	12
UNKNOWN/UNSPECIFIED	11
HULL STRUCTRE UNK/UNSPEC.	8
HULL STRUCTRE SIDE UNK/UNSPEC.	6
BALLAST TANK(S) SPEC. IN TEXT	3
F.PK/FOCSLE SPACE SPEC. IN T.	3
F.PK/FOCSLE SPACE UNK/USPEC	3
STERN	3
HOLD(S) SPEC. IN TEXT	2
HULL STRUCTRE SPEC. IN TEXT	2
RUDDER	2
SUPERSTRUCTURE(S) SPEC IN TEXT	2
BALLAST TANK(S) UNK/UNPEC	1
BUNKER TANK(S) UNK/UNSPEC	1
ENG RM STRUCTRE SPEC. IN TEXT	1
FORECASTLE UNK/UNSPEC	1
HULL STRUCTRE BOTTM UNK/UNSPEC	1
MAIN WEATHER DK SPEC. IN TEXT	1
TANK(S) HULL STRUCTRE	1
TANK(S) HULL STRUCTRE SIDE	1
WHOLE HULL/SHIP POSTN. SP. TXT	1
Collision	**355**

(b) Grounding

Event Component Decode	Number of cases
HULL/SHIP UNK/UNSPEC.	91
WHOLE HULL/SHIP	85
HULL STRUCTRE BTTM SPEC IN TXT	64
HULL STRUCTRE BOTTM UNK/UNSPEC	38
TANK(S) SPEC. IN TEXT	34
TANK(S) UNK/UNSPEC	11
HULL/SHIP CMPTMT SPEC. IN TEXT	10
RUDDER	8
BOW	7
HULL STRUCTRE UNK/UNSPEC.	5
PROPELLER	4
TANK(S) HULL STRUCTRE BOTTOM	3
BALLAST TANK(S) UNK/UNPEC	2
F.PK/FOCSLE SPACE ALL (NOT DK)	2
F.PK/FOCSLE SPACE UNK/USPEC	2
BALLAST TANK(S) SPEC. IN TEXT	1
BULKHEAD SPEC. IN TEXT	1
DOUBLE BOTTOM STRUCTURE BOTTOM	1
DOUBLE BOTTOM UNK/UNSPEC.	1
F.PK/FOCSLE SPACE SPEC. IN T.	1
HOLD(S) SPEC. IN TEXT	1
ST/GR & RUDDER SPEC. IN TEXT	1
SUPERSTRUCTURE(S) UNK/UNSPEC	1
TANK(S) WHOLE/ALL	1
(blank)	1
Grounding	**375**

The International Maritime Organization (1995) Interim Guidelines gives the probability density distributions for the longitudinal location, longitudinal extent, vertical penetration, transverse extent and transverse location expected from grounding damages as shown in Figure 5-35. Similarly, for collision accident the probability density distributions for the longitudinal location, longitudinal extent, transverse penetration, vertical extent and vertical location expected in the IMO guidelines are shown in Figure 5-36

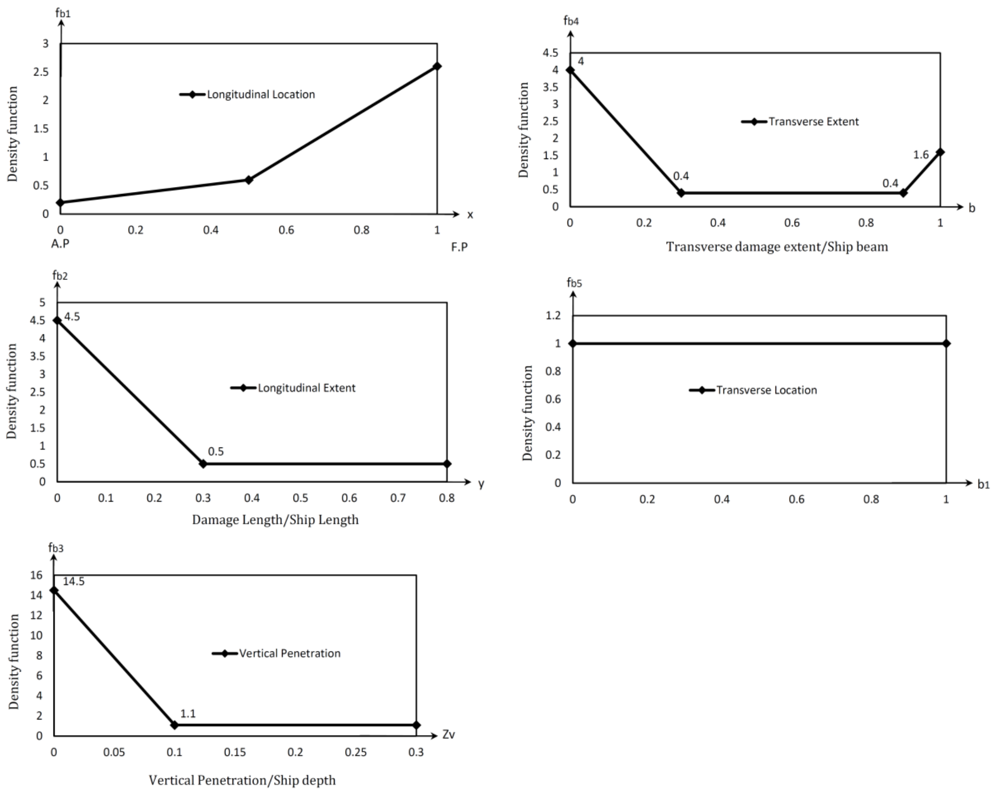


Figure 5-35 Bottom damage due to grounding: density functions f_{b1}, f_{b2}, f_{b3}, f_{b4} and f_{b5}

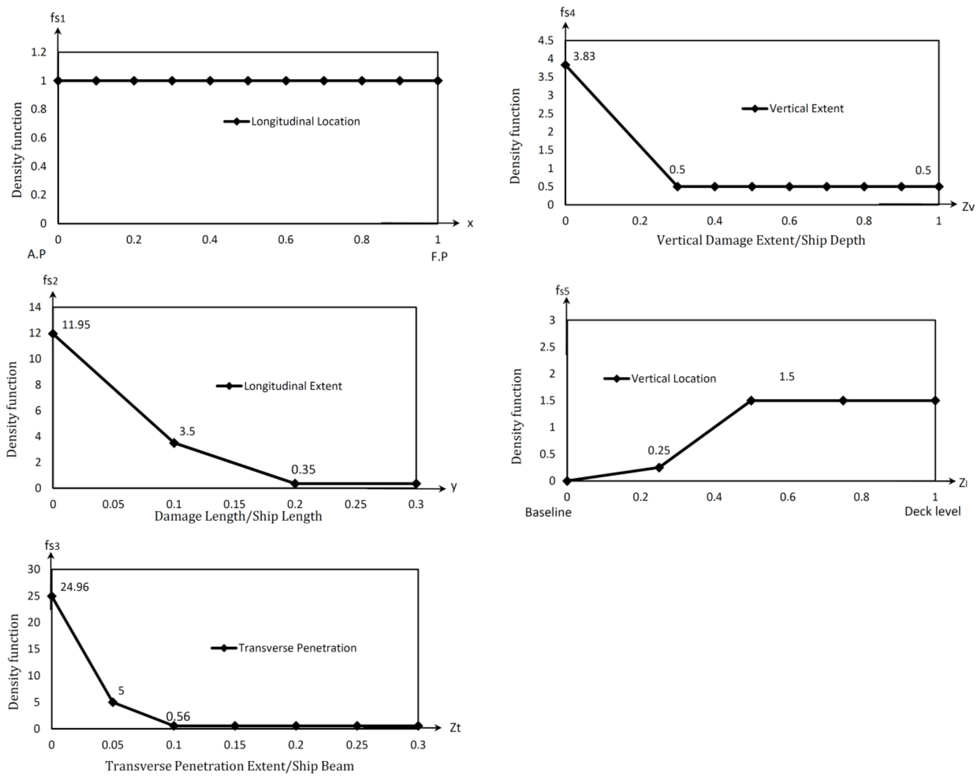


Figure 5-36 Side damage due to collision: density functions f_{s1}, f_{s2}, f_{s3}, f_{s4} and f_{s5}

For more information on the damage extent other sources such as accident investigation reports and project reports such as HARDER and IMO documents were used.

Several studies have been carried out concerning the collision damage for different ship types (Vanem *et al* 2004, Skong *et al* 2004). An extensive study on the development of damage extent modelling concerning oil tankers was carried out Mayoss *et al* (2005) which concluded that with respect to collision and grounding events, the MARPOL damage distribution fit better historical data.

For collision and grounding scenarios, the damage extent is highly related to the penetration of ship's damage. In the information paper on Formal Safety Assessment on crude oil tankers, submitted to IMO by Denmark, (IMO 2008), the Table 5-21 is included which specified typical damage penetrations and their associated probability of occurrence for the sample ships calculated based on Resolution MPEC.117(52) (2004) under collision and grounding accidents .

Table 5-21 Penetration depths and Probabilities for Crude Carriers (IMO, 2008)

(a) Collision

Ref. Ship	Bs(m)	y(m)	y/Bs	$P(y<Y)$
Panamax	32.2	2.075	0.0644	0.812
Aframax	43	2.18	0.0507	0.753
Suezmax	48	2.5	0.0521	0.759
ULCC	58	3.38	0.0583	0.787
			Average $P(y<Y)$	0.77775

(b) Grounding

Ref. Ship	Z_{DB}(m)	Ds(m)	z/Ds	$P(z<Z_{DB})$
Panamax	2.04	19.8	0.10303	0.783
Aframax	2.3	21	0.109524	0.784
Suezmax	2.8	23.1	0.121212	0.803
ULCC	3	31.25	0.096	0.776
			Average $P(z<Z)$	0.7865

It is seen from the table that the probability of penetrating the inner hull structure based on average value is approximately 0.22 in both collision and grounding accidents.

Zhu *et al* (2002) did a general statistics of ship grounding incidents considering the damage extent for Ro-Ro ships based on Lloyds database. It was seen that most grounding accident cause damage around the midship and midship to fore region as most ships operate with a bow up trim. This has significant strength implications because damages to the midship region will significantly reduce the global strength capability, which will be important when recovering from a grounding incident. It was shows that most damages are limited in breadth by B/2 and very rarely do incidents remove more material than this. There are significant number of incidents with damage less than B/5 and it is likely that a grounding incident will involve the removal of something around this percentage of this breath. For the damage length, it is seen that most damage lengths are limited to less than 5% of the ship length and that it is likely that a single damage will be much greater than 20% of the ship length.

Another source of information on the damage extent was HARDER project. The damage data processed by Lützen *et al.* (2003) from the HARDER database shows new and updated distributions for location, length, penetration, and vertical extent of damage. This has resulted in various statistical distributions for different types of collision and grounding scenarios. An interesting, but perhaps obvious relation is shown in Figure 5-37.

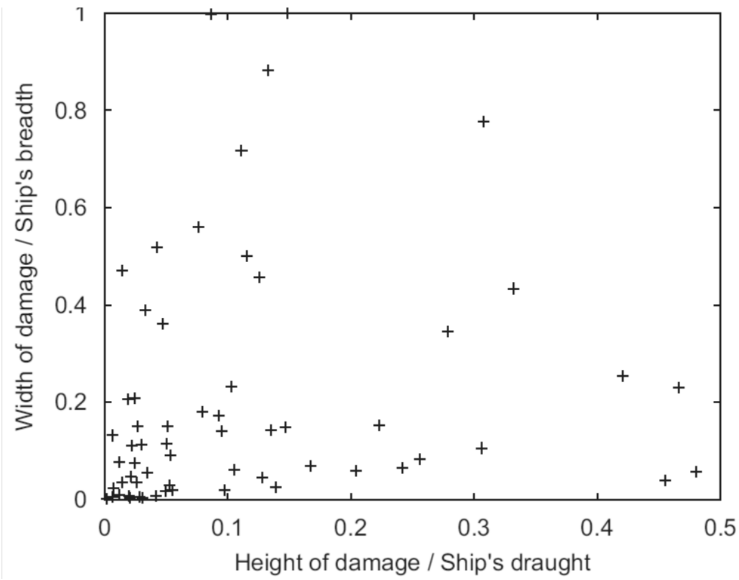
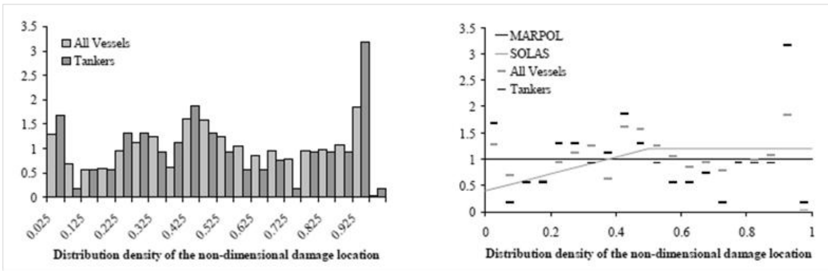


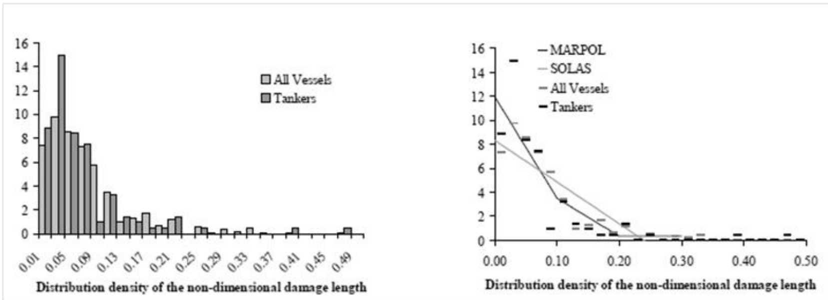
Figure 5-37Sampled data for HARDER project Lutzen *et al* (2003)

Even though the data points are scattered, trends can be found. If deformations go deep into the hull, the magnitude of structural damage is likely to be local. If, on the other hand, large parts of the ship breadth are damaged, the penetration will be small. In other words, the difference in structural damage can be attributed to the shape and size of the obstruction on the sea floor.

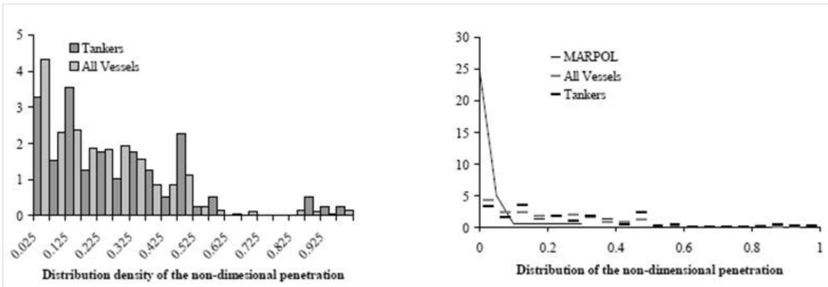
Other important findings for collision accidents from the report are shown in Figure 5-38.



(a)



(b)



(c)

Figure 5-38 The distribution density for (a) the non-dimensional damage location (b) the non-dimensional damage length (c) the non-dimensional damage penetration . Both data and regulation are compared for tankers and all vessels

From Figure 5-38, it can be seen that the location of accident is more or less uniform along the length of the ship with a slight skew towards the fore end and is comparable with the MARPOL plot. The non-dimensional damage penetration from the HARDER data compared to the MARPOL distribution shows significant difference, whereas the non-dimensional damage lengths are comparable.

5.7 Summary & Conclusion

The ship accident damage database was analysed in this chapter to identify useful information which could help in determining the relationship between different variables in the database.

The world ship statistics shows that, bulk carrier and oil tanker tonnage together constitute more than 71% of world fleet and 34% of cargo transported by sea is oil. The accident database analysis shows that majority of accidents in ships are collision and grounding, and interestingly tankers and bulk carriers are involved in majority of these accidents. It is seen that there is a gradual increase in the number of people and oil transported by sea over the years, which makes it necessary to carry out every effort to ensure that maritime transportation is safe and necessary actions taken to prevent any forms of accidents. The analysis shows clear relation between incident type and weather. Collision accidents are seen to occur more frequently when there is poor visibility and grounding accidents when the weather is heavy. The average age of ships involved in accidents are found to be between 14 to 16 years. More number of accidents happened while the ship was at sea, on voyage with loaded cargo. These are some of the typical relations which were observed from the database.

Data mining using classification tree was carried out using incident type, pollution indicator and killed indicator as target variables. It is seen that the significant predictor variables influencing Incident type (target variable) are cargo status, DSS, year of casualties and weather. For pollution indicator as the target variables the influencing target variables are cargo status, location, ship types, year of casualties and weather. For killed indicator the influencing target variables were cargo status, incident type, DSS, pollution and age of the ship. From pollution analysis it is clear that the implementation of ISM code has helped in reducing the number of pollution event following accidents.

The consequence of accidents, in terms of oil spill and damage extent on the structure was also studied. The oil spill statistics shows steady decrease in the number of accidents resulting in pollution.

The findings from this study will be used in subsequent chapters to construct probabilistic models to determine the causes and consequences of ship accidents.

Chapter 6. Bayesian Belief Network

6.1 Introduction

This chapter introduces Bayesian Belief Networks and demonstrations their use as an ideal tool to model probabilistic networks. The different methods of Bayesian network elicitation using database of cases and expert judgement are shown and the chapter concludes stating the merits and demerits of using Bayesian networks.

6.2 Bayesian Belief Network

A Bayesian network is a graphical structure that allows representing and reasoning about an uncertain domain. The nodes in a Bayesian network represent a set of random variables from the domain. A set of directed arcs (or links) connects pairs of nodes, representing the direct dependencies between variables. Assuming discrete variables, the strength of the relationship between variables is quantified by conditional probability distributions associated with each node. The only constraint on the arcs allowed in a BN is that there must not be any directed cycles: you cannot return to a node simply by following directed arcs. Such networks are called directed acyclic graphs, or simply DAG's. One of the most important features of Bayesian networks is the fact that they provide an elegant mathematical structure for modelling complicated relationships among random variables while keeping a relatively simple visualization of these relationships. Bayesian Network comprises of a Qualitative part describing the structure and construction of the network as well as a Quantitative part describing the probabilistic, numerical part (functional aspects) of the network. Bayesian networks work on the principle of Bayes theorem. Bayes' theorem (alternatively Bayes' law or Bayes' rule) links a conditional probability to its inverse. That is, it provides the relationship between P (A | B) and P (B | A).Further, details explaining Bayes rule and features of Bayesian networks are given in Appendix B.

Following is a simple example used to illustrate Bayesian network.

Mr Paul and Mr Ben work for EXxelTip Corporation, Glasgow. When there is no traffic jam in the city, they both reach office at their daily reporting time (9 am) with a probability of 0.9. In case of a traffic jam Paul and Ben, both have a probability of 0.8 and 0.85 respectively of being late. If the probability of traffic jam in Glasgow is 0.3 during peak hours, what is the probability of Paul being late if it is known that Ben is late on a given day?

In this example the probability of traffic jam forms the Information Variable. There is a direction relation between Traffic jam and the probability of Mr Paul & Mr Ben being late which is captured in the Bayesian network as shown Figure 6-1.

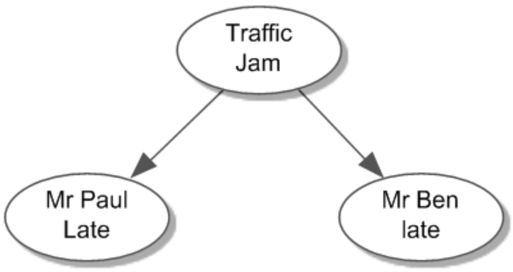


Figure 6-1 Bayesian Network

Table 6 1 shows the conditional probability table for Paul and Ben being late and its relation with Traffic Jam which forms our prior probability.

Table 6-1 Conditional probability Table

	Paul Late		Ben Late	
Traffic Jam	Yes	No	Yes	No
Yes	0.8	0.2	0.85	0.15
No	0.1	0.9	0.1	0.9

The most important use of BNs is in revising probabilities in the light of actual observations of events. Hence, for example, the observation that ‘Mr Ben Late=Yes’ forms the evidence (called instantiation) could be used to find

- the (revised) probability that Mr Paul too is late; and

- the (revised) probability of Traffic Jam

To calculate the revised probability, we use Bayes Rule. For any two events, A and B, Bayes rule can be written as:

$$P(A|B) = \frac{P(B|A) \times P(A)}{P(B)} \qquad \text{Equation 6-1}$$

For this problem:

The probability of Traffic Jam given information that Ben late is

$$P(Traffic\,Jam|\,BenLate) = \frac{P(Ben\,Late\,|\,Traffic\,Jam) \times p(Traffic\,Jam)}{P(Ben\,Late)}$$
$$= \frac{(0.85 \times 0.3)}{(0.85 \times 0.3 + 0.1 \times 0.7)}$$
$$= 0.785$$

Thus, given the evidence that Ben is late the probability of Traffic Jam increased from 0.3 to 0.785. Moreover we can use this revised probability to calculate probability of Mr Paul being late

$$p(Paul\,Late)$$
$$= p(Paul\,Late\,|Traffic Jam) \times p(Traffic Jam)$$
$$+ p(Paul\,Late\,|\,No\ Traffic Jam) \times p(No\ Traffic Jam)$$
$$= (0.8 \times 0.785) + (0.1 \times 0.215)$$
$$= 0.6495$$

Thus the observation that Mr Ben is late has increased the probability of Mr Paul too being late to 65%. When we enter evidence and use it to update the probabilities it is called propagation. These revised probabilities obtained are called the posterior probability.

6.3 Bayesian Network Elicitation Methods

There are three different approaches that can be taken in order to find the structure. The first is through the extraction of information from a domain expert. The second is through finding or mining the variable relationships directly from the observed data. The third method is a hybrid form, which attempts to combine the benefits of the first two approaches. In the case of the domain expert, the causal model (CM) is constructed based on the information supplied by an expert in the problem field. The expert is examined and asked a series of questions which are used to create dependencies between the different variables in the problem domain. The benefit to this approach is that the CM is based on the experience of an expert, without it having to be defined from the data. The second technique used to construct CMs is by extracting them directly from the observed data. Within this approach there are two sub-approaches, the constraint and metric based approaches. Although the constraint based techniques are sub-optimal in representing the variable relationships, they simple to implement and understand. The detailed explanation of the different Bayesian network elicitation methods are given in the following sections.

6.3.1 Data Driven Modelling

Data driven modelling is the task of finding a Bayesian network model from a source of data. It assumes that the underlying process follows a probability distribution (referred to as the underlying probability distribution of the process). The task of data-driven modelling is to fuse these information sources in order to induce a representative model of the underlying process. If the model is a good approximation of the underlying process, then it can be used to answer questions about properties of the underlying process. There exists different classes of algorithm for learning the structure of a Bayesian Network such as search and score algorithms and constraint based algorithms as well as combination of the two. Structure learning is the task of identifying the DAG structure that (best) encodes a set of Conditional Dependence and Independence Relation (CDIR). The set of CIDRs may for instance, be derived from the data source by statistical tests.

Bayesian networks can be learned from data when the data is available. In literature, many methods have been proposed for this purpose. The Bayesian network learning problem can be categorized as

- Parameter learning problem when the structure is known, and
- Structure learning problem when the structure is unknown.

Generally the parameter learning will be a part of the structure learning problem and used as an inner loop of structure learning in the score-and-search-based approach. The task in Bayesian network structure learning is to find a structure of Bayesian network that describes the observed data the most. There are two categories of approaches for Bayesian network structure learning. The first one is the score-and-search-based approach. The methods in this category start from an initial structure (generated randomly or from domain knowledge) and move to the neighbours with the best score in the structure space determinately or stochastically until a local maximum of the selected criteria is reached. The greedy learning process can re-start several times with different initial structures to improve the result. Another category of the Bayesian network structure learning approach is the constraint-based approach. The methods under this category start to test the statistical significance of the pairs of variables conditioning on other variables to induce conditional independence. The pairs of variables which pass some threshold are deemed as directly connected in the Bayesian networks. The complete Bayesian network structure is constructed from the induced conditional independence and dependence information.

6.3.1.1 Score-and-search-based approach

There are three main issues in the score-and-search-based approach for Bayesian network structure learning: the structure space, the search strategy and the model selection criterion. The search space in Bayesian network structure learning is all the possible structures of directed acyclic graphs (DAGs) given the number of variables in the domain. The efficiently computable recursive function to determine the number of possible DAGs that contain n nodes:

$$f(n) = \sum_{i=1}^{n} (-1)^{i+1} C_i^n 2^{i(n-i)} f(n-i) \qquad \text{Equation 6-2}$$

Besides the basic structure space described above, the Markov-equivalent structures as the search space. A set of Bayesian networks are equivalent if they imply exactly the same set of independence statements among variables. Markov-equivalent set of Bayesian network structures can be represented with complete partial DAG (CPDAG). The edges in a CPDAG can be either directed, denoting that the edge direction is the same in all equivalent Bayesian networks, or undirected, denoting that either direction is possible in some equivalent Bayesian networks. In the score-and-search-based approach, any search methods from artificial intelligence, such as brute-force, depth-first, width-first, best-first or simulated annealing, can be used. One of the widely used methods of search is the *greedy search method*.

Greedy Search

If we know nothing about the structure, we can treat the structure learning problem as a general optimization problem in a discrete space. Greedy search starts at a specific point (an initial structure) in the structure space, considers all nearest neighbours of the current point, and moves to the neighbour that has the highest score; if no neighbours have higher score than the current point (i.e., we have reached a local maximum), the algorithm stops.

The greedy search process for score-and-search-based approach is as follows:

- *Input of* the algorithm: Observational data set;
- Output of the algorithm: A Bayesian network construction using the following four steps.
    1. Generate the initial Bayesian network, evaluate it and set it as the current Bayesian network

2. Evaluate the neighbours of the current Bayesian network
3. If the best score of the neighbours is better than the score of the current Bayesian network set the neighbour with the best score as the current Bayesian network and return to Step 2;
4. Otherwise, stop the learning process

Three different ways to generate the initial Bayesian network structures are often used in practice:

- The structure without any arcs – it means every node is independent of any other nodes,
- The structure with complete arcs – it means there are links between any pairs of nodes; and
- Randomly generated structures.

The score can be calculated with any reasonable score function for Bayesian network. A common definition of "neighbour" is all structures that can be generated from the current structures by adding, deleting or reversing a single arc, subject to the acyclicity constraint. When the algorithm stops, it always reaches a local maximum. The local maximum reached by the algorithm is essentially dependent on the initial structure. If a good initial structure is chosen, we can reach a good model in a short time. If a bad initial structure is chosen, we will reach a reasonable good model in a very long time, or can't reach a reasonable good model. Although we know the initial structure is essential, we have no enough knowledge to justify which initial model is good. Instead of choosing one good initial structure, the alternative way is to restart the algorithm with different initial structures and choose the best model in the reached local maximums. Although the idea in greedy search is intuitive, it can reach good model in reasonable time compared with other methods. For a fixed amount of computational time, greedy search with random restarts produces better models than does either simulated annealing or best-first search.

In Bayesian network structure learning, a scoring function evaluates how well a given network G matches the data D. Given a scoring function, the best Bayesian network is the one that maximizes this scoring function. Scoring function is based on the maximum likelihood (ML) principle, cross-validation criterion, entropy score, and minimum message length (MML), are also used for Bayesian network structure selection.

6.3.1.2 Constraint-based approach

Constraint-based methods view the structure learning problem differently. Since a Bayesian network structure encodes many dependencies and (conditional) independencies of the underlying model, the algorithms of this approach try to discover the dependencies and conditional independencies from the data, and then use these dependencies and conditional independencies to infer the Bayesian network structure.

The dependency and conditional independency relationships are measured by using some kind of Conditional Independence (CI) test. The conditional independence tests that are used in practice are statistical tests on the data set. In order to use the results to reconstruct the structure, several assumptions have to be made: Causal Sufficiency assumption, Causal Markov assumption, and Faithfulness assumption.

Causal sufficiency assumption: There exist no common unobserved (also known as hidden or latent) variables in the domain that are parent of one or more observed variables of the domain.

Causal Markov assumption: Given a Bayesian network model G, any variable is independent of all its non-descendants in G given its parents.

Faithfulness assumption: A Bayesian network structure G and a probability distribution P generated by G are faithful to one another if and only if every conditional independence relationship valid in P is entailed by the Causal Markov assumption in G.

With these assumptions in place, one can ascertain the existence of an edge between two variables, or the direction of that link, though the latter is only being possible in certain cases. The output of constraint-based methods will be a partial DAG (PDAG) to represent the whole Markov equivalence class. The representative algorithms in this category are SGS algorithm, CI algorithm, and PC algorithm.

PC Algorithm

The most commonly used one is the PC algorithm. The input for this method is: a database D over a set of variables V, a test of conditional independence: I(x, y | S), a significance level: $0 < \alpha < 1$, and an ordering order (V) over V.

Steps:

1. Construct the complete undirected graph over V.
2. For all adjacent nodes x and y, try to separate nodes by checking first for lower-order, then for progressively higher-order conditional independencies between x and y. Check a conditional independence relation I(x, y |S) if and only if all variables in S are adjacent to either x or y. If a conditional independence relation is discovered between x and y, then remove the edge between x and y, thus decreasing the number of possible sets, S. Conditional independencies should be checked in the order specified by order (V).
3. For each triple of nodes (x, y, z) such that x is adjacent to y and y is adjacent to z but x is not adjacent to z, Orient x— y —z as $x \rightarrow$ y ← z if and only if y was not in the set S that separated x and z in step 2.
4. Repeat, until no more edges can be directed:
   a. Direct all arcs necessary to avoid new v-structures.
   b. Direct all arcs necessary to avoid cycles.

This method relies on arbitrary significance level to decide independencies, and they can be unstable in the sense that an error early on in the search can have a cascading effect that causes a drastically different graph to result. The score-and-search-based approach and constraint-based approach for Bayesian network structure learning can be combined together for Bayesian network structure learning by using the learned network from constraint-based methods as the start point for the search-and score-based methods. The PC algorithm produces a PDAG representing an equivalence class. Each step of the PC algorithm is described in the following sections where the task is to identify a graph G representing the independence model of the underlying process generating the database of cases.

6.3.1.3 Other Methods

Essential Search Graph

Essential graph search starts from a graph obtained by applying PC and then continues with a Greedy Thick Thinning search.

Naïve Classifier

A Naive Bayes classifier is a simple probabilistic classifier based on applying Bayes theorem with strong (Naive) independence assumptions. A more descriptive term for the underlying probability model would be 'independent feature model'.

In simple terms, a naive Bayes classifier assumes that the presence (or absence) of a particular feature of a class is unrelated to the presence (or absence) of any other feature. For example, a fruit may be considered to be an orange if it is orange in colour, round, and about 4" in diameter. Even if these features depend on each other or upon the existence of the other features, a naive Bayes classifier considers all of these properties to independently contribute to the probability that this fruit is an orange.

Figure 6-2 shows the DAG's obtained using different data driven modelling methods on the IHS Fairplay ship accident database, from which it can be seen that different methods results in different graphs for the same database. Also, it can be seen that the direction of arcs representing causal relationship between variables in one DAG to be different from arcs in another DAG.

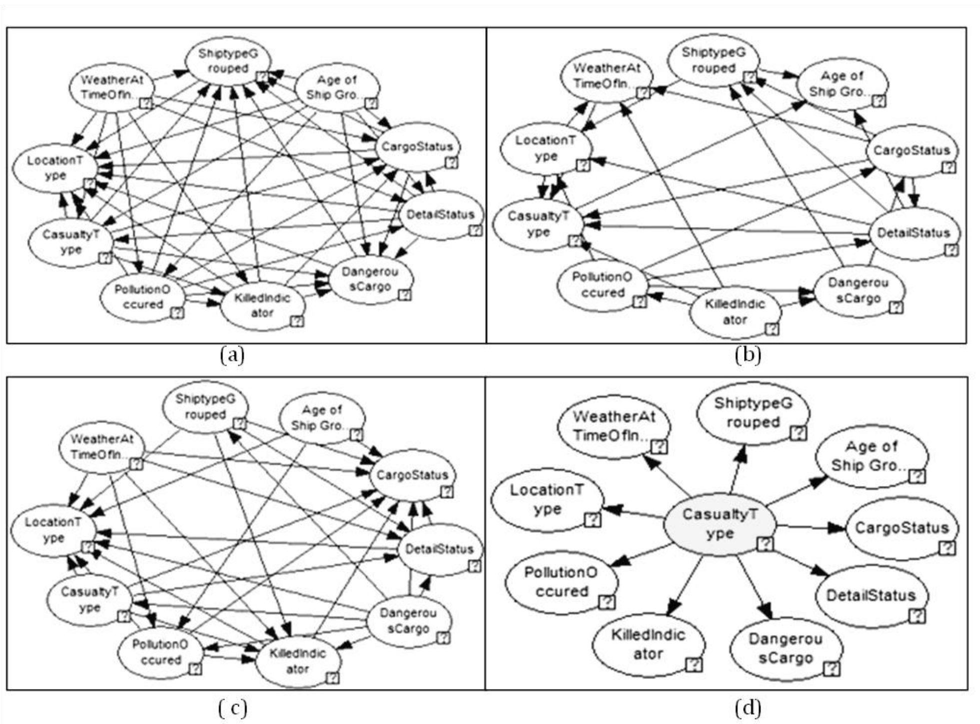


Figure 6-2 Structure of Probabilistic Network Model Using (a) PC Method (b) Greedy Search (c) Essential Search (d) Naïve Classifier

In total there are 40 arcs in PC method, 24 in GTT and 30 in EGS. A comparison based on the number of common links and directions of arcs are given in Table 6-2.

Table 6-2 Network Comparison

Methods→	PC Vs. GTT	PC Vs. EGS	GTT Vs. EGS
Common Links	24	29	19
Same arrow Direction	13	11	6

Comparison of different Methods:

- **PC algorithm**: In this method, an indirect complete graph is constructed from the observed data and then depending upon the relationship among the nodes, edges between independent nodes are deleted and based on adjacency relationships orient the edges between the dependent nodes. For a database with large number of variables, this method has a higher time complexity than the greedy thick thinning method. This happens due to the creation of an indirect complete graph at the initial step and then its gradual transformation to the final structure. But, if the database has less number of variables, this method proves to be an easy and simpler one.

- **Greedy Thick Thinning**: The algorithm used to generate the GTT model assumes no ordering on the nodes. It starts with an equivalence class corresponding to no dependencies and optimizes an existing structure by modifying the structure and scoring the result. By repeating this process a number of times, GTT is able to isolate the best scoring network by using the scoring function which makes it more advantageous than PC algorithm. GTT considers modifications to the existing network. These modifications involve adding an arc if one does not already exist, and removing or reversing an arc if it does already exist between two nodes. The very design of the algorithm makes the time and space complexity of GTT very less compared to PC algorithm and hence it's more suitable for database with large number of variables but faces difficulty of reliably extracting structural information from very small databases; in which case GTT is not able to generalize well. GTT can achieve statistically significant and large gains compared to the other methods.
- **Naive Classifier**: The naïve classifier is a probabilistic model that shows better result for smaller values of training record numbers. First, they are simple to construct and can be built with very constrained space and time complexity. Inference with naïve networks is also efficient. Despite their simplicity, these classifiers

have been shown to perform surprisingly well in practice. The low variance of the naïve classifier can mitigate the bias, resulting in overall accurate predictions and most importantly the naïve classifier converges quickly to its asymptotic error-level.

6.3.2 Expert Judgment

In situations where information is incomplete, decision makers want to know what the experts think and how confident they are. Empirical data are usually insufficient to quantify the uncertainty in the consequence of a course of action and judgmental probabilities provide a logical means for overcoming this limit. Expert Judgment is a term that refers specifically to a technique in which judgment is made based upon a specific set of criteria and/or expertise that has been acquired in a specific knowledge area, or product area, a particular discipline, an industry, etc. Expert judgment is an approach for soliciting informed opinions from individuals with particular expertise and it is typically desirable for utilization in the situations where there is little or no data, or when the data is unsuitable or difficult to understand.

Expert judgment can be used to gather information. Experts can be interviewed separately or brought together as a panel. Interviews can be structured or unstructured. A group process has the advantage of dialogue and discussion that may explore differences in perspectives. The group process can take the form of a group interview where everyone has to answer a set of specific questions. It can be free flowing, taking the form of a focus group. It can also take the form of a panel in which the experts are asked to make a formal presentation about specific issues and then discuss the issues among themselves.

The probability encoding in expert judgment is conducted as a joint undertaking between by a subject (an 'expert' in areas relevant to the quantity being assessed) and an analyst (who serves as the interviewer). There exists a common strategy for any analyst: the analyst strives to understand the indications and modes of information processing that the subject uses and attempts to infer from these the biases that are likely to exist in the subjects' response.

Statistics is an integral part of the analysis of expert judgment, providing mathematically rigorous methods for aggregating differing experts' responses, quantifying the accuracy of experts' predictions, combining different types and sources of data, and formulating models using the experts' responses.

Typically, expert judgment is used in two fundamental ways:

- To structure the technical problem. For example, experts may determine which data are relevant for analysis, which variables (input and response) or analysis methods are appropriate, and which assumptions are valid. Statisticians frequently use their expert judgment in this way.
- To provide estimates. For example, experts may estimate failure or incidence rates, determine weighting factors for combining data sources, or characterize uncertainty. These estimates could be quantitative, having a numerical value, or qualitative, having a textual description.

6.3.2.1 Expert elicitation techniques

There are two primary forms of the expert elicitation technique; Group Methods and Single Expert Methods i.e. it can be done either as a group or as an individual exercise. Group methods tend to be the more popular and widely used as they are more robust and are less subject to bias. Moreover, within the context of use, it is unusual for a single individual to possess all the required information and expertise to be able to solely estimate, in an accurate manner, the human reliability in question. In this thesis expert judgement is gathered using consensus group method. This is the most group-centred approach and requires that the group must come to a consensus on the estimates made through discussion and mutual agreement. This method maximizes knowledge sharing and the exchange of ideas and also *promotes* equal opportunity to participate in discussion.

6.3.2.2 Expert judgment procedure

The entire process of expert judgment is conducted in a sequence of seven stages. They are motivating the subject, structuring the uncertain variable to be assessed, conditioning the subject for encoding task, actually encoding the quantifying judgments, verifying the result, resolving expert differences and aggregating probabilities to form group probability assessments and discretizing continuous distributions. These seven steps can be described as follows;

- **Motivating**: The primary stage known as the motivating stage involves setting up a close relationship between the subject and the analyst for a better understanding and easy communication. The major task of this stage is to familiarize the subject with the exact cause of the analysis, corresponding decision model, and the effect of uncertainty on decision. The analyst in this stage has to clearly measure the scope for biases and deal with the situation accordingly.
- **Structuring**: The structuring stage serves the dual tasks of visualizing the uncertain quantity and associating them with well-defined variables suitable for encoding processes and also examining the subjects' response to such uncertain quantities. This gives an indirect measure of cognitive biases. The major steps in this stage involve defining the uncertain variable, identifying its range of outcomes, explore the advantage of breaking up this variable to simple ones, enumerating the subjects' opinion about the uncertain variable and finally developing an appropriate measuring scale.
- **Conditioning**: This stage aims to develop the subjects' awareness regarding the uncertain variables based on the all the necessary knowledge and information which the analyst has gathered. Here, anchoring and

availability biases in the subjects' response are dealt systematically and all the information useful for assessing uncertainty is clarified.

- **Encoding**: This stage is a quantitative stage which involves quantifying the uncertain variables (both discrete and continuous). The main methods used for this purpose are probability methods, value methods and probability/value methods. Each of these methods may be direct or indirect based on the subjects' answering mode.
- **Verifying**: This is a testing stage in which the judgments obtained from the encoding the uncertain variables are examined for validity. The encoded distribution is produced before the subject and his reaction determines the validity of stage 4. If found invalid; the encoding stage is repeated.
- **Aggregating**: To improve the assessment quality, probability judgments are collected from a group of subjects and then aggregated together. There are both behavioural and mechanical methods of aggregating. The major advantage of this stage is sharing of knowledge, which gives a common information base and hence reduces the difference among individual probability distributions.
- **Discretizing:** To facilitate computational simplicity, infinite number of possibilities involved is reduced to a finite number, so that they are dealt easily. We divide the range of possible values of uncertain variable to intervals, select a representative point from each of the interval and assign the probability of the actual interval to it. Finally we end up with pairs of uncertain variables and corresponding probabilities.

6.3.2.3 Merits and Demerits of Expert Judgment technique

Advantages of expert judgment technique

1. The method is relatively quick and straightforward to employ.
2. Expert judgment is not restricted to or specialized for use in a particular field; it is easily applicable to an HRA (Human reliability assessment) on any industrial sector thus making it a generic technique for use in a wide range of potential applications.

3. Useful suggestions may result from discussion as to ways in which a reduction in errors can be achieved.

Disadvantages of expert judgment technique

1. Expert judgment is prone to certain biases and group conflicts or problems. Selection of the correct group methodology or high-quality group facilitation may decrease the effect of these biases and increase the validity of the results.
2. Locating suitable experts for the Expert judgment exercise is a difficult stage of the process, more so due to the ambiguity with which the term 'expert' can be defined.
3. Because there may be little or no empirical and/or quantitative reasoning underpinning the experts' estimates, it is difficult to be certain of the validity of the final model i.e. there is no means by which guesses can be validated.

6.4 Software tools

There are different software tools available for carrying out network analysis such as Hugin, GeNIe etc. This Thesis used GeNIe (Graphical Network Interface) to model the Bayesian Network. It has been developed at the Decision Systems Laboratory, University of Pittsburgh. GeNIe can be used to create decision theoretic models intuitively using the graphical click-and-drop interface.

6.4.1 GeNIe

GeNIe is the graphical interface; fully portable Bayesian inference engine developed by the Decision Systems Laboratory and thoroughly tested in the field since 1998. GeNIe 2.0 is the latest version of GeNIe. GeNIe is a versatile and user-friendly development environment for graphical decision-theoretic models.

6.5 Merits and Demerits of Bayesian Network Analysis

The merits of Bayesian Networks are:

- The usefulness of BNs lies in the fact that by using Bayes's theorem, one can calculate not only the probability distributions of children given the values of their parents, but also the distributions of the parents given the values of their children. That is, one can proceed not only from causes to consequences, but also deduce the probabilities of different causes given the consequences
- Bayesian Networks visually represent all the relationships between the variables in the system with connecting arcs, hence easy to understand.
- Can be used in conjunction with database of cases and expert judgement.
- Help to model when the data set is small, many conditioning cases are represented by too few or no data records.
- Can be used to model any problem domain.
- Bayesian networks can also be supplemented with decision support tools ([Kuikka et al., 1999]and [Jensen, 2001]), which are a natural addition to the ability to treat uncertainty in the first place.

The demerits of Bayesian Networks are:

- All branches must be calculated in order to calculate the probability of any one branch.
- The network becomes complicated as the number of nodes and states increases.
- The quality of the results of the network depends on the quality of the prior beliefs or model. A variable is only a part of a Bayesian network if you believe that the system depends on it.
- Calculations and probabilities using Baye's rule and marginalization can become complex and are often characterized by subtle wording, and care must be taken to calculate them properly.

6.6 Summary & Conclusion

Bayesian belief networks became extremely popular models in the last decade, but their use in maritime industry has somewhat lagged behind other industry. This chapter gives an overview of Bayesian Network and the different methods available for Bayesian model elicitation. The graphical nature of Bayesian networks and its ability of describing uncertainty of complex relationships in a compact manner provide a method for modelling almost any type of data.

In short Bayesian learning is a simple process of:

- Specify a prior knowledge over our models.
- Use Bayes law with respect to all observed information (prior) to compute a posterior over our model.
- Predict based on the posterior.

Different methods of Bayesian model elicitation viz., Data Driven Modelling and Expert Judgement model was described in detail, together with the advantages and disadvantages of each method. The ship accident database was analysed using different data driven modelling techniques and the results compared in this chapter.

Chapter 7. Causes and Consequences of Ship Accidents

7.1 Introduction

This chapter investigates the probability of ship accidents, the causes and their consequences in terms of loss of life, pollution and the damage to the ship structure. Bayesian Belief Networks (BBN's) are used to create the causes and consequences models of accidents. To develop the BBN models, data from past accidents and expert judgment from people who have experience in the safety and structural aspects of ships are considered.

7.2 Bayesian Modelling of Damage Database

It was shown in the previous chapter that Bayesian networks are powerful tools to capture the relationship between different variable and to assist in decision making. The Bayesian network graphs gives a good understanding of the relation between different nodes and based on evidence, probability of occurrence of each state in any given node could be obtained which would help in decision making.

The database used for this study is IHS Fairlplay database of ship accidents from 1980-2009 (IHS Fairplay, 2009). The database records accidents on 8 ship types and include 9 types of accidents as described in Chapter 5. For this study only collision and grounding accidents on Bulk Carriers and Tankers is considered. The unknown data was removed from the database. Table 7-1 shows the nodes and states used in this study.

Table 7-1 Nodes and State

Nodes	**States**
Ship Type	Bulk Carrier Tanker
Incident Type	Collision Wrecked/Stranded
Initial Event	Collision Hull/Mchy/Equip.Damage/Failure Other Wrecked/Stranded
EventComponentDecode	Anchor/Moorg/Tow Etc Bow Structure Hull Structure Bottom Hull Structure Side Hull/Ship Other St/Gr/Rudder General Tank (S) Whole Hull/Ship
Weather	Fog/Mist/Poor Visibility Etc Good Weather/Good Visibility Heavy Weather Etc.
DSS	Manoeuvring With Or Without Assistance On Voyage Other
Cargo Status	Ballast Loaded Part Loaded
Geographical Location	Baltic Br.Isles, N.Sea, E.Chnl, Bay Of Biscay Canadian Arctic + Alaska +Iceland+Ussr, Arctic + Bering Sea E & W.Africa Coast E.Mediterranean + Black Sea Great Lakes (North Easter North America) Gulf Of Mexico Gulf+Bay Of Bengal+Red Sea Japan + Korea N. America Pacific Coast + U.S.Eastern Seaboard + New Foundland N. Atlantic + N & S.Pacific + Indian Ocean + Antartica S.Atlantic, E.Coast S.America S.China + E.Indies W.Coast S.America+Unknown+Australasia+Cape Horn W.Indies W.Mediterranean
Location	At Sea In Port/Harbour/Dock/At... Others Restricted Waters
Length	Length Btw 101-200m Length Btw 201-300m Length Less Than 100m Length More Than 300m
DWT	Btw 20K-30K Btw 30K-60K Btw60K-80K Btw80K-120K Btw120K-200K MoreThan200K
Flag	Africa Asia Australia Europe North America South America
YOC	Yoc Between 1980-89 YOC Between 1990-99 YOC Between 2000-08
Age	Age 0-8 Years Age 17-24 Years Age 9-16 Years Age More Than 24 Years
Killed/Missing	No Yes
Pollution	No Yes

7.2.1 Bayesian Damage Database Model

Greedy Thick Thinning Method, a search and score algorithm, available in GeNie (1998) is used to model the database. The typical quantification of the CPT's in BBN modelling requires elicitation for all combinations of parent nodes feeding the child node. During the procedure of data acquisition and definition of the model structure, GeNIe automatically calculated the different CPT's based on the frequencies calculated from the dataset. Figure 7-1 shows a sample CPT taken from the model. The final model is as shown in Figure 7-2.

WeatherDecode	Fog_Mist_Poor_Visibility_etc			Good_Weather_Good_Visibility			Heavy_Weather_ETC_		
Detailed Ship Status Decode	Manoeuvrin...	On_Voyage	Other	Manoeuvrin...	On_Voyage	Other	Manoeuvrin...	On_Voyage	Other
At_Sea	0.13333333	0.61864407	0.44444444	0.25	0.73333333	0.4	0.076923077	0.71153846	0.16304348
In_Port_Harbour_Dock_At__	0.26666667	0.059322034	0.33333333	0.125	0.033333333	0.2	0.46153846	0.13461538	0.58695652
Others	0.2	0.1779661	0.11111111	0.125	0.11666667	0.2	0.11538462	0.044871795	0.065217391
Restricted_Waters	0.4	0.1440678	0.11111111	0.5	0.11666667	0.2	0.34615385	0.10897436	0.18478261

Figure 7-1 Sample of a CPT

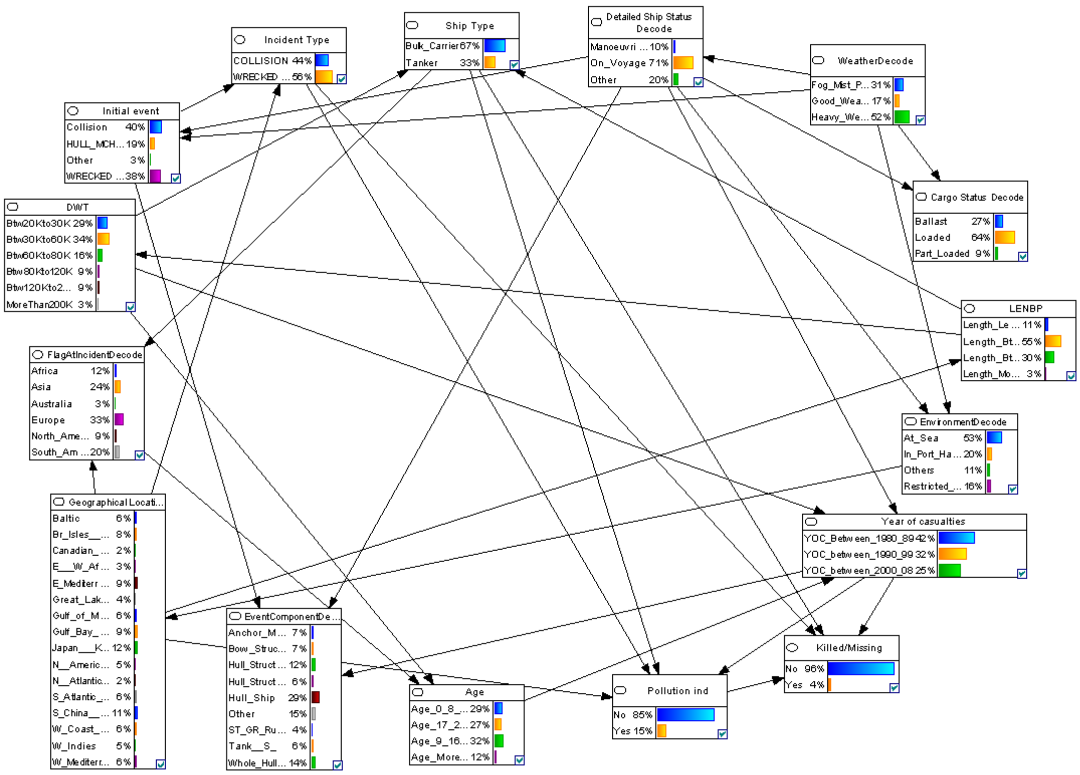


Figure 7-2 Bayesian Model of Damage Database

7.2.2 Results

Figure 7-2 shows the model obtained from database modelling. This network captures the conditional dependencies and interrelation of variables in the database. The direction of the arcs between different nodes in the network graphically depicts the underlying hidden relationship between the variables of the database. Hence, by conditioning on the state of any node (or number of nodes), the output on other nodes (which is the probability of realisation of state of those nodes given the evidence for the conditioned node) can be obtained. For example, if we have evidence about the incident type (Incident type = Collision), then conditioning on this evidence we could determine the probabilities of the states in other nodes.

Analysis of the model was carried out to predict the probability of each state within a node given the following evidence;

- Given, Accident type = Collision or Grounding as shown in Table 7-2.
- Given, Ship Type = Bulk Carrier or Tanker as shown in Table 7-3.
- Given, (a) Pollution = Yes (b) Killed =Yes as shown in Table 7-4

Since the nodes are conditional dependent on one another probabilities of states changes with different evidences. Even though this model is derived from the database its obvious advantages are, it can graphical captures the underlying hidden information and can be conditioned based on evidence to determine the probabilities of other nodes in the presence of evidence.

Table 7-2 Resutls from BBN Database Modelling for Incident Type

Nodes	States	Incident Type	
		Collision	Wrecked/Stranded
Ship Type	Bulk Carrier	66	67
	Tanker	34	33
Initial Event	Collision	89	2
	Hull/Mchy/Equip.Damage/Failure	7	28
	Other	3	3
	Wrecked/Stranded	1	67
EventComponentDecode	Anchor/Moorg/Tow Etc	3	9
	Bow Structure	13	3
	Hull Structure Bottom	2	20
	Hull Structure Side	10	2
	Hull/Ship	35	24
	Other	14	16
	St/Gr/Rudder General	2	5
	Tank (S)	7	6
	Whole Hull/Ship	14	15
Weather	Fog/Mist/Poor Visibility Etc	49	17
	Good Weather/Good Visibility	21	15
	Heavy Weather Etc.	30	68
DSS	Manoeuvring With Or Without Assistance	8	11
	On Voyage	75	67
	Other	17	22
Cargo Status	Ballast	24	29
	Loaded	68	61
	Part Loaded	8	10
Geographical Location	Baltic	7	6
	Br.Isles, N.Sea, E.Chnl, Bay Of Biscay	8	7
	Canadian Arctic + Alaska +Iceland+Ussr, Arctic + Bering Sea	2	2
	E & W.Africa Coast	3	3
	E.Mediterranean + Black Sea	9	9
	Great Lakes (North Easter North America)	4	4
	Gulf Of Mexico	7	6
	Gulf+Bay Of Bengal+Red Sea	9	10
	Japan + Korea	12	11
	N. America Pacific Coast + U.S.Eastern Seaboard + New Foundland	5	5
	N. Atlantic + N & S.Pacific + Indian Ocean + Antartica	1	2
	S.Atlantic, E.Coast S.America	6	6
	S.China + E.Indies	10	11
	W.Coast S.America+Unknown+Australasia+Cape Horn	5	6
	W.Indies	5	6
	W.Mediterranean	7	6
Location	At Sea	55	52
	In Port/Harbour/Dock/At...	17	23
	Others	13	9
	Restricted Waters	15	16
Length	Length Btw 101-200m	55	55
	Length Btw 201-300m	30	30
	Length Less Than 100m	12	11
	Length More Than 300m	3	4
DWT	Btw 20K-30K	29	29
	Btw 30K-60K	34	34
	Btw60K-80K	16	16
	Btw80K-120K	18	18
	Btw120K-200K	9	9
	MoreThan200K	3	3
Flag	Africa	12	12
	Asia	24	23
	Australia	3	3
	Europe	33	33
	North America	9	9
	South America	19	20
YOC	Yoc Between 1980-89	42	42
	YOC Between 1990-99	33	32
	YOC Between 2000-08	25	26
Age	Age 0-8 Years	29	29
	Age 17-24 Years	27	27
	Age 9-16 Years	32	32
	Age More Than 24 Years	12	12
Killed/Missing	No	93	98
	Yes	7	2
Pollution	No	86	83
	Yes	14	17

Table 7-3 Resutls from BBN Database Modelling for Ship Type

Nodes	States	Ship Type	
		Bulk Carrier	Tanker
Incident Type	Collision	44	44
	Wrecked/Stranded	56	56
Initial Event	Collision	40	40
	Hull/Mchy/Equip.Damage/Failure	19	18
	Other	3	3
	Wrecked/Stranded	38	39
EventComponentDecode	Anchor/Moorg/Tow Etc	7	7
	Bow Structure	7	7
	Hull Structure Bottom	12	12
	Hull Structure Side	6	6
	Hull/Ship	29	28
	Other	15	15
	St/Gr/Rudder General	4	4
	Tank (S)	6	6
	Whole Hull/Ship	14	15
Weather	Fog/Mist/Poor Visibility Etc	31	31
	Good Weather/Good Visibility	17	18
	Heavy Weather Etc.	52	51
DSS	Manoeuvring With Or Without Assistance	10	9
	On Voyage	70	72
	Other	20	19
Cargo Status	Ballast	27	27
	Loaded	64	65
	Part Loaded	9	8
Geographical Location	Baltic	6	6
	Br.Isles, N.Sea, E.Chnl, Bay Of Biscay	8	8
	Canadian Arctic + Alaska +Iceland+Ussr, Arctic + Bering Sea	2	2
	E & W.Africa Coast	3	3
	E.Mediterranean + Black Sea	10	9
	Great Lakes (North Easter North America)	5	3
	Gulf Of Mexico	7	5
	Gulf+Bay Of Bengal+Red Sea	10	9
	Japan + Korea	9	17
	N. America Pacific Coast + U.S.Eastern Seaboard + New Foundland	5	4
	N. Atlantic + N & S.Pacific + Indian Ocean + Antartica	2	2
	S.Atlantic, E.Coast S.America	7	5
	S.China + E.Indies	9	13
	W.Coast S.America+Unknown+Australasia+Cape Horn	6	5
	W.Indies	6	5
	W.Mediterranean	5	4
Location	At Sea	52	56
	In Port/Harbour/Dock/At...	21	20
	Others	11	9
	Restricted Waters	16	15
Length	Length Btw 101-200m	68	30
	Length Btw 201-300m	30	30
	Length Less Than 100m	1	32
	Length More Than 300m	1	8
DWT	Btw 20K-30K	35	10
	Btw 30K-60K	35	29
	Btw60K-80K	18	10
	Btw80K-120K	3	25
	Btw120K-200K	7	14
	MoreThan200K	1	11
Flag	Africa	12	12
	Asia	21	29
	Australia	2	5
	Europe	35	30
	North America	8	11
	South America	22	13
YOC	Yoc Between 1980-89	45	37
	YOC Between 1990-99	31	34
	YOC Between 2000-08	24	29
Age	Age 0-8 Years	29	29
	Age 17-24 Years	29	24
	Age 9-16 Years	32	33
	Age More Than 24 Years	10	14
Killed/Missing	No	96	95
	Yes	4	5
Pollution	No	89	76
	Yes	11	24

Table 7-4 Resutls from BBN Database Modelling for consequence in terms of Pollution and Killed/Missing

Nodes	States	Pollution? Yes	Killed/Missing? Yes
Ship Type	Bulk Carrier	47	58
	Tanker	53	42
Incident Type	Collision	48	71
	Wrecked/Stranded	52	29
Initial Event	Collision	44	64
	Hull/Mchy/Equip.Damage/Failure	17	13
	Other	3	3
	Wrecked/Stranded	36	20
EventComponentDecode	Anchor/Moorg/Tow Etc	6	5
	Bow Structure	8	11
	Hull Structure Bottom	12	8
	Hull Structure Side	6	8
	Hull/Ship	31	33
	Other	15	14
	St/Gr/Rudder General	4	3
	Tank(S)	7	8
	Whole Hull/Ship	11	10
Weather	Fog/Mist/Poor Visibility Etc	33	40
	Good Weather/Good Visibility	18	19
	Heavy Weather Etc.	49	41
DSS	Manoeuvring With Or Without Assistance	9	8
	On Voyage	73	75
	Other	18	17
Cargo Status	Ballast	27	25
	Loaded	65	67
	Part Loaded	8	8
Geographical Location	Baltic	6	7
	Br.Isles, N.Sea, E.Chnl, Bay Of Biscay	7	8
	Canadian Arctic + Alaska +Iceland+Ussr, Arctic + Bering Sea	4	3
	E & W Africa Coast	3	3
	E.Mediterranean + Black Sea	7	8
	Great Lakes (North Easter North America)	4	4
	Gulf Of Mexico	5	6
	Gulf+Bay Of Bengal+Red Sea	9	9
	Japan + Korea	13	12
	N. America Pacific Coast + U.S.Eastern Seaboard + New Foundland	5	5
	N. Atlantic + N & S.Pacific + Indian Ocean + Antartica	3	2
	S.Atlantic, E.Coast S.America	4	5
	S.China + E.Indies	13	10
	W.Coast S.America+Unknown+Australasia+Cape Horn	8	6
	W.Indies	5	5
	W.Mediterranean	4	7
Location	At Sea	55	55
	In Port/Harbour/Dock/At...	19	18
	Others	10	12
	Restricted Waters	16	15
Length	Length Btw 101-200m	48	51
	Length Btw 201-300m	30	31
	Length Less Than 100m	17	14
	Length More Than 300m	5	4
DWT	Btw 20K-30K	19	28
	Btw 30K-60K	32	34
	Btw60K-80K	15	16
	Btw80K-120K	16	9
	Btw120K-200K	12	10
	MoreThan200K	7	4
Flag	Africa	12	11
	Asia	26	24
	Australia	4	4
	Europe	30	32
	North America	9	9
	South America	19	20
YOC	Yoc Between 1980-89	45	35
	YOC Between 1990-99	36	49
	YOC Between 2000-08	19	16
Age	Age 0-8 Years	30	29
	Age 17-24 Years	25	27
	Age 9-16 Years	32	30
	Age More Than 24 Years	13	14
Killed/Missing	No	88	NA
	Yes	12	
Pollution	No	NA	56
	Yes		44

The variations of accident type, ship type, pollution and human casualty during the last 3 decades, as given by the data driven BBN Model, is as shown in Figure 7-3. It is clear that after the introduction of ISM Code there has been a significant reduction in occurrence of pollution and human casualties. Pollution for the period from 2000-2008 was reduced to 11% compared to 17% during the period from 1990-1999, similarly human causality also has reduced during the last decade.

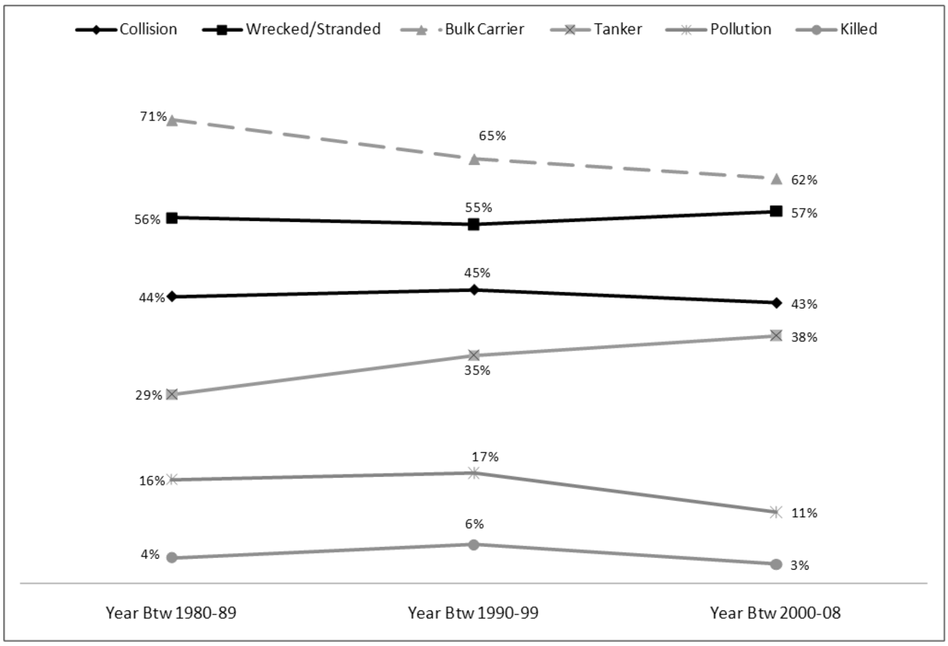


Figure 7-3 The variations of accident type, ship type, pollution and human casualty given the Year of Casualty

Figure 7-4 and Figure 7-5 shows the result of the analysis with Accident Type being collision and grounding respectively. Here, accident types are analysed against the year of casualty, pollution and human causalities.

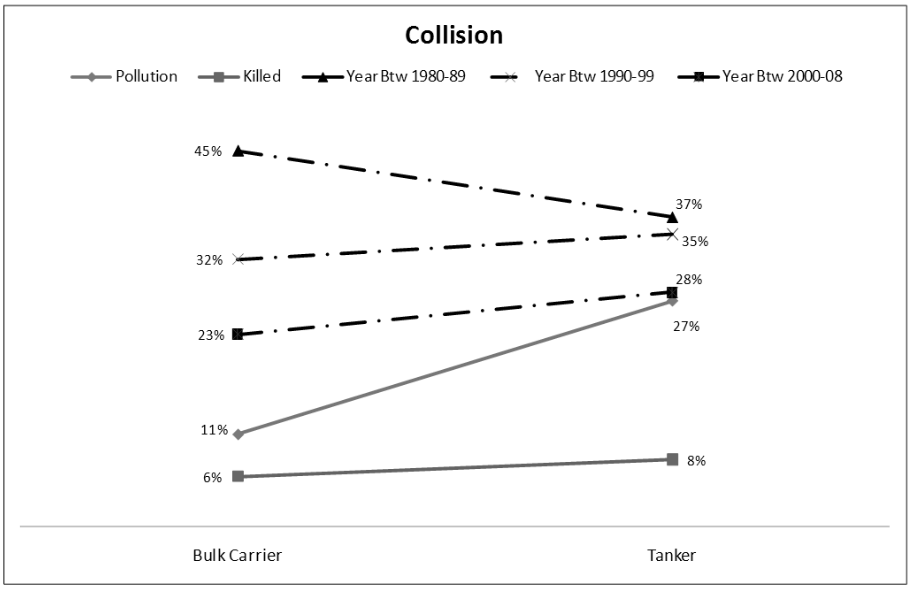


Figure 7-4 The variations of probability of Pollution, Killed, Year of Accident given Ship Type

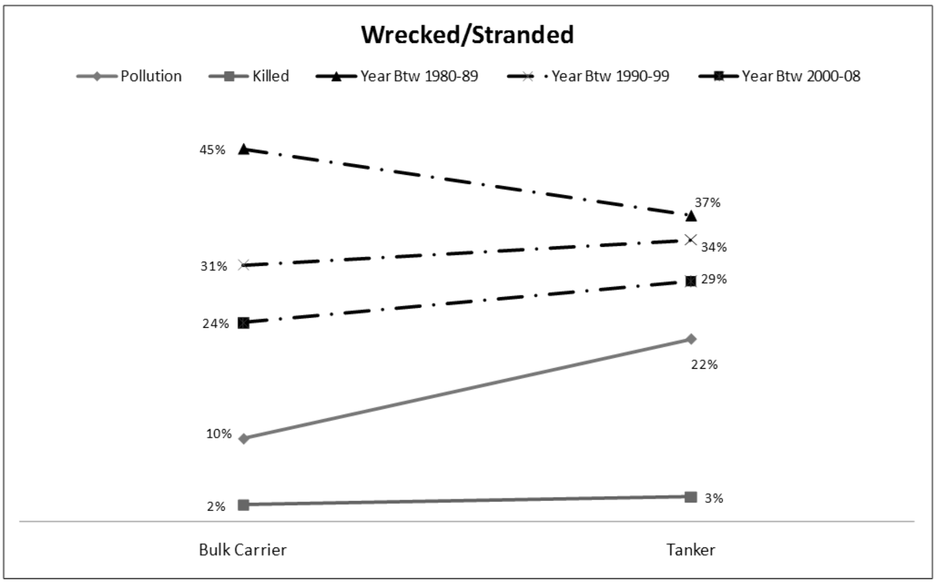


Figure 7-5 The variations of probability of Pollution, Killed, Year of Accident given Incident Type

7.3 Elicitation of Cause and Consequence BBN Models

The procedure adopted to construct the ship accident cause and consequence models is described in this section.

The ship accident database (IHS Fairplay, 2009) does not include detailed description of the causes or consequence of accidents. The database does give incomplete information (some data unrecorded) on occurrence of pollution and the amount of oil spilled. Hence, to determine the causes of accidents, and the resulting oil spill and damage extent, a four stage BBN elicitation procedure as shown in Figure 7-6 is carried out.

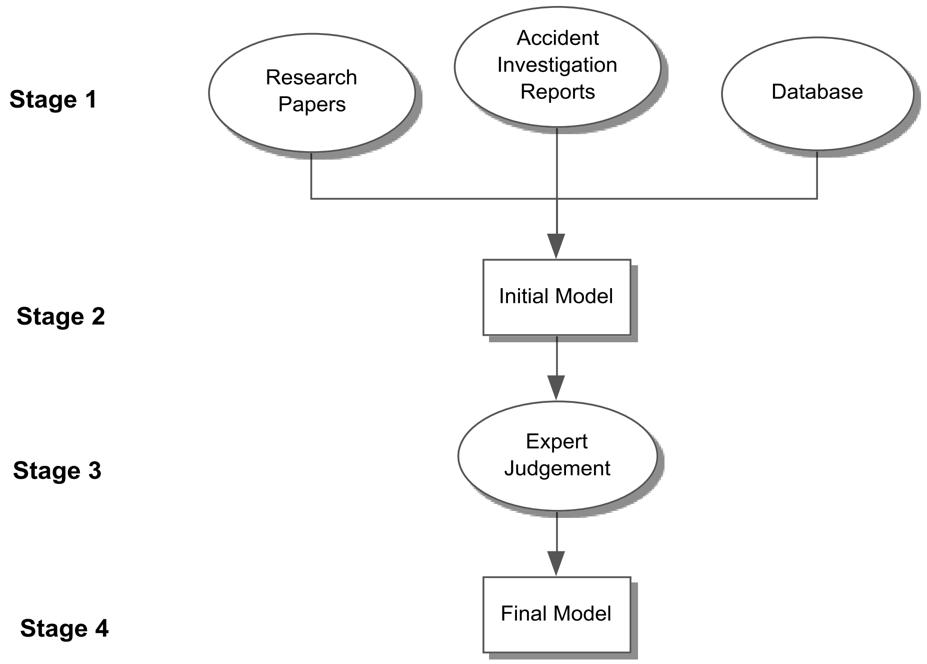


Figure 7-6 Elicitation Process

Stage 1: Background Knowledge: Here, an in-depth study on the existing literature was carried out by searching into several electronic databases (e.g. Science Direct, etc) to identify research articles on cause and consequence of ship accidents using the following search items: Human error, cause of ship accidents, collision, grounding, damage extent, pollution, alternative design etc. Accident description from agencies such as Marine Accident Investigation Bureau (MAIB) which examines and investigates all types of marine accidents to or on board UK ships worldwide, and other ships in UK territorial waters, National Transportation Safety Board (NTSB) which investigates major marine accidents on navigable waters of the United States, involving U.S. merchant vessels in international waters, and collisions involving U.S. public and non-public vessels and Australian Transport Safety Bureau (ATSB) reports which gives detailed description of accidents mentioning the cause, consequence and other related data of interest were studied. Also, reports by institutions that had conducted work in these areas (including government bodies) were sourced through search engines.

Stage 2: Initial Model: Based on the study carried out in stage 1 an initial model was developed at stage 2 which identified the different variables to be considered in the BBN model and their relationship. The variables in a Bayesian network are probability distributions rather than fixed values. In principle, they can be either discrete probabilities, with a finite number of possible values, or continuous, with an infinite number of possible values. In practice, Bayesian network software, including the GeNIe software used in this thesis assumes a discrete probability distribution. In order to use the software, the continuous variables were discretized.

Stage 3: Expert Judgement: Stage 3 involves expert judgement. There are two ways to fill in parameters in the model: by fitting it to data and by elicitation from experts. Here, a hybrid approach, using both database of cases and expert judgement (to quantify variables which are not in the database) is used for the final model elicitation. This is one of the reasons for using the Bayesian approach; because Bayesian models can be fit using both measured data and elicited information. Figure 7-7 shows the various stages of expert judgement elicitation.

First, the initial model was taken to a group of experts who work within the maritime industry and have extensive knowledge about ship accidents and consequences. In this study, 2 groups of experts were consulted. The first group of experts included two senior specialists on ship structures from a premier classification society and a professor of Marine structures. The experts were interviewed to verify the correctness of the initial model and to provide information to elicit the model. The individual probability of events considered in the model and their relationship between each other was derived at this step.

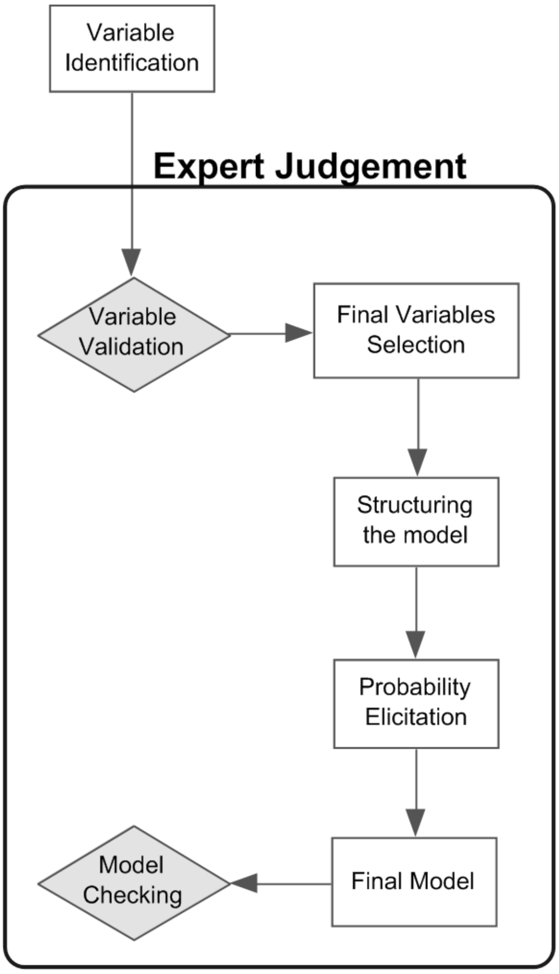


Figure 7-7 Expert judgement procedure

This model together with the background information was taken to the second group of experts, which included Captain of a ship and 2 senior structural engineers from the ship repair and operation department of a reputed Shipyard. In all cases the goal of the elicitation is a conditional probability table (CPT). A CPT contains the probability of an event given—or conditional upon—a set of conditions. For example, a CPT might answer, "What is the probability that stress level of crew is high given that there is a technical failure with the ship, the training of crew is average, physical condition is poor and the external factors are not good". Some of the variables in the model have a direct analogue with an observable state of the world while others do not. This means that sometimes the experts are evaluating their experience or belief about the relationship between directly observable events and objects and sometimes they are reflecting their interpretation of a more abstract concept. In this step, the CPT of the event variables in the network models were sought from the experts.

In short, the construction of Bayesian networks from domain knowledge include three main steps as shown;

Step 1:Determine the number and the meanings of the variables in the interested domain;

Step 2:Determine the direct influence relationships among variables in the domain; and

Step 3:Determine the conditional probabilities given the structure of the Bayesian networks from step 2.

There are different methods to capture the CPT from experts, in this thesis direct elicitation which is the most common approach in the literature is used; it is the most convenient or appropriate way to elicit the information. GeNIe has built-in tools to support direct elicitation, as shown in Figure 7-8.

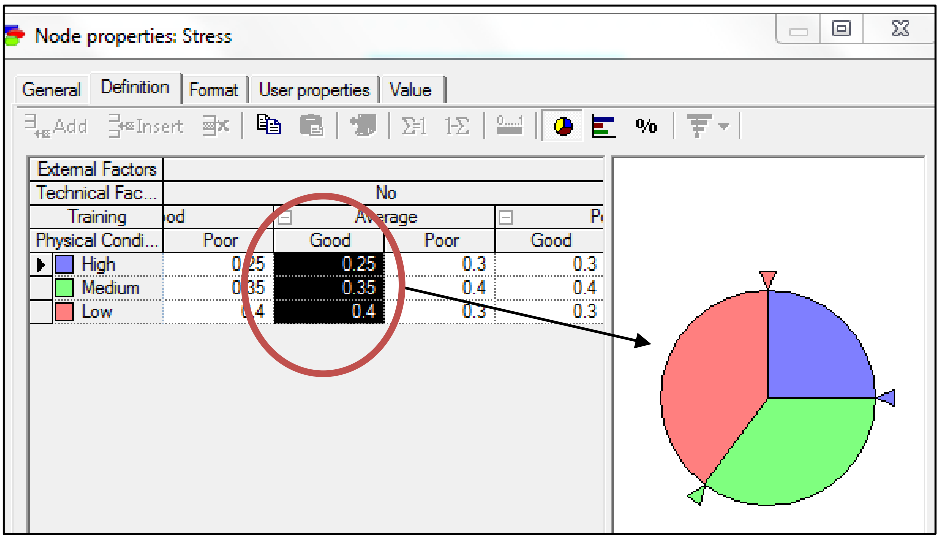


Figure 7-8 GeNIe's pie chart elicitation tool

For example, the pie chart in Figure 7-8 represent the belief of the experts on the states of stress level conditioned on external factors, internal factors, training and physical condition of the crew. This process was more elaborate and time consuming because the conditional probabilities of events are sought in this stage.

Stage 4: Final Model and Model checking: In stage 4, the final model incorporating the conditional probabilities of event is obtained, which could be used to determine the probability of realisation of states within a variable given evidence or conditioned on other variables. The final models are checked by conditioning on different states and checking the output to see whether the outcome is as expected by the experts.

7.4 Overview of causes for ship accidents

The reasons for ship accidents are many and complex. Major disasters are rarely caused by any one factor. They arise from the unforeseeable concatenation of several diverse events, each one necessary but singly insufficient. Accidents may take place anywhere, anytime and under any conditions – day or night, in clear weather or restricted visibility, in narrow straits, canals, inland waterways, coastal waters or on the high seas; and even due to defective or off-station navigational marks.

One of the primary causes for ship accidents is the use of increased size ships, which helps to achieve more profits and reduced transport costs. As the size of ship grows bigger its capacity to carry cargo and passengers increases; hence when an accident or a casualty occurs, the risk it pose to life and property onboard also becomes higher. It also reduces the ships manoeuvrability which inturn acts as a contributing factor in marine accidents.

From the previous accident reports, research paper and expert judgement it can be inferred that the cause of accidents can be broadly classified as: natural conditions, technical failures, route conditions, ship-related factors, human or personal errors and cargo related factors.

· *Natural conditions* could be natural phenomena such as current, tide and tidal stream, severe wind, reduced visibility (fog, heavy snow and rain), storm seas, darkness etc. affecting the ship or those controlling her.

· *Technical failures* are shortcomings within the ship, such as corrosion, steering failure, engine failure, or hull failure rising from defective materials or construction, or by the shore-based installations, such as aids to navigation

· *Route conditions* may include navigational error like over dependence on inaccurate nautical charts, charts of suspect reliability or based upon old surveys, narrow channels with abrupt and angular windings, allowing for very limited manoeuvrability and exposed to dense marine traffic, such as the Turkish Straits, anchorage contiguous to traffic separation lanes, confined marine areas within sufficient sea-room as well as navigational hazards such as shoals, reefs, wrecks etc.

· *Ship-related factors* could be the weakness of a ship, associated with her larger size, hence less manoeuvring capability and stability or draught constraints.

· *Human errors* may include, a lack of adequate knowledge and experience, technical inability, bad look-out, not paying proper attention to procedures and rules, carelessness in commanding a ship, misinterpretations of radar information, fatigue and lack of alertness, overworking, tiredness, insufficient rest periods, etc.

· *Cargo-related factors* mostly include dangerous goods and heavy cargoes; i.e. their hazardous characteristics (oils, chemicals, nuclear substances), the place / compartment they are stowed onboard ships (on deck or under deck), and degree of diligence that such cargoes need (grain, timber), all of which are related to ships' seaworthiness.

These 6 factors can be grouped into 3 categories as follows

- Human Factors which includes human errors etc
- Technical Factors; which include technical failure, Ship related factors and cargo related factors
- External Factors; which include Natural conditions, route conditions

These factors act independently or together to cause ship accidents. From previous studies [Akten, 2006; Hetherington, 2006], reports from Marine Accident Investigation Branch, Expert Judgement and from the specification giving in the damage database the contribution of each factor was determined. From Figure 7-9, it is seen that major share of accidents have human factor as the main cause.

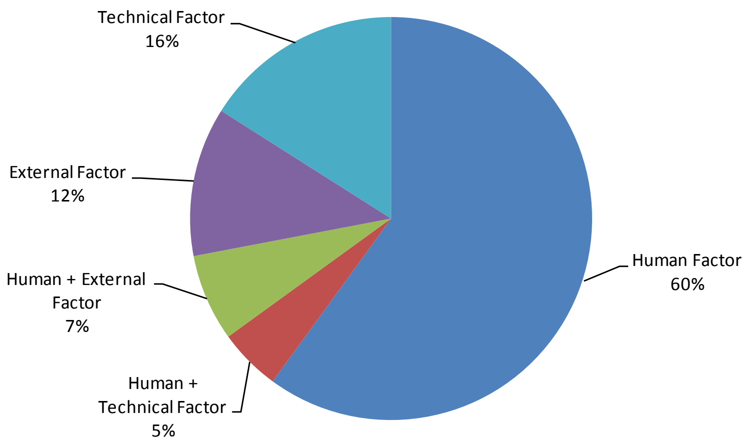


Figure 7-9 Causes of Accidents

Table 7-5 shows four accidents during the last two decades showing the cause and consequences of each accident.

Table 7-5 Vessel Accidents its cause and consequences

Year	Vessel name	Event	Cause	Consequences
1993	Mount Ymitos (Bulk Carrier)	Collision of the Maltese bulk carrier Mount Ymitos and NetherlandsAntilles passenger ship Noordam in the Gulf of Mexico November 6, 1993	The human errors that were pinpointed by the corresponding investigation were the failure of officers on the Noordam to maintain a vigilant watch, the preoccupation of Noordam bridge crew with arrival activities and a certain lack of communication betwixt the two ships.	Both ships moderately damaged, Mount Ymitos has damages to its bow
2002	Qin you 4 (Tanker)	Wrecked/stranded, stranded off Shantou, Guangdong in heavy weather on 11/09/02 subsequently broke in two and sank in lat. 23 22n., long. 117 07e.,	Human error + external factor: Due to communication error and Heavy weather stranded and subsequently caught fire due to a crew member firing a flare	• 950 tonnes of cargo leaked • Caught fire • 2 crew dead,14 crew rescued.
2006	Giant step (Bulk Carrier)	Stranded off the port of Kashima, Japan in approximately lat. 35 52n., long. 140 45e., at 1520 hours lt on 06/10/06 in heavy weather. Hull subsequently broke into three.	Human error + external factors: Vessel had been anchored off the port awaiting a berth and the incident occurred during manoeuvres to counter the effects of heavy weather. Strong winds struck the ship which subsequently stranded.	• The hull broke into three sections • Oil pollution was reported. • 16 crew rescued 8 dead and 2 missing. • Some cargo was washed into the sea.
2008	Princess of the stars(Passenge r Ship)	Sustained engine failure, stranded, took water and capsized in the South China Sea, 1 nm off San Fernando, Sibuyan Island, Romblon, Philippines at 1200 hours on 21/06/08 in typhoon 'Fengshen'.	Human error: The inquiry report blamed human error, and ruled that the ship's captain, "miscalculated" the risk of continuing the trip to Cebu while the storm raged: "there was a failure of the master to exercise extraordinary diligence and good seamanship thereby committing an error of judgment.the immediate cause of the capsizing of MV Princess of the stars.	• Sustained hole amidships below the waterline. • 56 persons rescued. • Reported 747 passengers, 111 crew and 29 non crew personnel on board at the time of the incident. • Oil slick

7.4.1 Human Factor

Marine system is a people system as can be seen from Figure 7-10 in which people interact with technology, the environment, and organization. Humans are prone to make mistakes and in many cases it can be seen that the weak link in this network is with the people themselves; but more often the weak link is the way that technological, environmental, or organizational factors influence the way people perform.

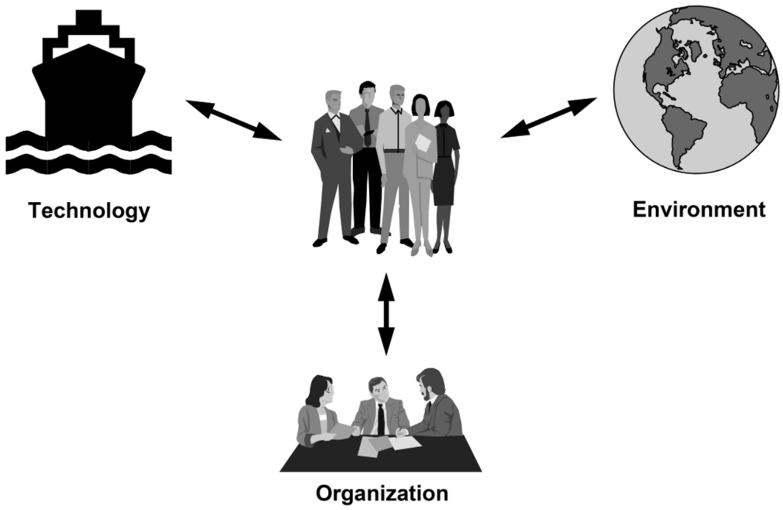


Figure 7-10 The Maritime System is A People System

The role of Human factor in marine accidents is more compared to any other factor, as shown in Figure 7-9, and has been a subject of study for more than three decades. Human factors alone has led to around 60% of accidents and in 12% cases it was human factor with the combination of either external or Technical factors which has resulted in accidents.

IMO (2002) provided guideline for Formal Safety Assessment (FSA) for use in IMO rule making process. It groups human factors into two categories viz., Involved human factors, where human action is required to control the risk but where failure of the human action will not in itself cause an accident or allow an accident sequence to progress and the second category is Critical human factors where human action is critical to control the risk either where failure of the human action will directly cause an accident or will allow an accident sequence to progress. The guidelines classify human error as shown Table 7-6 .

Table 7-6 Typical Human Errors (IMO, 2002)

Physical Errors	Mental Errors
Action omitted	Lack of knowledge of system/situation
Action too much/little	Lack of attention
Action in wrong direction	Failure to remember procedures
Action is mistimed	Communication breakdowns
Action on wrong object	Miscalculation

Table 7-7 Distribution of Human Errors which lead to accidents

Contributing Cause	%
Misjudgement (Captain)	11
Misjudgement(Pilot)	34
Communication Problems	10
Misunderstanding	9
Attention Problems (Pilot & Officers)	23
Other Human Errors	13

Figure 7-11 shows the organizing framework which relates to the levels at which errors can occur, which can subsequently develop into precursors to incidents. This framework was adapted to reflect issues present (more specifically those that been researched) within the maritime industry, from more general organizing frameworks developed by Stanton (1996), the UK Health and Safety Executive (HSE, 1997), and Jorgensen (2002).

As show in Figure 7-11 three issues will be discussed in the following sections.

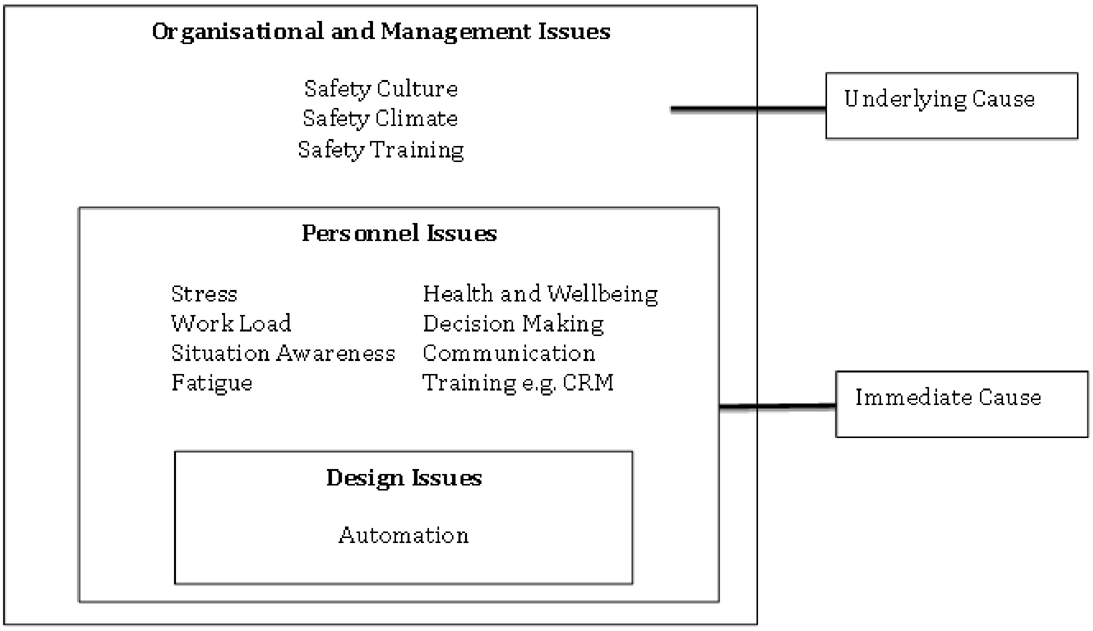


Figure 7-11 An organising framework for human factors which contribute to organisational accidents in shipping adapted from Stanton (1996), Jorgensen (2002) and HSE (1997)

7.4.1.1 Design Issues

Automation

The rapid growth of science and technology has led to the adaptation of automation in all aspects of life. In the shipping industry also there is an increased level of automation of tasks, particularly with regard to navigation systems, which has led to reduced work load and higher efficiency. This has changed the role of seafarers to a large extent. The operator has to keep track of numerous systems, what they are doing and what they will do next, which mode they are operating in and so on, this is termed 'mode awareness'. Automation in normal cases helps in reducing errors if the system is working properly and the operators keeps a good watch of the whole process.

Alternatively, there is this view that operators will monitor less effectively when automation has been installed and even less effectively if the automation has been functioning efficiently for a period of time (Lützhöft & Decker, 2002).

7.4.1.2 Personnel Issues

Fatigue

With higher levels of marine traffic, reduced manning, shorter sea passages, the conditions in which seafarers work are becoming increasingly demanding. The extended hours on duty leads to fatigue with disastrous outcomes in terms of poor health and also diminished performance. In 24 hours prior to the grounding of the Exxon Valdez in 1989, the watch keeper had only 5 or 6 hours of sleep (National Transportation Safety Board [NTSB], 1990), suggesting that fatigue may have been a contributing factor to this environmentally catastrophic grounding.

Despite the introduction of work rest mandates by the IMO, there are still occasion where individuals simply have to work for more than 12 hours with a 6 hour break. In a study conducted by the National Union of Marine Aviation and Shipping Transport Officers (NUMAST, 1995) on 563 seafarers, 50% indicated that they worked more than 85 hours in a week and 66% felt that extra manning was necessary to reduce fatigue.

The factors affecting fatigue are, working hours, sleep problems, tour length, shift length, job demands, stress at work and standing watch.

Situation Awareness (SA)

Situation awareness is the ability to understand a situation properly and anticipate how it might unfold. It is dependent on attention, perception, memory, anticipation and decision-making abilities of a person and therefore will be different for different individuals. For a mariner, capacities like these are particularly essential. Without proper situation awareness, one might run into a well buoyed wreck or make a steep turn and unknowingly collide with another overtaking vessel. In other words, situation awareness is the capability of an individual to correctly make a mental model of what is going on at any one time and also to make projections as to how the situation will develop. Endsley (1988) postulates three levels of situation awareness (a) first, individuals must have the correct perception of the elements in the situation in order to form an accurate picture; (b) the second level involves the combination, interpretation, storage, and retention of the acquired information to form a picture of the situation whereby the significance of particular objects and events are understood; and (c) the third level of situation awareness is projection, and occurs as a result of the combination of levels one and two. This stage is an extremely important component of SA, as it means possessing the ability to use information from the environment to predict possible future states and events, in order to reduce surprise.

Stress & Health

Stress has been identified as a causative factor to the productivity and health costs of an organization as well as to personnel health and welfare. The causes of stress are primarily related to the quality of sleep, missing home, environmental hardships at sea, broken rests, work schedules and feeling fatigued.

It is supposed that both individual characteristics and work conditions influence a person's perception of stress and health. The properties of work and living conditions expose the individual to potential health risks and stress factors. They may be biological, psychological, social, or socio-cultural. The individual's perception of these factors is especially important, not only because of the modifying effect of consciousness, but also because these perceptions guide behaviour, e.g., the health behaviour of the individual.

Communication and Cultural Diversity

One of the essential skills central to effective and safe production and performance in all high risk industries is communication; its is also related to situation awareness, team working and effective decision making. The advantages of effective communication are many and obvious as they enhance all aspects of our personal and professional lives. Ineffective or misunderstood communications in professional lives results in serious consequences. A study at the Seafarers International Research Centre (SIRC) illustrated that approximately only one third of ships have a single nationality crew. This can create language issues and eventually lead to communication problems, therefore flag states require that each ship must have a working language that each employee must speak to a certain standard, deemed competent.

In maritime industry people of many cultures and nationalities work with the same environment. In the world of international shipping, with seafarers from many countries sailing on ships trading to all parts of the world, effective communication between those on board and between ship and shore is vitally important.

IMO analyses reports of casualties and accidents to see if there are any lessons to be learned for the future. Many accidents are found to be due mainly to operational issues of proper procedure, maintenance and design, rather than to proper implementation of regulations but effectiveness of bridge resource management and particularly ineffective relationships between masters, crew and pilot are recurrent themes. Communication difficulties often occur in these areas due in part to cultural differences but also due to language ‘barriers’. Organizational and Management Issues

Training and Teamwork

The concept of teamwork is extremely important to the success of any team and the lack of it could cause for accidents. The United States National Transport Safety Board (NTSB) have reported that lack of proper crew interaction as a factor in many marine incidents and has made several recommendations and suggestion to introduce Bridge Resource Management (BRM) in training for deck officers on U.S. flag vessels.

It is obvious from the many of the cases reviewed that proper education and training of ship personnel is important. In and of itself, this might constitute one of the most important risk reduction measures. Training with marine simulators and proper training would help to reduce the general level of risk on an average basis.

7.4.2 External Factors

Review of accident database shows that many of the accidents were due to external factors such as bad weather and poor visibility. But, it is fair to say that in most such cases it was the combination of the external factor and the human factor that led to the accident. For instance, in a number of cases the accident could have been avoided had the Captain of the ship took the proper measures (such as reduce speed, change the course, go to a safe place, send distress signal, etc).

It is easier to judge distance and make necessary course during daytime and when the surroundings are clear. However, to judge distances and to estimate the visibility at night is at times quite difficult. Therefore, navigation, even on a dark clear night, requires special care for certain reasons such as:

- areas where there exist bright and scattered background lighting from the shore can cause confusion, and,
- reduction of the nominal range of visibility of the lights thereby, and,
- sailing lights being hardly visible,
- Unlit navigational hazards affect also the navigational safety.

The reasons above are contributing factors in shipping accidents. It is a universal prerogative of the Master to decide whether or not to sail in situations of adverse weather, or how to sail the ship in general.

7.4.3 Technical Factors

As shown in Figure 7-9 Technical factors accounts for 16% of accidents and in 5% cases technical factors together with human factors are responsible for accidents.

Technical factors which cause accidents may be related to the improper functioning of the ship due to steering failure, engine failure, or hull failure arising from defective materials or construction, or by the shore-based installations, such as aids to navigation.

The accident investigation report infers that risk of accidents to a large extent could have been avoided had there been advanced navigational technologies such as such as Vessel Traffic Management Information System (VTMIS), Electronic Chart Display and Information System (ECDIS), Collision avoidance systems etc. This would not happen automatically just because these systems would exist, but because of the assistance to the human operator that these systems would provide. So again the human factor would be the prevalent factor, but in this case the ability of the human element would be enhanced due to these systems.

7.4.4 Bayesian Modelling-Cause of Ship Accidents

The nodes and states for BBN modelling were identified and their relation with other variable determined using the elicitation procedure shown in Section 6.3. The nodes considered and their relations with other variables are described below:

Probability of Accident: Probability of accidents depends on Communication, mental stress, Internal factors and External factors. When one or more of these factors have corresponding lower values then the probability of accident increases.

Human Factors: Human error which leads to accidents are due to the stress level at work, bad or poor communication and also due to the poor physical condition of the staff ;

- ***Mental Stress:*** Fatigue and stress to the staff on duty depends on their physical condition, the weather condition, the level of training or experience they have, self-awareness and the ship condition. At increased fatigue/stress level the human performance decrease and hence there is increased chance that errors occur which may eventually lead to accidents.
- ***Communication:*** The level of communication depends on the stress level on the staff, the training and experience they have. And it has a direct effect on probability of accident.
- ***Physical Condition of Staff:*** Physical conditions have a direct impact on stress and communication. A healthy person will be able to handle more stress and will be able to make quicker decisions or appropriate actions.

Technical Factors: The presence of technical problems with the ship increases stress level of staff and increases the probability of accidents.

External Factors: When the external factors are severe or bad it affects the performance and increases the probability of accidents.

The final BBN model to identify the cause of maritime accidents is as shown in Figure 7-12. This model was elicited using expert judgment, where the final model and the conditional probability of each node were obtained using the procedure described in Section 7.3. This model can be used to determine the probability of accident given different evidence; for example, when the stress level of the staff are high or when there is a technical failure in the ship etc.

This model capture the different factors essential for a ship accident to happen. These factors individually are not sufficient to lead to accident, but they act together making the ship vulnerable to accidents. This model shows how the different cause nodes are related to each other

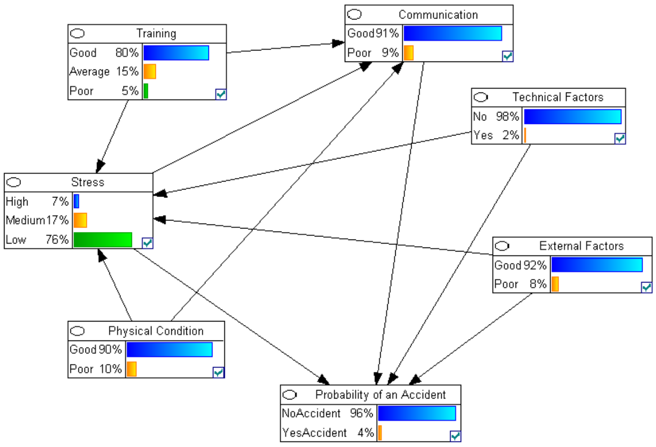


Figure 7-12 Bayesian Network for Cause of Ship Accidents

When the factors are in the state shown in Figure 7-12, the probability of accident is 4%. When all the states have corresponding safe limits then the probability of an accident occurring is less than zero.

In Figure 7-13 shows the probability of accident when the cause model is conditioned using different evidences. It can be seen that when all of the factors are in their worst conditions then there is 60% chance of an accident.

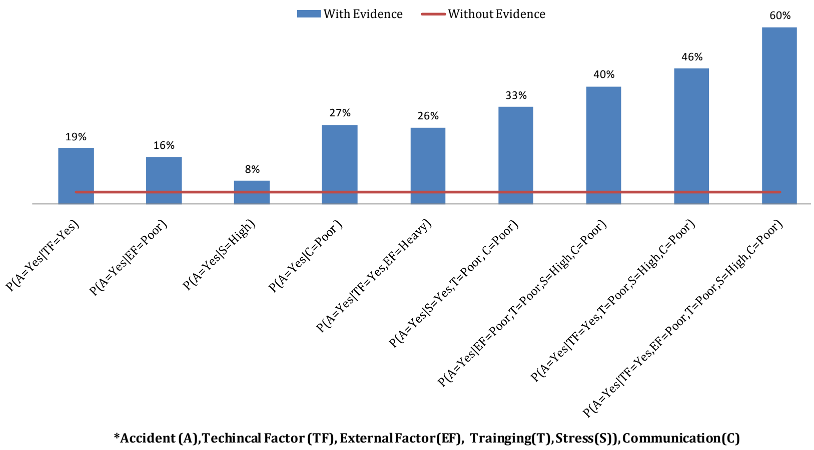


Figure 7-13 Probability of Accident under different scenarios

7.5 Consequence of Ship Accidents

Over the past decades there has been a rapid increase in the public concern about general risk issues. Whenever a catastrophic accident occurs it receives large media coverage and there is an immediate political and public demand to take action to prevent similar type of accident in future and to minimize the consequence. There have been lot of research done in this area to determine the consequences. Most of these researches have been carried out to make analytical or theoretical model (Brown 2002, Brown and Chen 2002, Pedersen and Zhang 2000, Rawson, Crake and Brown 1998).

In this section probabilistic models using BBN is developed which could help to determine the consequences resulting from accidents.

7.5.1 Damage Extent in Ships

The damage resulting on the structure of a ship due to accidents can be so severe as to cause the ship to sink and result in total loss of the vessel. Hence, it is of great importance to understand the extent of damage resulting from an accident so as to make the necessary salvage operation. The kind and degree of structural damage depends mainly on the magnitude of the forces of contact, as well as the strength properties of the structural members in that vicinity.

The collision or grounding event occurs over a time interval ranging from a few second to a few minutes, during which the forces of contact undergo variations in direction and magnitude. The behaviour of these contact forces depends on the initial speed and mass, as well as other properties of the ship and on the behaviour of the affected structural members.

The IMO (1995) probabilistic procedure for assessing the oil outflow performance of an oil tanker design in collision and grounding used 5 variables as shown in Table 7-8 to define damage extent.

Table 7-8 Variables to estimate damage extent

Collision	Grounding
Longitudinal Location of damage	Longitudinal Location of damage
Vertical Location of Damage	Transverse Location of damage
Longitudinal Extend of damage	Longitudinal Extend of damage
Transverse Penetration of damage	Vertical Penetration of damage
Vertical Extend of damage	Transverse Extend of damage

This study uses the above parameters to define the damage extent resulting from grounding and collision accidents.

7.5.1.1 Grounding

Grounding events consists of scenarios where the vessel accidentally comes into contact with the sea bed or shore. Grounding is predominantly caused by navigation failure (powered grounding) or by propulsion, power or steering failure (drift grounding). Compared to drift grounding the impact is stronger in the case of powered grounding since the speed is greater in the latter.

The determination of the damage to a ship involved in a specific grounding scenario comprises the description of the speed of the ship, striking location, loading condition-full load and ballast conditions are usually considered, draft, trim, height of obstruction below the water level, rock eccentricity, rock tip radius and apex angle, form of ship hull, sea conditions, wind and current, location of the incident, the structural crashworthiness and ship maintenance level. Human response may also affect the consequence.

Table 7-9 shows the main factors which determine the damage extent resulting from grounding accidents.

Table 7-9 Factors which determine damage extent in Ship Grounding

Ship Particulars	Ship hull form (Single hull , double hull, double bottom, double side) Length , breadth , depth of ship Displacement Crashworthiness of the structure Speed of ship at the time of accident
Bottom or Obstruction description	The height of obstruction Rock eccentricity Rock tip/edge angle Rock edge radius/width The slope or inclination angle Type of bottom (rock, sand , mud) Type of obstruction (narrow rock, pinnacle, hard/soft ground)
Other	Longitudinal location of accident The depth of water

Neither the damage database nor the accident reports present a detailed description about the above factors. Also, there is inadequate information on sea floor topology. Most of the analysis models for ship grounding in the past published works assumed that a rock opened a large part of the ships bottom structures. Hence in this study the information from the damage database together with expert judgement and other published works on grounding accidents is used to make the probabilistic model for ship grounding.

The following assumptions were made on the final model to keep model manageable,

- The ship is assumed to be double hull.
- Fully loaded condition is assumed.
- Type of bottom is assumed to be rock.
- No trim.

The schematic representation of damage extent due to grounding is shown in Figure 7-14.

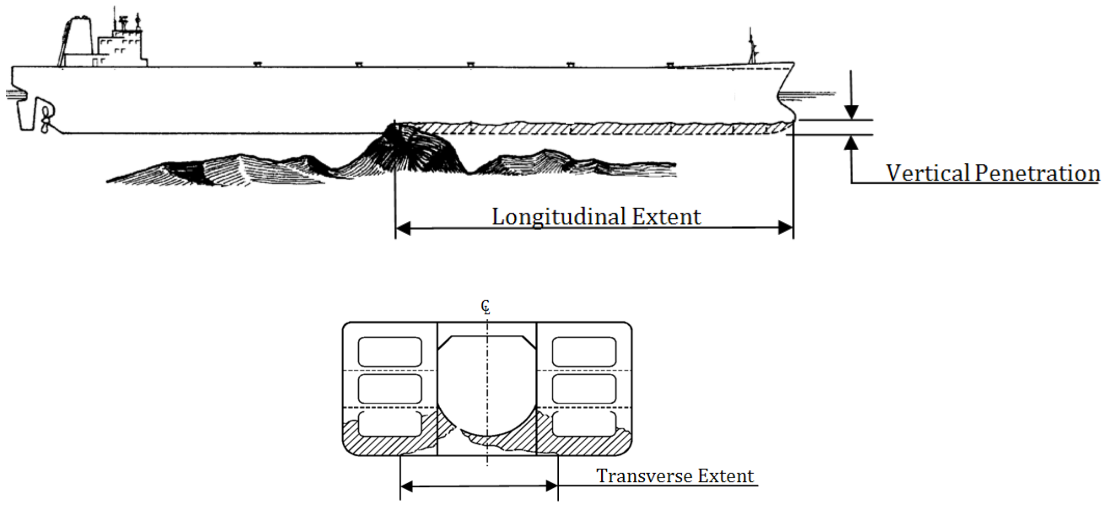


Figure 7-14 Description of Damage Extent in grounding

The variables to determine grounding damage extent and their relations with other variables are given below; based on which the grounding model was elicited

Vertical Penetration: The vertical height of damage from the bottom of the ship is known as the vertical penetration. It depends on the following

- *Draft of Ship*: For ships with deeper draft the probability of vertical penetration extending deeper into the hull is more compared to when the draft is less.
- *Obstruction depth below water level*: If the depth of obstruction from the water level is less and the draft of ship is more then the amount of penetration will be the more, than when the obstruction depth is more from the water level and the draft of ship is small.
- *Obstruction tip radius:* When the tip radius is small then the damage caused to structure will be local structural damage, large shoals or dish like obstruction deform large parts of the hull structure.
- *Kinetic Energy of Ship:* The initial kinetic energy possessed by the ship help to tear open the bottom. With higher kinetic energy, increased penetration is expected.

The vertical penetration is grouped into 3 intervals1) Less than 5 percentage of ship depth 2) Between 5 to 15 percentage of ship depth 3) More than 15 percentage of ship depth to classify as minor, medium and major scenarios respectively.

Transverse Extent: Transverse extent is used to predict the length of damage occurring along the breadth of the ship. Transverse extent depends on the following

- *Obstruction tip radius*: The resulting damage extent will be determined mainly by the tip radius. If the tip radius of obstruction is more then there is every chance that the resulting transverse damage extent will also be more (Alsos *et al* (2007)).
- *Vertical Penetration:* If the deformation go deep into the hull, the magnitude of structural damage is likely to be local. On the other hand, if large part of ship breadth is damaged, the penetration will be small.
- *Breadth of ship*: For smaller ships grounding on large rocks the probability that the ratio of transverse damage extent to the ship breadth is higher compared to larger ship grounding on large rock.

The transverse extent is grouped into 3 intervals 1) Less than 15 percentage of ship breadth 2) Between 15 to 40 percentage of ship breadth 3) More than 40 percentage of ship breadth to classify as minor, medium and major scenarios respectively.

Longitudinal Extent: Longitudinal extent is the length or extent to which the damage occurred along the length of ship. Longitudinal extent depends on the following

- *Kinetic Energy at the time of incident*: The resulting longitudinal extent depends largely on the initial kinetic energy and the impact resistance of the structure. High speed grounding results in larger part of the ship length being damaged.

- *Length of ship*: For smaller ships the ratio of longitudinal damage extent to the ship length is higher compared to larger ship with same damage extent.
- *Vertical penetration*: If the penetration goes deep into the hull the damage length will be less, because more resistance is offered by the structure and hence more energy dissipated.

The longitudinal extent is grouped into 3 intervals 1) Less than 15 percentage of ship length 2) Between 15 to 40 percentage of ship length 3) More than 40 percentage of ship length to classify as minor, medium and major scenarios respectively.

7.5.1.2 Collision

The sea route traffic has increased by leaps and bounds and there has also been a sharp increase in the speed levels. This has led to an increase in the probability of ships confronting collision. Also, higher the velocity, greater the damage caused to the ship. If the ship has high tonnage and is heavily loaded, the effects of collision can be more drastic in nature. Ship collisions have been the reason for many major sea accidents in the past.

Ship collision involves the crashing of ship into a still or floating object. Ship collision cases can be a ship to ship, ship to floating object, ship to submarine or ship to still structure collisions. Ship collision is considered to be the worst of marine accidents as it leads to extreme adverse effects on human and marine life. Collision occurs mainly as a result of human error. Amateur manoeuvring and loose presence of mind of the master, pilot or navigational officer during the time of manoeuvring, is the root cause of many collision. Apart from that, fault in the propulsion system, rudder or any other machinery can also lead to a collision. Error or negligence by a shore personnel assisting in manoeuvring activity can also be a reason for such mishap.

Similar to grounding accident, the determination of the damage to a ship involved in a specific collision comprises the definition of the speed of the colliding ships, collision geometry, i.e. striking location, impact angle, relative orientation between striking and struck vessels, loading condition-full load and ballast conditions are usually considered, draft, trim, bow shape, ship hull and striking bow structural arrangement, sea conditions, wind and current, and ship maintenance level. Human response may also affect the consequence, in particular the possibility of occurrence and the details of the scenario itself.

Table 7-10 Factors which determine damage extent in ship collision

Striking ship particulars	Hull form (Single hull, double hull, double side) Speed Displacement Length, Breadth, Depth etc. Bow Height Bow Shape crashworthiness of the structure
Struck ship particulars	Hull form (Single hull, double hull, double side) Speed Displacement crashworthiness of the structure
Other	Collision Angle Loading Condition Strike Location

In this study the damage extent resulting from ship-ship collisions is only considered. A collision involves at least two ships and in statistics each collision event is registered as two casualties- one for each involved vessel. This study tries to find the resulting damage in the struck vessel.

The following assumptions as shown below were made on the final model to keep model manageable without losing the accuracy,

- The struck ship is at a standstill before the collision.
- Fully loaded condition is assumed for both struck and striking ship.
- The ship is assumed to be double hull.
- The striking ship impacts the midship section of the struck ship.
- No trim.

The schematic representation of damage extent due to collision is shown in Figure 7-15.

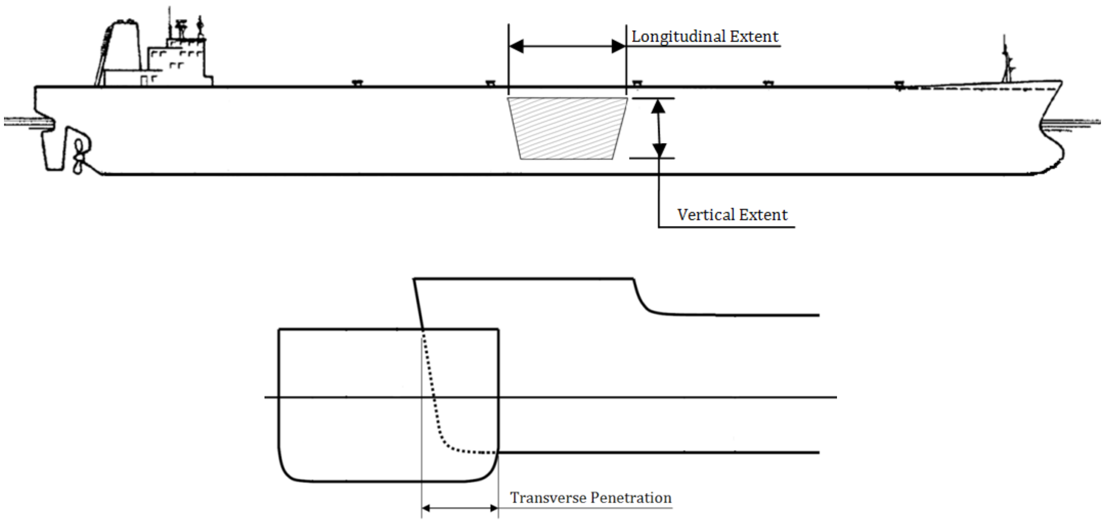


Figure 7-15 Description of Damage Extent in collision

Transverse penetration: Transverse penetration is the distance along the breadth of the ship damaged due to the collision. It depends on the following

- *Kinetic energy of the striking ship*: The resulting transverse penetration depends largely on the initial kinetic energy and the impact resistance of the structure. For ships colliding with higher speed the transverse penetration will be higher compared to that with smaller velocities.
- *Collision Angle: S*hips colliding at 90 degree results in higher transverse penetration compared to other angles.
- Breadth of Struck Ship: For smaller ships collided by larger ships the ratio of transverse penetration to the struck ship breadth will be more compared to the smaller ship colliding on a large ship.

The transverse penetration is grouped into 3 intervals 1) Less than 5 percentage of ship breadth 2) Between 5 to 10 percentage of ship breadth 3) More than 10 percentage of ship breadth to classify as minor, medium and major scenarios respectively.

Vertical Extent: Vertical extent is used to determine the length of damage occurring along the depth of the ship. Vertical extent depends on the following

- *Transverse Penetration*: The resulting damage extent will be determined mainly by the tip radius. If the tip radius of obstruction is more then there is every chance that the resulting transverse damage extent will also be more.
- *Struck and Striking ship Depth*: Larger ships striking on smaller ships cause extensive vertical damage to the struck vessel and vice versa.

The vertical extent is grouped into 3 intervals 1) Less than 15 percentage of ship depth 2) Between 15 to 30 percentage of ship depth 3) More than 30 percentage of ship depth to classify as minor, medium and major scenarios respectively.

Longitudinal Extent: Longitudinal extent is used to predict the length or extent to which the damage occurred along the length of ship. Longitudinal extent depends on how deeper the damage has penetrated. It is also dependent on the breadth and half entrance angle of the striking vessel.

The longitudinal extent is grouped into 3 intervals 1) Less than 10 percentage of ship length 2) Between 15 to 15 percentage of ship length 3) More than 15 percentage of ship length to classify as minor, medium and major scenarios respectively.

7.5.2 Oil Spill

Oil spills include releases of crude oil from tankers, offshore platforms, drilling rigs and wells. In this study Oil Spill resulting from ship accident is studied.

The impact or fate and effect of a spill are the correct metric and this is most conveniently quantified as a cost. There are five major categories of oil spill cost (1) commercial; (2) social and recreational; (3) ecological; (4) restoration; and (5) ship owners/cargo owners/insurance. Cost is extremely sensitive to the specific spill scenario, the location of spill etc. As a result, the use of an average spill unit cost is very controversial.

Four metrics can be used to examine the severity of the consequence:

- Area of slick
- Length of oiled shoreline
- Area of oiled shoreline
- Toxicity of the water column

The amount of oil spilled following an accident depend on the following factors;

- Size and Loading condition: Bigger size brings corresponding increases in cargo and passenger capacity; hence when an accident or a casualty occurs, the risk of life and property immediately becomes higher.
- The damage extent: The amount of oil spilled is directly related to the extent of damage. Larger the damage size more the amount of spill.
- Spill Response: The options available for spill mitigation and cleanup include containment and elimination. Although the ship may have some onboard capability for containment, waterway assets, waterway management, and ship management are most important to the mitigation and cleanup function. Typically only 10-20% of the spilled oil is ever contained and recovered. The type and quantity of oil spilled, availability of personnel and equipment, environmental conditions and various human factors determine the effectiveness of the mitigation and cleanup efforts.
- In the side damage cases, the oil outflow is equal to the total amount of oil carried in the damaged compartments. In the bottom damage cases, the vessel is assumed to rest at its initial drafts, with zero trim and heel. Oil outflow from the damaged compartments is based on hydrostatic balance principles, i.e., oil outflows from a compartment until the hydrostatic pressure of the fluid in the tank is equal to the hydrostatic pressure of sea water at the bottom of the compartment.

- Other factors include the tidal and current variation, the density and type of oil which leads to the spread of oil.

7.5.3 Bayesian Modelling of Consequence of Accidents

Based on the information and understanding of grounding and collision scenarios and their consequences described in section 7.5 and using the Bayesian model construction method described in section 7.3, probabilistic models were elicited which could help to determine the probability of realisation of different consequences (damage extent and oil spill) given a grounding or collision accident.

7.5.3.1 Grounding Accident

The nodes considered for eliciting Bayesian grounding model is as shown in Table 7-11.

Table 7-11 Nodes for BBN Grounding Model

Category	Nodes
Struck Ship Particulars	Length Breadth Depth Draft Deadweight Tonnage Speed Kinetic Energy
Environmental Condition	Weather Location
Obstruction Related Variables	Obstruction Depth below Waterline Obstruction Tip Radius Obstruction Apex Angle
Consequence Variable	Longitudinal Extent of Damage Transverse Extent of Damage Vertical Penetration Oil Spill

The final model which captures the relation between the different nodes is as shown in Figure 7-16. This model can be used to determine the consequence of an accident given the evidence.

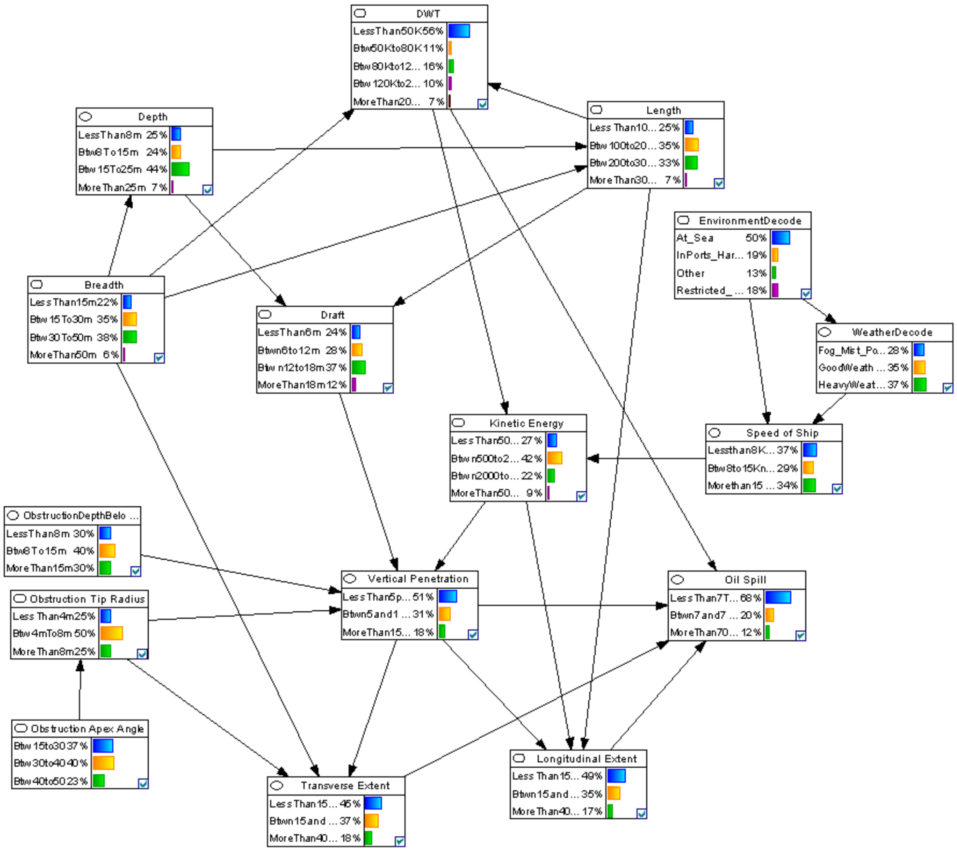


Figure 7-16 BBN Grounding Model

Figure 7-16 shows the probability of each node without initiating any evidence. The probability of realisation of different consequences following a grounding accident under the given conditions are;

- The probability that the vertical penetration is more than 15% of the depth of ship is 18%, it is between 5% and 15% of the ship depth is 31% and it being less than 5% of ships depth is 51%.
- The probability that the Transverse Extent is more than 40 % of ship breadth is 18%, it is between 15% to 40% of ship breadth is 37% and it being less than 15% of ship breadth is 45%.

- The probability that the Longitudinal Extent of damage is more than 40% of ship length is 17%, it being between 15% to 40% ship length is 35% and it being less than 15% of ship length is 49%.
- The amount of oil spill is directly related to the transverse, vertical and longitudinal damage extent and the probability for oil spill to be more than 700 ton is 12%, it being between 7 and 700 ton is 20% and it being less than 7% is 68%.

7.5.3.2 Collision Accident

The nodes considered for eliciting Bayesian collision model is as shown in Table 7-12.

Table 7-12 Nodes for BBN Collision Model

Category	**Nodes**
Struck and Striking Ship Particulars	Length
	Breadth
	Depth
	Draft
	Deadweight Tonnage
	Speed
	Kinetic Energy
	Striking Ship Bow Half Entrance Angle
Environmental Condition	Weather
	Location
	Collision Angle
Consequence Variable	Longitudinal Extent
	Vertical Extent
	Transverse Penetration
	Oil Spill

The final collision model which captures the relation between the different nodes is as shown in Figure 7-17. This model can be used to determine the consequence of a collision accident given the evidence.

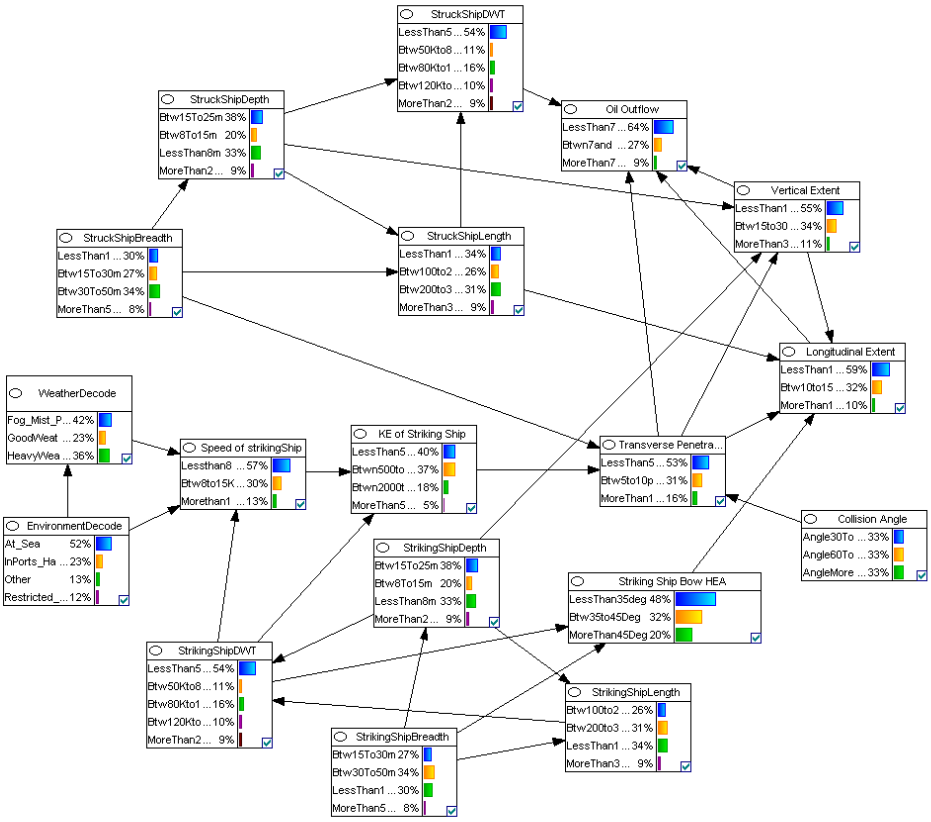


Figure 7-17 BBN Collision Model

Figure 7-17 shows the probability of each node without initiating. The probability of realisation of different consequences following an accident under the given conditions is;

- The probability that the Transverse Penetration is more than 10% of the depth of ship is 16%, it is between 5% and 10% of the ship depth is 31% and it being less than 5% of ships depth is 53%.
- The probability that the Longitudinal Extent is more than 15 % of ship length is 10%, it is between 10% to 15% of ship length is 32% and it being less than 10% of ship length is 59%.
- The probability that the Vertical Extent of damage is more than 30% of ship depth is 11%, it being between 15% to 30% ship depth is 34% and it being less than 15% of ship depth is 55%.
- The amount of oil spill is directly related to the transverse, vertical and longitudinal damage extent and the probability for oil spill to be more

than 700 ton is 9%, it being between 7 and 700 ton is 27% and it being less than 7% is 64%.

7.6 Summary & Conclusion

The determination of causes and consequences of ship accidents are important so as to ensure the safety of ship and its cargo, also to prevent similar incidents happening in the future. In this chapter an in-depth study on cause and consequence of ship accidents were made and based on which BBN models were developed which can determine the probability of an accident given evidence on different probable causes and gives the consequence in terms of structural damage extent and oil spill.

IHS Fairplay ship accident database from 1980 – 2009 was used to construct the data driven Bayesian model. This model graphically captures the relationship between different variable in the database and can be used to determine the probability of any state in a node by conditioning on the available evidence. This model helps to determine the type of weather, the geographical location, the environmental condition, loading condition etc. at the time of accident, the knowledge of which may help in reducing accidents and its consequences.

The variables to be considered for the cause and consequence study were determined by a step by step process involving in-depth study of the literature to make the initial BBN model which was then validated by expert judgement to elicit the final model. The final model developed could determine the probability of realisation of different causes of ship accidents and the consequences to be expected from it.

Chapter 8. Strength Analysis of Intact and Damaged Ships

8.1 Introduction

In this chapter the strength analysis of intact and damaged ships are carried out. Different damage scenarios at the side and bottom are analysed to determine the strength of ships following collision and grounding accidents, based on which simple equations to calculate residual strength are formulated which could be an obvious advantage in cases of emergency or salvage operations. Finally, design modification factors (DMF) are applied to damaged ships to study their influence on the residual strength.

8.2 Ultimate Strength of Ships

A ship's hull is typical a box girder structure composed of stiffened plating, and is subjected to loads such as distributed weights, buoyancy forces and wave loads. Hence, it is very important to estimate the load carrying capacity of a ship's hull as a whole from the viewpoints of safety and economy.

Ultimate strength of structural members and systems is a real measure in strength assessment in a sense that the ultimate strength is the maximum capacity that they can have. No additional load can be carried beyond the ultimate strength. Under general combined loads, buckling and yielding dominate the ultimate strength when compressive stress is dominant, whereas only yielding dominates the ultimate strength when tensile stress is dominant.

Various definitions of the ultimate strength of a hull have been proposed, but the most acceptable one is the recommendation reported by Committee 10 in the proceedings of the Third International Ship Structures Congress, Vol.2, 1967, as quoted as:

"This occurs when a structure is damaged so badly that it is can no longer fulfil its function. The loss of function may be gradual in the case of lengthening fatigue crack or spreading plasticity, or sudden, when failure occurs through plastic instability or through a propagation of brittle crack. In all cases, the collapse load may be defined as the minimum load which will cause this loss of function."

Thus, besides instability (buckling), yielding, and spreading of plasticity, fracture may also be a significant mechanism of a hull girder failure under certain circumstances of repeated load cycle. Other than these factors the damages occurring due to collision or grounding are of significant interest to consider the residual strength after accidents. During a damage scenario the structural strength of ship reduces significantly and active wave loads acting on the hull may lead the ship to definite structural failure. Longitudinal Strength of Ship

The midship ultimate strength analysis is the single most important structural parameter for large ocean-going vessels. The ultimate strength is the maximum load that a ship's primary structure can withstand and is dependent on the structural robustness which can vary over the life time of ships and hence it is necessary to evaluate the ultimate strength not just at the design phase, but also during various stages of service life.

There are three main types of hull bending which a ship could encounter are (Figure 8-1);

1. Vertical Bending
2. Horizontal Bending
3. Torsion

Vertical bending is the most critical factor for a ship; this is due to fact that most conventional vessels have quite low D/L (Depth/ Length) values, compared to the other ratios, indicating that critical stress and strain values can be more easily reached for vertical longitudinal bending. This is particularly true for tankers, with their low depths, long lengths and wide beams. For ships with large deck opening, such as container vessels, torsional effects may be significant. The horizontal components of bending and shear strength and the torsional strength may all be important at sections where damage has occurred.

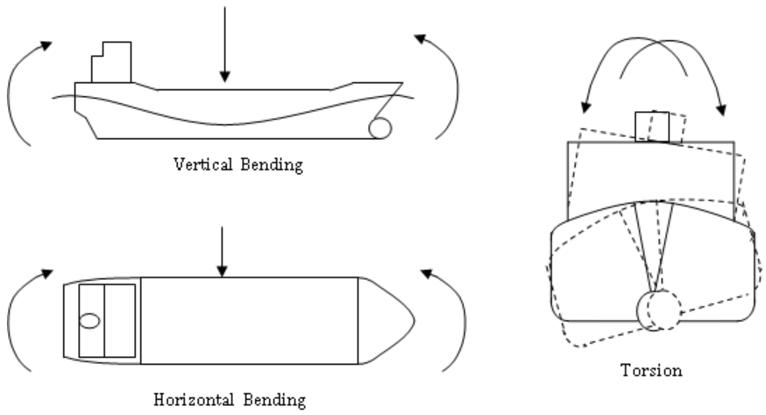


Figure 8-1 Types of Hull Bending

The hull strength against longitudinal bending/shearing load is called *longitudinal* strength, which may be the most fundamental strength of a ship structure. This is because the buckling/plastic collapse of the deck and/or bottom structure takes place and a ship's hull may break if the working longitudinal bending capacity exceeds the capacity of the cross-section.

In carrying out the limit state design of ship hull, it is necessary to estimate the ultimate longitudinal strength of hull girders. The collapse strength of the ship hull is governed by buckling, yielding, tension tearing rupture and brittle failure of materials. Moreover, the strength against each failure mode is influenced by initial deformations, residual stresses, corrosion damages, and fatigue cracks. Structural failure of a hull beam from extreme bending has huge consequences.

Over the past few decades there have been numerous examples of hull girder failures of tankers causing wide spread environmental damage. A few key case studies include the 20,000ton ship Erica which cracked in half on the 12th December 1999 in the Bay of Biscay and the 81,000ton Prestige which snapped in half on the 13th November 2002 off the coast of Portugal during a storm polluting kilometres of coastline, and damaging the local fishing industry These case studies consist of tankers highlight that this class of ship is susceptible to vertical longitudinal failure. These results demand that a detailed study into their longitudinal strength should be carried out.

Although the probability of critical vertical bending moments being encountered is greater than the occurrence of the other loads, it may only occur once in its lifetime. This allows the ship to go into the plastic range of the materials when these large loads are applied. This complicates the analysis and will require non-linear study. However to estimate the probability of failure it is necessary not just to understand the random nature of the loading a ship encounters but to understand the random behaviour of the strength of the hull beam. If the maximum bending moment a ship could withstand could be evaluated then it would be possible to predetermine the ultimate strength of a ship. This maximum bending moment is called the ultimate bending moment.

8.3 Methods to Calculate Longitudinal Strength

The first attempt to calculate the ultimate hull girder strength was by Caldwell (1965). He idealised the cross-section composed of stiffened panels as that composed of panels with equivalent thickness. Then, he calculated the fully plastic bending moment of the cross-section considering the influence of buckling. For the buckled part, the yielding stress is multiplied by a strength reduction factor, the magnitude of which was not clearly known at that time. Smith (1977) proposed a simple but effective method to study the collapse behaviour of box girder structures under longitudinal bending load. This method is now generally known as Smith's method. This method enables to execute progressive collapse analysis on the cross-section of a hull girder subjected to longitudinal bending. Following these works there has been lot of research in this area to assess the ultimate strength of ships. According to ISSC report (2000), the existing methods to evaluate the ultimate hull girder strength can be grouped into two, which are simple methods and advanced methods.

Simple methods

- Initial yielding
- Elastic analysis; and
- Assumed stress distribution

On the other hand, advanced methods are

- Progressive collapse methods
- Non-Linear Finite Element Method
- Idealised Structural Unit Method (ISUM)

All the methods are discussed in brief in the following sections.

8.3.1 Simple Methods

Initial yielding denotes that the ultimate hull girder strength can be estimated by the initial yielding strength simply calculated by

$$M_{IY} = SM.\sigma_Y \quad \text{Equation 8-1}$$

where SM and σ_Y are the elastic section modulus of the cross-section and the yielding stress of the material respectively.

In elastic analysis the value of σ_Y in Equation 8-1 is substituted by the buckling strength of local panel or stiffened panel in the deck and/or bottom structure.

Assumed stress distribution is based on an presumed stress distribution over hull section at limit state, from which ultimate hull girder strength is approximately calculated taking into account buckling in compression flange and yielding in tension flange.

8.3.2 Non-Linear Finite Element Method

Ever since the development of computer technology with regards to both hardware and software the role of finite element analysis in the structural nonlinear analysis has increased.

Six types of modelling can be considered in determining the extent of progressive hull collapse; (1) the entire hull model, (2) the three cargo hold model, (3) the two cargo hold model, (4) the one cargo hold model, (5) the two-bay sliced hull model, and (6) the one-bay sliced hull model.

The computational accuracy may worsen from (1) to (6), but the computational efficiency improves. In reality, the application of the conventional non-linear FEM to (1) the entire hull model is usually impractical because of the great computational effort required. So depending on the accuracy of the results and the other factor one of the above mentioned modelling method is followed.

Finite element analysis could be used to determine the strength of ships under different damage scenarios and can also incorporated weld induced initial imperfections and residual stresses into the models.

Of all the methods available to determine the strength, the results from finite element are closer to the actual values of ultimate strength experienced by structures. But it require lot of computational efforts also the details about boundary condition, material properties, imperfection etc., have a significant effect on the results.

8.3.3 Idealised Structural Unit Method (ISUM)

The Idealised Structural Unit Method (ISUM) is a simple method to calculate the ultimate strength of a ship. In this method, a larger structural unit is considered as one element, which reduces the computation time. The essential point of this method is to develop effective and simple element (dynamical model) considering the influences of both buckling and yielding.

Ueda *et al*. (1984), developed plate and stiffened plate elements that accurately simulate buckling/plastic collapse behaviour under combined biaxial compression/tension and shear loads. In their method, a simplified plate surrounded by longitudinal girders and transverse frames is considered as one unit (element), and the stiffness matrix in an incremental form is derived for this unit taking account of the influences of buckling and yielding. Paik improved this unit, and performed different progressive collapse analysis (Paik *et al.* 1990a, 199b, 1992a, 1992b). Ueda and Rashed (1991) also performed a progressive collapse analysis on a double hull tanker applying their newly improved units. Paik (1994b) tried to introduce the influence of tensile behaviour of elements in ISUM. Bai *et al.* (1993) developed beam element, plate element and shear element based on the Plastic Node Method (Ueda and Yao, 1982) and using these elements he achieved progressive collapse analysis.

8.3.4 Progressive Collapse Analysis

The progressive collapse analysis method follows the general approach presented by Smith (1977). Smiths method is basically an extension of the methods proposed by Caldwell. The advantage of Smiths methods is its ability to takes into account of the progressive loss in stiffness of a cross-section due to buckling and yielding of structural components.

The only difficulty in the Smith's method is the derivation of the stress-strain relationships of component elements taking into account of the buckling and yielding. There are two methods available to obtain the this relation

- Performing elasto-plastic large deflection analysis by the Finite Element Method. Such analysis, however, may require much work especially when the number of elements is large.
- Derive the stress-strain relationships analytically.

In this thesis the ultimate strength analysis has been carried out using MARS 2000 (BV, 2000), which is based on Smiths methods. This program uses analytical stress-strain relation to determine ultimate strength of the structure.

The method adopted by MARS 2000 is discussed in detail in the following section.

8.3.4.1 Modelling of Ship's Cross Section

As hull strength assessment is based on the strength of stiffened panels, the modelling of the ship's cross section consists of discrediting the hull into stiffened plate elements which are representative of panel behaviour. These elements are known as beam columns. Figure 8-2 shows the example of beam column.

There are three main types of beam columns; beam columns representing stiffened plates and beam columns representing un-stiffened plate and a beam column representing edges. For stiffened plating the beam column usually consists of the plate plus one stiffener.

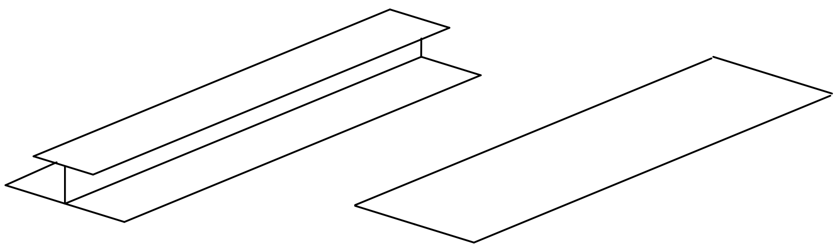


Figure 8-2 Example of Beam Column

8.3.4.2 Loads affecting the beam columns

In actual case the beam columns, which make up a ship, undergoes a complex loading. The current program assumes that these forces are independent and therefore can be analysed individually.

The three dissected load conditions are defined below and are as shown in Figure 8-3:

- An axial load that represents direct compressive/tensioned loads induced in longitudinal bending.
- A plane load, applied to the beam columns from hydrostatic pressure.

- The beam columns will be subjected to a shearing force simulating the shear stresses that the beam columns will absorb when the ship undergoes longitudinal bending.

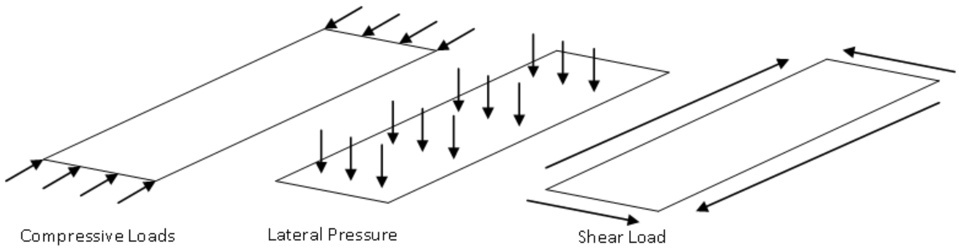


Figure 8-3 Loading conditions

From simple beam theory the maximum axial load occurs where the largest bending moment is experienced. Shear stress can be calculated by differentiating the bending moment curve. Since the gradient of the bending moment is zero where the maximum moment occurs, the shear will be zero at that point. Therefore the shear load is a minimum when the compression load reaches maximum. The lateral pressure is a relatively simple load, which can be considered locally, however this type of load can create imperfections in the plate causing premature buckling.

From this it is usually assumed that the only load required to create the load shortening curves used in Smith's method is the axial load.

For tension the stress strain relationship is simple. For compression it is more complex. Under compression the members will yield, reach an ultimate strength then buckle. Beams under compressive loads will fail by buckling. The averaged stress strain curve is usually represented by the normalised stress against the normalised strain as given below;

$\phi_n = \sigma / \sigma_y$ where ϕ_n is the normalised stress

$\varepsilon_n = \varepsilon / \varepsilon_y$ where ε_n is the normalised strain

8.3.4.3 Local Strength Assessment

The key function of longitudinal stiffeners in a stiffened plate panel is to provide the necessary support to the plates and hence ensure that they have the required strength. To satisfy this function, stiffeners need to have sufficient rigidity and the spacing between them must be selected according to the main characteristics of the plate namely, its thickness and yield stress. The slenderness of the plate has to be designed in such a way that the ultimate average stress remains nearer to the yield stress as much as possible.

The analysis of stiffened plates has been performed by several researchers and many solutions to the problem were presented over the years. The prediction of the panel behaviour has led to the development of several techniques such as non-linear finite element methods or more simplified formulations applying the beam-column concept. Common to all is the need for the application of an incremental end shortening if a realistic description of the post buckling behaviour is required. Also common to later formulation is the use of load end shortening curves for simply supported plates carried out on separate studies, which are able to describe the loss of plate stiffness after buckling.

Failure of panel is usually classified as follows and are illustrated in Figure 8-4,

- Plate induced collapse
- Stiffener induced collapse
- Tripping failure
- Overall grillage failure

Plate induced failure occurs when the stiffener is sufficiently stocky and the plate has a critical elastic stress lower than yield stress. Stiffener induced failure is mainly due to the excessive slenderness of the column (stiffener and effective associated plate acting together) and failure may be towards the plate or towards the stiffener, depending on the column's initial shape and the type of loading considered, i.e., eccentrically applied or not, following the shift of the neutral axis or not. In a continuous panel it is usual that the failure is towards the plate in one span and towards the stiffener in the adjacent span. Tripping failure can normally be avoided by ensuring that transverse frames are of adequate size therefore it is not considered generally.

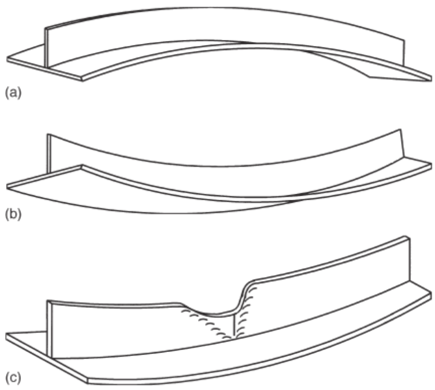


Figure 8-4 Possible collapse modes of stiffened panels under compressive loads. (a) Plate induced collapse; (b) Stiffener induced collapse, (c) Tripping failure

Sometimes the first and the second modes are incorporated in the same group because the buckled shape of the panel is similar and is normally towards the stiffener.

One of the major theoretical methods used for predicting the ultimate strength of stiffened panels is the plate stiffener combination approach (also called beam-column approach). This approach uses a representative plate-stiffener combination to represent the behaviour of a stiffened panel since the spacing of stiffeners is normally the same in each direction. Various column strength formulations have been used as the basis of such approaches. Three common types are,

- Johnson – Ostenfeld formulation
- Perry – Robertson formulation
- An empirical formulation obtained by curve fitting experimental or numerical data.

A stocky panel that has a high value of computed elastic buckling strength will not buckle in elastic domain, but will actually reach the ultimate strength with a certain degree of plasticity. In the most design rules of classification societies, the Johnson-Ostenfeld formulation is used to account for this behaviour, which is given by,

$$\sigma_c = \begin{cases} \sigma_E & \text{for } \sigma_E \leq 0.5\sigma_y \\ \sigma_y\left(1 - \dfrac{\sigma_y}{4\sigma_E}\right) & \text{for } \sigma_E > 0.5\sigma_y \end{cases} \qquad \text{Equation 8-2}$$

Where σ_c is the critical stress and σ_y is the yield stress of element in MPa and $\sigma_E = \sigma_y/\lambda^2$, is the Euler column buckling stress for a plate stiffener combination pin-joined at both the ends under axial compression. In ship rules from different sources (e.g., ABS 2003), the above equation may appear with somewhat different constants depending on the structural proportional limit value assumed. The above form assumes a structural proportional limit of 50% of the applicable yield value.

The Perry – Robertson formulation assumes that the stiffener with associated plating will collapse as a 'beam-column' when the maximum compressive stress in the extreme fiber reaches the yield strength of the material. The two possible collapse modes for the Perry – Robertson formulation are usually considered depending on the failure of the most highly stressed fiber, i.e., 'plate induced failure' and 'stiffener induced failure'. The plate induced failure mode is related to yielding of associated plating due to compression. The stiffener induced failure mode may result from either yielding of the extreme stiffener fiber (without rotation of stiffener) or tripping of stiffener (with rotation of stiffener). For a pin ended plate stiffener combination under axial compression in the x direction, the Perry-Robertson formula accounting for the effect of initial deflection (without either local buckling or tripping of the stiffener) may be given as compression taken as positive is as follows (Paik and Thayamballi, 2003)

$$\frac{\sigma_u}{\sigma_y} = \frac{1}{2}\left(1 + \frac{1+\eta}{\lambda^2}\right) - \left[\frac{1}{4}\left(1 + \frac{1+\eta}{\lambda^2}\right)^2 - \frac{1}{\lambda^2}\right]^{0.5} \qquad \text{Equation 8-3}$$

where σ_u is the ultimate stress, σ_y is the yield stress, λ is the column slenderness parameter, $\eta = \delta_0 . y_e / r^2$, is a parameter representing initial deflection. δ_0 is the maximum initial deflection, $y_e$is the distance to the extreme fibre at the compression side of the effective beam column section and r is the radius of gyration.

8.3.4.4 Basic Assumption of the Method

The basic assumptions of the method followed in this method are as follows;

- each cross section is made of an assembly of independent elements or "components" : plate panels, stiffened plate panels and hard corners, thus enabling to determine the structural behavior for each "component",
- transverse cross-sections of the ship hull remain plane after deformation and perpendicular to the neutral surface, enabling to calculate the strain ε_e for any curvature χ, according to the following formula : $\varepsilon_e = z\chi$ (z distance from the element under consideration to the neutral axis),
- collapse occurs for panels located between two adjacent transverse primary members,
- elasto-plastic behavior of each "component" is determined both in tension and compression,
- influence of shear stresses is neglected.

The method takes advantage of the possibility to determine for each "component" the relevant load-end curves "$\sigma - \varepsilon$", as indicated hereafter. The load-end curves "$\sigma - \varepsilon$" are based on the elasto-plastic collapse for lengthened components and on the buckling collapse for shortened components.

The method adopted for determination of the load-end shortening curves "$\sigma - \varepsilon$" is based on the following two assumptions:

- Variation of the "effective width of attached plating" with the strain ε_ℓ, as originally proposed by Gordo and Soares (1993),
- Generalization of the Johnson-Ostenfeld correction to any strain level.

8.3.4.5 Procedure of the method

The procedure to obtain the moment-curvature relation is described as follows;

1. The curve $M-\chi$ is to be obtained by means of an incremental-iterative approach, summarized in the flow chart in Figure 8-5.
2. Each step of the incremental procedure is represented by the calculation of the bending moment M_i which acts on the hull transverse section as the effect of an imposed curvature χ_i.
3. For each step, the value χ_i is to be obtained by summing an increment of curvature $\Delta\chi = \dfrac{0.01\dfrac{R_{eH}}{E}}{z_D - N}$ (z_d being the Z co-ordinate, in m, of strength deck at side) to the value relevant to the previous step χ_{i-1}.This increment of curvature corresponds to an increment of the rotation angle of the hull girder transverse section around its horizontal neutral axis.
4. This rotation increment induces axial strains ε_j in each hull structural element, whose value depends on the position of the element, since $\varepsilon_j = z_j\chi$. In hogging condition, the structural elements above the neutral axis are lengthened, while the elements below the neutral axis are shortened. The opposite takes place in sagging condition.
5. The stress σ_j induced in each structural element by the strain ε_j is to be obtained from the load-end shortening curve $\sigma-\varepsilon$ of the element, which takes into account the behavior of the element in the non-linear elasto-plastic domain. These curves are to be calculated, for the failure

mechanisms of the element, from the formulae specified in Appendix 1. The stress σ is selected as the lowest among the values obtained from each of the considered load-end shortening curves σ - ε.

6. The distribution of the stresses induced in all the elements composing the hull transverse section determines, for each step, a variation of the neutral axis position, since the relationship σ - ε is non-linear. The new position of the neutral axis relevant to the step considered is to be obtained by means of an iterative process, imposing the equilibrium among the stresses acting in all the hull elements, i.e. $\sum_j \sigma_j A_j = 0$ (usually the tolerance on the zero value is 10^{-4}).
7. Once the position of the neutral axis is known and the relevant stress distribution in the section structural elements is obtained, the bending moment of the section M_i around the new position of the neutral axis, which corresponds to the curvature χ_i imposed in the step considered, is to be obtained by summing the contribution given by each element stress: $M_i = \sum_j \sigma_j A_j z_j$.

The procedure is to be repeated for each step, until the value of the imposed curvature reaches the value χ_F, in m^{-1}, in hogging and sagging condition, obtained from the following formula: $\chi_F = \pm 0.003 \frac{M_Y}{EI_Y}$, where M_Y is the lesser of the values M_{Y1} and M_{Y2}, in kN.m: $M_{Y1} = 10^{-3} \sigma_Y Z_{AB}$ and $M_{Y2} = 10^{-3} \sigma_Y Z_{AD}$.

If the value χ_F is not sufficient to evaluate the peaks of the curve $M - \chi$, the procedure is to be repeated until the value of the imposed curvature permits the calculation of the maximum bending moments of the curve.

The flowchart of the above procedure is given in Figure 8-7.

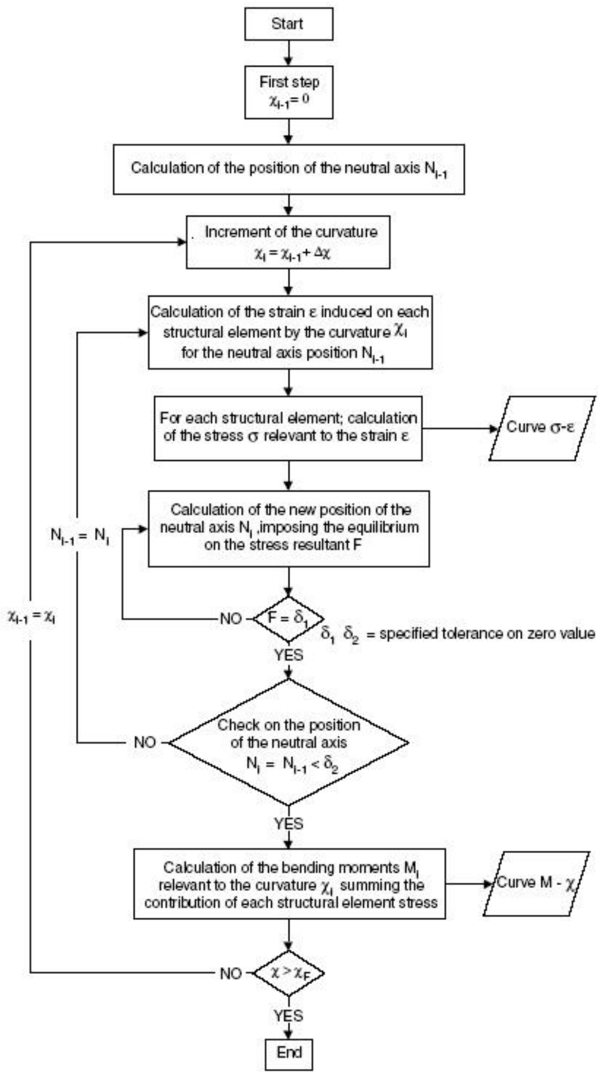


Figure 8-5 Flowchart of the procedure

8.3.5 Comparison of different Methods

In the ISSC report (2000), the methods introduced in previous sections are assessed from the viewpoint of applicability. Each method was quantitatively graded with respect to 15 capabilities by scoring 1-5. It was also done qualitatively by showing the consequence of omitting capabilities by low, medium and high. The results are shown in Table 8-1.

Table 8-1 Assessment of available methods to evaluate ultimate hull girder strength in longitudinal bending

Capability	Sample methods			Advanced methods				Consequence of omitting capability
	Initial yeilding	Elastic analysis	Assumed stress distribution	Progressive collapse analysis with idealised σ–ε curves	Progressive collapse analysis with calculated σ–ε curves	ISUM	Non-linear FEM	
Corresponding methods in benchmark calculations in Chapter 4	—	—	Astrop Rigo(2)	Cho Rigo(1)	Dow Yao Scores	Chem Masaoka	—	—
Plate buckling	—	2	3	4	5	5	5	H
Stiffened plate buckling	—	2	3	3	5	3	5	H
Plate initial deflection	—	1	2	2	5	5	5	M
Stiffener initial deflection	—	1	3	3	5	3	5	M
Plate welding residual stress	—	2	3	3	4	4	4	H
Stiffener welding residual stress	—	1	2	3	3	4	4	M
Post-buckling behaviour	—	—	—	3	5	5	5	H
Multi–span–model	—	—	—	2	5	5	5	M
M–S curve (collapse prediction)	—	—	—	3	5	5	5	H
Post-ultimate strength	—	—	—	3	5	4	5	M
Damage	2	2	2	3	5	3	5	—
Material modelling	1	1	1	3	5	5	5	—
Modelling/data preparation	5	4	4	3	3	3	1	—
Analysis/ checking results	5	3	3	3	3	3	1	—
Accuarcy/reliability of results	2	1	2	3	4	3	4	—
Total (full score: 75)	15	19	30	43	67	56	63	—

Score: 1. not available, 2. poor ability, 3. inefficient accuracy, 4. acceptable, 5. excellent. Consequence of omitting capability: L. low, M. medium, and H. high.

The method based on Initial yielding is an empirical one. Methods based on Elastic Analysis and Assumed stress distribution are direct methods, whereas the remaining methods have the capability to trace out the full sequence of progressive collapse behaviour of the hull girder. It is seen that the most effective among all methods is the progressive collapse analysis with calculated $\sigma - \varepsilon$ curves, that involves the use of numerical methods to determine the stress-strain curves of individual plate and stiffened plate elements, which are then integrated following the assumptions of simple beam theory in order to trace out the progressive collapse curve. The ISUM may also be an efficient method, but more rational elements have to be developed which can account the overall buckling as a stiffened panel and the tripping of stiffeners as well as the localisation of yielding and deformation in the post-ultimate strength range of individual structural members

8.4 Intact Ship Strength Analysis

In this study 4 Double Hull Tankers (DHT) are considered. The principal dimensions of the ships are as shown in Table 8-2, and Figure 8-6 shows the mid-ship cross section of the sample vessels. Henceforth the double hull tankers will be denoted as DHT310, DHT275, DHT264 and DHT233.

Table 8-2 Ship Particulars

Sample Ship	Length(m)	Breadth (m)	Depth (m)	C_b
DHT 310	310	58	31	0.82
DHT 275	275	46	23.3	0.83
DHT 264	264	43.9	24.4	0.83
DHT 233	233	42	20	0.84

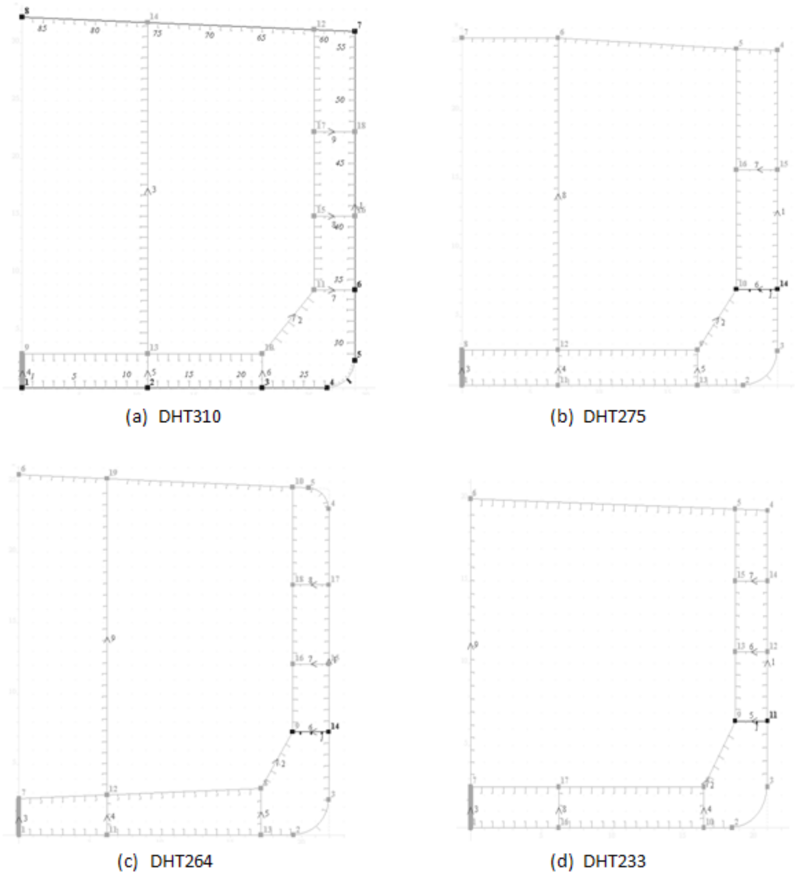


Figure 8-6 Mid-ship cross of sample ships

The ultimate strength and section modulus of the sample ships are calculated in intact condition to define the pre-damage strength. Smith's method has been extensively by many researches Gordo and Soares, 1996, 1997, 200; Fang and Das, 2004; Luis *et* al; Jia and Moan, 2008; Khan and Das, 2007) to determine hull girder ultimate strength of the intact ship. In this study MARS 2000 (BV, 2000) which is based on Smith's method is used for the ship ultimate strength calculations.

Since aging ships suffer structural degradation due to corrosion, the Intact ship ultimate strength and section modulus are calculated for the two scantlings, one corresponding to new build ships and other representing ships in operation, as given below;

- Gross scantling (t_{grs}) based on the test ship reference scantlings
- Hull girder net scantling (t_{net50}) , based on 50% corrosion deduction applied to all structural members, $t_{net50} = t_{grs} - 0.5t_{corr}$

The results based on these two scantlings are presented in Table 8-3 and Table 8-4. The results of t_{net50} scantlings compared to gross scantlings show almost 10% loss in section modulus and approximately 5% reduction in ultimate strength capacity. It should be noted that degradation of scantling below t_{net50} everywhere in the same transverse section is improbable as the t_{net50} hull girder scantling requirements will trigger necessary plate and stiffener renewals before such extensive corrosion arises. Hence, in this study the reliability analysis is carried out considering t_{net50} scantlings.

Table 8-3 Section Modulus (SM) & Ultimate Strength (US) of Intact Ship (t_{grs})

Sample Ship	SM Bottom (m^3)	SM Deck (m^3)	US Hogging (GNm)	US Sagging (GNm)
DHT310	108.04	78.04	25.98	21.46
DHT275	58.80	48.55	14.64	12.87
DHT264	53.67	44.19	13.45	11.63
DHT233	37.52	28.34	8.94	7.55

Table 8-4 Section Modulus (SM) & Ultimate Strength (US) of Intact Ship (t_{net50})

Sample Ship	SM Bottom (m^3)	SM Deck (m^3)	US Hogging (GNm)	US Sagging (GNm)
DHT 310	98.06	70.07	25.13	20.42
DHT 275	53.54	43.71	13.99	12.31
DHT 264	48.62	39.59	12.87	11.04
DHT 233	34.04	25.37	8.52	7.17

In this study the used scantlings are the net scantlings +50% of the corrosion addition according to CSR, tnet50. These scantlings are the strength scanting as defined in the IACS CSR rules (IACS, 2006a) which corresponds to the minimum strength the ship might have and which is considered during the design phase.

8.5 Damaged Ship Residual Strength Analysis

When a ship is damaged, the damaged part is considered to be ineffective in its contribution towards the global strength of the ship. So in progressive collapse analysis method the damaged elements are considered to be inert and absent. The damage is simulated by removing the damaged elements from the midship section and re-calculating the ultimate strength of the section.

Every accident is different and also the resulting damage varies. Hence, different damages sizes at various locations along the side and bottom are analysed. Figure 8-7 shows a schematic representation of grounding and collision damage at the mid-ship section of ship. For grounding, it is assumed that the bottom shell and the attached bottom longitudinal are lost. The plate and stiffeners in the damage zone are removed to calculate the strength and section modulus after damage.

This study investigates a broader range of side and bottom losses. To simulate minor to severe grounding damages, the damage size is varied from 10% to 50% of ship breadth. Similarly, for Collision it is assumed that the side shell and the attached longitudinals are lost and the damage extent is varied from 10% damage to 50% side damage. Only one parameter is used to describe the grounding damage, b/B (Damage Width over Ship Breadth), similarly, for collision d/D (Damage Width over Ship Depth).

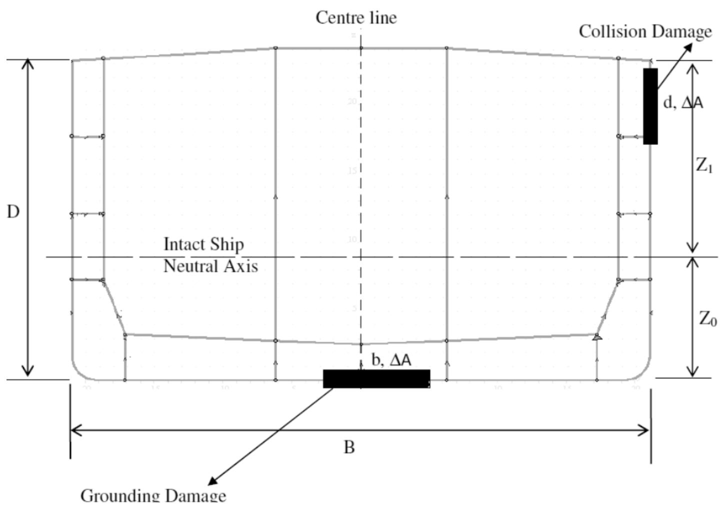


Figure 8-7 Illustration of Damage Extent in ship mid-ship section

The residual strength index is a way of comparing the ultimate strength of the damaged hull with the intact one. The residual strength index (RSI) used in this study is defined by Fang and Das (2004) as

$$RSI = \frac{M_{Ult,Damage}}{M_{Ult,Intact}} \quad \text{Equation 8-4}$$

where $M_{Ult,Damage}$ is the ultimate bending capacity of the damage section and $M_{Ult,Intact}$ is the ultimate capacity of the intact section.

Similarly, the residual section modulus (RSM) after damage is calculated by comparing the section modulus of the damaged hull with the intact one, which is given as;

$$RSM = \frac{SM_{Damage}}{SM_{Intact}} \quad \text{Equation 8-5}$$

where SM_{Damage} is the section modulus of the damage section and SM_{Intact} is the section modulus of the intact section.

The residual strength of sample ships is calculated by Smith's progressive collapse method using MARS 2000, where the damage is simulated by removing the damaged elements from the midship section and re-calculating the ultimate strength of the section.

To derive simplified equations to determine the ultimate strength of damaged ship which depends only on damage extent and section modulus at intact condition the Equation 8-1 for yield bending moment is modified by introducing a reduction factor. To obtain this reduction factor, the model uncertainty factor was determined which is the ratio of actual bending moment over yield bending moment. This model uncertainty factor is plotted against the damage extent and using curving fitting an equation for the resulting plot is obtained. This equation shows how much the yield moment deviates from the actual bending moment of the ship and hence an analytical equation for the ultimate strength of ship could be obtained by multiplying this factor with the initial yield as shown in Equation 8-6.

$$M_{Ult\ (Calculated)} = k \times SM_{Intact} \times \sigma_Y \qquad \text{Equation 8-6}$$

Where k is the factor by which yield moment should be multiplied to get the actual bending moment.

The determination of model uncertainty factors, section modulus and ultimate strength of intact and damaged ships are discussed in detail in the following sections.

8.5.1 Residual Strength following Grounding Accident

As observed from the previous chapters, the reasons for ship grounding are many and the consequence of such an accident has high financial and environmental impact. This necessitates the determination of strength of ships after damage to identify the immediate action to prevent or to reduce such risk and to facilitate subsequent salvage operation.

To study the effect of transverse location of damage on the strength of ships a comprehensive study was carried out by assuming damage at different locations along the bottom from the left side and proceeding to the right side, as shown in Figure 8-8. In Figure 8-8 only 3 locations are shown but 6 locations along the bottom for each damage size were considered and corresponding analysis carried out

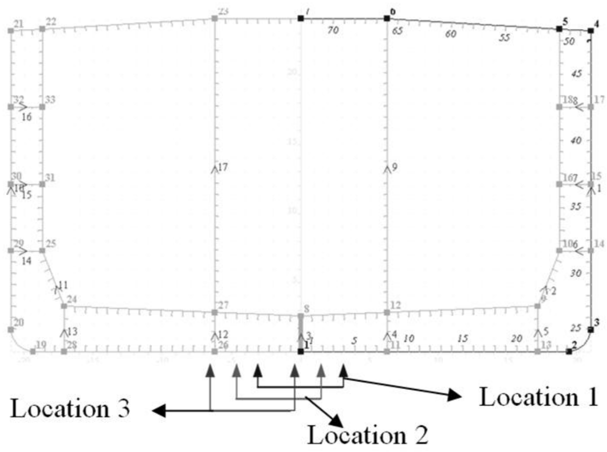


Figure 8-8 Transverse location of damage

In the first scenario a damage size of B/6 (where B is the breadth of the ship) is assumed to starts from the keel part of the ship with the center of the damage along the center line of the ship, the stiffeners in this area are assumed to be inactive. The ultimate strength is calculated. In the second scenario the B/6 damage size is assumed to move left of the section as shown in figure (Location 2). Again the Ultimate strength is calculated. In this way the location of damage keeps moving towards the left until it reaches the bilge.

In the next scenarios a damage size of B/5, B/4, B/3 and B/2 is assumed and the above procedure repeated for each scenario and the corresponding residual strengths taken.

The reduction in residual strength after grounding by considering the location of damage at different location is as shown in Figure 8-9, from which it can be concluded that in grounding accidents the transverse location does not have a significant influence on the strength. But compared to other locations the loss in strength is slightly more when the keel is damaged. Hence, this study considers the loss in strength due to accident occurring in the keel of the ship.

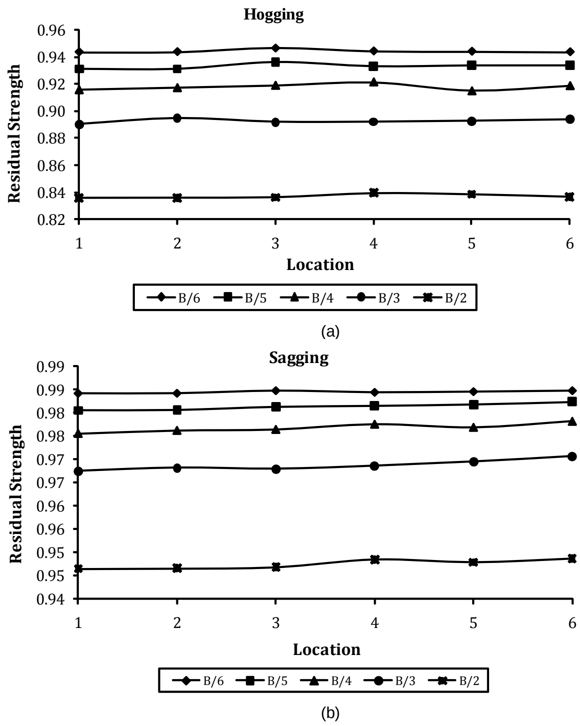


Figure 8-9 Residual Strength after bottom damage at different locations (a) Hogging (b) Sagging

8.5.1.1 Loss in Section Modulus

After accident there will be reduction in section modulus because of the loss of stiffeners and plates in the region of damage. Therefore, the section modulus after damage has to be determined to check whether the ship meets the required minimum rule section modulus.

The section modulus to the bottom & deck and their respective RSM values are calculated under different damage scenarios and presented in Table 8-5.

Table 8-5 Section Modulus after grounding accident

Ship	Damage Scenario	Damage Size (b/B)	SM Bottom (m^3)	SM Deck (m^3)	RSM Bottom	RSM Deck
DHT310	Intact	0	98.06	70.07	1	1
	10% Damage	0.1	90.73	68.88	0.93	0.98
	20% Damage	0.2	83.50	67.55	0.85	0.96
	30% Damage	0.3	76.34	66.04	0.78	0.94
	40% Damage	0.4	70.13	64.56	0.72	0.92
	50% Damage	0.5	62.05	62.33	0.63	0.89
DHT275	Intact	0	53.54	43.71	1	1
	10% Damage	0.1	49.56	43.17	0.93	0.99
	20% Damage	0.2	45.56	42.54	0.85	0.97
	30% Damage	0.3	41.95	41.89	0.78	0.96
	40% Damage	0.4	38.32	41.14	0.72	0.94
	50% Damage	0.5	34.24	40.15	0.64	0.92
DHT264	Intact	0	48.62	39.59	1	1
	10% Damage	0.1	45.47	39.10	0.94	0.99
	20% Damage	0.2	41.92	38.50	0.86	0.97
	30% Damage	0.3	38.76	37.89	0.80	0.96
	40% Damage	0.4	35.19	37.11	0.72	0.94
	50% Damage	0.5	31.61	36.21	0.65	0.91
DHT233	Intact	0	34.04	25.37	1	1
	10% Damage	0.1	31.65	25.06	0.93	0.99
	20% Damage	0.2	28.93	24.67	0.85	0.97
	30% Damage	0.3	26.49	24.25	0.78	0.96
	40% Damage	0.4	24.03	23.77	0.71	0.94
	50% Damage	0.5	21.24	23.13	0.62	0.91

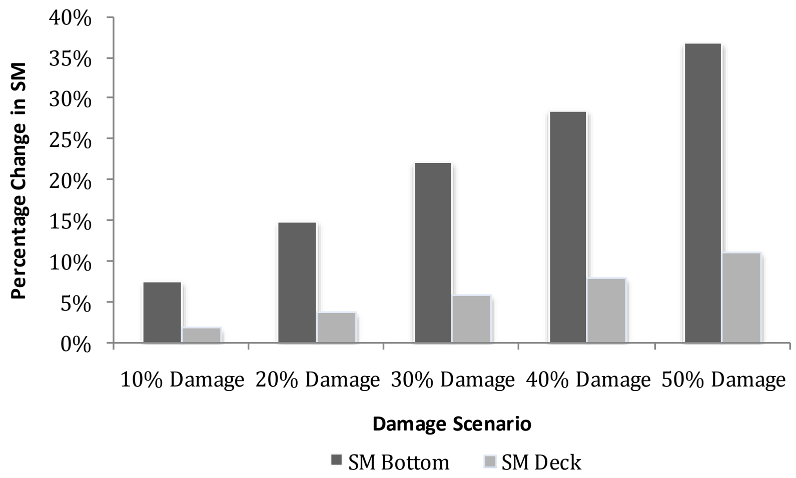


Figure 8-10 Percentage reduction in Section Modulus to deck & bottom after grounding accident

It can be seen from Table 8-5 and Figure 8-10 that as the damage size increase the reduction in section modulus to the bottom is more drastic compared to that of deck. For a 50% bottom damage the section modulus of bottom reduces by around 36% of the intact value, whereas, the deck section modulus reduces by around 12%.

At the midship cross-section, the net vertical hull girder section modulus, Z_{min}, at the deck and keel is not to be less than the rule minimum hull girder section modulus which is defined as

$$Z_{min} = 0.9KC_{wv}L^2B(C_B + 0.7)10^{-6}\ m^3 \qquad \text{Equation 8-7}$$

where K is the high-strength steel factor = 0.72, C_{wv} the wave coefficient, L the rule length in *meter*, B the moulded breadth in m and C_B the block coefficient. Table 8-6 shows the rule required section modulus for each of the four sample ships

Table 8-6 Rule required Section Modulus

Ship	Rule SM
DHT310	59.02
DHT275	36.65
DHT264	31.95
DHT233	23.21

Figure 8-11 shows the normalized values of the section modulus to the bottom and deck under different damage scenarios. The values are normalized to the rule value, i.e. value 1 corresponds to the rule values.

It can be seen from the Figure 8-11 (a) that for up to 40% bottom damage the section modulus to bottom for all the sample ships still complies with the rule requirement, but when the damage size increases to 50% of ship breadth all the ships other than DHT310 falls below the rule value. From Figure 8-11 (b) it can be seen that the loss in section modulus to deck is not as significant as that of the bottom and all the ship satisfies the minimum section modulus requirement up to 40% damage to the bottom, and as the damage size increase to 50% of ship breadth DHT233 falls a little beyond the minimum rule requirement.

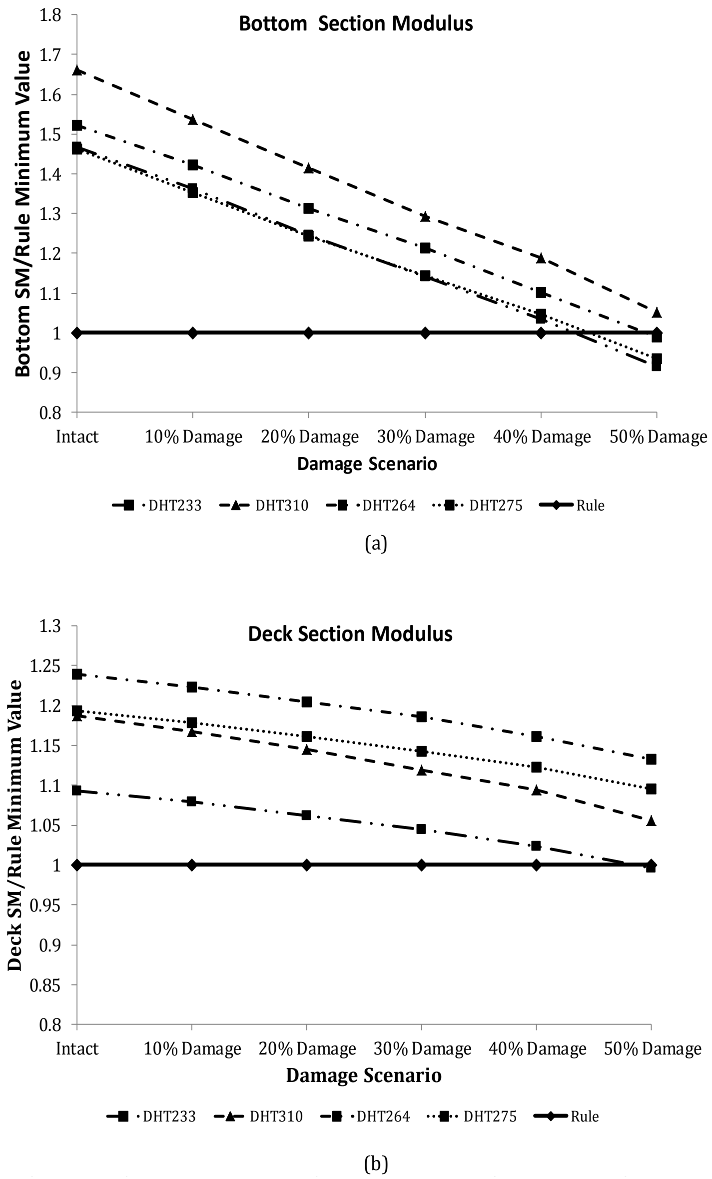


Figure 8-11 Normalised values of Section modulus to bottom and deck after damage

The residual section modulus to the deck and bottom for all the ships shows the similar values under same damage extent. The average of RSM values under different damage size was taken and using curve fitting equations dependent on the damage size as shown in Figure 8-12 were derived.

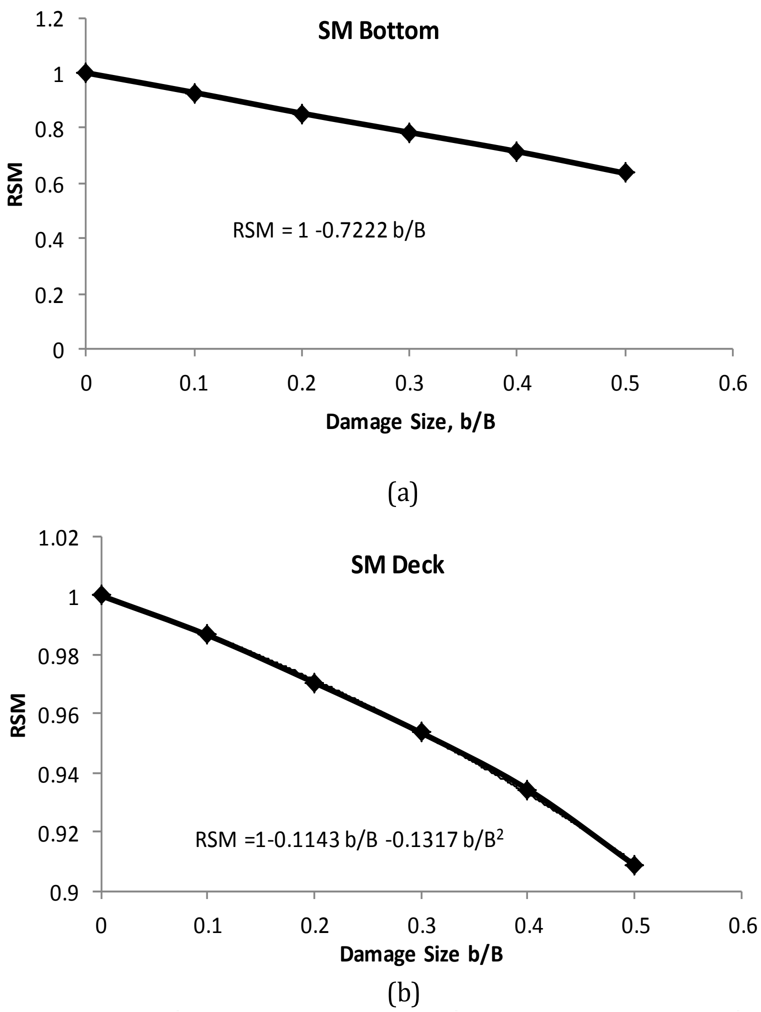


Figure 8-12 RSM formula (a) for loss in SM of bottom (b) for loss in SM of deck

Equation 8-8 and Equation 8-9 can be used to determine the section modulus under any damage scenario given the damage extent and intact section modulus. The results based on these equations are comparable with the actual values of section modulus after damage and shows no more than 2% deviation from actual values.

$$SM_{Analytical,Bottom} = \left(1 - 0.722 \times \frac{b}{B}\right) SM_{Intact,Bottom} \qquad \text{Equation 8-8}$$

$$SM_{Analytical,Deck} = \left(1 - 0.114 \times \frac{b}{B} - 0.13 \times \frac{b}{B}^2\right) SM_{Intact,Deck} \qquad \text{Equation 8-9}$$

8.5.1.2 Residual Strength after Damage

The ultimate strength of the ships under different damage scenarios were calculated using progressive collapse methods. The results of this analysis are shown in Table 8-7.

Table 8-7 Ultimate strength of ship after grounding

Ship	Damage Scenario	Damage Size (b/B)	M_{utl} Hogging (GN.m)	M_{utl} Sagging (GN.m)	RSI Hogging	RSI Sagging
DHT310	Intact	0	25.13	20.42	1	1
	10% Damage	0.1	23.64	20.41	0.94	1.00
	20% Damage	0.2	22.33	19.97	0.89	0.98
	30% Damage	0.3	21.03	19.40	0.84	0.95
	40% Damage	0.4	19.90	18.82	0.79	0.92
	50% Damage	0.5	18.30	17.81	0.73	0.87
DHT275	Intact	0	13.99	12.31	1	1
	10% Damage	0.1	13.18	12.17	0.94	0.99
	20% Damage	0.2	12.38	11.92	0.88	0.97
	30% Damage	0.3	11.73	11.62	0.84	0.94
	40% Damage	0.4	10.90	11.27	0.78	0.92
	50% Damage	0.5	9.99	10.72	0.71	0.87
DHT264	Intact	0	12.87	11.04	1	1
	10% Damage	0.1	12.26	10.92	0.95	0.99
	20% Damage	0.2	11.57	10.68	0.90	0.97
	30% Damage	0.3	10.97	10.42	0.85	0.94
	40% Damage	0.4	10.19	10.08	0.79	0.91
	50% Damage	0.5	9.42	9.63	0.73	0.87
DHT233	Intact	0	8.52	7.17	1	1
	10% Damage	0.1	8.08	7.09	0.95	0.99
	20% Damage	0.2	7.53	7.00	0.88	0.98
	30% Damage	0.3	7.07	6.86	0.83	0.96
	40% Damage	0.4	6.50	6.65	0.76	0.93
	50% Damage	0.5	5.85	6.35	0.69	0.89

The Residual strength for all the sample ships under same damage scenarios are almost similar and hence the average for each scenario was plotted as shown in Figure 8-13 and using curve fitting equations were derived which could help to determine the residual strength of damaged ships in hogging and sagging given the damage size. It can be seen from above table that the loss in ultimate strength in hogging is more compared to that in sagging; this is because with grounding damage ship has lost material in the bottom which contribute to the resistance of the ship in hogging.

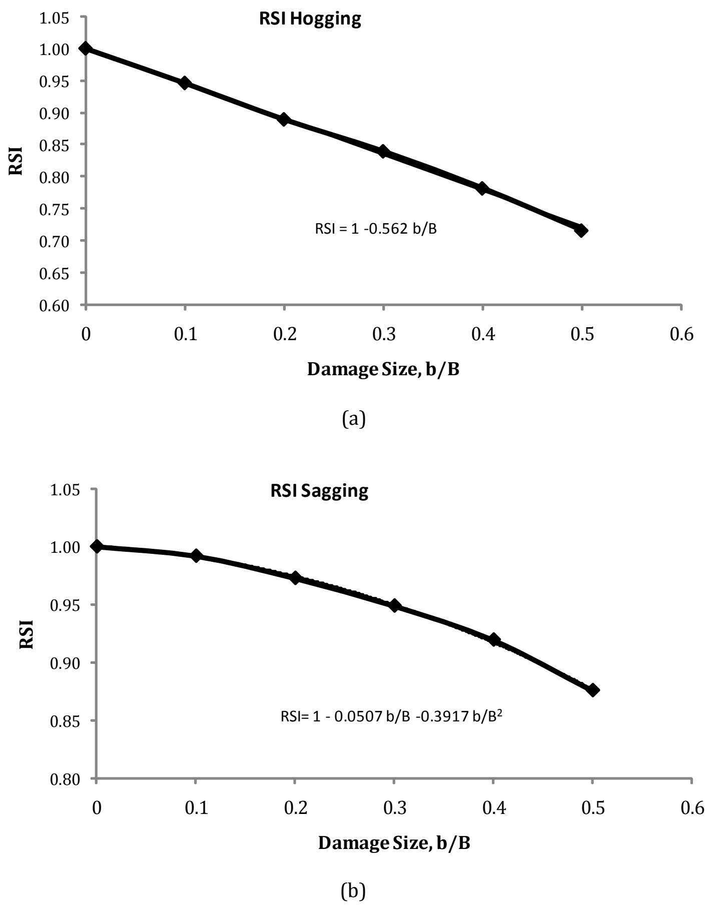


Figure 8-13 RUS formula (a) hogging (b) sagging

The residual section modulus and ultimate strength of ship in different grounding scenarios are shown in Figure 8-14.

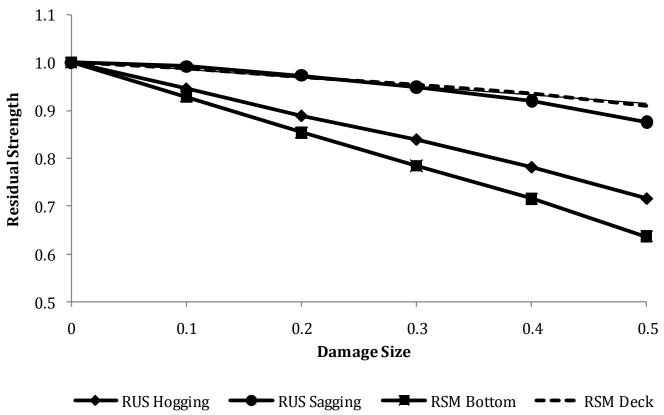


Figure 8-14 Residual Strength of ships with grounding damage

The following conclusions could be drawn from Figure 8-14.

- The section modulus to the bottom is the most sensitive indicator of the bottom damage, followed by hull girder ultimate strength in hogging. Ultimate strength in sagging and section modulus to bottom is less sensitive and follows almost the same pattern.
- The hull girder exhibits more reserve in the section modulus to the deck than in the hull girder strength in sagging. On the other hand, the hull shows less reserve in the section modulus to the bottom than in the hull girder ultimate strength for hogging.

8.5.1.3 Simplified Equations for Residual Strength Calculation following Bottom Damage

To obtain the simple equation first the yield bending moment is calculated, based on Equation 8-1, which is the product of Section modulus and yield strength of the material. The results of this calculation are shown in Table 8-8.

Table 8-8 Yield Bending capacity of ships in different damage scenarios

Ship	Damage Scenario	Damage Size (b/B)	M_{Yield} Hogging (GN.m)	M_{Yield} Sagging (GN.m)
DHT310	Intact	0	30.89	22.07
	10% Damage	0.1	28.66	21.67
	20% Damage	0.2	26.44	21.28
	30% Damage	0.3	24.21	20.88
	40% Damage	0.4	21.98	20.48
	50% Damage	0.5	19.76	20.08
DHT275	Intact	0	16.86	13.77
	10% Damage	0.1	15.65	13.52
	20% Damage	0.2	14.43	13.27
	30% Damage	0.3	13.22	13.02
	40% Damage	0.4	12.00	12.78
	50% Damage	0.5	10.79	12.53
DHT264	Intact	0	15.31	12.47
	10% Damage	0.1	14.21	12.24
	20% Damage	0.2	13.11	12.02
	30% Damage	0.3	12.00	11.79
	40% Damage	0.4	10.90	11.57
	50% Damage	0.5	9.80	11.34
DHT233	Intact	0	10.72	7.99
	10% Damage	0.1	9.95	7.85
	20% Damage	0.2	9.18	7.70
	30% Damage	0.3	8.41	7.56
	40% Damage	0.4	7.63	7.41
	50% Damage	0.5	6.86	7.27

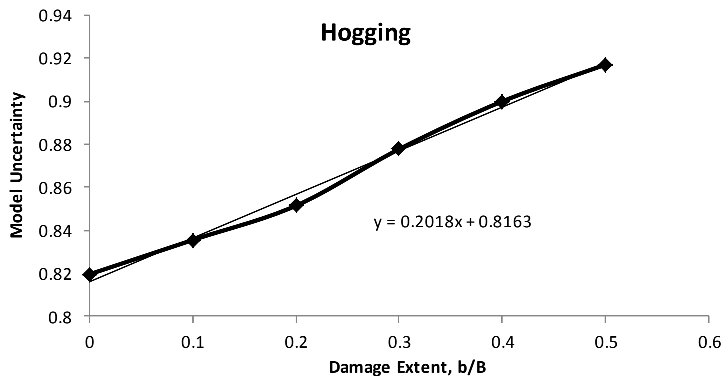
Based on the results from Table 8-7 and Table 8-8 the model uncertainty factor is calculated, which is the ratio between the ultimate bending capacity (actual value) over the yield capacity (predicted value). Table 8-9 shows the calculated model uncertainty for grounding accident.

Table 8-9 Model Uncertainty in bending moment

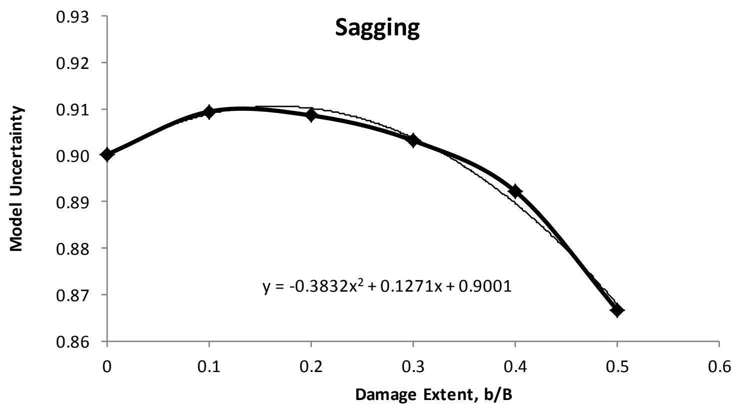
Ship	Damage Scenario	Damage Size (b/B)	Model Uncertainty Factor Hogging	Model Uncertainty Factor Sagging
DHT310	Intact	0	0.81	0.93
	10% Damage	0.1	0.82	0.94
	20% Damage	0.2	0.84	0.94
	30% Damage	0.3	0.87	0.93
	40% Damage	0.4	0.91	0.92
	50% Damage	0.5	0.93	0.89
DHT275	Intact	0	0.83	0.89
	10% Damage	0.1	0.84	0.90
	20% Damage	0.2	0.86	0.90
	30% Damage	0.3	0.89	0.89
	40% Damage	0.4	0.91	0.88
	50% Damage	0.5	0.93	0.86
DHT264	Intact	0	0.84	0.89
	10% Damage	0.1	0.86	0.89
	20% Damage	0.2	0.88	0.89
	30% Damage	0.3	0.91	0.88
	40% Damage	0.4	0.93	0.87
	50% Damage	0.5	0.96	0.85
DHT233	Intact	0	0.79	0.90
	10% Damage	0.1	0.81	0.90
	20% Damage	0.2	0.82	0.91
	30% Damage	0.3	0.84	0.91
	40% Damage	0.4	0.85	0.90
	50% Damage	0.5	0.85	0.87

It can be seen from Table 8-9 the model uncertainty factor for different damage sizes for all the sample ships follows similar trend and hence the average of each damage scenarios was plotted as shown in Figure 8-15 and using curve fitting the equation for the curves were obtained.

It can be seen from Figure 8-15 (a) that the model uncertainty for hogging increases with damage size and follows a linear trend and hence a linear curve is used to fit the data and derive the equation, whereas from Figure 8-15 (b) it can be seen that the model uncertainty in sagging first increases and then decreases with increase in damage extent and hence a polynomial function is used to fit data and derive the equation.



(a)



(b)

Figure 8-15 Model Uncertainty in (a) Hogging (b) Sagging

Since the model uncertainty shows how much the yield moment deviates from the ultimate moment capacity the product of the uncertainty and the yield moment will give a result close to the actual ultimate strength of the ship. The derived equation is shown below;

$$M_{Ult}, Hog = \left[0.82 - 0.39\frac{b}{B} - 0.15\frac{b}{B}^2\right] SM_{Bottom} \times \sigma_y \qquad \text{Equation 8-10}$$

$$M_{Ult}, Sag = \left[0.9 - 0.035\frac{b}{B} - 0.4\frac{b}{B}^2 + 0.07\frac{b}{B}^3\right] SM_{Deck} \times \sigma_y \qquad \text{Equation 8-11}$$

The results based on the above simplified equation are given in Table 8-10, from which it could be seen that the percentage difference in results for hogging and sagging based on these equations and actual ultimate strength calculation are small and the maximum difference is less than ±5%.

Table 8-10 Results of ultimate strength based on analytical equation for grounding

Ship	Damage Scenario	Modified Formula Hogging	Modified Formula Sagging	Percentage Difference, Hogging	Percentage Difference, Sagging
DHT310	Intact	25.22	19.95	0.36%	-2.32%
	10% Damage	23.98	19.78	1.41%	-3.06%
	20% Damage	22.64	19.45	1.40%	-2.62%
	30% Damage	21.22	18.95	0.90%	-2.31%
	40% Damage	19.71	18.30	-0.98%	-2.76%
	50% Damage	18.11	17.51	-1.06%	-1.72%
DHT275	Intact	13.77	12.44	-1.61%	1.09%
	10% Damage	13.09	12.34	-0.70%	1.39%
	20% Damage	12.36	12.13	-0.13%	1.80%
	30% Damage	11.59	11.82	-1.22%	1.69%
	40% Damage	10.76	11.42	-1.23%	1.33%
	50% Damage	9.89	10.92	-1.01%	1.88%
DHT264	Intact	12.50	11.27	-2.84%	2.07%
	10% Damage	11.89	11.18	-3.02%	2.33%
	20% Damage	11.23	10.99	-2.98%	2.84%
	30% Damage	10.52	10.71	-4.08%	2.75%
	40% Damage	9.77	10.34	-4.10%	2.60%
	50% Damage	8.98	9.89	-4.72%	2.65%
DHT233	Intact	8.76	7.22	2.79%	0.78%
	10% Damage	8.32	7.16	3.06%	0.93%
	20% Damage	7.86	7.04	4.46%	0.53%
	30% Damage	7.37	6.86	4.29%	0.01%
	40% Damage	6.80	6.62	4.71%	-0.40%
	50% Damage	6.11	6.34	4.30%	-0.27%

8.5.2 Residual Strength following Collision Accident

In order to calculate the minimum damage ultimate bending moment different damage scenarios at side are assumed. Damages at 6 locations along the depth of the ship are studied starting from the deck and extending till half the depth of ship. The damage size progresses from D/6 to D/2 (D depth of ship).

In the first scenario, the damage starts from the upper part of the side and extends D/6 towards the bottom as shown in Figure 8-16. The Stiffeners in this area are assumed to be inactive. The ultimate strength is calculated. In the second scenario its starts from second location and extends D/6 towards the bottom. Again the Ultimate strength is calculated. In this way the location of damage keeps moving towards the bottom and in each case the Ultimate strength is noted.

The same calculations are repeated for different damage sizes; D/5, D/4, D/3 and D/2 and the ultimate strength noted.

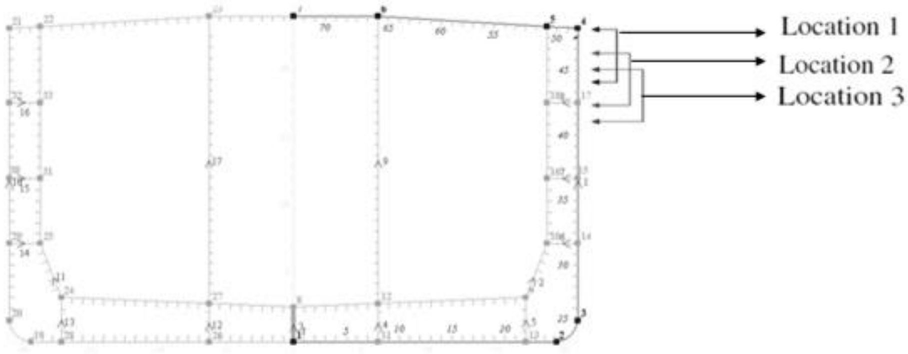


Figure 8-16 Vertical Location of accident

The results of this analysis is shown in Figure 8-17.

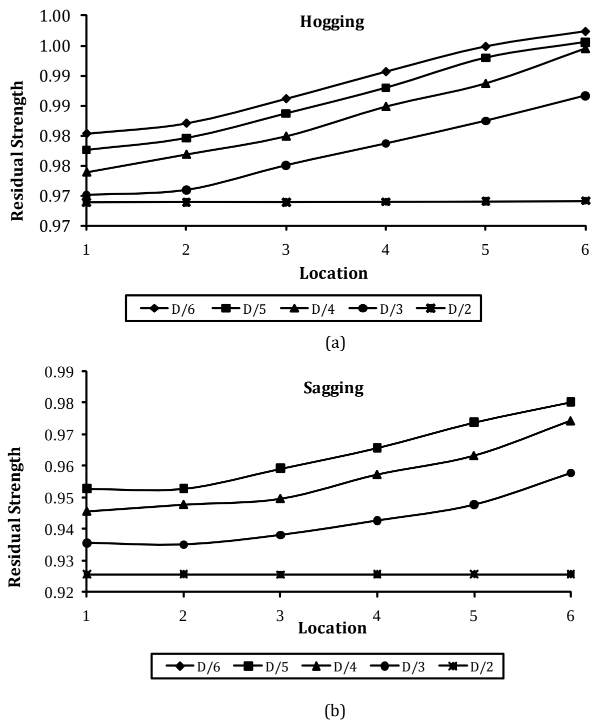


Figure 8-17 Residual Strength after side damage at different locations (a) Hogging (b) Sagging

Figure 8-17 shows the variation of Ultimate strength at each location for Double Hull Tanker, from which it is clear that the minimum residual strength always occurs when the upper part is damaged. As the damage moves downwards it could be seen that there is actually an increase in residual strength compared to the residual strength when the upper part is damaged. Furthermore as expected bigger the damage is smaller the residual strength.

8.5.2.1 Loss in Section Modulus

Figure 8-18 shows the normalized values of the section modulus to the bottom and deck under different damage scenarios due to side damage. The values are normalized to the rule value, i.e. value 1 corresponds to the rule values. It can be seen from Figure 8-18 (a) that under any damage size the section modulus to bottom does not fall below the rule value for collision accidents. The section modulus to deck is very sensitive to side damage and shows a steep decrease from intact value as shown in Figure 8-18 (b). It can be noted from the figure that section modulus to deck is more sensitive to side damage.

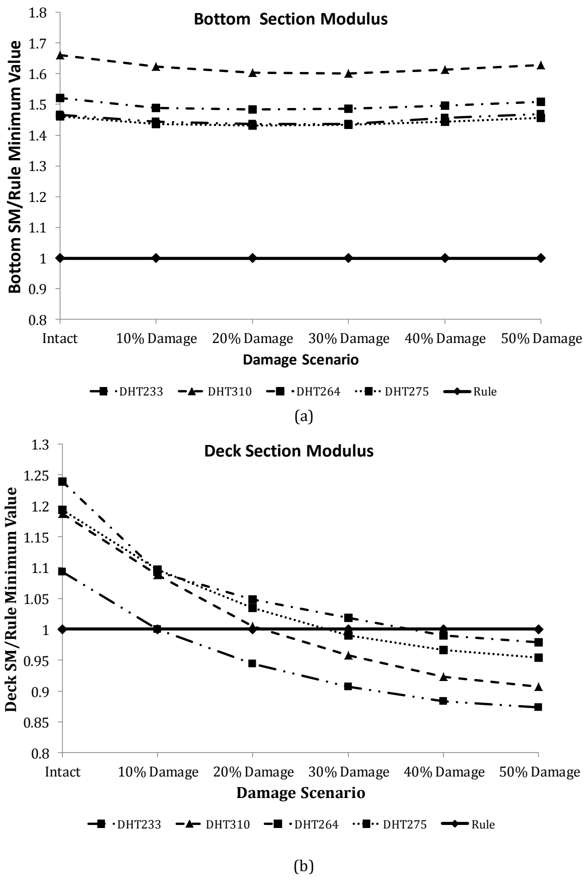


Figure 8-18 Normalised values of Section Modulus after side damage to the (a) Bottom and (b) Deck

The loss in section modulus to the deck and bottom after different collision scenarios were analysed and the results are shown in Table 8-11.

Table 8-11 Section modulus after collision accident

Ship	Damage Scenario	Damage Size (b/B)	SM Bottom (m^3)	SM Deck (m^3)	RSM Bottom	RSM Deck
DHT310	Intact	0	98.06	70.07	1	1
	10% Damage	0.1	95.85	64.24	0.98	0.92
	20% Damage	0.2	94.63	59.29	0.97	0.85
	30% Damage	0.3	94.54	56.56	0.96	0.81
	40% Damage	0.4	95.24	54.50	0.97	0.78
	50% Damage	0.5	96.16	53.51	0.98	0.76
DHT275	Intact	0	53.54	43.71	1	1
	10% Damage	0.1	52.67	40.17	0.98	0.92
	20% Damage	0.2	52.41	37.90	0.98	0.87
	30% Damage	0.3	52.57	36.28	0.98	0.83
	40% Damage	0.4	52.92	35.43	0.99	0.81
	50% Damage	0.5	53.33	34.97	1.00	0.80
DHT264	Intact	0	48.62	39.59	1	1
	10% Damage	0.1	47.60	34.93	0.98	0.88
	20% Damage	0.2	47.40	33.48	0.97	0.85
	30% Damage	0.3	47.47	32.54	0.98	0.82
	40% Damage	0.4	47.83	31.66	0.98	0.80
	50% Damage	0.5	48.18	31.27	0.99	0.79
DHT233	Intact	0	34.04	25.37	1	1
	10% Damage	0.1	33.49	23.20	0.98	0.91
	20% Damage	0.2	33.36	21.91	0.98	0.86
	30% Damage	0.3	33.37	21.06	0.98	0.83
	40% Damage	0.4	33.80	20.51	0.99	0.81
	50% Damage	0.5	34.09	20.27	1.00	0.80

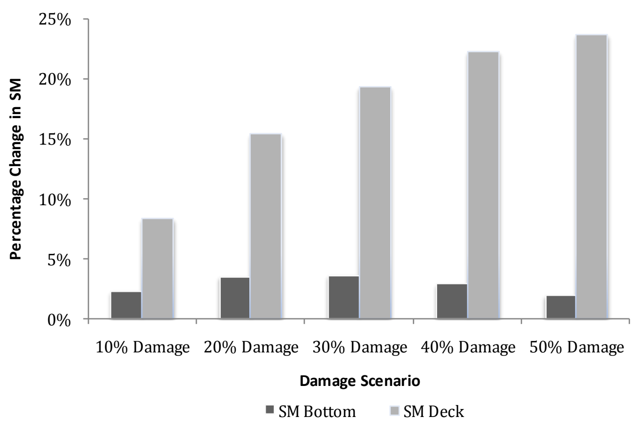
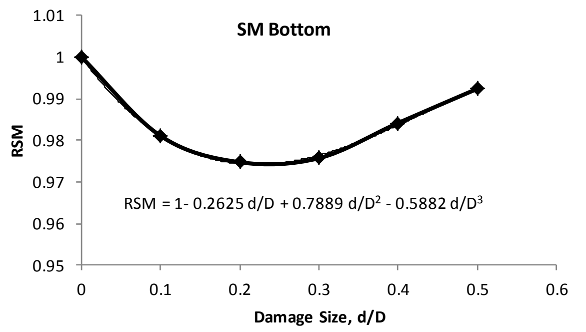
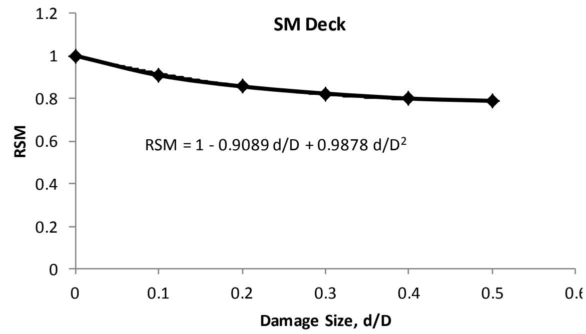


Figure 8-19 Percentage reduction in Section Modulus to deck & bottom after collision accident

Since the residual section modulus to the deck and bottom for all the ships under same damage extent shows the similar trend, the average of RSM values was taken and using curve fitting equations dependent only on the damage size were derived as shown in Figure 8-20.



(a)



(b)

Figure 8-20 RSM formula for (a) loss in SM of Bottom (b) loss in SM of Deck

The equations in Figure 8-20 when multiplied with intact section modulus give the analytical section modulus for any damage scenario, as given below, which is comparable and shows no more than 2% deviation from the actual values.

$$SM_{Analytical,Bottom} = \left(1 - 0.26 \times \frac{d}{D} + 0.79 \times \frac{d}{D}^2 - 0.59 \times \frac{d}{D}^3\right) SM_{Intact,Bottom} \quad \text{Equation 8-12}$$

$$SM_{Analytical,Bottom} = \left(1 - 0.91 \times \frac{d}{D} + 0.99 \times \frac{d}{D}^2\right) SM_{Intact,Bottom} \quad \text{Equation 8-13}$$

8.5.2.2 Residual Strength after Collision Accident

The residual strength of the ships under different damage scenarios were calculated using progressive collapse methods. The results of this analysis are shown in Table 8-12. It could be seen that the loss in ultimate strength in sagging is more compared to that in sagging following a collision accident; this is because of the loss in material from the side which is essential for strength of ships in sagging.

Table 8-12 Ultimate strength of ship after collision

Ship	Damage Scenario	Damage Size (b/B)	M_{utl} Hogging (GN.m)	M_{utl} Sagging (GN.m)	RSI Hogging	RSI Sagging
DHT310	Intact	0	25.13	20.42	1	1
	10% Damage	0.1	23.70	18.75	0.94	0.92
	20% Damage	0.2	22.65	17.29	0.90	0.85
	30% Damage	0.3	21.76	16.19	0.87	0.79
	40% Damage	0.4	20.91	14.76	0.83	0.72
	50% Damage	0.5	20.30	14.01	0.81	0.69
DHT275	Intact	0	13.99	12.31	1	1
	10% Damage	0.1	13.35	11.26	0.95	0.92
	20% Damage	0.2	12.84	10.54	0.92	0.86
	30% Damage	0.3	12.36	9.80	0.88	0.80
	40% Damage	0.4	11.99	9.44	0.86	0.77
	50% Damage	0.5	11.71	9.19	0.84	0.75
DHT264	Intact	0	12.87	11.04	1	1
	10% Damage	0.1	11.91	9.66	0.93	0.88
	20% Damage	0.2	11.55	9.15	0.90	0.83
	30% Damage	0.3	11.25	8.86	0.87	0.80
	40% Damage	0.4	10.90	8.34	0.85	0.76
	50% Damage	0.5	10.64	8.08	0.83	0.73
DHT233	Intact	0	8.52	7.17	1	1
	10% Damage	0.1	8.06	6.42	0.95	0.90
	20% Damage	0.2	7.71	6.07	0.90	0.85
	30% Damage	0.3	7.39	5.62	0.87	0.78
	40% Damage	0.4	7.14	5.41	0.84	0.76
	50% Damage	0.5	6.91	5.30	0.81	0.74

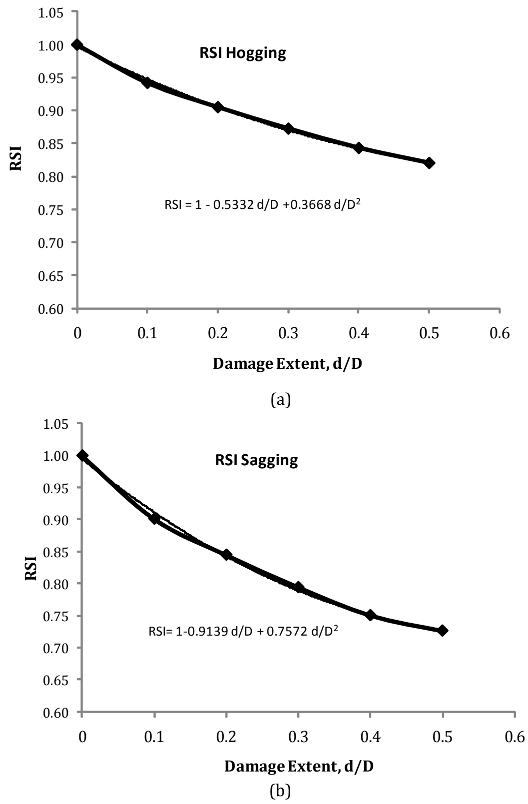


Figure 8-21 RUS formula (a) Hogging (b) Sagging

The Residual ultimate strength for all the ships are almost similar and hence the average for each scenario was plotted as shown Figure 8-21 and using curve fitting equations were derived which could help to determine the residual ultimate strength of damaged ships in hogging and sagging given the damage size.

The residual strength in section modulus and ultimate strength under different damage scenarios were plotted as shown in Figure 8-22.

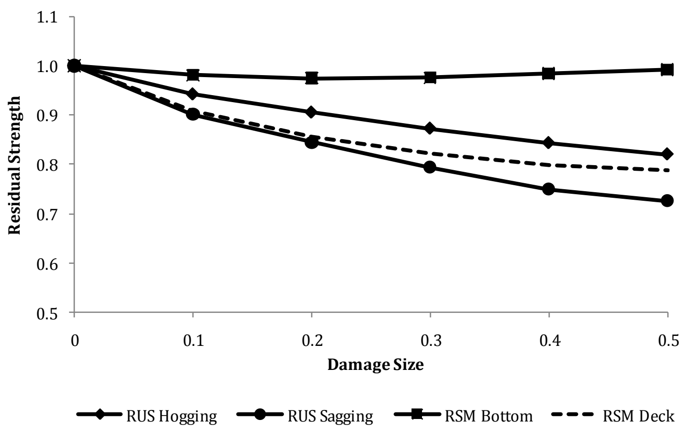


Figure 8-22 Residual Strength of ships with collision damage

The following conclusions could be drawn from Figure 8-22;

- The hull girder ultimate strength in sagging is the most sensitive indicator of the side damage followed by section modulus to deck. Section modulus to bottom is the least sensitive. Hull girder ultimate strength in hogging fall in between the extremes.
- Hull girder exhibits less reserve in ultimate strength in sagging than the deck section modulus. On the other hand, the hull girder shows more reserve in the section modulus to the bottom than in the hull girder ultimate strength for hogging.

8.5.2.3 Simplified Equation for Residual Strength Calculation following Side Damage

In this section a simplified equations dependent only on the section modulus and yield strength of the ship is derived for calculating the residual strength of ship with collision damage.

To obtain the simple equation first the yield bending moment is calculated, the results are shown in Table 8-8.

Table 8-13 Yield Bending Capacity of Ships in different damage scenarios

Ship	Damage Scenario	Damage Size (b/B)	M_{Yield} Hogging (GN.m)	M_{Yield} Sagging (GN.m)
DHT310	Intact	0	30.89	22.07
	10% Damage	0.1	30.30	20.28
	20% Damage	0.2	30.10	18.93
	30% Damage	0.3	30.16	18.02
	40% Damage	0.4	30.38	17.54
	50% Damage	0.5	30.65	17.49
DHT275	Intact	0	16.86	13.77
	10% Damage	0.1	16.55	12.65
	20% Damage	0.2	16.43	11.81
	30% Damage	0.3	16.47	11.24
	40% Damage	0.4	16.59	10.94
	50% Damage	0.5	16.74	10.91
DHT264	Intact	0	15.31	12.47
	10% Damage	0.1	15.02	11.46
	20% Damage	0.2	14.92	10.70
	30% Damage	0.3	14.95	10.18
	40% Damage	0.4	15.06	9.91
	50% Damage	0.5	15.20	9.88
DHT233	Intact	0	10.72	7.99
	10% Damage	0.1	10.52	7.34
	20% Damage	0.2	10.45	6.85
	30% Damage	0.3	10.47	6.52
	40% Damage	0.4	10.55	6.35
	50% Damage	0.5	10.64	6.33

Based on the results from

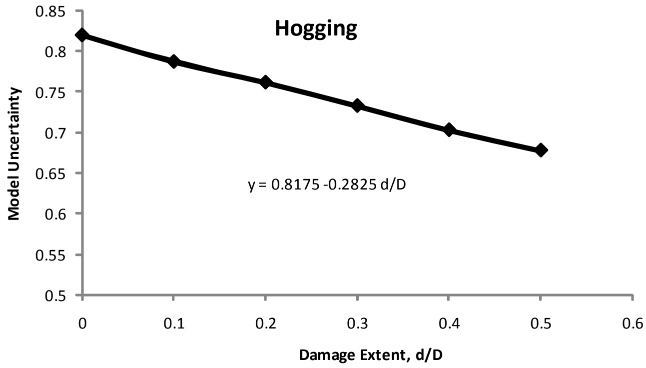
Table 8-12 and Table 8-13 the model uncertainty is calculated, which is the ratio between the ultimate bending capacity over the yield capacity. Table 8-14 shows the calculated model uncertainty for collision accident.

Table 8-14 Model Uncertainty of Bending Moment

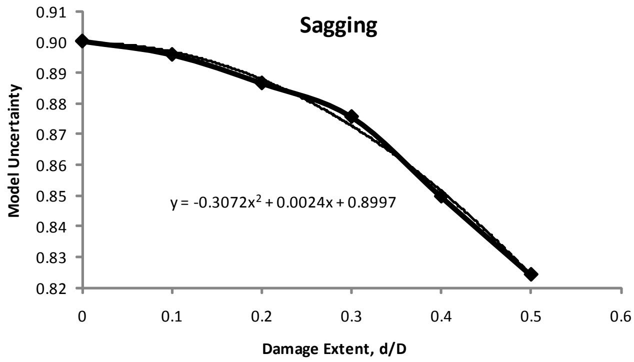
Ship	Damage Scenario	Damage Size (b/B)	Model Uncertainty Factor Hogging	Model Uncertainty Factor Sagging
DHT310	Intact	0	0.81	0.93
	10% Damage	0.1	0.78	0.92
	20% Damage	0.2	0.75	0.91
	30% Damage	0.3	0.72	0.90
	40% Damage	0.4	0.69	0.84
	50% Damage	0.5	0.66	0.80
DHT275	Intact	0	0.83	0.89
	10% Damage	0.1	0.81	0.89
	20% Damage	0.2	0.78	0.89
	30% Damage	0.3	0.75	0.87
	40% Damage	0.4	0.72	0.86
	50% Damage	0.5	0.70	0.84
DHT264	Intact	0	0.84	0.89
	10% Damage	0.1	0.79	0.84
	20% Damage	0.2	0.77	0.86
	30% Damage	0.3	0.75	0.87
	40% Damage	0.4	0.72	0.84
	50% Damage	0.5	0.70	0.82
DHT233	Intact	0	0.79	0.90
	10% Damage	0.1	0.77	0.87
	20% Damage	0.2	0.74	0.89
	30% Damage	0.3	0.71	0.86
	40% Damage	0.4	0.68	0.85
	50% Damage	0.5	0.65	0.84

It could be seen from Table 8-14 the model uncertainty follows the same trend for all ship type and hence the average of each damage scenarios was plotted as shown in Figure 8-23. From Figure 8-23(a), it could be seen that the model uncertainty for hogging decreases with damage size and follows a linear trend and hence a linear curve fitting is used to derive the equation, whereas from Figure 8-23(b) it can be seen that the model uncertainty in sagging first decreases then increases with increase in damage extent and then decreases steadily hence a polynomial function is used to derive the equation.

Since the model uncertainty shows how much the yield moment deviates from the ultimate moment capacity the product of the uncertainty and the yield moment will give a result close to the actual ultimate strength of the ship. The product of equations in Equation 8-14 and Equation 8-15 gives the simple equation to determine the ultimate strengths in hogging and sagging.



(a)



(b)

Figure 8-23 Model Uncertainty in (a) Hogging (b) Sagging

$$M_{Ult}, Hog = \left[0.82 - 0.5\frac{d}{D} + 0.72\frac{d}{D}^2 - 0.7\frac{d}{D}^3 + 0.16\frac{d}{D}^4\right] SM_{Bottom} \times \sigma_y \qquad \text{Equation 8-14}$$

$$M_{Ult}, Sag = \left[0.9 - 0.82\frac{d}{D} + 0.58\frac{d}{D}^2 - 0.28\frac{d}{D}^3 - 0.3\frac{d}{D}^4\right] SM_{Deck} \times \sigma_y \qquad \text{Equation 8-15}$$

The results based on the above analytical equation are given in Table 8-15. It can be seen the percentage difference in hogging and sagging for the results based on equation and actual ultimate strength is small with maximum difference being less than ±5%.

Table 8-15 Results of ultimate strength based on analytical equation for collision

Ship	Damage Scenario	Modified Formula Hogging	Modified Formula Sagging	Percentage Difference, Hogging	Percentage Difference, Sagging
DHT310	Intact	25.22	19.87	0.36%	-2.70%
	10% Damage	23.89	17.92	0.82%	-4.42%
	20% Damage	22.89	16.77	1.05%	-3.00%
	30% Damage	22.09	15.79	1.54%	-2.47%
	40% Damage	21.41	14.90	2.35%	0.93%
	50% Damage	20.74	14.42	2.16%	2.92%
DHT275	Intact	13.77	12.40	-1.61%	0.70%
	10% Damage	13.05	11.18	-2.26%	-0.76%
	20% Damage	12.50	10.46	-2.68%	-0.75%
	30% Damage	12.06	9.85	-2.42%	0.48%
	40% Damage	11.69	9.29	-2.55%	-1.61%
	50% Damage	11.33	9.00	-3.29%	-2.08%
DHT264	Intact	12.50	11.23	-2.84%	1.68%
	10% Damage	11.85	10.12	-0.51%	4.75%
	20% Damage	11.35	9.47	-1.75%	3.60%
	30% Damage	10.95	8.92	-2.62%	0.67%
	40% Damage	10.61	8.42	-2.67%	0.95%
	50% Damage	10.28	8.15	-3.35%	0.81%
DHT233	Intact	8.76	7.19	2.79%	0.39%
	10% Damage	8.30	6.49	2.93%	1.03%
	20% Damage	7.95	6.07	3.10%	0.03%
	30% Damage	7.67	5.72	3.73%	1.78%
	40% Damage	7.43	5.39	4.14%	-0.39%
	50% Damage	7.20	5.22	4.18%	-1.41%

8.5.3 Design Modification Factor

The capacity in hogging is significantly higher than that in sagging. Sagging failure is governed by the ultimate capacity of the deck hence in this section a design modification factor is applied to the deck to analyse to what degree strengthening the deck could help in improving the ultimate strength in sagging. This factor is to be multiplied by the original deck plating thickness. When the modification factor is bigger than 1, it will result in improved ultimate strength and increase the section modulus of the midship section. If this factor is considered during the design the ship will have acceptable section modulus and strength after damage.

This study considers a DMF ranging from 0.8 to 1.5. The deck plating is increased by these values and the ultimate strength is calculated for each case.

8.5.3.1 DMF Intact Ship

Table 8-16 shows the results of strengthening the deck on the section modulus and ultimate strength.

Table 8-16 DMF for sample ships in intact condition

Ship Type	Parameter	DMF							
		0.8	**0.9**	**1**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
DHT310	SM Deck	64.57	67.32	70.07	72.80	75.57	78.31	81.05	83.79
	SM Bottom	95.51	96.82	98.06	99.23	100.34	101.39	102.39	103.35
	M_{ult} Hogging	23.87	24.40	25.13	25.44	25.93	26.42	26.89	27.35
	M_{ult} Sagging	18.39	19.36	20.42	21.27	22.20	23.14	24.09	25.02
DHT275	SM Deck	39.08	41.40	43.71	46.03	48.35	50.68	53.01	55.34
	SM Bottom	51.96	52.78	53.54	54.24	54.89	55.49	56.06	56.59
	M_{ult} Hogging	13.19	13.60	13.99	14.37	14.73	15.06	15.38	15.69
	M_{ult} Sagging	10.69	11.48	12.31	13.17	14.03	14.82	15.59	16.32
DHT264	SM Deck	35.62	37.60	39.59	41.57	43.56	45.55	47.55	49.54
	SM Bottom	47.15	47.91	48.62	49.27	49.88	50.46	51.00	51.50
	M_{ult} Hogging	12.15	12.52	12.87	13.19	13.51	13.81	14.10	14.38
	M_{ult} Sagging	9.76	10.38	11.04	11.74	12.45	13.13	13.79	14.44
DHT233	SM Deck	22.93	24.27	25.37	26.95	28.29	29.63	30.96	32.30
	SM Bottom	33.16	33.66	34.04	34.55	34.94	35.31	35.65	35.97
	M_{ult} Hogging	8.05	8.31	8.52	8.81	9.03	9.24	9.44	9.62
	M_{ult} Sagging	6.28	6.75	7.17	7.77	8.31	8.85	9.37	9.84

The relation of DMF to the section modulus and ultimate strength is almost linear for all the ships. The ratio of the strengthened value of section modulus and ultimate strength were normalised with their actual values.

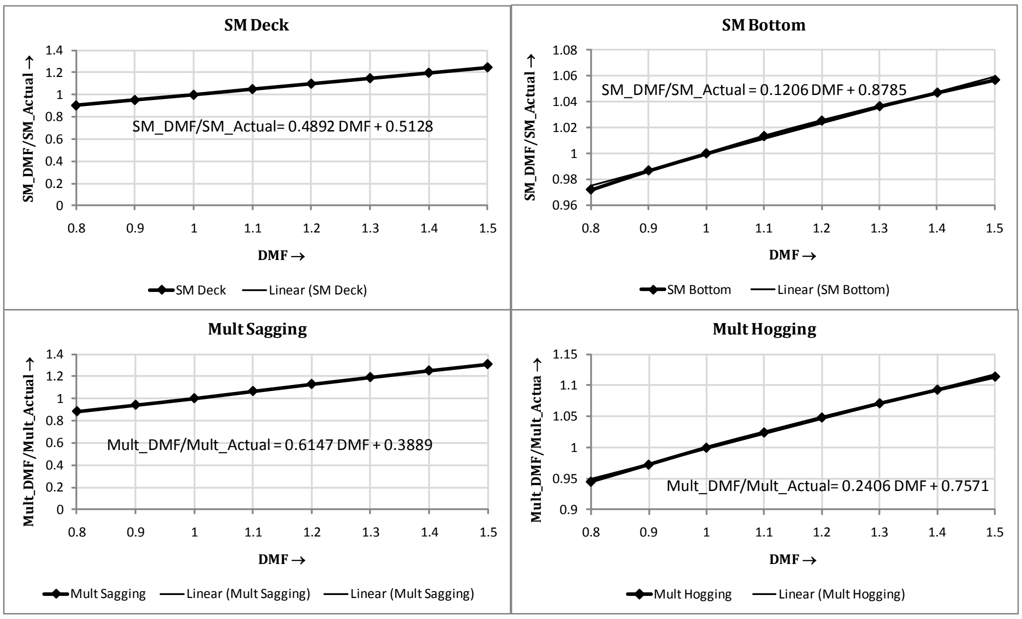


Figure 8-24 DMF versus Section and Ultimate strength

Since the ratio for all the sample ship is almost equal, their average was taken and this result was plotted in Figure 8-24 with an equation which gives the relation between the required increase in section modulus or ultimate strength and the corresponding increase in deck plating.

8.5.3.2 DMF Damaged Ships

The Residual Strength Index is determined for all the cases, comparing the strength after damage to the intact, to compare the results of both original and strengthened sections. The purpose of this comparison is to study how the strengthened section will behave if it is subjected to the same damage, since the objective of strengthening the section is to achieve scantlings which when damaged the section will still have sufficient strength to satisfy the minimum requirement.

Table 8-17 and Table 8-18 shows the RIS for the strengthened section for all the sample ships for both bottom and side damages. It is clear that for bottom damage the strengthening of deck leads to only a very marginal improvement in the strength whereas for side damage the deck strengthening leads to higher strength in both hogging and sagging.

Table 8-17 RSI of strengthened sections under bottom damage

Ship Type	Damage Extent (b/B)	DMF							
		1		1.1		1.2		1.3	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
DHT310	10% Damage	0.94	1.00	0.96	1.03	0.98	1.08	1.00	1.12
	20% Damage	0.89	0.98	0.91	1.01	0.93	1.05	0.95	1.09
	30% Damage	0.84	0.95	0.86	0.98	0.88	1.02	0.89	1.06
	40% Damage	0.79	0.92	0.81	0.95	0.83	0.99	0.84	1.03
	50% Damage	0.73	0.87	0.75	0.90	0.76	0.94	0.78	0.98
DHT275	10% Damage	0.94	0.99	0.97	1.05	0.99	1.12	1.01	1.18
	20% Damage	0.88	0.97	0.91	1.03	0.93	1.09	0.95	1.15
	30% Damage	0.84	0.94	0.86	1.00	0.88	1.06	0.89	1.11
	40% Damage	0.78	0.92	0.80	0.97	0.81	1.02	0.83	1.07
	50% Damage	0.71	0.87	0.73	0.92	0.74	0.97	0.75	1.01
DHT264	10% Damage	0.95	0.99	0.98	1.05	1.00	1.11	1.02	1.17
	20% Damage	0.90	0.97	0.92	1.02	0.94	1.08	0.96	1.14
	30% Damage	0.85	0.94	0.87	1.00	0.89	1.05	0.91	1.11
	40% Damage	0.79	0.91	0.81	0.96	0.83	1.01	0.84	1.06
	50% Damage	0.73	0.87	0.75	0.92	0.76	0.97	0.78	1.01
DHT233	10% Damage	0.95	0.99	0.97	1.05	0.99	1.11	1.01	1.17
	20% Damage	0.88	0.98	0.90	1.03	0.92	1.09	0.94	1.14
	30% Damage	0.83	0.96	0.85	1.01	0.86	1.06	0.88	1.11
	40% Damage	0.76	0.93	0.78	0.98	0.79	1.03	0.80	1.07
	50% Damage	0.69	0.89	0.70	0.93	0.70	0.97	0.71	1.01

Table 8-18 RSI of strengthened sections under side damage

Ship Type	Damage Extent (d/D)	DMF							
		1		1.1		1.2		1.3	
		Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
DHT310	10% Damage	0.94	0.92	0.97	0.96	1.00	1.01	1.02	1.06
	20% Damage	0.90	0.85	0.93	0.98	0.95	0.92	0.97	0.97
	30% Damage	0.87	0.79	0.89	0.83	0.92	0.87	0.94	0.92
	40% Damage	0.83	0.72	0.86	0.76	0.88	0.81	0.91	0.85
	50% Damage	0.81	0.69	0.83	0.73	0.86	0.78	0.89	0.83
DHT275	10% Damage	0.95	0.92	0.98	0.98	1.00	1.05	1.03	1.11
	20% Damage	0.92	0.86	1.03	1.03	0.95	1.10	1.09	1.18
	30% Damage	0.88	0.80	1.00	0.96	0.92	1.04	1.06	1.11
	40% Damage	0.86	0.77	0.97	0.93	0.91	1.01	1.04	1.08
	50% Damage	0.84	0.75	0.95	0.91	0.88	0.98	1.03	1.06
DHT264	10% Damage	0.93	0.88	0.95	0.93	0.98	1.00	1.01	1.06
	20% Damage	0.90	0.83	0.93	0.89	0.96	0.95	0.98	1.01
	30% Damage	0.87	0.80	0.91	0.86	0.94	0.92	0.96	0.99
	40% Damage	0.85	0.76	0.88	0.82	0.91	0.88	0.94	0.95
	50% Damage	0.83	0.73	0.86	0.80	0.90	0.86	0.93	0.93
DHT233	10% Damage	0.95	0.90	0.97	0.96	1.00	1.02	1.02	1.08
	20% Damage	0.90	0.85	0.93	0.91	0.96	0.97	0.98	1.03
	30% Damage	0.87	0.78	0.90	0.85	0.93	0.91	0.95	0.97
	40% Damage	0.84	0.76	0.87	0.82	0.90	0.88	0.93	0.94
	50% Damage	0.81	0.74	0.85	0.80	0.88	0.87	0.91	0.93

8.6 Summary & Conclusion

The determination of the strength of ships in intact and damaged conditions is very essential from the viewpoint of safety and economy. In this regard, it is essential to calculate the ultimate strength of the structure to identify its true safety margin against the loads to which it is subjected. The different methods available to determine the longitudinal ultimate strength of ships were discussed along with the merits and demerits of each method. Progressive collapse method, which is used in this study to determine the ultimate strength of ships, was discussed in detail.

In order to determine the effect of age related structural degradation due to corrosion, the ultimate strength of sample ships in intact condition were determined using two scantlings, one corresponding to new build ships(gross scantlings) and one using gross scantling -50% corrosion deduction (t_{net50} scantling) as defined in the IACS new common structural rules. It was seen that the results of t_{net50} scantlings compared to gross scantlings show almost 10%

losses in section modulus and approximately 5% reduction in ultimate strength capacity.

The ultimate strength of the ships in sagging condition is lower compared to that in hogging condition. This is due to the fact that during the sagging condition the elements above the neutral axis undergo compression and these elements contribute less to the total strength of the ship structure, since the bottom elements are stockier compared to the deck elements. The residual strength of the ship structure in damage scenarios have shown significant decrease compared to that in the intact scenarios, since due to the collision or grounding the damaged elements remain ineffective to contribute in the overall global strength. It is observed that the residual strength of ship after damage is a function of damage extent, the bigger the damage the lesser the strength. To determine the effect of location of damage on the strength reduction, different damage scenarios at the side and bottom were considered. It was seen in grounding damages that even though the strength reduction was more when the keel is damage the sensitivity of bottom damage on the transverse location is not as significant compared to collision damage were the ships shows less strength when the upper part is damaged compared to other damage location down from the upper part.

The loss in section modulus due to damage is calculated to check if after damage the ship will have section modulus less than the minimum value defined by the rule.

Simplified equations for calculating the ultimate strength of ship under different damage scenarios dependent only on the section modulus and yield strength of the ship were derived. These equations give comparable results with the results using MARS 2000 with maximum ±5% difference. These equations are later used in the reliability analysis which could help do determine the probability of failure under different damage scenarios.

Finally, a design modification factor was applied to the deck to compensate for the loss in the ultimate strength due to damage. A simple equation is given to estimate the required DMF as a function of the loss in ultimate strength.

Chapter 9. Reliability Analysis of Intact and Damaged Ships

9.1 Introduction

This chapter presents the reliability assessment of ships with the focus on hull girder ultimate limit state of intact and damaged ships. For the damaged ships different loading scenarios are considered to simulate the loading condition expected to act on the ship at sea following an accident. Followed by which sensitivity analysis to determine important design variables from the limit state function and finally, partial safety factors for code based design corresponding to a set target reliability are determined.

9.2 Need and Measure of Reliability Analysis

What is reliability? As far as the structural integrity is being concerned, most of the parameters related to load and resistance are random quantities. The primary task of planning and structural design is to ensure satisfactory performance, i.e., to ensure that the capacity or resistance is greater than demand or load during the system's useful life. In view of the uncertainties in the problem, satisfactory performance cannot be absolutely assured. Instead, assurance can only be made in terms of the probability of success in satisfying some performance criterion. In engineering terminology, this probabilistic assurance of performance is referred to as reliability. Reliability is the compliment of the failure probability and is a rational measure of safety.

Need for reliability: The traditional approach of considering the uncertain parameters to be deterministic and accounted for the uncertainties through the use of empirical safety factors derived based on the past experience do not absolutely guarantee the adequate level of safety or satisfactory performance. These safety factors do not provide any information on the influence the different parameters of the system have on safety. The engineering design is basically a trade-off between maximising safety levels and minimising cost. The above mentioned deterministic safety factors do not provide adequate information to achieve optimal use of the available resources to maximise safety. On the other hand, probabilistic analysis brings rationality to the consideration of uncertainty in design by incorporating the experience and expertise in determining the uncertainties and hence provides the required information for optimum design. This capability of reliability analysis is accepted and appended in various codes like American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRDF) (1986, 1994) specifications, European and Canadian structural design specifications etc.

Measures of reliability: Reliability is the probability of successful performance associated with a particular performance criterion. The commonly used term for the measure of reliability is the 'probability of failure' and is the converse of reliability. An engineering system will have several components and performance criteria. The reliability or probability of failure should be considered for the individual components against all the performance criteria. Apart from that, overall system reliability also comes into picture based on the series or parallel arrangement of these components.

A measure of reliability in the context of design specification is the safety factor, whose value provides a qualitative measure of safety. The nominally observed value of load (service load) is multiplied with the safety factor known as the load factor which is greater than 1 to obtain the design load. The nominal value of the resistance of the system is multiplied by safety factor known as the resistance factor which is less than 1 to obtain the allowable resistance.

For practical structures and performance criteria, the computation of probability of failure is difficult due to various reasons. A first-order estimate of the minimum distance from the mean point to the failure surface is used in the probabilistic design specifications as the reliability index or safety index denoted by β.

9.3 Uncertainties in Reliability Assessment

Reliability analysis requires information about uncertainties in the system. There are different types of uncertainty in engineering systems, and each type of uncertainty requires a different approach for data collection and use in the reliability evaluation. In a broad sense, uncertainties in a system come from cognitive (qualitative) and no cognitive (quantitative) sources

9.3.1 Quantitative (Objective) Sources of Uncertainty

Quantitative sources of uncertainty or randomness can be classified into three types for discussion purposes.

- The first source is the inherent randomness in all physical observation. That is, repeated measurements of the same physical quantity do not yield the same value, due to numerous fluctuations in the environment, test procedure, instruments, observer, and so on. This may be referred to as inherent uncertainty. The engineer tries to address this type uncertainty by collecting a large number of observations. This provides good information about the variability of measured quantity, and leads to high confidence in the value used in the design. However, the number of observations that can be collected is limited by the availability of resources such as money and time.
- The second source of uncertainty is known as statistical uncertainty. In this case, one does not have precise information about the variability of the physical quantity of interest due to limited data. The information on variability will vary, depending on the number of samples used. Therefore, quantitative measures of confidence based on the number of data are added to the reliability evaluation.
- A third type of uncertainty is referred to as modelling uncertainty. System analysis models are only approximate representations of system behaviour. Computational models strive to capture the essential

characteristics of system behaviour through idealized mathematical relationships or numerical procedures, such as finite element methods for structural analysis. In the process, some of the minor determinants of system behaviour are ignored, leading to differences between computational prediction and actual behaviour. Probabilistic methodology is able to include modelling uncertainty. Past experience on the difference between a computational model and actual behaviour can be used to develop a statistical description of modelling error, to be included as an additional variable in the reliability analysis.

These three sources of uncertainty can be illustrated with a simple example. Suppose the wind load or pressure acting on building needs to be estimates (in units of pounds per square inch). Recorded wind speed data, in miles per hour, can be collected for the site. Wind speed cannot be predicted with certainty; thus, it is inherently random. Its statistical uncertainty can be estimated by considering past observations, and more data lead to a better estimate. However, the statistical information on wind speed needs to be converted to wind pressure. Bernoulli's theorem is commonly used for this purpose. This introduces another source of uncertainty, known as modelling uncertainty.

9.3.2 Qualitative (Subjective) sources of uncertainty

Qualitative sources of uncertainty relate to the vagueness of the problem arising from intellectual abstractions of reality. They may come from (1) the definitions of certain parameters, such as structural performance (failure or survival), quality , deterioration, skill and experience of construction workers and engineers, environmental impact of projects and conditions of existing structures; (2) other human factors; and (3) definitions of the interrelationships among the parameters of the problems, especially for complex systems

9.4 Generalised Reliability Problem

In general, reliability analysis starts with the identification of basic variables to define the load and strength parameters. Mathematically, this relationship is described as

$$Z = g(X_1, X_2 \ldots., X_n) \qquad \text{Equation 9-1}$$

The failure of the limit state of interest can then be defined as $Z = 0$, which defines the boundary between the safe and unsafe regions and it also represents the state beyond which the structure fail to fulfil the function for which it was designed. A limit state can be an implicit or explicit function of the basic random variables and it can be in simple or complicated form.

From Equation 9-1 it could be seen that failure occurs when Z < 0. Therefore the probability of failure, P_f, is given by the integral

$$P_f = \int \ldots.. \int_{g(\ \ )<0} f_X\,(x_1, x_2 \ldots, x_n) dx_1 dx_2 \ldots..dx_n \qquad \text{Equation 9-2}$$

in which $f_X(x_1, x_2 \ldots, x_n)$ is the joint probability density function for the basic random variables $X_1, X_2 \ldots., X_n$ and the integration is performed over the failure region, that is g( ) < 0. The computation of P_f by Equation 1-2 is called the *full distributional approach* and is the fundamental equation of reliability analysis.

The solution of Equation 9-2 can be performed in the following ways:

- direct integration (possible only in some special cases)
- simulation methods, such as using Monte Carlo simulation, and
- Analytical approximation by simplifying the integral in Equation 9-2 is another method of solving obtaining the failure probability. In which the probability density function $f_x(\ )$ in the integrand will be simplified. There are two methods which can be used for this purpose which are as follows:

First-order reliability methods (FORM): FORM can be used to evaluate Equation 1-2 when the limit state function is a linear function of uncorrelated normal variables or when the nonlinear limit state function is represented by a first-order (linear) approximation with equivalent normal variables.

Second-order reliability methods (SORM): SORM can for nonlinear limit state function, including a linear limit state function with correlated non-normal variables, by a second-order representation.

9.5 Procedure of Reliability Analysis of Hull Girders

In general, the objective in structural design is to ensure that the strength of structure or the system is higher than the loads to which the system can be exposed. The problem is to account for the uncertainty associated with quantification of the load or the strength of the structure. The uncertainty stems from physical uncertainties (natural loads and materials), statistical uncertainty (sparse data) and model uncertainty. The overall objective of structural reliability methods is to quantify these uncertainties to provide a better basis for decision-making regarding the dimensions of the structure or with respect to maintenance issues.

In general, for calculating structural reliability, the following procedure is suggested.

- Establish target reliability, i.e. decision model
- Identify all possible and significant failure modes of the structure or operation under consideration.
- Formulate failure criteria and establish a relevant failure limit state function for each of mode of failure.
- Choose and identify stochastic variables and parameters for each failure mode of the structure or operation under consideration.

- Calculate the reliability or failure probability of the structure of each failure mode of the structure or operation under consideration.
- Assess the structure reliability against the given target reliability.

  A design is safe if

  $\beta > \beta_0$

  where,

  β is the safety index as estimated from analysis

  β_0 is the target reliability index
- Repeat the above steps as required after changes to relevant design parameters
- Document to the structure design.

9.6 Target Reliability

Target reliability is a standard that has to be met in design or in service in order to ensure that certain safety levels are achieved. A Reliability analysis can be used to verify that such target reliability is achieved for a structure or structural element. One of the difficulties in this context is that the uncertainties included in a structural reliability analysis will deviate from those encountered in real life.

The methods to select the target safeties and reliability can be categorised into the following three groups:

1. Guesstimation: An appropriate target value is selected based on recommendations from regulatory bodies or professionals on the basis of prior experience. This method can be employed for new types of structures for which a statistical database on past failures does not exist.
2. Analysis of existing design rules: The level of risk one has traditionally lived with is estimated by calculating the reliability that is implicit in existing design rules that have successful. This method is often used for revision of existing design rules, particularly from a traditional experience-based format to a reliability based format.

3. Economic value analysis: The target value of safety and reliability is determined so as to optimise the total expected costs during the life of the structure.

Figure 9-1 shows the reliability indices of some types of ships based on data that have been obtained by different investigators using different calculation methods, as a function of the year of publication Paik *et al* (2001).

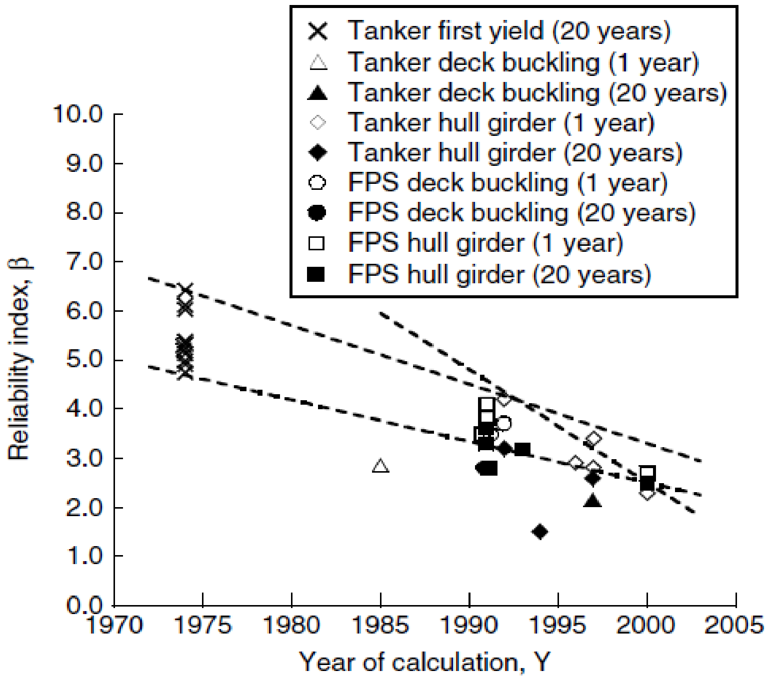


Figure 9-1 Variation of the calculated notional reliability indices over the passage of the years for ships from 1974 to 2000 (FPS = floating, production, and storage unit).

It is seen from Figure 9-1 that the calculated reliability index has decreased for the assessments conducted in more recent years. The trend shown in Figure 9.1 does not necessarily mean that vessels considered in more recent years are becoming less reliable, rather this decrease is because the ship structure design has become more efficient mainly due to the availability of imporved and advanced technologies.

The higher notional value of β obtained by Mansour (1974) is mainly a consequence of obtaining the probability of failure under a wave load criterion that is different from, and less than, the lifetime extreme load. Mansour *et* al (1997) made further improvement in to the reliability assessment by applying unified calculation procedures that are applicable to wave load criteria ranging from a mild storm to the most severe during a vessel's life. Also, many early pioneering calculations typically used 'first yield' as the failure criterion.

The first-yield criterion ignores loss of plate effectiveness due to buckling which lead inaccurate location of neutral axis of a ship's hull girder during the actual ultimate failure process, which may results in somewhat lower levels of stress being determined for the compression region of the hull girder in addition to the basic panel strength being too high in some cases, implying a higher predicted hull girder bending strength and similarly higher reliability when compared with a reliability based on a more refined prediction of ultimate hull girder bending strength.

Many of the prior studies ignore age-related degradation effects, which will decrease the β values further in comparative terms. Even today's calculations result in reliability indices are not anything other than notional and comparative, mostly because of the uncertainties in the loads involved, and this situation is expected to continue into the foreseeable future. We can, however, improve the value of comparative and notional reliability measures further by appropriately taking advantage of continuing advances in load prediction and ultimate strength assessment procedures to higher levels of refinement, while also considering age-dependent strength degradation and other types of structural damage considered.

It is seen from Figure 9-1 that the β values determined in 1991 average around 3.5, whereas those calculated in 2000 average around 2.5. Based on the above varied results, and for purposes of use with evolving and recent (advanced) methodologies for ultimate hull girder strength calculations, it is considered that $\beta = 2.5$ may be a speculative but good target reliability index to aim for in respect to ultimate hull girder strength.

9.7 Loads Acting On Ship

The still water and wave bending moments acting on the ships are calculated using the International Association of Classification Societies' (IACS) recommendation as given below;

The specified maximum still water bending moment according to IACS (2007a, b), for conventional ships in a design life of 20 years, M_{sw}, is given by;

$$M_{sw} = \begin{cases} 0.01C_{wv}L^2B(11.97 - 1.9C_b), & (kNm, Hogging) \\ -0.05185C_{wv}L^2B(C_b + 0.7), & (kNm, Sagging) \end{cases} \quad \text{Equation 9-3}$$

WhereL, B and $C_b$are the rule length (in metre), moulded breadth (in metre) and block coefficient of the ship respectively.$C_{wv}$is the wave coefficient (as known in IACS Rules, since this coefficient is used in the wave load calculations as well) and is given by:

$$C_{wv} = \begin{cases} 10.75 - \left(\frac{300 - L}{100}\right)^{3/2}, & if\ 100 < L \leq 300(m) \\ 10.75, & if\ 300 < L \leq 350(m) \\ 10.75 - \left(\frac{L - 350}{150}\right)^{3/2}, & if\ L > 350(m) \end{cases} \quad \text{Equation 9-4}$$

It may be noticed that the Rule moment given by Equation 9-3 are not intended for production ships. The maximum still water bending moment for production ships should be determined on a case to case basis. According to the data presented by Moan & Jiao (1988), the maximum midship sagging and hogging moments specified in the load manual are 72.6% and 79.2 % of the corresponding Rule moment, respectively. Although these values are all below the Rule moments, the experienced maximum moments have some time exceeded the specified maximum moments in the load manual (Wang & Moan, 1996). So, the Rule moments are used as a convenient reference in this study.

Similarly, the unified formula for estimating the design wave induced vertical bending moment is according to IACS (2007a, b), for a design life of T_0=20 years is given as;

$$M_{wv} = \begin{cases} -0.11 C_{wv} L^2 B (C_b + 0.7), & kNm, Sagging \\ 0.19 C_{wv} L^2 B C_b, & kNm, Hogging \end{cases} \qquad \text{Equation 9-5}$$

This equation is based on the results of linear calculations of hull-girder wave response with non-linear correlation and the calculation formulae established by various classification societies.

The still water and wave bending moment calculated according to the Equation 9-3 and Equation 9-5 for the sample ships are given in Table 9-1.

Table 9-1 Still Water and Wave Bending Moment values for different Ship Types

Ship Type	Bending Moment	Still water bending moment, M_{sw} (GNm)	Wave bending Moment, M_{wv} (GNm)
DHT310	Hogging	6.24	9.34
	Sagging	4.72	10.02
DHT275	Hogging	3.84	5.83
	Sagging	2.93	6.22
DHT264	Hogging	3.35	5.08
	Sagging	2.56	5.42
DHT233	Hogging	2.41	3.71
	Sagging	1.86	3.94

9.8 Uncertainties in Reliability Analysis of Ship Structures

Decision based on structural reliability analysis depends on the mathematical model which is set up for the analysis by the engineer. However, if careful real life decisions are to be made, it is necessary that considerations about the uncertainty of the model itself are quantified within the model. Model uncertainty can be quantified by comparison with actual field or laboratory data collected, or using others models which shows a closer representation to our model. These so called data are, however, also representatives of model outputs, because there is some model behind any performance of data collection and data processing which is never a faultless and much less- a complete model of reality. Consistent with this view, uncertainty caused by less perfect measuring procedures is classified as model uncertainty.

The two sources for model uncertainty in structural reliability analysis are; first, the numbers of basic physical variables are limited to finite number *n,* leaving out an infinite set of parameters which are judged to be of negligible or secondary importance for the problem in hand in the model idealisation process. The second type of model uncertainty is caused by idealisation down to operational mathematical expressions. Besides this cause of pragmatic simplification, it may be due to lack of knowledge about the detailed interplay between the considered variables. For a given set of values of the neglected parameters, the lack of knowledge beyond the actual modelling of the limit state surface invites to consider the 'true' failure surface as some perturbation of the idealised limit state surface. If this perturbation is considered to be an unknown element from a set of possible perturbations, an evaluation of the uncertainty may be given as some deviations from the idealised surface in terms of entirely of perturbations. In this view, the second source of uncertainty can also be modelled probabilistically, even if the adopted probability measure should not be interpreted in the relative frequency sense.

9.8.1 Uncertainties in Ultimate Strength Calculations

Uncertainties in the ultimate strength calculation considered in this thesis are as given;

Yield Strength: If steel comes from the same mill and same batch, for a long term period the yield strength of ship structure shows an uncertainty of 7-8%. Uncertainty in ultimate strength of ship is primarily a function of uncertainty of yield strength of steel used in the ship hull. The uncertainty associated with yield strength is assumed to have a log-normal distribution with coefficient of variation equal to 0.08.

Section Modulus: The uncertainty associated with section modulus is assumed to have a log-normal distribution with coefficient of variation equal to 0.03.

Damage extend: For damaged ships the affected area is removed to calculate the residual strength after damage. The uncertainty associated with damage extend calculation is assumed to have a Normal distribution with coefficient of variation equal to 0.03.

9.8.2 Non-Linear Effects of Wave Bending Moment

According to Guedes Soares (GuedesSoares, 1999) the non-linear effects are expected to be mainly related to the non-linearity of the hydrostatic component and thus ships of fine form and with flare would be of more proof to this effect. However, Guedes Soares and Schellin (Guedes Soares*et al.* 1998) showed that even in some cases of tankers with full forms the vertical bending moments were non-linear, a result that had also been obtained for a different tanker by Jensen *et al.* (1994) using a different approach. It appears that the relatively short length and a bulbous bow in tanker is the cause for this non-linearity. As a result, when the bulb comes out of the water in large motions, the midship bending moments are increased.

Following IACS's rule, for long term prediction of loads acting on ships 2D strip theory is used. It could be argued that the 3D panel methods represents the actual wave pattern and hence gives more accurate value of maximum wave induced and still water bending moments. Generally a coefficient of non-linearity is multiplied with the values obtained through 2D strip theory to incorporate 2D method according to 3D method. Mansour *et al.* (1993, 1994) considered these non-linearities as model uncertainty factors (x_s) and predicted it to follow Normal distribution with a mean value of 1.15 and coefficient of variation 0.03.

9.8.3 Uncertainties in the Still Water & Wave Bending Moments

The calculation of wave induced loads effect are normally made with programs based on the linear strip theory that differ in the detailed way in which the hydrodynamic coefficients are calculated. The long term distributions calculated based on transfer functions obtained by the different methods have demonstrated that a large degree of uncertainty is associated with the predicted midship wave induced loads (Guedes Soares& Moan, 1991). Based on the results of a benchmarking study presented by Schellin*et al.* (1996), a random variable(X_w) is used in the reliability calcualtions to introduce the uncertainty in the wave induced load calculations. Following Paik *et al.* (2001) a Normal distribution function was assumed, with mean value of 1 and with a coefficient of variation equal to 0.15.

9.9 Limit State Function

The limit state equation corresponding to hull girder failure under vertical bending is given as;

$$g(X) = M_u - (M_{sw} + M_w) \qquad \text{Equation 9-6}$$

where, M_u is the ultimate capacity of the ship with model uncertainty factor X_u . For intact ship M_u is given in Table 8-5 (Chapter 8) and for damaged ships depending on the accident type and bending condition the equation for M_u is as shown in Table 9-2.

Table 9-2 : Equation for Ultimate capacity under different damage scenarios

Accident Type	Bending	Equation of M_u
Grounding	Hogging	$\left(0.82 - 0.39 \cdot \frac{b}{B} - 0.145 \cdot \frac{b}{B}^2\right) Z_{Bottom} \cdot \sigma_{yB}$
	Sagging	$\left(0.9 - 0.035 \cdot \frac{b}{B} - 0.41 \cdot \frac{b}{B}^2 + 0.07 \frac{b}{B}^3\right) Z_{Deck} \cdot \sigma_{yD}$
Collision	Hogging	$\left(0.82 - 0.49 \cdot \frac{d}{D} + 0.72 \cdot \frac{d}{D}^2 - 0.7 \frac{d}{D}^3 + 0.16 \frac{d}{D}^4\right) Z_{Bottom} \cdot \sigma_{yB}$
	Sagging	$\left(0.9 - 0.82 \frac{d}{D} + 0.58 \frac{d}{D}^2 - 0.28 \frac{d}{D}^3 - 0.3 \frac{d}{D}^4\right) Z_{Deck} \cdot \sigma_{yD}$

M_{sw} is the random still-water bending moment and M_w is the wave bending moment. The maximum value of the sum of still water and wave bending moment is generally less than the sum of the individual maxima that can occur at any time. The vertical load acting on the ship can be given as:

$$M_v = M_{sw} + \psi M_w \qquad \text{Equation 9-7}$$

According to Guedes Soares (1992) and Wang *et al* (1996) the load combination factor ψ normally ranges from 0.8 to 0.95. For tankers the value is considered to be 0.9. Considering the load combination factor and the uncertainties in the prediction of load and resistance, the limit state function in Equation 9-6 can be rewritten as:

$$g(X) = X_u M_u - X_{sw} M_{sw} - X_w X_s \psi M_w \qquad \text{Equation 9-8}$$

where X_{sw} is the model uncertainty factor for predicting the still water bending moment; X_w and X_s are model uncertainty factor in wave bending moment for the linear response calculation and non-linear effects respectively. All the random variables with their distribution type, mean and coefficient of variation are summarised in Table 9-3

Table 9-3 The properties of random variables for the reliability analysis of ship structures

Parameter	Description	Distribution	Mean	COV
b/B, d/D	Damage Extent	Normal	TABLE 8.8	0.03
SM_{Bottom}, SM_{Deck}	Section Modulus	Lognormal	TABLE 8.5	0.03
σ_{yB}, σ_{yD}	Yield Strength (N/mm^2)	Lognormal	315	0.08
M_{sw}	Still water Bending Moment	Normal	TABLE 9.1	0.05
M_w	Wave Bending Moment	Weibull	TABLE 9.1	0.2
X_u	Model Uncertainty in Ultimate Strength	Normal	1	0.15
X_{sw}	Model Uncertainty in Still Water Bending Moment	Normal	1	0.05
X_w	Error in Wave Bending Moment due to analysis over Prediction	Normal	0.9	0.15
X_s	Uncertainty of model that takes non linearities in to account	Normal	1.15	0.03

9.10 Results of Reliability Analysis

The reliability analysis on the sample ships is performed using CALREL; reliability analysis software developed in the University of California at Berkeley (Liu et al). First order reliability method (FORM) has been used to calculate the Reliability Index (β) and the probability of failure.

9.10.1 Intact Ship

The reliability of intact ships was calculated using the limit state function given in Equation 9-8 with M_u value at intact condition obtained in Chapter 8 and the wave induced loads and still water bending moments calculated using IACS (2007) for tankers. The results of reliability analysis based on hull girder net scantlings (t_{net50}) and gross scantling (t_{grs}) are given in Table 9-4 and Figure 9-2.

Table 9-4 Reliability Index and Probability of Failure for Intact Ships

Bending Type	Sample Ship	Reliability Index, β		Probability of Failure, P_f	
		t_{grs}	t_{net50}	t_{gross}	t_{net50}
Hogging	DHT310	4.67	4.02	1.50E-06	2.93E-05
	DHT275	4.55	3.92	2.72E-06	4.34E-05
	DHT264	4.64	3.99	1.72E-06	3.34E-05
	DHT233	4.58	3.94	2.31E-06	4.12E-05
Sagging	DHT310	3.32	2.65	4.54E-04	3.97E-03
	DHT275	3.33	2.68	4.40E-04	3.68E-03
	DHT264	3.37	2.70	3.75E-04	3.45E-03
	DHT233	3.37	2.62	3.82E-04	4.34E-03

It is seen that the reliability index decreases by almost 15% in hogging and 20% in sagging going from gross to t_{net50} scantling. Similarly, the probability of failure increases by almost 20 times in hogging and around 10 times in sagging going from gross to t_{net50} scantling.

Considering the hull girder net scantling (t_{net50}), the lowest probability of failure in hogging occurs for DHT310 (2.93E-05) and in sagging for DHT264 (3.45E-03) and the highest probability of failure in hogging occurs for DHT275 (4.34E-05) and in sagging for DHT233 (4.34E-03).

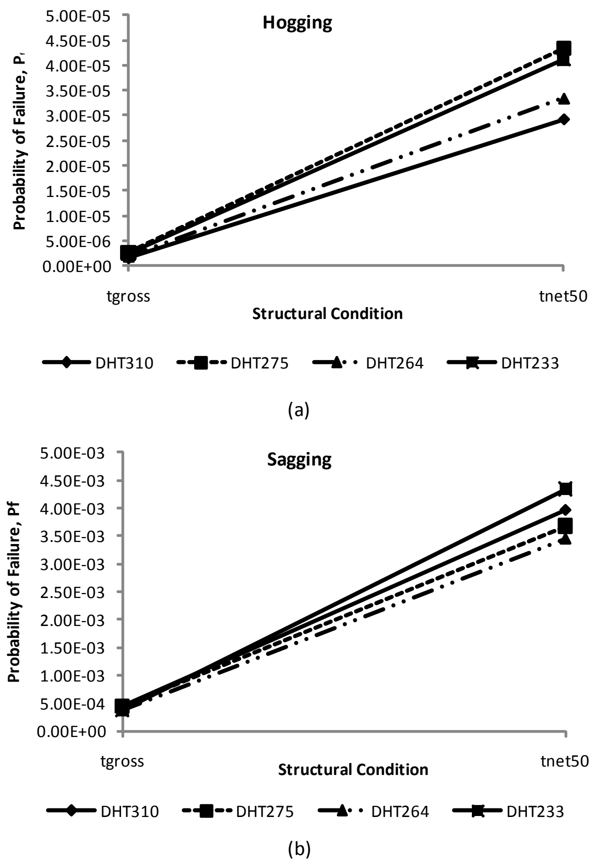


Figure 9-2 Probability of failure results for Gross and Net scantling

With t_{net50} scantlings the reliability of intact ships under hogging condition is approximately 1.5 times more than that in sagging condition, similarly the probability of failure is 5E-02 times less in hogging than in sagging which indicates that the capacity in hogging is usually significantly higher than in sagging.

9.10.2 Damaged Ship

The loss in ultimate strength after grounding and collision damages has been considered in Chapter 8. The ultimate strength used in the reliability analysis will be decreased by the RSI's value for each damage scenario.

In the damaged condition, the ship should not operate with a very high speed, and also it avoids very rough sea. Therefore, the wave-induced bending moment may be smaller than that for the normal design extreme condition. On the other hand, damage to vessel's hull may result in the ingress of water and, for fluid cargoes, cargo outflow which result in a change of the loading condition and a variation to the still water bending moment. Due to the complication of the damage situation, the equation for prediction of the external loads presented by IACS can be used to evaluate load effects on the damaged vessel, and the dynamic moment is ignored. When both the still water and wave-induced bending moments are calculated from the intact design bases, the ABS safe hull guide (ABS, 1995) suggests the following load combination depending on the damage situation;

$$M_v = k_{us} M_{sw} + k_{uw} M_w \qquad \text{Equation 9-9}$$

where k_{us} and k_{uw} are load combination coefficients for the still water and wave induced bending moments, respectively, and their values are different in different condition. These values are shown in Table 9-5.

Table 9-5 Combination factor for bending moment (ABS, 1995)

Coefficient		Condition		
		Intact	Grounding	Collision
Hogging	k_{us}	1	1.1	1
	k_{uw}	1	0.5	0.7
Sagging	k_{us}	1	0.9	1
	k_{uw}	1	0.5	0.7

For damaged ships Equation 9-8 can be rewritten considering the changed in load given by Equation 9-9 as follows.

$$g(X) = X_u M_u - k_{us} X_{sw} M_{sw} - k_{uw} X_w X_s \psi M_w \qquad \text{Equation 9-10}$$

The results of reliability analysis for tankers following grounding and collision accidents using load combination factor proposed by ABS is given in Table 9-6 and Table 9-7 respectively.

Table 9-6 Reliability and Probability of Failure for Tanker under Grounding Accidents

Ship Type	Damage Extent (b/B)	Hogging		Sagging	
		β	P_f	β	P_f
DHT310	Intact	4.02	2.93E-05	2.65	3.97E-03
	10% Damage	6.04	7.82E-10	5.42	2.99E-08
	20% Damage	5.70	5.89E-09	5.32	5.19E-08
	30% Damage	5.32	5.30E-08	5.17	1.18E-07
	40% Damage	4.87	5.68E-07	4.96	3.46E-07
	50% Damage	4.34	7.09E-06	4.70	1.30E-06
DHT275	Intact	3.92	4.34E-05	2.68	3.68E-03
	10% Damage	5.83	2.72E-09	5.44	2.60E-08
	20% Damage	5.49	1.98E-08	5.35	4.51E-08
	30% Damage	5.10	1.70E-07	5.19	1.03E-07
	40% Damage	4.64	1.72E-06	4.99	3.04E-07
	50% Damage	4.11	1.98E-05	4.73	1.14E-06
DHT264	Intact	3.99	3.34E-05	2.70	3.45E-03
	10% Damage	5.93	1.53E-09	5.48	2.15E-08
	20% Damage	5.59	1.14E-08	5.38	3.74E-08
	30% Damage	5.20	1.00E-07	5.23	8.54E-08
	40% Damage	4.75	1.04E-06	5.02	2.53E-07
	50% Damage	4.21	1.25E-05	4.76	9.59E-07
DHT233	Intact	3.94	4.12E-05	2.62	4.34E-03
	10% Damage	5.87	2.17E-09	5.36	4.09E-08
	20% Damage	5.53	1.59E-08	5.26	7.09E-08
	30% Damage	5.14	1.38E-07	5.11	1.61E-07
	40% Damage	4.68	1.41E-06	4.90	4.70E-07
	50% Damage	4.15	1.65E-05	4.64	1.75E-06

It is seen from the above results that the reliability of ships following bottom damage is more than that in intact condition for all the damage scenarios both in hogging and sagging.

Table 9-7 Reliability and Probability of Failure for tanker under collision Accidents

Ship Type	Damage Extent (d/D)	Hogging		Sagging	
		β	P_f	β	P_f
DHT310	Intact	4.02	2.93E-05	2.65	3.97E-03
	10% Damage	4.83	6.83E-07	3.20	6.90E-04
	20% Damage	4.58	2.35E-06	2.81	2.45E-03
	30% Damage	4.36	6.42E-06	2.46	6.90E-03
	40% Damage	4.15	1.63E-05	2.12	1.68E-02
	50% Damage	3.92	4.51E-05	1.94	2.62E-02
DHT275	Intact	3.92	4.34E-05	2.68	3.68E-03
	10% Damage	4.70	1.29E-06	3.22	6.32E-04
	20% Damage	4.45	4.37E-06	2.84	2.27E-03
	30% Damage	4.23	1.17E-05	2.49	6.43E-03
	40% Damage	4.02	2.93E-05	2.15	1.58E-02
	50% Damage	3.78	7.96E-05	1.96	2.48E-02
DHT264	Intact	3.99	3.34E-05	2.70	3.45E-03
	10% Damage	4.77	9.07E-07	3.25	5.70E-04
	20% Damage	4.52	3.11E-06	2.87	2.06E-03
	30% Damage	4.30	8.44E-06	2.52	5.87E-03
	40% Damage	4.09	2.13E-05	2.18	1.45E-02
	50% Damage	3.85	5.86E-05	2.00	2.29E-02
DHT233	Intact	3.94	4.12E-05	2.62	4.34E-03
	10% Damage	4.73	1.13E-06	3.15	8.12E-04
	20% Damage	4.47	3.85E-06	2.76	2.86E-03
	30% Damage	4.26	1.04E-05	2.41	7.98E-03
	40% Damage	4.05	2.60E-05	2.07	1.93E-02
	50% Damage	3.81	7.09E-05	1.88	2.99E-02

For side damage also the reliability index increases following an accident but, as the damage size increases the reliability index drops and following a 50% damage to the side the reliability in hogging drops below the intact value and in sagging the reliability index drops below the intact value after a 30% damage and following a 50% damage it drops below the target reliability (a drop of almost 30% of the intact reliability).

The increase in reliability index following an accident is because, according to the load combination factor proposed by ABS, the reduction in load acting on the ship is more compared to the reduction in the strength of the structure due to damage.

The author strongly feels that this may not be the case in real life accidents. But it should be noted that the present method shows an approach to quantify the reliability index and probability of failure, which is very much a function of the actual still water and wave loads acting on the ship during damage scenarios. Currently ABS is the only classification society, which has studied the load combination factors for the damage scenarios. However, the author fells that more research needs to be done in this area to evaluate more accurate values of these factors and hence a detailed study is carried out considering the variation of SWBM and WBM under different damage scenarios.

In this section, a detailed study is carried out on the sample ships by changing the k_{sw} and k_w values under different damage scenarios. This result is compared with the intact and target reliabilities. Table 9-8 and Table 9-9 shows the results of reliability analysis for DHT310 following grounding and collision accidents. The values in table are normalised with respect to the intact values. The normalised values of reliability index for other ships also shows similar trend. Figure 9-3 to Figure 9-6, which shows the variation of reliability under different scenarios in hogging and sagging for both grounding and collision accidents.

Table 9-8 Variation of Reliability index under different combinations of Ksw and Kw in hogging and sagging following different bottom damage scenarios.

WBM	SWBM	Intact	β Target	Damage Extent (b/B)									
				10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
				Hogging					Sagging				
	1.5	1	0.62	0.61	0.57	0.52	0.44	0.34	0.65	0.59	0.53	0.48	0.42
	1.4	1	0.62	0.64	0.61	0.55	0.48	0.38	0.68	0.62	0.56	0.51	0.45
	1.3	1	0.62	0.68	0.64	0.59	0.51	0.42	0.71	0.65	0.59	0.54	0.48
	1.2	1	0.62	0.72	0.68	0.63	0.55	0.46	0.74	0.68	0.63	0.57	0.52
	1.1	1	0.62	0.75	0.72	0.66	0.59	0.50	0.77	0.71	0.66	0.61	0.55
1	1	1	0.62	0.79	0.75	0.70	0.63	0.53	0.80	0.74	0.69	0.64	0.58
	0.9	1	0.62	0.83	0.79	0.74	0.66	0.57	0.83	0.77	0.72	0.67	0.61
	0.8	1	0.62	0.86	0.83	0.77	0.70	0.61	0.87	0.80	0.75	0.70	0.65
	0.7	1	0.62	0.90	0.86	0.81	0.74	0.65	0.90	0.84	0.78	0.74	0.68
	0.6	1	0.62	0.94	0.90	0.85	0.78	0.68	0.93	0.87	0.82	0.77	0.71
	0.5	1	0.62	0.97	0.94	0.88	0.81	0.72	0.96	0.90	0.85	0.80	0.75
	1.5	1	0.62	0.78	0.74	0.68	0.61	0.51	0.76	0.69	0.64	0.59	0.53
	1.4	1	0.62	0.82	0.78	0.72	0.65	0.55	0.79	0.73	0.67	0.62	0.56
	1.3	1	0.62	0.86	0.82	0.76	0.69	0.59	0.82	0.76	0.71	0.65	0.59
	1.2	1	0.62	0.90	0.86	0.80	0.73	0.63	0.86	0.79	0.74	0.69	0.63
	1.1	1	0.62	0.93	0.90	0.84	0.77	0.67	0.89	0.83	0.77	0.72	0.66
0.9	1	1	0.62	0.97	0.94	0.88	0.81	0.71	0.92	0.86	0.81	0.76	0.70
	0.9	1	0.62	1.01	0.98	0.92	0.85	0.75	0.96	0.89	0.84	0.79	0.73
	0.8	1	0.62	1.05	1.02	0.96	0.89	0.79	0.99	0.93	0.88	0.83	0.77
	0.7	1	0.62	1.09	1.05	1.00	0.93	0.83	1.02	0.96	0.91	0.86	0.80
	0.6	1	0.62	1.13	1.09	1.04	0.97	0.87	1.06	1.00	0.94	0.89	0.84
	0.5	1	0.62	1.17	1.13	1.08	1.01	0.92	1.09	1.03	0.98	0.93	0.87
	1.5	1	0.62	0.97	0.93	0.87	0.80	0.70	0.88	0.81	0.76	0.70	0.64
	1.4	1	0.62	1.01	0.97	0.92	0.84	0.74	0.91	0.85	0.79	0.74	0.68
	1.3	1	0.62	1.05	1.02	0.96	0.88	0.78	0.95	0.88	0.83	0.78	0.72
	1.2	1	0.62	1.10	1.06	1.00	0.92	0.83	0.98	0.92	0.87	0.81	0.75
	1.1	1	0.62	1.14	1.10	1.04	0.97	0.87	1.02	0.96	0.90	0.85	0.79
0.8	1	1	0.62	1.18	1.14	1.09	1.01	0.91	1.06	0.99	0.94	0.89	0.83
	0.9	1	0.62	1.22	1.19	1.13	1.05	0.96	1.09	1.03	0.98	0.92	0.87
	0.8	1	0.62	1.26	1.23	1.17	1.10	1.00	1.13	1.07	1.01	0.96	0.90
	0.7	1	0.62	1.31	1.27	1.21	1.14	1.05	1.16	1.10	1.05	1.00	0.94
	0.6	1	0.62	1.35	1.31	1.26	1.18	1.09	1.20	1.14	1.09	1.04	0.98
	0.5	1	0.62	1.39	1.35	1.30	1.23	1.13	1.23	1.17	1.12	1.07	1.02
	1.5	1	0.62	1.19	1.15	1.09	1.01	0.91	1.01	0.94	0.89	0.83	0.77
	1.4	1	0.62	1.23	1.19	1.13	1.05	0.95	1.05	0.98	0.93	0.87	0.81
	1.3	1	0.62	1.28	1.24	1.18	1.10	1.00	1.09	1.02	0.97	0.91	0.85
	1.2	1	0.62	1.32	1.28	1.23	1.15	1.05	1.12	1.06	1.01	0.95	0.89
	1.1	1	0.62	1.37	1.33	1.27	1.19	1.10	1.16	1.10	1.05	0.99	0.93
0,7	1	1	0.62	1.41	1.38	1.32	1.24	1.14	1.20	1.14	1.09	1.03	0.97
	0.9	1	0.62	1.46	1.42	1.37	1.29	1.19	1.24	1.18	1.13	1.07	1.02
	0.8	1	0.62	1.51	1.47	1.41	1.34	1.24	1.28	1.22	1.17	1.11	1.06
	0.7	1	0.62	1.55	1.51	1.46	1.38	1.29	1.32	1.26	1.21	1.16	1.10
	0.6	1	0.62	1.60	1.56	1.51	1.43	1.33	1.36	1.30	1.25	1.20	1.14
	0.5	1	0.62	1.64	1.61	1.55	1.48	1.38	1.40	1.34	1.29	1.24	1.18
	1.5	1	0.62	1.43	1.39	1.33	1.25	1.15	1.16	1.09	1.03	0.98	0.92
	1.4	1	0.62	1.48	1.44	1.38	1.30	1.20	1.20	1.13	1.08	1.02	0.96
	1.3	1	0.62	1.53	1.49	1.43	1.35	1.25	1.24	1.17	1.12	1.07	1.00
	1.2	1	0.62	1.58	1.54	1.48	1.40	1.30	1.28	1.22	1.16	1.11	1.05
	1.1	1	0.62	1.63	1.59	1.53	1.45	1.35	1.32	1.26	1.21	1.15	1.09
0.6	1	1	0.62	1.68	1.64	1.58	1.51	1.41	1.36	1.30	1.25	1.20	1.14
	0.9	1	0.62	1.73	1.69	1.64	1.56	1.46	1.41	1.35	1.29	1.24	1.18
	0.8	1	0.62	1.78	1.74	1.69	1.61	1.51	1.45	1.39	1.34	1.29	1.23
	0.7	1	0.62	1.83	1.79	1.74	1.66	1.57	1.49	1.43	1.38	1.33	1.27
	0.6	1	0.62	1.88	1.85	1.79	1.71	1.62	1.54	1.48	1.43	1.38	1.32
	0.5	1	0.62	1.93	1.90	1.84	1.77	1.67	1.58	1.52	1.47	1.42	1.36
	1.5	1	0.62	1.71	1.67	1.61	1.52	1.42	1.32	1.25	1.19	1.14	1.08
	1.4	1	0.62	1.76	1.72	1.66	1.58	1.48	1.36	1.30	1.24	1.19	1.13
	1.3	1	0.62	1.82	1.78	1.72	1.64	1.54	1.41	1.34	1.29	1.24	1.17
	1.2	1	0.62	1.87	1.83	1.78	1.70	1.59	1.45	1.39	1.34	1.28	1.22
	1.1	1	0.62	1.93	1.89	1.83	1.75	1.65	1.50	1.44	1.38	1.33	1.27
0.5	1	1	0.62	1.99	1.95	1.89	1.81	1.71	1.55	1.49	1.43	1.38	1.32
	0.9	1	0.62	2.04	2.00	1.95	1.87	1.77	1.59	1.53	1.48	1.43	1.37
	0.8	1	0.62	2.10	2.06	2.00	1.93	1.83	1.64	1.58	1.53	1.48	1.42
	0.7	1	0.62	2.15	2.12	2.06	1.99	1.89	1.69	1.63	1.58	1.53	1.47
	0.6	1	0.62	2.21	2.18	2.12	2.04	1.95	1.73	1.68	1.63	1.58	1.52
	0.5	1	0.62	2.27	2.23	2.18	2.10	2.01	1.78	1.73	1.68	1.63	1.57

Table 9-9 Variation of Reliability index under different combinations of Ksw and Kw in hogging and sagging following different side damage scenarios.

WBM	SWBM	Intact	β Target	Damage Extent (d/D) Hogging 10%	20%	30%	40%	50%	Sagging 10%	20%	30%	40%	50%
	1.5	1	0.62	0.65	0.59	0.53	0.48	0.42	0.40	0.26	0.14	0.01	-0.05
	1.4	1	0.62	0.68	0.62	0.56	0.51	0.45	0.44	0.30	0.17	0.05	-0.01
	1.3	1	0.62	0.71	0.65	0.59	0.54	0.48	0.48	0.34	0.21	0.09	0.03
	1.2	1	0.62	0.74	0.68	0.63	0.57	0.52	0.52	0.38	0.25	0.13	0.07
	1.1	1	0.62	0.77	0.71	0.66	0.61	0.55	0.55	0.42	0.29	0.17	0.11
1	1	1	0.62	0.80	0.74	0.69	0.64	0.58	0.59	0.45	0.33	0.21	0.15
	0.9	1	0.62	0.83	0.77	0.72	0.67	0.61	0.63	0.49	0.37	0.25	0.19
	0.8	1	0.62	0.87	0.80	0.75	0.70	0.65	0.67	0.53	0.41	0.29	0.23
	0.7	1	0.62	0.90	0.84	0.78	0.74	0.68	0.70	0.57	0.45	0.33	0.27
	0.6	1	0.62	0.93	0.87	0.82	0.77	0.71	0.74	0.61	0.49	0.37	0.31
	0.5	1	0.62	0.96	0.90	0.85	0.80	0.75	0.78	0.65	0.53	0.41	0.35
	1.5	1	0.62	0.76	0.69	0.64	0.59	0.53	0.57	0.43	0.30	0.17	0.10
	1.4	1	0.62	0.79	0.73	0.67	0.62	0.56	0.61	0.47	0.34	0.21	0.15
	1.3	1	0.62	0.82	0.76	0.71	0.65	0.59	0.65	0.51	0.38	0.26	0.19
	1.2	1	0.62	0.86	0.79	0.74	0.69	0.63	0.69	0.55	0.42	0.30	0.23
	1.1	1	0.62	0.89	0.83	0.77	0.72	0.66	0.73	0.59	0.46	0.34	0.27
0.9	1	1	0.62	0.92	0.86	0.81	0.76	0.70	0.77	0.63	0.51	0.38	0.32
	0.9	1	0.62	0.96	0.89	0.84	0.79	0.73	0.81	0.67	0.55	0.43	0.36
	0.8	1	0.62	0.99	0.93	0.88	0.83	0.77	0.85	0.71	0.59	0.47	0.40
	0.7	1	0.62	1.02	0.96	0.91	0.86	0.80	0.89	0.75	0.63	0.51	0.45
	0.6	1	0.62	1.06	1.00	0.94	0.89	0.84	0.93	0.80	0.67	0.56	0.49
	0.5	1	0.62	1.09	1.03	0.98	0.93	0.87	0.97	0.84	0.72	0.60	0.53
	1.5	1	0.62	0.88	0.81	0.76	0.70	0.64	0.76	0.61	0.48	0.35	0.28
	1.4	1	0.62	0.91	0.85	0.79	0.74	0.68	0.80	0.65	0.52	0.39	0.32
	1.3	1	0.62	0.95	0.88	0.83	0.78	0.72	0.84	0.70	0.57	0.44	0.37
	1.2	1	0.62	0.98	0.92	0.87	0.81	0.75	0.89	0.74	0.61	0.49	0.42
	1.1	1	0.62	1.02	0.96	0.90	0.85	0.79	0.93	0.79	0.66	0.53	0.46
0.8	1	1	0.62	1.06	0.99	0.94	0.89	0.83	0.97	0.83	0.70	0.58	0.51
	0.9	1	0.62	1.09	1.03	0.98	0.92	0.87	1.02	0.88	0.75	0.62	0.56
	0.8	1	0.62	1.13	1.07	1.01	0.96	0.90	1.06	0.92	0.79	0.67	0.60
	0.7	1	0.62	1.16	1.10	1.05	1.00	0.94	1.10	0.96	0.84	0.72	0.65
	0.6	1	0.62	1.20	1.14	1.09	1.04	0.98	1.15	1.01	0.88	0.76	0.70
	0.5	1	0.62	1.23	1.17	1.12	1.07	1.02	1.19	1.05	0.93	0.81	0.74
	1.5	1	0.62	1.01	0.94	0.89	0.83	0.77	0.97	0.82	0.68	0.55	0.48
	1.4	1	0.62	1.05	0.98	0.93	0.87	0.81	1.02	0.87	0.73	0.60	0.53
	1.3	1	0.62	1.09	1.02	0.97	0.91	0.85	1.06	0.92	0.78	0.65	0.58
	1.2	1	0.62	1.12	1.06	1.01	0.95	0.89	1.11	0.96	0.83	0.70	0.63
	1.1	1	0.62	1.16	1.10	1.05	0.99	0.93	1.16	1.01	0.88	0.75	0.68
0.7	1	1	0.62	1.20	1.14	1.09	1.03	0.97	1.21	1.06	0.93	0.80	0.73
	0.9	1	0.62	1.24	1.18	1.13	1.07	1.02	1.25	1.11	0.98	0.85	0.78
	0.8	1	0.62	1.28	1.22	1.17	1.11	1.06	1.30	1.16	1.03	0.90	0.83
	0.7	1	0.62	1.32	1.26	1.21	1.16	1.10	1.35	1.21	1.08	0.95	0.88
	0.6	1	0.62	1.36	1.30	1.25	1.20	1.14	1.39	1.25	1.13	1.00	0.93
	0.5	1	0.62	1.40	1.34	1.29	1.24	1.18	1.44	1.30	1.18	1.05	0.99
	1.5	1	0.62	1.16	1.09	1.03	0.98	0.92	1.21	1.06	0.92	0.78	0.71
	1.4	1	0.62	1.20	1.13	1.08	1.02	0.96	1.26	1.11	0.97	0.84	0.76
	1.3	1	0.62	1.24	1.17	1.12	1.07	1.00	1.31	1.16	1.03	0.89	0.82
	1.2	1	0.62	1.28	1.22	1.16	1.11	1.05	1.37	1.22	1.08	0.95	0.87
	1.1	1	0.62	1.32	1.26	1.21	1.15	1.09	1.42	1.27	1.13	1.00	0.93
0.6	1	1	0.62	1.36	1.30	1.25	1.20	1.14	1.47	1.32	1.19	1.06	0.99
	0.9	1	0.62	1.41	1.35	1.29	1.24	1.18	1.52	1.38	1.24	1.11	1.04
	0.8	1	0.62	1.45	1.39	1.34	1.29	1.23	1.57	1.43	1.30	1.17	1.10
	0.7	1	0.62	1.49	1.43	1.38	1.33	1.27	1.63	1.48	1.35	1.22	1.16
	0.6	1	0.62	1.54	1.48	1.43	1.38	1.32	1.68	1.54	1.41	1.28	1.21
	0.5	1	0.62	1.58	1.52	1.47	1.42	1.36	1.73	1.59	1.46	1.34	1.27
	1.5	1	0.62	1.32	1.25	1.19	1.14	1.08	1.49	1.33	1.19	1.05	0.98
	1.4	1	0.62	1.36	1.30	1.24	1.19	1.13	1.54	1.39	1.25	1.11	1.04
	1.3	1	0.62	1.41	1.34	1.29	1.24	1.17	1.60	1.45	1.31	1.17	1.10
	1.2	1	0.62	1.45	1.39	1.34	1.28	1.22	1.66	1.51	1.37	1.24	1.16
	1.1	1	0.62	1.50	1.44	1.38	1.33	1.27	1.72	1.57	1.43	1.30	1.22
0.5	1	1	0.62	1.55	1.49	1.43	1.38	1.32	1.77	1.63	1.49	1.36	1.29
	0.9	1	0.62	1.59	1.53	1.48	1.43	1.37	1.83	1.69	1.55	1.42	1.35
	0.8	1	0.62	1.64	1.58	1.53	1.48	1.42	1.89	1.75	1.61	1.48	1.41
	0.7	1	0.62	1.69	1.63	1.58	1.53	1.47	1.95	1.81	1.67	1.55	1.48
	0.6	1	0.62	1.73	1.68	1.63	1.58	1.52	2.01	1.87	1.74	1.61	1.54
	0.5	1	0.62	1.78	1.73	1.68	1.63	1.57	2.07	1.92	1.80	1.67	1.60

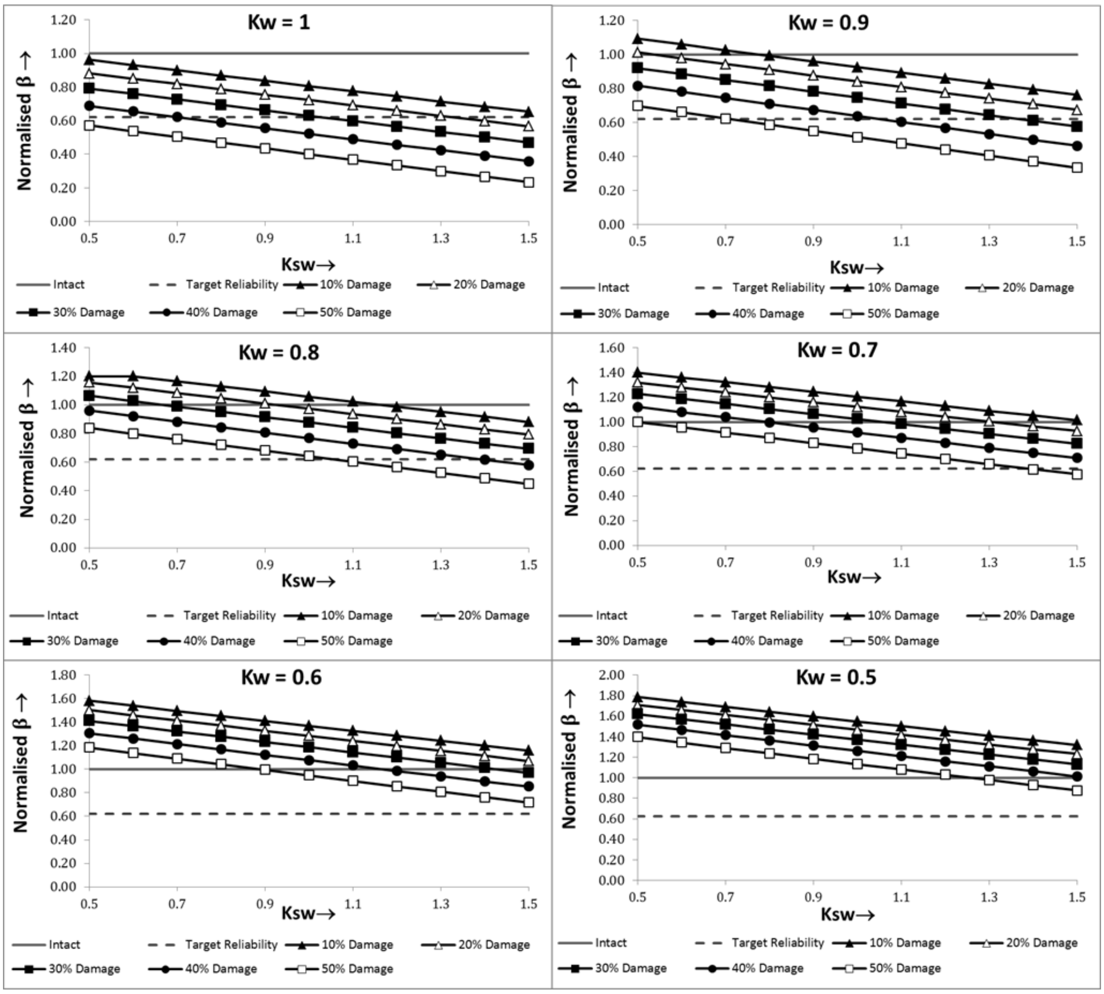


Figure 9-3 Variation of Reliability index under different combinations of Ksw and Kw in hogging following a grounding accident.

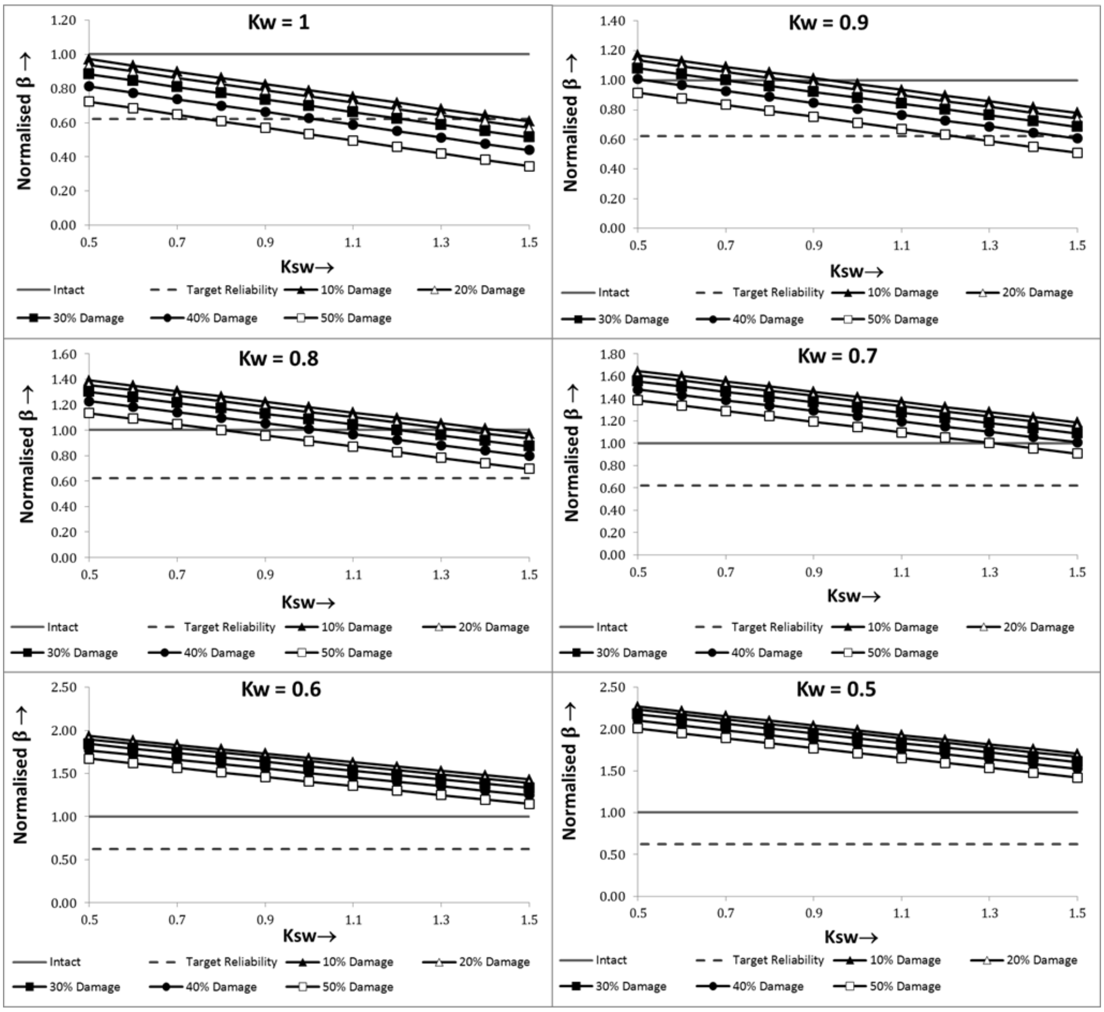


Figure 9-4 Variation of Reliability index under different combinations of Ksw and Kw in Sagging following a grounding accident.

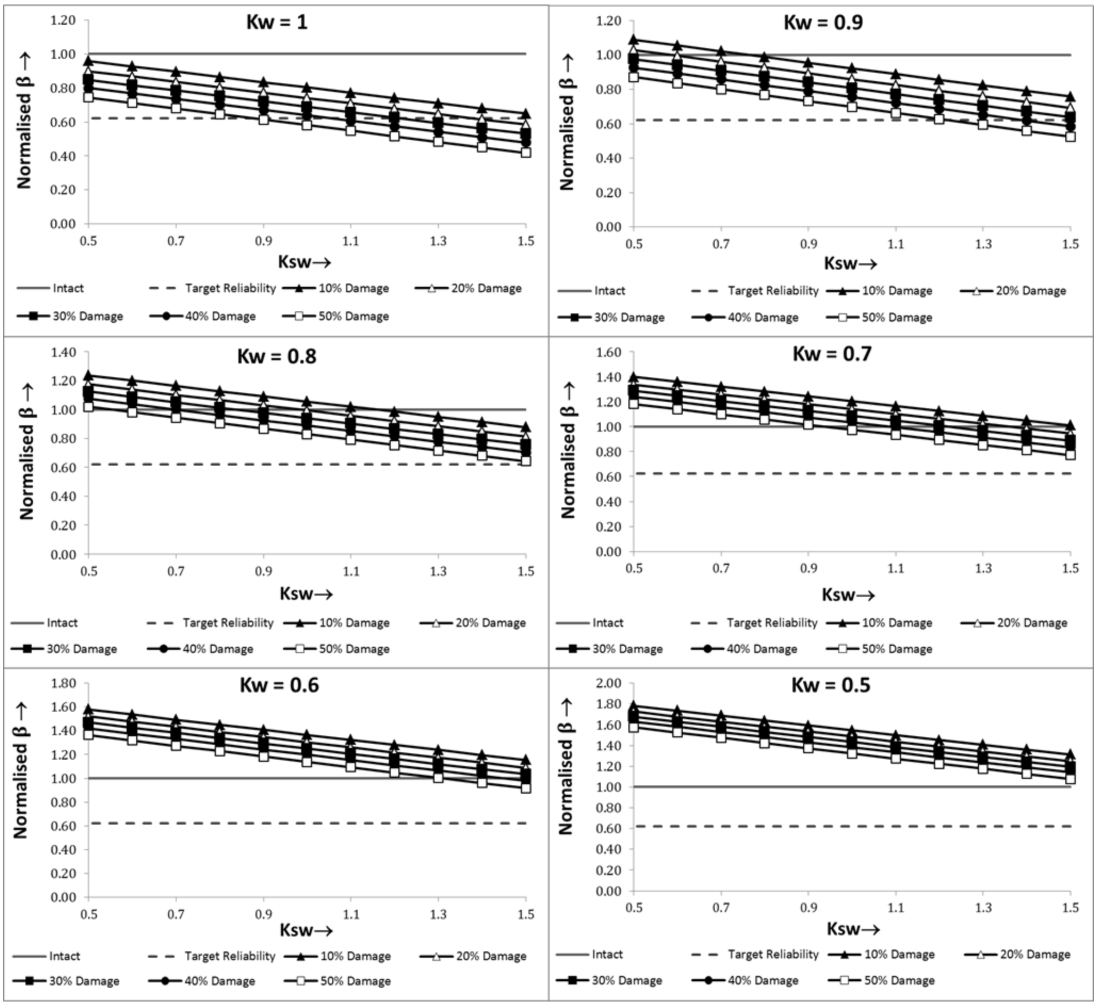


Figure 9-5 Variation of Reliability index under different combinations of Ksw and Kw in hogging following a collision accident.

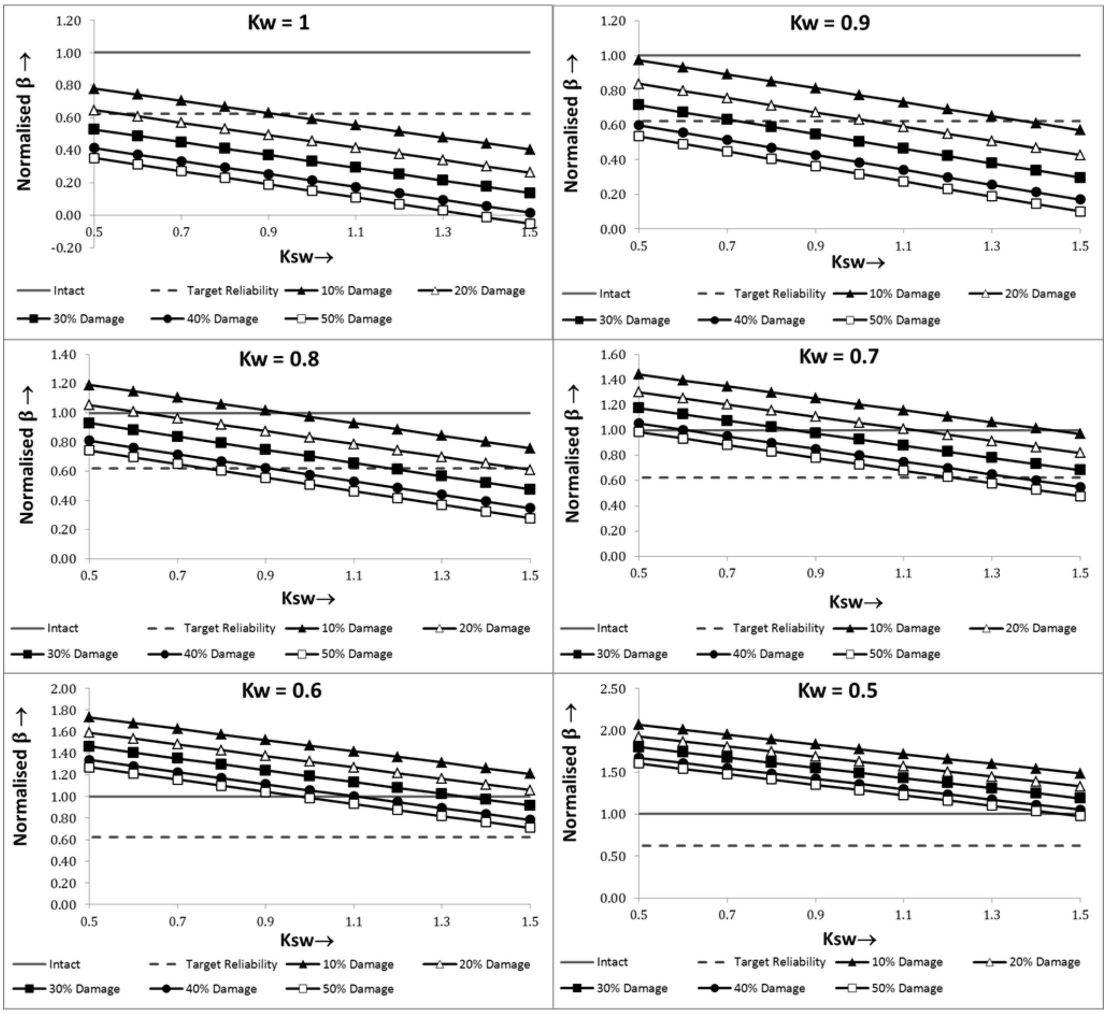


Figure 9-6 Variation of Reliability index under different combinations of Ksw and Kw in sagging following a collision accident.

From the above graphs it is seen that following bottom and side damages the minimum reliability occurs in hogging and sagging condition respectively. These graphs shows the reliability index to be expected under different damage scenarios. For example, if there is a 50% side or bottom damage and the Ksw corresponding to an increase in still water bending moment is 1.5, then the Kw value expected so as to meet the target reliability is 0.6.

9.11 Sensitivity Analysis

The sensitivity factors of a reliability index β to the distribution parameters (e.g. mean and standard deviation) of any random variable appearing in a limit state function is the derivative of β with respect to the distribution parameter. The sensitivity factors can be normalized by multiplying the derivative of β by the mean and standard deviation of the variable. The net effect is computing the change in β relative to a fractional change in the variable. The larger the resulting quantity in each case, the more important the parameter is relative to other parameters. The derivative may be taken with respect to the coefficient of variation, instead of standard deviation, to determine the sensitivity factor.

Thus two sensitivity factors for β can be defined: (a) sensitivity to mean; and (b) sensitivity to uncertainty. Sensitivity to mean value quantifies the effect on the safety index (or the probability of failure) by changing the mean (or nominal design value) of one of the variables. For example, what is the effect on risk on increasing the required section modulus of a hull or of increasing the yield strength of the material? The factor is particularly important for those variables over which the designer has control. It can provide guidance to designers regarding benefits and payoffs in making design decisions.

The design point is the point on the limit state that is the 'most portable' and is therefore called the most portable point (MPP). The design point for a random variable x_i may be given as:

$$u_i = \frac{\partial g(x)}{\partial x_i} \qquad \text{Equation 9-11}$$

The sensitivity factor for a random variable is given by the following equations:

$$\alpha_i = \frac{\partial \beta}{\partial u_i}|_{u^*} = \frac{u_i^*}{\beta} = \frac{u_i^*}{\sqrt{(u_1^*)^2 + (u_2^*)^2 \dots (u_n^*)^2}} \qquad \text{Equation 9-12}$$

It can be checked that $\sum_{i=1}^{n} \alpha_i^2 = 1$

The importance factor α_i is a relative measure of sensitivity of the reliability index with respect to the standard normal variate u_i^*, that is, a larger α_i implies more sensitivity of β to the standard variate u_i^*.

Sensitivity to the mean is referred as δ in the output of the CALREL result and is given by:

$$\delta_i = \frac{\partial \beta}{\partial \mu_i} \sigma_i \qquad \text{Equation 9-13}$$

where μ and σ represent the mean and standard deviation of random variables respectively. Positive δ indicates that the safety index increases with the increasing mean of the variable (e.g. the strength parameter) and negative δ indicates that β decreases with increasing mean (e.g. load parameters). δ_i is normalized by the standard deviation. As shown in the output. Sensitivity to uncertainty is defined as η_i and is given by:

$$\eta_i = \frac{\partial \beta}{\partial \sigma_i} \sigma_i$$

η_i plays two roles. The first is that of an analytical tool. A variable having a relatively small η can be treated as a constant in future analysis. The number of random variables considered in the limit state function greatly influences the efficiency of most reliability analyses. The second role of η is that of a design tool. For some variables, it specifies the level of uncertainty. The sensitivity factor η can be thus used to quantify the effect on risk of reducing or increasing, the uncertainty associated with the variable.

The other importance factor, γ_i, is a measure of sensitivity of β with respect to the basic variables x at x^* in the original space. Thus, γ_i gives a relative measure of importance among the basic random variables. The γ_i are normalized such that

$$\sum_{i=1}^{n} \gamma_i^2 = 1 \qquad \text{Equation 9-14}$$

The normalization of γ_i is such that, with a_i as a normalization factor, $\gamma_i$is given by:

$$\gamma_i = a_i \frac{\partial \beta}{\partial x_i^*} = \frac{a_i}{\sigma_i} \frac{\partial \beta}{\partial u_i^*} = \frac{a_i}{\sigma_i} \alpha_i \qquad \text{Equation 9-15}$$

$\sum_{i=1}^{n} \gamma_i^2 = 1$gets satisfied if a_i=σ_i, since $\sum_i \alpha_i^2 = 1$

The results of the sensitivity factor (α) for intact and damage condition are shown below. Positive value of sensitivity indicates that an increase in this variable leads to an increase in the reliability. The importance of the variables does not change from one ship to the other.

Figure 9-7 shows a typical result for one sample ship (DHT310), the sensitivity for other sample ships are also similar, which shows clearly the importance of each variable. The ultimate bending moment and its associated uncertainty have the highest sensitivity followed by the wave bending moment and its uncertainty, the rest of the variables have almost the same importance.

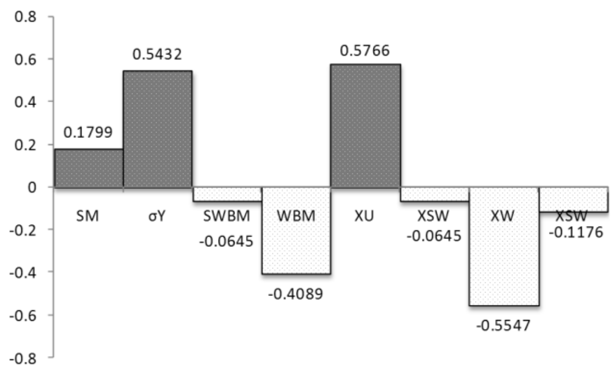


Figure 9-7 Sensitivity factor (α) of ships in intact condition

The change in sensitivity after damage was studied. Figure 9-8 to Figure 9-11 shows the change in sensitivity factors with damage, which is interpreted as increase in still water bending moment. It could be seen from the figures that sensitivity factor follows the same trend for all cases and it could be concluded that the importance of section modulus changes marginally with increasing still water bending moment and the uncertainty to ultimate capacity also show marginal change, it shows somewhat a cyclic trend. The importance of still water and wave bending moment and their associated uncertainties shows more sensitive to change in SWBM. The sensitivity factor for SWBM and associated uncertainty increases rapidly with damage. The importance of wave bending moment and the corresponding uncertainty decreases with increasing damage.

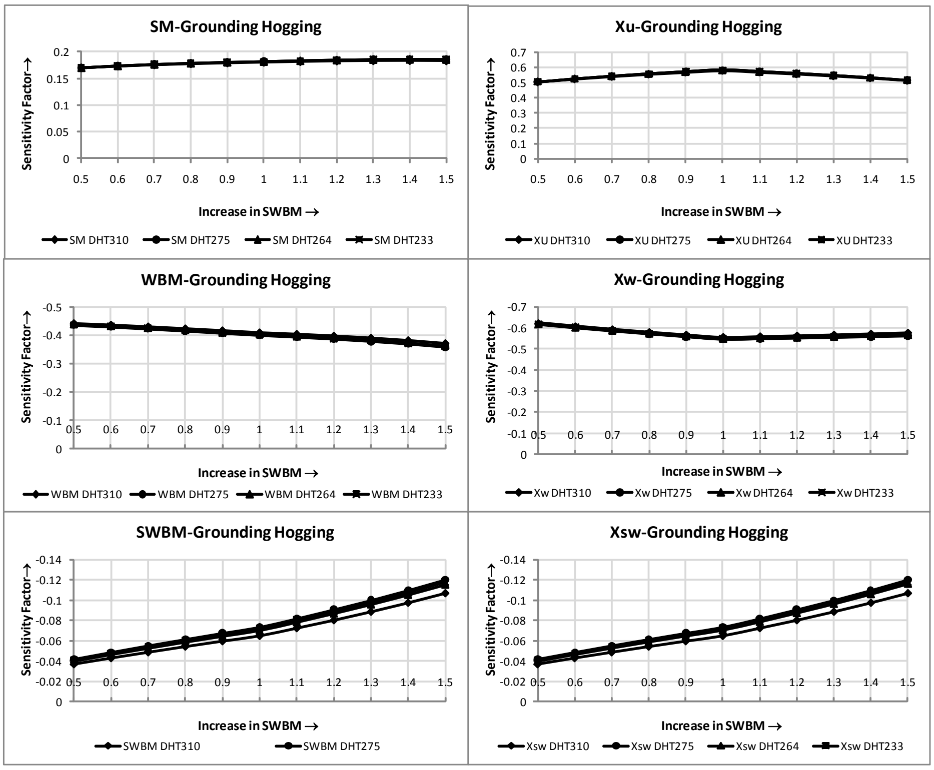


Figure 9-8 Variation of Sensitivity factor (α) for SM, WBM, Xu and Xw with increasing SWBM in hogging condition after grounding

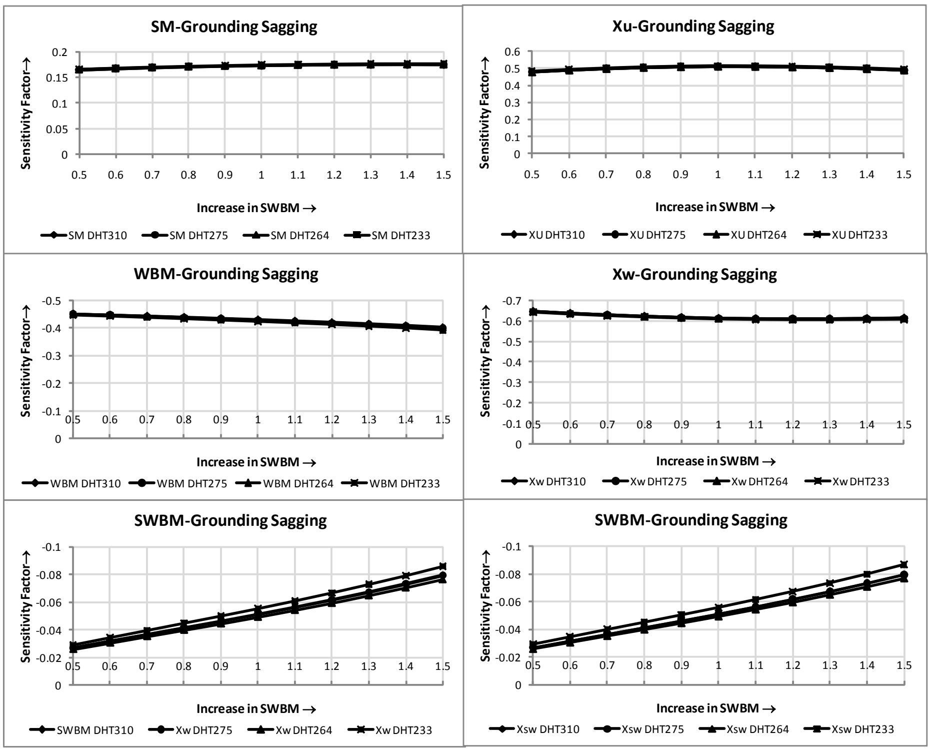


Figure 9-9 Variation of Sensitivity factor (α) for SM, WBM, Xu and Xw with increasing SWBM in sagging condition after grounding

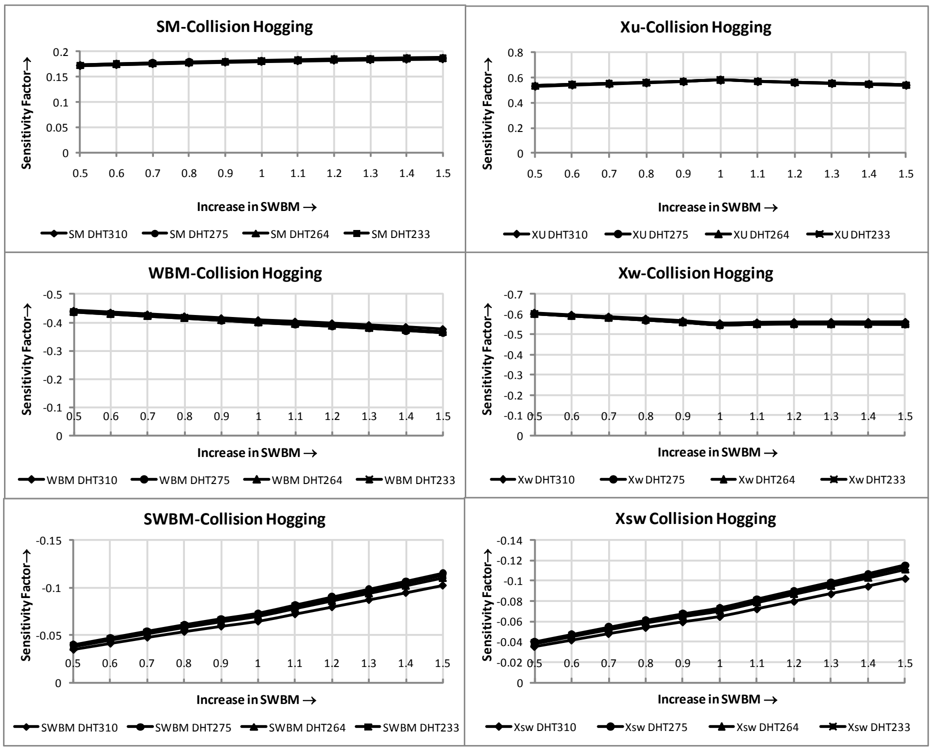


Figure 9-10 Variation of Sensitivity factor (α) for SM, WBM, Xu and Xw with increasing SWBM in hogging condition after collision

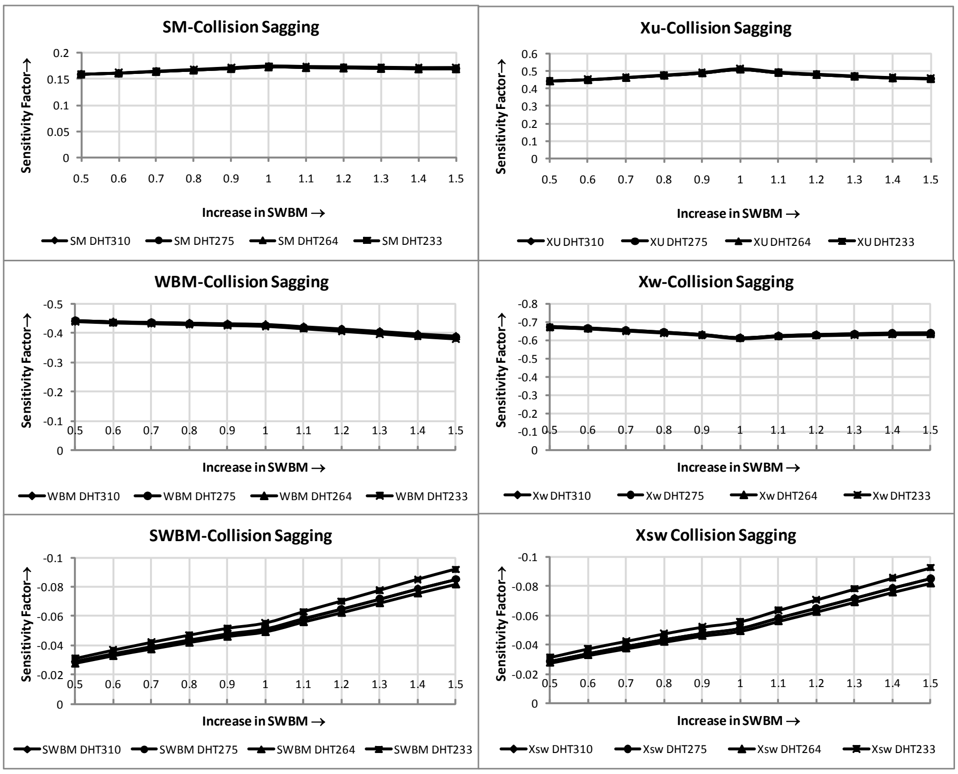


Figure 9-11 Variation of Sensitivity factor (α) for SM, WBM, Xu and Xw with increasing SWBM in sagging condition after Collision

9.12 Partial safety factors

Standard deterministic design methods result in designs against specific limit states by application of design values of the governing basic variables, where each design value is formed by the product of a partial coefficient and the characteristic value for the variable in question. Traditionally, the design should assume that at the limit state, there will be higher load acting on the structure than expected and the strength of the structure is lower than imagined. So at the limit state, the load will be higher and strength will be lesser.

$$\gamma_r R - \gamma_s S > 0;\ \gamma_r < 1 \ and \ \gamma_s > 1 \qquad \text{Equation 9-16}$$

where γ_r and γ_s are the corresponding resistance and load factors.

The structure should be designed to overcome this expected strength reduction due to γ_r. The safety redundancy in traditional deterministic design is ensured by these deterministic safety factors. The drawbacks of these kinds of safety factors usually are shortage of strict theory derivations and they are determined with more objective ingredients. With a reliability method available, a set of partial coefficients can be derived which will result in designs with a given target reliability. The general steps of determining reliability partial safety coefficients of a structure in question are,

1. Calculate the structural reliability with the initial design of structure. This part includes establishing physical modelling, limit state function, identification of random variables and their distribution types and parameters and the reliability calculation.
2. Adjust the design and calculate the structure reliability again until the given target reliability is met.
3. Determine partial safety factors: these coefficients shall be determined on the basis of the relationships between the characteristic values of the design variables and the corresponding values in the design points.

Partial coefficients are introduced in pairs, one partial coefficient associated with a load variable and another associated with a resistance variable. If there are n number of stochastic variables in a limit state equation, a partial coefficient γ_{xi} for the stochastic variable x_i can be defined as,

$$\gamma_{x_i} = \frac{x_i^*}{x_{ic}}, where\ i = 1 \ldots \ldots n \qquad \text{Equation 9-17}$$

Where x_i^* and x_{ic} are the design point and characteristic values of the stochastic variable x_i. Since the design point is the nearest point on the failure surface from the origin or the characteristic point, the limit state function tends to zero if the stochastic variables are assigned the design point values x_i^*.

The traditional deterministic design approach uses a fixed factor of safety to modify all variables to achieve the desired safety factor. In reliability design approach, the partial coefficients corresponding to each stochastic variable are used to modify the characteristic values into design values to achieve the target structural reliability.

In the reliability approach, the structural strength at the limit state will be designated with the most pessimistic combination of stochastic variables from within their probability distribution. The Limit sate equation at the design point will give an estimate of the load and resistance at failure with the corresponding stochastic variables in terms of partial factors. So the partial coefficients should be used sensibly with the participating stochastic variables in order to achieve the corresponding design values. In general, the load should be multiplied with the respective partial factor to get the design load and the resistance should be divided with the corresponding partial factor to get the design strength.

In a design process, the number of partial coefficients can be equal to or less than the number of stochastic variables. If the partial coefficients are less than or are not applied to all stochastic variables, it must be applied to the most sensitive variables identified from the sensitivity study carried out with the reliability analysis. For all other variables the design value shall be taken directly as the characteristic or design value.

The partial safety factors for ultimate structural failure of the hull girder, might be expressed in a code or design format as,

$$\gamma_s M_{sw} + \gamma_w M_w \leq \frac{M_{ult}}{\gamma_r} \qquad \text{Equation 9-18}$$

where γ_r is the partial safety factor applied to the nominal ultimate vertical bending moment as obtained from ultimate strength analysis of the midship cross section of the ship, γ_s and γ_w are the partial safety factors applied to the nominal values of the still water and wave induced bending moment, respectively, defined according to the IACS unified requirements. The definition of partial safety factors for ship structures under specified stochastic actions implies the determination of the design values of the variables (m_u^*, m_{sw}^*, m_w^*) defined as those points on the limit state function that have the maximum conditional probability when failure occurs. Then meaningful partial factors can be calculated as;

$$\gamma_{sw} = \frac{M_{sw,DP}}{M_{sw}} \;, \gamma_w = \frac{M_{w,DP}}{M_w} \; and \; \gamma_r = \frac{M_{ult}}{M_{ult,DP}} \qquad \text{Equation 9-19}$$

The results in Figure 9-12 show the range of the partial safety factors as a function of safety level and may be used as guidance when doing the final optimization of the partial safety factors.

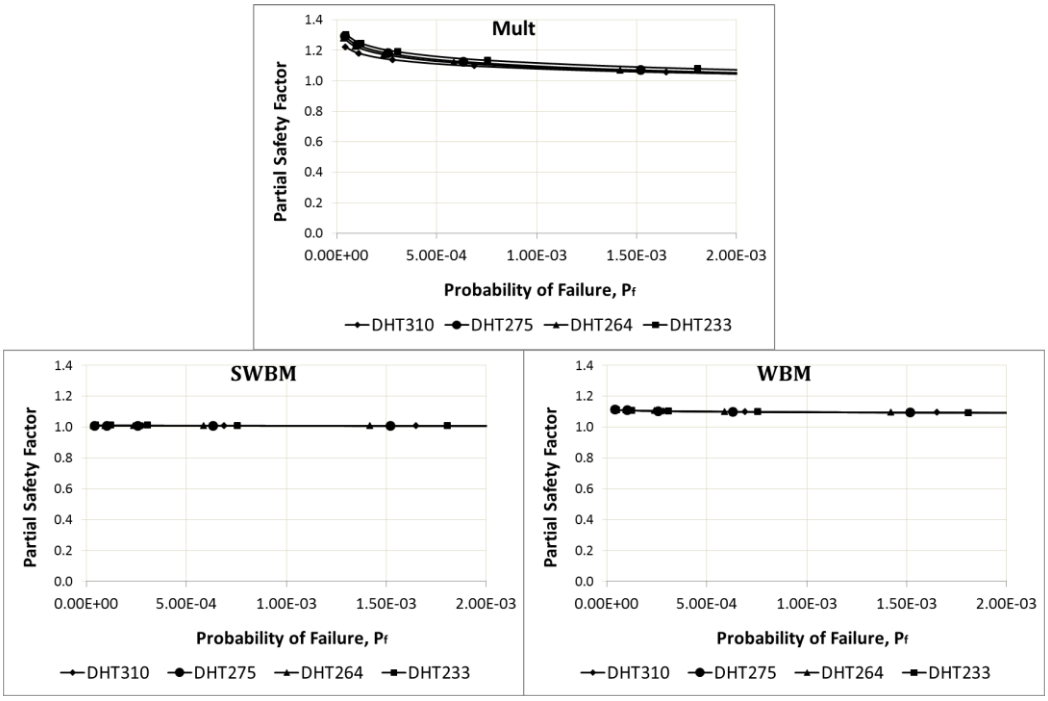


Figure 9-12 Partial safety factor as a function of target reliability level

The following comments are made in respect of Figure 9-12:

1. The partial safety factors (γ_{sw}) for the still water bending moment is almost constant at unity for all the sample ships.

2. The partial safety factors (γ_r) for the ultimate bending capacity increases slightly for increased probability of failure and are near 1.1 at target probability levels between 10^{-3} and 10^{-4}.
3. The partial safety factors for the wave bending moment are almost linear corresponding to a value of 1.1.

9.13 Reliability Analysis using Design Modification Factor

Design modification factor was applied to the deck plating in Chapter 8 to compensate for the loss in ultimate strength and the section modulus. In this section a reliability analysis on intact and damage ships considering the design modification factor is carried out to determine its effect on reliability index.

9.13.1 Intact Ship

The design modification factor is varied from 0.8 to 1.3 and the ultimate strength recorded based on which the reliability analysis is carried out. The result of this analysis is shown in Table 9-10 and Figure 9-13 from which it can be seen that the reliability index in sagging increases by 10% for every 10% increase in DMF whereas the reliability index in hogging shows a very small change 1.75% increase for every 10% increase in DMF.

Table 9-10 Reliability of strengthened section in intact condition

ShipType		DMF											
		0.8		0.9		1		1.1		1.2		1.3	
		β	P_f	β	P_f	β	P_f	β	P_f	β	P_f	β	P_f
Hogging	DHT310	3.87	5.5E-05	3.94	4.0E-05	4.01	3.0E-05	4.08	2.2E-05	4.15	1.6E-05	4.22	1.2E-05
	DHT275	3.77	8.0E-05	3.85	6.0E-05	3.92	4.4E-05	3.99	3.3E-05	4.06	2.4E-05	4.13	1.8E-05
	DHT264	3.84	6.2E-05	3.91	4.6E-05	3.98	3.4E-05	4.05	2.5E-05	4.12	1.9E-05	4.19	1.4E-05
	DHT233	3.79	7.6E-05	3.86	5.7E-05	3.93	4.2E-05	4.00	3.1E-05	4.07	2.3E-05	4.14	1.7E-05
Sagging	DHT310	2.08	1.9E-02	2.38	8.6E-03	2.67	3.8E-03	2.94	1.7E-03	3.20	6.9E-04	3.45	2.8E-04
	DHT275	2.11	1.7E-02	2.41	8.0E-03	2.69	3.6E-03	2.96	1.5E-03	3.22	6.3E-04	3.47	2.6E-04
	DHT264	2.13	1.7E-02	2.43	7.6E-03	2.71	3.3E-03	2.98	1.4E-03	3.24	5.9E-04	3.49	2.4E-04
	DHT233	2.05	2.0E-02	2.35	9.4E-03	2.64	4.2E-03	2.91	1.8E-03	3.17	7.6E-04	3.42	3.1E-04

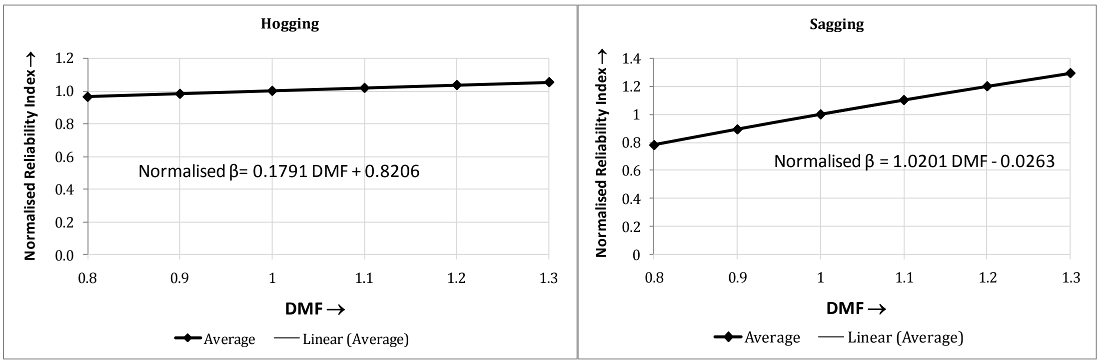


Figure 9-13 DMF versus reliability-Intact condition

9.13.2 Damaged Ship

It was seen in Table 9-6 and Table 9-7 that the least reliability following an accident occurs when the ship is sagging following and side damage and it was seen the reliability falls almost 30% below the intact level and fell below the target probability level. Hence, in this section the effect of strengthening the deck on the reliability of damaged ship is studied on sample ships. Table 9-11 and Figure 9-14 shows the result of strengthening the deck of DHT310.

From Figure 9-14 it is clear with a DMF of 1.1 the reliability index falls marginally below the target level following 40% damage to the side and with 50% damage it is well below the target level, whereas with DMF of 1.2, the ship has adequate reliability level even for 50% damage. Hence, it is clear that this ship has to be strengthened on the deck by at least 20% to be able to maintain the target reliability index following a major accident to the side.

Table 9-11 Reliability of strengthened section in damaged condition

Damage Extent (d/D)	DMF 1		1.1		1.2		1.3	
	β	P_f	β	P_f	β	P_f	β	P_f
Intact	2.65	3.97E-03	2.94	7.13E-04	3.20	6.92E-04	3.45	2.83E-04
10% Damage	3.20	6.90E-04	3.46	2.74E-04	3.69	1.13E-04	3.91	4.58E-05
20% Damage	2.81	2.45E-03	3.04	1.16E-03	3.31	4.72E-04	3.56	1.85E-04
30% Damage	2.46	6.90E-03	2.77	2.83E-03	3.05	1.13E-03	3.33	4.33E-04
40% Damage	2.12	1.68E-02	2.46	6.92E-03	2.81	2.45E-03	3.16	7.96E-04
50% Damage	1.94	2.62E-02	2.33	9.82E-03	2.75	3.02E-03	3.14	8.43E-04

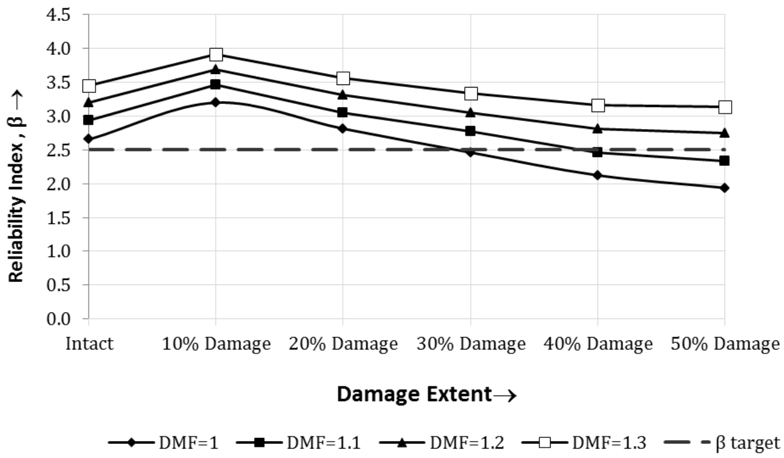


Figure 9-14 Reliability of strengthened section in damaged condition

9.14 Summary &Conclusion

Reliability analysis allows the designer to make decisions based on probabilistic approach to determine the safety level and probability of failure of the ship structure. Determinations of the uncertainties are most important factor to achieve accurate results from reliability analysis. Detailed discussions on the uncertainties associated with ultimate strength calculation, still water bending moment, non-linear effects and wave loads have been presented. The limits state function considering the load and resistance acting on the structure was discussed. Reliability analysis has been performed for intact and different damage scenarios. The framework shown in this chapter should be treated as a model for the reliability analysis and it should be noted that the values of the reliability analysis is very much dependent on the distribution type, mean value and coefficient of variation chosen for the random variables.

First order reliability method (FORM) has been used to evaluate the reliability indices and probability of failures for tankers in different scenarios. It was observed that during intact scenario, the reliability index in hogging condition has higher values compared to that in sagging condition and the reverse true for probability of failure.

The still water bending moment and wave induced bending moments have been calculated using IACS's recommendations for tankers. Since load effects decrease in the damage scenarios, combination factors proposed by ABS have been used to evaluate the combined effect of still water and wave induced vertical loads. According to the ABS rule, during damage scenarios the value of the combined effect of vertical loads are decreasing to a larger extent than their counterparts in strength. So for this reason the reliability indices for the damaged scenario are observed to be higher than the intact scenario. The author feels that it is rather opposite the case in the real life scenario. Hence a detailed study considering different combination of still water and wave induced loads acting on the ship for each damage scenario was studied.

The sensitivity analysis showed the important variables to be considered during the design process. From the sensitivity analysis it can be observed that the wave induced bending moment, section modulus, yield strength and the uncertainty associated with ultimate strength are most important parameters, which affects the safety of ship to a larger extent.

The partial safety factor analysis was carried out on the sample ships to determine the safety factors to be used for probability based design rule of tankers in order to achieve pre-defined target safety levels

Finally, a parametric study considering the influence of design modification factor on the reliability of intact and damaged ships was carried out. The DMF was applied to the deck thickness, and the analysis carried out for sagging condition of ship following side damage.

Chapter 10. Discussion & Conclusion

10.1 Introduction

On the basis of the work outlined in this thesis, this chapter discusses and concludes the results and their implications in more detail.

The primary objective of this research was to develop a risk based procedure to analyse the probability of realisation of different consequence (damage extent, oil spill and reliability) given a ship accident.

The various aspects of this thesis can be summarised under the following categories,

1. Statistical analysis of accidents
2. Causes and consequences of accidents
3. Reserve and residual strength of ships
4. Reliability analysis of intact and damages ships

10.2 Statistical Analysis of Accidents

The thesis begins with the statistical analysis of ship accident using IHS Fairplay ship accident database from 1980-2009, other reports such as ITOPF (2009), IMO (2008, 2009), HARDER (2003) etc. were also analysed, based on which the parameters which influence accidents were determined. From the database analysis it was seen that grounding and collision accidents are more frequent and the more number of accidents has happened for bulk carriers and tankers. Accidents on tankers have more serious environmental consequences due to the huge amount of oil transported by them. The oil spill data was obtained from ITOPF (2009) which gives details about the location and amount of oil spilled. The determination of damage extent resulting from accidents was most challenging because it is neither recorded in databases nor given in detail in accident investigation reports. In 1995, IMO introduced guidelines for the probabilistic procedure for assessing the oil outflow performance of an oil tanker design in collision and grounding. One of the important elements in the guidelines is the damage density distributions which were derived from the actual damage data. The HARDER project has also contributed greatly to improve the quantity, quality and understanding of available accident data. These studies give the probability density distributions for the damage extent following grounding and collision accidents.

Data mining techniques which involve methods from statistics and artificial intelligence were used to extract hidden predictive information from the databases. The accident data was processed through a classification and regression tree analysis which enabled the classification of various accident factors. The classification tree may be utilized in the context of a potential decision support system and/or a risk management information system that will record, evaluate and process data for shipping accidents. The analysis of Lloyd's damage database revealed that, there is substantial evidence in support of the ISM-Code effective control over shipping accidents during the post-ISM period.

10.3 Causes and Consequences of Ship Accidents

The consequences of ship accident have both financial and environmental impacts hence, the determination of cause and consequence of ship accidents is important to ensure the safety of ship and its cargo, also to prevent similar incidents happening in the future.

The maritime system is a people system and hence it is obvious that there can be errors at various stages of operations. The role of human factors in marine accidents is more compared to any other factors. The other factors being the external factors such as weather, wave etc. and technical factors such as hardware failure etc. A Bayesian model was developed to capture the probability of accidents given various factors which could go wrong.

Since the accident database do not include details about the damage extent, expert judgement was used to obtain the resulting damage on the ship structure due to collision and grounding accident. The variables considered for this study were determined by a step by step process involving in-depth study of the literature to make the initial BBN model which was then validated by expert judgement to elicit the final model.

Different methods to develop Bayesian models from the databases were shown. The final cause and consequence models were developed by combining information from database and expert judgement. The Bayesian network models so developed considers the conditional dependencies and mutual exclusiveness of events and are more suitable for risk analysis compared to models developed using other methods. The final model developed could determine the probability of accidents given various factors which could go wrong and the consequences to be expected from accidents.

The results from such a study helps ship designers, classification societies, regulators etc. to identify the problem in maritime transportation and learn from previous accidents, which helps to determine the factors to be considered or taken into account for safer maritime operations and direct their efforts with regards to rulemaking, establishing design criteria and standards, planning operations, or directing future ship design or research and development efforts.

10.4 Reserve and Residual Strength of Ship Structures

The accurate determination of ultimate capacity of ships is important to determine strength of ships against the loads to which it is subjected and in the evaluation of reliability indices and the probability of failure. The strength analysis in this thesis is being carried out using Smith's progressive collapse method which is easier to apply, efficient and gives adequate estimation of the ultimate capacity much quicker compared to other methods.

Accident to ship could happen at any location along its side and bottom and hence, it was necessary to determine the location of accidents which leads to maximum strength reduction. Different accidents scenarios at the side and bottom were analysed by changing the location of damage and it was observed that minimum residual strength in grounding occurs when the keel is damaged and in collision when the damage happens to the upper part of the side. Four sample ships (Double hull tankers) were analysed with different side and bottom damages. The ship structural design has a very significant influence on the damaged hull girder's ultimate strength. Its capacity depends on the thickness of outer shell, inner shell, side stringers, transverse webs, width of the side ballast tank and width of lower and upper wing tankers.

In order to take into account the effect of age related degradation analysis the ultimate strength of sample ships were calculated under intact condition using both gross scantling and net scantling +50% corrosion additions defined in the IACS new common structural rules. It was seen that the results of t_{net50} scantlings compared to gross scantlings show almost 10% losses in section modulus and approximately 5% reduction in ultimate strength capacity.

The ultimate strength of the ships in sagging condition is lower compared to that in hogging condition. This is due to the fact that during the sagging condition the elements above the neutral axis undergo compression and these elements contribute less to the total strength of the ship structure, since the bottom elements are stockier compared to the deck elements. The existence of damage induced by both grounding and collision reduces the ultimate strength (i.e. residual strength) of the ship hull girder. The degree of reduction varies with the damage locations and the extents. It is observed that the residual strength of ship after damage is a function of damage extent, the bigger the damage the lesser the strength.

The loss in section modulus due to damage is calculated to check if after damage the ship will have section modulus less than the minimum value defined by the rule. Since the ships have a robust bottom scantling they are seen to have the required residual strength following grounding accident, but with collision accidents the section modulus to deck drops drastically and with a damage size of about 30% of ship depth the section modulus to the bottom drop below the rule requirement.

Simplified equations for calculating the ultimate strength of ship under different damage scenarios dependent only on the dame extent, section modulus and yield strength of the ship were derived. These equations give comparable results with the results using Smith's progressive collapse method with maximum ±5% difference. These equations are later used in the reliability analysis which could help do determine the probability of failure under different damage scenarios.

Finally, a design modification factor was applied to the deck to compensate for the loss in the ultimate strength due to damage. Simple equations are derived to estimate the required design modification factor as a function of the loss in ultimate strength.

10.5 Reliability Analysis of Intact and Damaged Ships

In the design and operation of ship structures, there are a number of uncertainties that must be dealt with. Wherever there are uncertainties, a risk of failure exists. Hence, the derivation of the limit state function is one of the most important early steps for the reliability analysis; since it gives the due consideration to those random variable an engineer should be giving more importance, in the design process of a ship structure. For this study a time-independent limit state formulation corresponding to the hull girder failure under vertical bending was derived.

Following damage there will be change in load acting on the ships. The ship should not operate with a very high speed, and also it avoids very rough sea. Therefore, the wave-induced bending moment may be smaller than that for the normal design extreme condition and there can be change in still water loads due to water ingress or cargo outflow and hence change in buoyancy. Also with damage there is capacity reduction. The effects of load combination factors under different damage scenarios were studied to determine the variation of reliability index and probability of failure.

The sensitivity analysis showed the important variables to be considered during the design process. From the sensitivity analysis it can be observed that the wave induced bending moment, section modulus, yield strength and the uncertainty associated with ultimate strength are most important parameters, which affects the safety of ship to a larger extent.

The partial safety factor analysis was carried out on the sample ships to determine the safety factors to be used for probability based design rule of tankers in order to achieve pre-defined target safety levels

The Parameter study carried out shows the influence of design modification factor on the reliability of intact and damaged ships which shows the minimum required increase in deck thickness to achieve the target reliability.

10.6 Achievements and Contributions

Main contributions of this research work are summarized as follows;

- A risk based format for the analysis of ship accidents and their consequences is developed.
- The ability of data mining tools to extract hidden information from database is shown by the use of classification tree.
- The use of Bayesian network as an ideal risk analysis tool to capture the interrelations and dependencies of events is shown.
- The capability of Bayesian networks to be constructed using database and expert judgement are illustrated by eliciting ship accident cause and consequence models.

- Simple equations to determine the residual strength of damaged ships dependent only on the damage extent are developed, which is an obvious advantage in case of rescue and recovery operations.
- Reliability and sensitivity analysis are performed which allows engineers to concentrate on important influencing factors during design. Also, partial safety factors were obtained corresponding to certain target reliability.

10.7 Recommendations for Future Research

- The Bayesian model for predicting damage extent could be further enhanced by considering the structural details of the ships.
- Following accidents, there is effect of horizontal bending moment and torsion which should be included in the ultimate strength and reliability analysis.
- More rigorous studies are needed to model the damaged scenarios in 3D methods to calculate the still water and wave induced loads acting on the ship structure. No method has been presented in IACS rule to evaluate the still water and wave induced load for the damaged scenarios.
- The load combination factors after damaged proposed by ABS may be too conservative. So further research could be done to evaluate the correct value of these combination factors.

References

ABS (1995). Guide for Assessing Hull-Girder Residual Strength of Tankers. American Bureau of Shipping. Houston TX, USA.

ABS (2003). Rules for building and classing steel vessels, American Bureau of shipping, Houston TX, USA.

ABS (2006). Trending the Causes of Marine Incidents. Conference on Learning from Marine Incidents 3, London.

Akita, Y (1982). Lessons learned from failure and damage of ships. In Joint Session I , Sth Int. Ship Structures Congress, Gdansk.

Akten, N (2006). Shipping Accidents: A Serious Threat for Marine Environment. Journal of Black Sea/Mediterranean Environment 12, pp 269-304.

Alegeest L J M (1995). Non-linear hull girder loads in ships. Ph.D Thesis. Delft University of Technology.

Alsos, H S and Amdahl J (2007a). On the resistance of tanker bottom structures during stranding. Marine Structures 20, pp 218-237.

Amlashi, H and Moan, T (2007b). Ultimate Strength Analysis of a Bulk Carrier Hull Girder under Alternate Hold Loading Condition-A case Study: Part 1: Nonlinear Finite Element Modelling and Ultiamte Hull girer capacuty

Antão, P and Guedes Soares, C (2010). Analysis of the Influence of Waves in the Occurrence of Accidents in the Portuguese Coast using Bayesian Belief Networks. Journal of KONBiN, 1 (13).ISSN 1895-8281.

Antão, P., Grande, O., Trucco, P and Guedes Soares, C (2008). Analysis of Maritime Accident Data with BBN modelling, Safety, Reliability and Risk Analysis-Theory, Methods and Applications, Martorell, S., Guedes Soares, C. & Barnett, J. (Eds), Balkema, Taylor & Francis Group, Vol 4, pp 3265-3274.

Baker, C C and Seah, A K (2004). Maritime Accidents and Human Performance: The Statistical Trial. MarTech 2004 Conference, Singapore.

Biggs, D., DeVille, B and Suen, E (1991). A Method of Choosing Multiway Partitions for Classification and Decision Trees. Journal of Applied Statistics18 (1):49–62.

Bilal, M A and McCuen, R H (2000). Probability, Statistics and Reliability for Engineers and Scientists', Chapman & Hall/CRC press.

Booker, L B and Hota, N (1986). Probabilistic Reasoning about Ship Images. Second Annual Conference on Uncertainty in Artificial Intelligence, University of Pennsylvania, Philadelphia, PA.

Borresen R and Tellsgard, F (1980). Time history of simulation of vertical motion and loads on ships in regular head waves of large amplitude. Norwegian Maritime Research, 3.

Brieman, L., Friedman, J H., Olshen, R A and Stone, C J (1984). Classification and Regression Trees. Belmont, CA: Wadsworth International Group.

Brown A J (2002). Collision Scenarios and Probabilistic Collision Damage. Marine Structures 15: 335-364.

Brown, A J and Chen, D (2002). Probabilistic Method of Predicting Ship Collision Damage. Ocean Engineering International Journal. Vol.6. No.1. pp. 54-65.

Bureau Veritas (2000). MARS2000 User Manual. Marine Division Development Department.

Caldwell, J B (1965). Ultimate longitudinal strength. Trans RINA, 107 pp 411-30.

Carlsen, C A and Czujko, J (1978). Specification of post-welding distortion tolerances for stiffened plates in compression. The Structural Engineer, Vol. 56A, No.5, pp 133-141.

Celik, M., Lavasani, S M. and Wang. J (2010). A risk-based modelling approach to enhance shipping accident investigation. Safety Science 48, pp 18-27.

Chan, H S., Atlar, M and Incecik, A (2002). Large-amplitude motion responses of a Ro-Ro Ship to regular oblique waves in intact and damaged condition. Journal of Marine Science and Technology, Vol. 7, pp 91-99.

Chan, H S., Atlar, M and Incecik, A (2003). Global wave loads on Intact and Damaged RO-RO Ships in Regular Oblique Waves. Journal of Marine Structures, Vol. 16, pp 323-344.

Chan, H S., Incecik, A and Atlar, M (2001). Structural Integrity of a Damaged Ro-Ro Vessel. Proceeding of the second International Conference on Collision and Grounding of Ships, Technical University of Denmark, Lybgby, pp 253-258.

Chan, H S., Voudouris, G., Servis, D P and Samuelides, M (2000). Residual Strength of a Damaged RO RO Ship , DTR-4.3-UNEW-04-00, DEXTREMEL Project BE97-4375.

Charniak, E (1991). Bayesian Networks without Tears. AI Magazine, 12, 50-63.

Charniak, E and Goldman, R P (1989a). Plan Recognition in Stories and in Life. Fifth Workshop on Uncertainty in Artificial Intelligence, Mountain View, California.

Charniak, E and Goldman, R P (1989b). A Semantics for Probabilistic Quantifier-Free First-Order Languages with Particular Application to Story Understanding. Eleventh International Joint Conference on Artificial Intelligence, August 1989, Detroit, Michigan, USA.

Chen, Y K, Kutt L M, Piaszczyk, CM and Bieniek, M P (1983). Ultimate Strength of Ship Structures. SNAME Trans. Vol.91, pp 149-168.

Cheng, J. and Druzdzel, M J (2000). AIS-BN: An Adaptive Importance Sampling Algorithm for Evidential Reasoning in Large Bayesian Networks. Journal of Artificial Intelligence Research, 13, 155-188.

Clausen, H B., Lützen, M., Friis-Hansen, A and Bjørneboe (2001). Bayesian and Neural Networks for Preliminary Ship Design. Marine Technology, Vol.28, No.4, pp 268-277.

Cooper, G F (1987). Probabilistic Inference using Belief Networks is Np-Hard. Paper No. SMI-87-0195. Knowledge Systems Laboratory, Stanford University. Stanford, CA, USA.

Couser, P., Mason, A., Mason, G., Smith, C R and Von Konsky, B R (2004). Artificial neural networks for hull resistance prediction. COMPIT, Siguenza, Spain.

Dagum, P and Luby, M (1993). Approximating Probabilistic Inference in Bayesian Belief Networks is Np-Hard. Artificial Intelligence, 60, 141-153.

Dalkey, N and Helmer, O (1963). An experimental application of the Delphi method to the use of experts. Management Science. 9(3) 458-467.

Dalzell, J F., Maniar, N M and Hsu, M W (1979) Examination of service and stress data of three ships for development of hull girder load criteria. Report No. SSC-287, Ship Structure Committee, Washington, DC, USA.

Das, P K and Fang, C (2005). Survivability and reliability of damaged ships after collision and grounding. Ocean Engineering, Vol.32, pp 293-307.

Das, P K and Fang, C L (2007). Residual Strength and Survivability of bulk carriers after grounding and Collision. Journal of ship research, Vo.51, no.2, p 137-149.

Das, P K., Frieze, P A and Faulkner, D (1984). Structural Reliability Modelling of Stiffened Components of Floating Structures. Structural Safety, Vol. 2 (1), 3-16.

Das, P., Moan, T., Gu X K., Friis-Hansen, Hovem, L., Parmentier, G., Rizzuto, E., Shigemi, T. and Spencer, J (2006). Reliability Based Structural Design and Code Development. 16th International Ship and Offshore Structures Congress, Vol.2, Southampton, UK.

De Kat, J O (1990). The Numerical Modeling of Ship Motions and Capsizing in Severe Seas. Journal of Ship Research, Vol. 34, pp 289-301.

Det Norske Veritas (DNV-CN) (1992). Structural Reliability of Marine Structures, Classification Notes 30.6, Norway.

Ditlevsen, O and Madsen, H O (1996). Structural Reliability Methods, John Wiley & Sons Ltd, ISBN 0 471 96086

DnV (1994). Hull structural design ships with length 100 metres and above, Rules for classification of ships. Part 3 Chapter 1, Det norske Veritas, Norway .

Druzdzel, M J and Yuan, C (2003). An Importance Sampling Algorithm Based on Evidence Pre-Propagation. Nineteenth Annual Conference on Uncertainty in Artificial Intelligence. Acapulco, Mexico.

Fang C and Das, P K (2005). Survivability and Reliability of Damaged Ships after Collision and Grounding. Ocean Engineering 32: 293-307.

Fang C and Das, P K (2007). Residual strength and survivability of ships after grounding and collision. Journal of Ship Research, 51(2) pp 137-148.

Fang, C C., Chan, H S. and Incecik, A (1997). Investigation of Motions of Catamarans in Regular Waves-II. Journal of Ocean Engineering, Vol. 24, pp 949-66.

Fang, M C and Her, S S (1995). The non-linear SWATH Ship Motion in Large Longitudinal Waves. International Shipbuilding Progress, Vol. 42, pp 197-220.

Faulkner, D (1977). Compression tests on welded eccentrically stiffened plate panels. Steel plated structures. P.J. Dowlinf et al., (Eds), Crosby Lockwood Staples, London, pp 581-617.

Ferry-Borges, J and Castenheta, M (1971). Structural Safety. Laboratoria Nacional de Engenhera Civil, Lisbon.

Frieze, P A., Dogliani, M., Huss, M., Jensen, J J., Kunow, R., Mansour, A E., Murot su, Y and Valsgard, S (1991). Applied design. Report of Committee V. 1, In 11th Int. Ship and Offshore Structures Congress, China.

Friis-hanse, P and Chin, B. (2010). Using Bayesian Networks for Identification of Risk Performance Indicatiors. Proceeding of 5th International ASRANet Conference, Edinburgh, UK.

Friis-Hansen, A (2000). Bayesian Networks as a Decision Support Tool in Marine Applications. PhD Thesis. Technical University of Denmark, Denmark.

Friis-Hansen, P and Simonsen, B C (2002).GRACAT: Software for Grounding and Collision Risk Analysis. Marine Structures 15, pp 383-401.

Fujino, M and Yoo, B S (1985). A study on wave loads acting on ship in large amplitude 3rd report. Journal of Society of Naval Architects of Japan, Vol. 158.

Fung, R. and Chang, K C (1989). Weighing and Integrating Evidence for Stochastic Simulation in Bayesian Networks. In M. Henrion, R. D. Shachter, L. N. Kanal & J. F. Lemmer (Eds.), Uncertainty in Artificial Intelligence 5 (pp. 209-219). New York, NY, USA: Elsevier Science Publishing Company, Inc.

Fung, R. and Del Favero, B (1994). Backward Simulation in Bayesian Networks. Tenth Annual Conference on Uncertainty in Artificial Intelligence. San Francisco, CA, USA.

Geritsma, J and Beukelman, W (1967). Analysis of the modified strip theory for the calculation of ship motions and wave bending moments. International Ship Building Progress, Vol. 14, No. 156.

Gerritsma, J and Beukelman, W (1967). Analysis of the modified strip theory for the calculation of ship motions and wave bending moments. International Shipbuilding Progress. Vol. 14. No. 156.

GL (2004). Rules for classification and Construction I Ship Technology Part-1 Seagoing Ships Chapter 1 Hull Structures Section 33 Strengthening against Collisions, Germanischer Lloyds, Hamburg, Germany.

Goodman , L E., Rosenblueth, E and Newmark, N M (1954). Aseismic design of firmly founded elastic structures. Trans. ASCE , Proceeding paper 2762.

Gordo, J M and Guedes Soares, C (1996a). Approximate method to evaluate the hull girder collapse strength. Marine Structures 9(1), 449-470.

Gordo, J M and Guedes Soares, C (2000). Residual Strength of Damaged Ship Hulls. In proceeding of Ninth IMAM conference; Napoli, Italy, pp. 79-86.

Gordo, J M., Guedes Soares, C. and Faulkner, D (1996b). Approximate assessment of the ultimate longitudinal strength of the hull girder. Journal of Ship Research 4(1). 60-69.

Gougoulidis, G (2008). The utilization of Artificial Neural Networks in Marine Applications: An Overview. Journal of Naval Engineers, Vol. 120, Issue 3, pp 19-26.

Grech, M., Horberry, T. and Koester, T (2008). Human factors in the Maritime Domain. CRC Press.

Guedes Soares, C (1999). On the uncertainty in long-term predictions of wave induced loads on ships. Journal of Marine structures, Vol 13, pp 107-108.

Guedes Soares, C and Hussein, A W (2009). Reliability and Residual Strength of Double Hull Tankers Designed According to the new IACS common Structural Rules. Ocean Engineering 36, 1446-1459.

Guedes Soares, C and Moan, T (1988). Statistical Analysis of still water load effects in ship structures. Transaction of Society of Naval Architects and Marine Engineers, Vol. 96 (4), 129-156.

GuedesSoares, C and Schellin T E (1998). Nonlinear effects on long-term distributions of wave-induced loads for tankers. Journal of offshore Mechanics and Arctic engineering, Vol. 120 (2), pp 65-70.

Hansson, O and Mayer, A (1989). Heuristic Search as Evidential Reasoning. Fifth Workshop on Uncertainty in Artificial Intelligence. Windsor, Ontario, Canada.

HARDER (2003). Final publishable report, HARDER Consortium.

Heckerman, D E (1991). Probabilistic Similarity Networks. Massachusetts Institute of Technology Press. ISBN 0-262-01114-X.

Heckerman, D., Mamdani, A. and Wellman, M P (1995). Real-World Applications of Bayesian Networks. Communications of the ACM, 38(3), 24-68.

Henrion, M (1988). Propagation of Uncertainty by Probabilistic Logic Sampling in Bayes Networks. In J. F. Lemmer & L. N. Kanal (Eds.), Uncertainty in Artificial Intelligence 2 (pp. 149-163). New York, NY, USA: Elsevier Science Publishing Company, Inc.

Holyland. A and Marvin R (1994). System Reliability Theory Models and Statistical Methods, John Wiley & Sons Ltd.

Hørte T., Wang, G and White, N (2007). Calibration of the Hull Girder Ultimate Capacity Criterion for Double Hull Tankers. In proceedings of the conference on Practical Design of Ships and Offshore Structures. Houston, USA.

Hu, Y., Zhang, A and Sun, J (2001). Analysis on the ultimate longitudinal strength of bulk carrier by using a simplified method. Journal of Marine Structures 14 pp 311-330.

Hughes, O F (1988). Ship Structural Design: a rationally based, computer-aided optimization approach, The Society of Naval Architect and Marine Engineers, New Jersey.

Inglis, R B (1980). A three-dimensional analysis of the motion of a rigid ship in waves. Ph.D Thesis, University College, London.

International Association of Classification Societies (IACS) (2006a). Common Structural Rules for Double Hull Tankers. Rules.

International Association of Classification Societies (IACS) (2006b). Unified requirements S11. Longitudinal Strength Standards. Rev.5.

International Maritime Organization (1997). Interim Guidelines for the Application of Formal Safety Assessment (FSA) to the IMO Rule-Making Process. MSC/Circ. 829, MEPC Circ. 335.

International Maritime Organization (2002). Guidelines for Formal Safety Assessment (FSA)for use in the IMO rule-making process. MSC/Circ.1023/MEPC/Circ.392.

International Maritime Organization (2003). Revised interim guidelines for approval of alternative methods of design and construction of oil tankers under regulation 13F (5) of Annex I of Marpol 73/78. Technical Report, Resolution MEPC.110 (49).

International Maritime Organization (2004). The International Safety Management Code. Chapter IX of the International Convention for the safety of life at sea, 1974, as amended (2004 Consolidated Edition).

International Maritime Organization (2009). International Shipping and World Trade: Facts and Figures. Compiled by the IMO Library Services.

Ivanov, L and Madjarov, H (1975). The statistical estimation of SWBM (still water bending moment) for cargo ships. Shipping World & Shipbuilder, 168, 759-762.

Jacob, W R (1958). The analytical calculation of ship bending moments in regular waves. Journal of Ship Research, June, pp 20-29.

Jacob, W R., Dalzell, J and Lalangas, P (1960). Guide to computational procedure for analytical evaluation of ship bending moments in regular waves, US Navy, Davidson Laboratory, Report NO. 791.

Jacobs, W R (1958). The analytical Calculation of Shipbuilding Moments in Regular Waves. Journal for Ship Research. Vol. 2. No. 1.

Jensen, F V (2001). Bayesian Networks and Decision Graphs. New York, NY, USA: Springer-Verlag. ISBN 978-0-387-68281-5.

Kaplan, M., Benatar, M., Bentson, J and Achtarides, T A. (1984). Analysis and assessment of major uncertainties associated with ship hull ultimate failure. Report No. SSC-322, Ship Structure Committee, Washington DC, USA.

Kass, G., 1980. An exploratory technique for investigating large quantities of categorical data. Applied Statistics 29, 119–127.

Khan, I A. And Das, P K (2008). Reliability analysis of intact and damaged ships considering combined vertical and horizontal bending moment. Journal of Ships and Offshore Structures 3, pp 371-384.

Kim et al. , Chou, F S, Tien. D (1980). Motions and hydrodynamic loads of a ship advancing in oblique waves. Trans SNAME; 88:225–56.

Kim, C H., Chou F S and Tien, D (1980). Motions and Hydrodynamic Loads of a Ship Advancing in Oblique Waves. Trans SNAME, Vol. 88, pp 225-56.

Kjærulff, U B and Madsen, A L (2008). Bayesian Networks and Influence Diagrams: A Guide to Construction and Analysis. Springer Science + Business Media, LLC. ISBN: 978-0-387-74100-0.

Kokotos, D and Smirlis, Y (2005), A classification tree application to predict total ship loss, Journal of Transportation and Statistics, Vol 8, No 2 Oct. 2005

Kokotos, D X and Linardatos, D S (2011). An application of Data Mining tools for the study of Shipping Safety in Restricted Waters. Safety Science 49, Issue 2, pp 192-197.

Korb, K B and Nicholson, A E (2004). Bayesian Artificial Intelligence. Chapman & Hall/CRC Press LLC. ISBN 1-58488-387-1.

Korvin-Kroukovsky, B V and Jacobs, W R (1957). Pitching and Heaving Motions of a ship in Regular Waves. Trans. SNAME. Vol. 65.

Kozlyakov, V V and Egorov, G V (1991). On the requirements to Hull Girder strength of sea-going ships insuring their survivability when damaged, SUDOSTROENIE (Shipbuiliding), 6, 7 – 10.

Kuikka, S., Hildén, M., Gislason, H., Hansson, S., Sparholt, H and Varis, O (1999). Modelling environmentally driven uncertainties in Baltic cod (Gadus morhua) management by Bayesian influence diagrams, Can. J. Fish. Aquat. Sci. 56 (1999), pp. 629–641.

Kutt L M, Chen, Y K and Piaszczyk, CM (1985). Evaluation of Longitudinal Ultimate Strength of Various Ship Hull Configurations. SNAME Trans, Vol. 93, pp 33-55.

Laboratory Decision Systems. 1998. GeNIe User Manual. University of Pittsburgh, Available on http://genie.sis.pitt.edu/about.html#genie.

Langseth, H and Nielsen, T (2003). Fusion of Domain Knowledge with Data for Structured Learning in Object-Oriented Domains. Journal of Machine Learning Research, Special Issue on the Fusion of Domain Knowledge with Data for Decision Support, vol. 4, pp. 339-368.

Larrabee, R D (1978). Stochastic analysis of multiple loads: load combinations and bridge loads. Ph.D. Thesis, Department of Civil Engineering, MIT, Cambridge, MA, USA.

Larrabee, R D and Cornell, C A (1981). Combination of various load processes. J. Struct. Div., ASCE , 107, 223-238.

Lauritzen, S and Spiegelhalter, D J (1988). Local Computation and Probabilities on Graphical Structures and their Applications to Expert Systems. Journal of Royal Statistical Society, 50(2), 157-224.

Lee, C M and Curphey, R M (1977). Prediction of motion, stability and wave load of small-waterplane-area, twin-hull ships. Trans SNAME, Vol. 85, pp 94-130.

Lee, D., Lee, S S., Park, B J nad Kim, S Y (2005). A study on the framework for survivability assessment system of damaged ships. Journal of Ocean Engineering, Vol. 32, pp 1122-1132.

Lewis, E V et al (1973). Load criteria for ship structural design. Report No. SSC-224, Ship Structure Committee, Washington, DC, USA.

Liu, P L., Lin, H Z and Der Kiureghian, A (1989). CALREL (CAL-Reliability): A general purpose structural reliability analysis program. Report UCB/SEMM 89/18, University of California, Berkeley.

IHS Fairplay (2009). Maritime Intelligence and Publications: IHS Fairplay. London, UK.

Loh, W Y and Shih, Y S (1997). Split Selection Methods for Classification Trees. Statistical Sinica 7:815–840.

Lützen M., Simonsen B C (2003). Grounding damage to conventional vessels,. World Maritime Technology Conference, San Francisco.

Lützen, M (2001). Ship Collision Damage, Ph.D. Thesis. Technical University of Denmark, www.mt.mek.dtu.dk/reports/PHDthesis/index.htm.

Lützen, M and Simonsen, B C (2003). Grounding damage to conventional vessels. World Maritime Technology Conference, San Francisco.

Lützen, M., Simonsen, B C and Pedersen, P T (2000). Rapid Prediction of Damage to Struck and Striking Vessels in a Collision Event. Proceedings of Ship Structures for the New Millennium: Supporting Quality in Ship Building. Arlington.

Maestro, M and Marino, A (1989). An Assessment of the structural capability of damaged ships, the plastic approach in longitudinal unsymmetrical bending and influence of buckling. Journal of international shipbuilding progress, 36 (408): 355-365.

Mansour , A E and Thayamballi, A (1993). Probability-based ship design procedures. Draft Report SR-1337, Ship Structure Committee, Washington, DC, USA (1993).

Mansour, A E (1974). Approximate probabilistic method of calculating ship longitudinal strength, Journal of Ship Research, 18 (3), 201–213.

Mansour, A E and Thayamballi, A (1994). Loads and load combinations. ship structure committee Report No. SSC-373.

Mansour, A E., Wirsching, P., Luckett, M., and Plumpton, A (1997). Assessment of Reliability of Ship Structures, Ship Structure Committee report SSC-398, Washington, DC.

Mayoss, R., Moore, C., Tagg, R and Letizia, L (2005). Development of damage extents, Deliverable of POP&C project [8], D3-31-RD-2005-14-1-0.

Melchers. R E (1999). Structural Reliability Analysis and Prediction, John Wiley & Sons Ltd. ISBN: 978-0-471-98771-0.

Merkhofer, M W (1987). Quantifying Judgmental Uncertainty: Methodology, Experiences and Insights. IEEE transactions on systems, man and cybernetics. Vol. SMC 17 No 5.

Meyerhoff, W K., Arai, M., Chen, H H., Dai,Y S., Isaacson, M., Jankowski, J., Jefferys, E R., Lee, S C., Mathisen, J., Richer, J.-P h., Riska, K and Rfmeling , J U (1991). Loads. Report of Committee 1.2, I n 11th Int. Ship & Offshore Structures Congress, Wuxi, China.

Moan , T (1995). Safety levels across different types of structural forms and materials - implicit in codes for offshore structures. SINTEF Report STF70 F95210, Trondheim, Norway.

Moan, T and Jiao, G (1988). Characteristic still-water load effects for production ships. Report M K / R 104/88, The Norwegian Institute of Technology, Trondheim, Norway.

Murphy, K (1998). Dynamic Bayesian Networks: Representation, Inference and Learning. Doctoral Dissertation, University of California. Berkeley, CA, USA.

Neapolitan, R E (1990). Probabilistic Reasoning in Expert Systems: Theory and Algorithms. New York, NY, USA: John Wiley and Sons, Inc.

Neapolitan, R E (2004). Learning Bayesian network. Prentice Hall. ISBN-10: 0130125342.

Newman, J N (1978). The theory of ship motions. Advance in Applied mechanics, Vol. 18, pp 221-83.

Norrington, L., Quigley, J., Russell, A and Van der Meer, R (2008). Modelling the Reliability of Search and Rescue Operations with Bayesian Belief Networks. Reliability Engineering & System Safety 93, Issue 7, pp 940-949.

NRC (1982). CBD-221 Limit State Design, Canadian Building Digest, Institute for Research in Construction, National Research Council, Canada.

Ochi, M K (1973) On prediction of extreme values. Journal of Ship Research. Vol. 17, No.1, pp 29-37.

Ochi, M K (1981). Principles of extreme value statistics and their application. Extreme Loads Response Symposium (SNAME), Arlington, VA, SNAME, pp 15-30.

Ogilive, T F and Tuck, E O (1969). A rational strip theory for ship motions, part I, Report No. 013, University of Michigan.

Ogilvie, T F and Tuck, E O (1969). A Rational Strip-Theory of Ship Motion: Part I. Dept. of Naval Architecture, The University of Michigan. Report No. 013.

Oliver, R M and Smith, J Q (1990). Influence Diagrams, Belief Nets and Decision Analisys. 1st edition. New York, NY, USA: John Willey & Sons Inc.

Ozguc, O., Das, P K. And Barltrop, N (2006). A proposed method to evaluate hull girder ultimate strength. Journal of Ship and Offshore Structures. Vol.1, No.4, pp 335-345.

Paik, J K and Thayamballi, A (2008). Reliability Assessment of Ships. CRC Press, Pages 9-1-9-38, ISBN: 978-1-4200-5132-9.

Paik, J K, Thayamballi, A K and Yang, S H (1998). Residual Strength Assessment of Ships after Collision and Grounding, Journal of Marine Technology, 35 (1):38-54.

Paik, J K. and Frieze, P A (2001). Ship structural safety and reliability, Progress in Structural Engineering and Materials. , 3 (2), 198–210.

Paik, J K. and Thayamballi, A K (2003). Ultimate limit state design of steel plated structures. John Wiley & Sons. ISBN 0-471-48632-9

Paik, J K., Thayamballi, A K and Lee, J M (2004). Effect of initial deflection shape on the ultimate strength behaviour of welded steel plates under biaxial compressive loads. Journal of Ship Research, vol. 48, No.1, pp 45-60.

Pearl, J (1988). Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference. San Mateo, CA, USA: Morgan Kaufmann Publishers.

Pedersen, P T (1994). Ship grounding and hull girder strength, Marine Structures, 7, 1-29.

Pedersen, P T (1995). Collision and grounding mechanics, WEMT, The Danish Society of Naval Architects and Marine Engineers.

Pedersen, P T (2002). Collision risk for fixed offshore structures close to high-density shipping lanes, Journal of Engineering for the Maritime Environmental, 216: M1, 29-44.

Pedersen, P T and Li, Y (2004). On the Global Ship Hull Bending Energy in Ship Collisions, Third International Conference on Collision and Grounding of Ships (ICCGS), 1–7, Izu, Japan, 25-27 October 2004.

Pedersen, P T and Zhang, S (2000a). On impact mechanisms in ship collisions, Journal of Marine Structures, 11, 429-449.

Pedersen, P T and Zhang, S (2000b). Absorbed energy in ship collision and grounding – revising Minorsky's empirical method, Journal of Ship Research, 44:2, 40-154.

Pedersen, P T and Zhang, S (2000c). Effect of Ship Structure and Size on Grounding and Collision Damage Distribution. Ocean Engineering 27: 1161-1179.

Pedersen, P T, Gluver, H and Dosen, D (1998). Proceedings of the International Symposium on Advances in Ship Collision Analysis, Copenhagen, Denmark, Ed., A.A. Balkema, Rotterdam, the Netherlands.

Pu, Y., Das, P K and Faulkner, D (1997), A Strategy for Reliability-Based Optimisation, Journal of Engineering Structures, vol. 19 (3), 276-282.

Rawson, C., Crake, K and Brown, A J (1998). Assessing the Environmental Performance of Tankers in Accidental Grounding and Collision. SNAME Transactions 106, pp 41-58.

Reason, J (1990). Human error. Cambridge University Press, Cambridge. ISBN 0-521-31419-4

Reason, J (2000). Managing the risks of organizational accidents. Ashgate, London.

Rice, S O (1954) Mathematical analysis of random noise. In Selected Papers on Noise and Stochastic Processes, (ed. N. Wax) Dover, NY, pp. 133-294.

Rutherford, S E. and Caldwell, J B (1990). Ultimate strength of Ships: a case study. Trans SNAME, 98: 441-71.

Salvesen, N., Tuck, E O and Faltinsen, O (1970). Ship motion and sea loads, SNAME Trans Vol. 78, pp 1-30.

Samuelidesa, M S., Ventikosa, N P and Gemelosa, I C (2009). Survey on grounding incidents: Statistical analysis and risk assessment. Journal of Ships and Offshore Structures, Volume 4, Issue 1, Pages 55 - 68.

Sandia National Laboratories (1998). Data and Methods for the Assessment of the Risks Associated with the Maritime Transport of Radioactive Materials Results of the SeaRAM Program Studies, SAND98-1171/2, Albuquerque, NM.

Shachter, R D. and Peot, M A (1990). Simulation Approaches to General Probabilistic Inference on Bayesian Networks. In M. Henrion, R. D. Shachter, L. N. Kanal & J. F. Lemmer (Eds.), Uncertainty in Artificial Intelligence 5. New York, NY: Elsevier Science Publishing Company, Inc.

Sirkar, J., Ameer, P., Brown, A J, Goss, P., Michel, K., Nicastro, F. and Willis, W (1997). A Framework for Assessing the Environmental Performance of tankers in accidental grounding and collision. SNAME Transactions.

Skjong, R and Vanem, E (2004a). Damage stability evaluation in collision and grounding of ships, Third International Conference on Collision and Grounding of Ships ICCGS, 97-103, Izu, Japan.

Skjong, R and Vanem, E (2004b). Damage stability evaluation in Collision of Bulk Carriers. ThirdInternational Conference on Collision and Grounding of Ships, ICCGS, Izu, Japan.

Skjong, R., Bitner-Gregersen, E., Cramer, E., Croker, A., Hagen,Ø., Korneliussen, G., Lacasee, S., Lotsberg, I., Nadim, F and Ronold, Ko (1995). Guidelines for Offshore Structural Reliability Analysis-General. Det Norske Veritas Report No 95-2018.

Smith, C S (1977). Influence of local compressive failure on ultimate longitudinal strength of a ship's hull. in: Proceedings of the PRADS: International Symposium on Practical Design in Ship Building, N. Zosengakkai, ed., Society of Naval Architects of Japan, Tokyo, Japan, pp.73-79.

Smith, C S and Dow, R (1981). Residual Strength of Damaged Steel Ships and Offshore Structures. Journal of Constructional Steel Research, Vol. 1, No. 4.

Smith, W E and Salvesan, N (1970).Comparison of Ship-Motion Theory and Experiment for Destroyer with Large Bulb. Journal of Ship Research. Vol. 14. No. 1.

Soding, H. (1979). The prediction of still-water wave bending moments in containerships. Schiffstechnik, 26, pp 24-41.

Sowa, J F (2000). Knowledge Representation: Logical, Philosophical, and Computational Foundations. Pacific Grove, CA, USA: Brooks/Cole.

Spiegelhalter, D J., Franklin, R., and Bull, K (1989). Assessment, Criticism, and Improvement of Imprecise Probabilities for a Medical Expert System. In Proceedings of the Fifth Conference on Uncertainty in Artificial Intelligence, pages 285-294. Mountain View, CA.

Svein Kristiansen (2005). Maritime Transportation, Safety Management and risk analysis. Elsevier, ISBN 0-7506-5999-8

Tagg, R., Bartzis, P., Papanikolaou, A., Spyrou, K. and Lützen, M (2002). Updated Vertical Extent of Collision Damage. Marine Structures, 15, pp 475-498.

Takikawa, M., d'Ambrosio, B and Wright, E (2002). Real-Time Inference with Large-Scale Temporal Bayes Nets. In Proceedings of the Eighteenth Conference on Uncertainty in Artificial Intelligence (UAI-2002), pp 477-484, University of Alberta. Edmonton, Alberta, Canada.

The International Tanker Owners Pollution Federation Limited (ITOPF) (2009). Oil tanker spill statistics. London (UK): ITOPF. http://www.itopf.com/

Tikka, K K (2001). Prediction of Structural Response in Grounding: Application to Structural Design. Ship Structure Committee Report, SSC-417.

Toro , G R (1984). Probabilistic analysis of combined dynamic responses. PhD. Thesis, Dept. of Civil Engineering, Stanford University, Stanford, USA.

Turkstra , C J (1970). Theory of structural design decisions study no. 2. Solid Mechanics Division, University of Waterloo, Waterloo, Ontario, USA.

Tzannatos, E (2002). GMDSS Operability: the operator-equipment interface. Journal of Navigation 55, pp 75-82.

Tzannatos, E (2005). Technical Reliability of the Greek Coastal Passenger Fleet. Marine Policy 29, pp 85-92.

Ueda, Y and Rashed, S M H (1984). The idealised structural unit method and its application to deep girder structures. Computers and Structures, Vol. 18, No. 2, pp 227-293.

UNCTAD (2008). Review of maritime transport. In: United Nations Conference on Trade and Development. United Nations, New york and Geneva.

Ursell, F (1949). On the heaving motion of a circular cylinder on the surface of a fluid. Journal of Mechanics and Applied Mathematics, Vol.2, pp 218-31.

Vanem E and Skjong R (2004), Collision and grounding of passenger ships—risk assessment and emergency evacuations, Proc. 3rd International Conference on Collision and Grounding of Ships, ICCGS 2004, Izu, Japan, October 25–27, 2004.

Wang, G., Chen, Y., Zhang, H and Peng, H (2002a). Longitudinal Strength of ships with accidental damages. Journal of Marine Structures 15,119-138.

Wang, G., Spencer, J and Chen, Y (2002b). Assessment of Ship's Performance in Accidents. Journal of Marine Structures, 15, 313-333.

Wang, X (1995). Reliability analysis of production ships with emphasis on load combination and ultimate strength. PhD Thesis, Department of Marine Structures, The Norwegian Institute of Technology, Trondheim, Norway.

Wang, X., Moan, T and Jiao, G (1994). Reliability analysis of production ships. Int. J. Offshore & Polar Engng,4, pp 302-311.

Watson, D G M (1998). Practıcal Shıp Desıgn. Elsevier Science ,ISBN: 9780080429991

Wen, Y K (1977). Statistical combination of extreme loads. J. Struct. Division, ASCE , 103,079-1093.

Wen, Y K (1990). Structural Load Modelling and Combination for Performance and Safety Evaluation, Elsevier, The Netherlands.

Yamamoto, Y., Fujino, M and Fukasawa, T (1978). Motion and longitudinal strength of a ship in head sea and effects of nonlinearities, 1st and 2nd Reports. Journal of Society of Naval Architects of Japan, pp 143-144.

Yao T (2000). Ultimate hull girder strength. Proceedings of the 14th International Ship and Offshore Structures Congress (ISSC), Japan, pp 321-91.

Yao, T (2003). Review Article: Hull Girder Strength. Journal of Marine Structures 16 pp 1-13.

Yao, T and Nikolov, P I (1991). Progressive collapse analysis of a ship's hull under longitudinal bending. Journal of Society of Naval Architects, Japan 170, pp. 449–461.

Zhang, S (2002). Plate tearing and bottom damage in ship grounding. Journal of Marine Structures 15, pp 101-117.

Zhu, L., James, P and Zhang, S (2002). Statistics and damage assessment of ship grounding. Journal of Marine Structures 15, pp 515-530.

List of Publications by the author (during the PhD Studies)

Subin, K K., Das, P K., Quigley, J and Hirdaris, S E (2011). Risk Analysis of Damaged Ships- A Data Driven Bayesian Approach. Journal of Ship and Offshore Structure, DOI:10.1080/17445302.2011.59235

Das, P K., Paul, P C and Subin, K K (2011). A revisit on design and analysis of stiffened shell structures for offshore applications. Marstruct 3rd International Conference on Marine Structures, Hamburg Germany.

Subin, K K, Das, P K and Quigley, J (2011). Ship accident consequence estimate using Bayesian Expert Judgement. International Conference on Mathematical Modelling and Applications to Industrial Problems, Calicut, India.

Subin, K K, Das, P K., Quigley, J and Hirdaris, S E (2010). Risk Analysis of Damaged Ships. 5th International Asranet Conference, Edinburgh, Scotland.

Subin, K K and Das, P K (2010). Reliability of Damaged Ship Structures. 5th International Asranet Conference, Edinburgh, Scotland.

Nana, Y., Subin, K K. and Das, P K (2010). Application of Response Surface Method for the Reliability Analysis of Stiffened Laminated Plates. 5th International Asranet Conference, Edinburgh, Scotland.

Paul, P C., Subin, K K And Das, P K (2010). Reliability Analysis of Stiffened Shell structures for Offshore Applications. 5th International Asranet Conference, Edinburgh, Scotland.

Appendix A: Marsden Grid

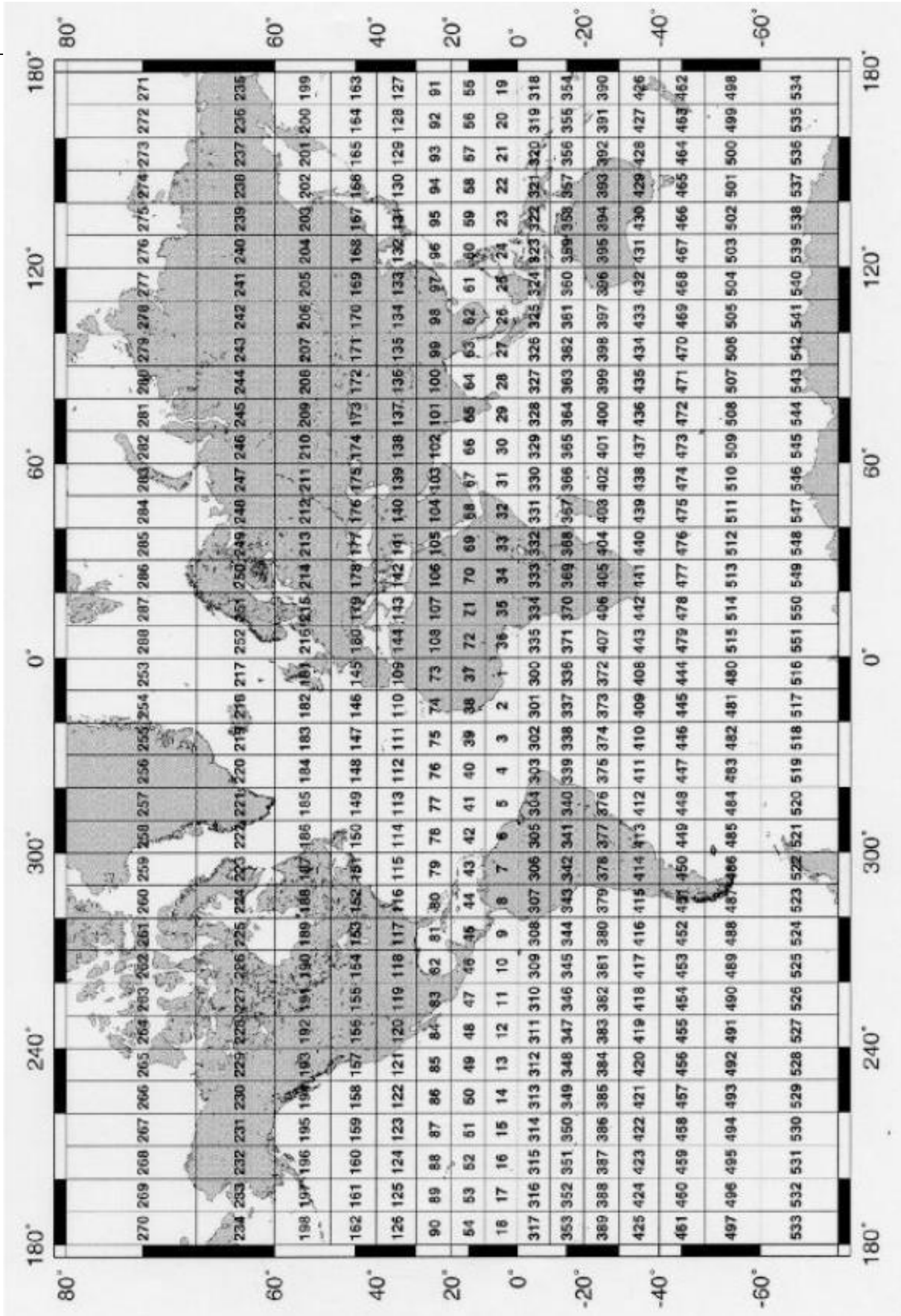


Figure A-1 Marsden Grid Map

Appendix B:

Introduction to Bayesian Belief Network

B.1 Probability Calculus

Theorem 1.1 (The fundamental rule).

$$P(A|B)P(B) = P(A \cap B) \qquad \text{Equation B-1}$$

That is, the fundamental rule tells how to calculate the probability of seeing both A and B when we know the probability of A given B and the probability of B. By conditioning on another event C, the fundamental rule can also be written as;

$$P(A|B \cap C)P(B|C) = P(A \cap B|C) \qquad \text{Equation B-2}$$

Since $P(A \cap B)$= $P(B \cap A)$ (and also $P(A \cap B|C) = P(B \cap A)|C$), we get that $P(A|B)P(B) = P(A \cap B) = P(B|A)P(A)$ from the fundamental rule. This yield the well-known *Baye's Rule:*

Theorem 1.2 (Bayes' Rule)

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \qquad \text{Equation B-3}$$

Baye's rule provides us with a method for updating our beliefs about an event A given that we get information about another event B. For this reason $P(A)$ is usually called the *prior* probability of A, whereas $P(A|B)$ is called the *posterior* probability of A given B; the probability $P(B|A)$ is called the likelihood of A given B.

B.2 Marginal and Conditional probability

The language of probabilities consists of statements (propositions) about probabilities of events. The probability of an event 'a' is denoted P (a). An *event* can be considered as an outcome of an experiment (e.g., a coin flip), a particular observation of a value of a variable (or set of variables), an assignment of a value to a variable (or set of variables), etc. As a probabilistic network define a probability distribution over a set of variables, V, in our context an event is a configuration, x ∈ Dom(X), (i.e., a vector of values) of a subset of variables X⊆ V. Computing P(X) from P (X, Y) using the rule of total probability is often called marginalization, and is written compactly as:

$$P(X) = \sum_i P(X, Y = y_i) = P_y(X, Y) \qquad \text{Equation B-4}$$

The conditional probability distributions of probabilistic networks are of the form P (X|Y), where X is a single variable and Y is a (possibly empty) set of variables. X and Y are sometimes called the head and the tail, respectively, of P(X|Y). If Y = φ (i.e., the empty set), P (X|Y) is often called a marginal probability distribution and is then written as P(X). This relation between X and Y = {$y_1 . . . y_n$} can be represented graphically, where the child vertex is labeled "X" and the parent vertices are labeled "y_1", "y_2", etc.

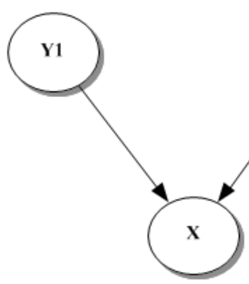


Figure B-1 Graphical representation of P (X|Y1. . . Yn).

The fundamental rule of probability for two variables X and Y is given by:

$$P(X, Y) = P(X/Y)P(Y)$$
$$= P(Y/X)P(X)$$

Bayes' rule follows immediately as:

$$P(Y/X) = \frac{P(X\ /\ Y))P(Y)}{P(X)} \qquad \text{Equation B-5}$$

$$= \frac{P(X/Y)P(Y)}{P(X/Y = y_1)P(Y = y_1) + \cdots + P(X/Y = y_n)P(Y = y_n)}$$

In fact Bayesian Network basically uses the fact that

$$Posterior = \frac{Likelihood \ \times Prior}{Probability\ of\ Evidence} \qquad \text{Equation B-6}$$

This is extended to the case of multiple events by the multiplication rule .If $A_1, A_2, \ldots, A_n$ are events of a probability space, we can impose multiple conditioning on them by using the conditional probability theorem.

$$P(A_1 \cap A_2) = P(A_2/A_1)P(A_1)$$

$$P(A_1 \cap A_2 \cap A_3) = P(A_3/A_1 \cap A_2)P(A_2/A_1)P(A_1)$$

$$P(A_1 \cap A_2 \cap A_3 \cap A_4) = P(A_4/A_1 \cap A_2 \cap A_3)\ P(A_3/A_1 \cap A_2)P(A_2/A_1)P(A_1)$$

$$P(A_1 \cap A_2 \cap A_3 \cap A_4 \cap A_5) \\ = P(A_5/A_1 \cap A_2 \cap A_3 \cap A_4)\ P(A_4/A_1 \cap A_2 \cap A_3)P(A_3/A_1 \cap A_2)P(A_2/A_1)P(A_1)$$

.

.

.

In general,

$$P(A_1 \cap A_2 \ldots \cap A_n) = \prod_{i=2}^{n} P(A_i/A_1 \cap \ldots \cap A_{i-1})P(A_1)$$

B.3 Introduction to Bayesian Networks

A Bayesian network is a graphical structure that allows us to represent and reason about an uncertain domain. The nodes in a Bayesian network represent a set of random variables from the domain. A set of directed arcs (or links) connects pairs of nodes, representing the direct dependencies between variables. Assuming discrete variables, the strength of the relationship between variables is quantified by conditional probability distributions associated with each node. The only constraint on the arcs allowed in a BN is that there must not be any directed cycles: you cannot return to a node simply by following directed arcs. Such networks are called directed acyclic graphs, or simply DAG's. One of the most important features of Bayesian networks is the fact that they provide an elegant mathematical structure for modelling complicated relationships among random variables while keeping a relatively simple visualization of these relationships. Bayesian Network comprises of a Qualitative part describing the structure and construction of the network as well as a Quantitative part describing the probabilistic, numerical part (functional aspects) of the network.

B.3.1 Bayesian Network - Qualitative Part

The graphical aspect of a probabilistic network is referred to as its *qualitative* aspect. Graphs have proven themselves as an intuitive language for representing such dependence and independence statements, and thus provide an excellent language for communicating and discussing dependence and independence relations among problem-domain variables. A large and important class of assumptions about dependence and independence relations expressed in factorized representations of joint probability distributions can be represented compactly in a class of graphs known as directed acyclic graphs (DAGs). The DAG is structurally classified into the nodes and the edges connecting the nodes.

A *chance variable* represents an exhaustive set of mutually exclusive events, referred to as the *domain* of the variable. These events are also often called states, levels, values, choices, options, etc. The domain of a variable can be discrete or continuous; discrete domains are always finite. The nodes represented as circles in the DAG are symbolic representation for the random variables from the domain. There are basically two categories of variables, namely variables representing random events and variables representing choices under the control of some, typically human, agent. Consequently, the first category of variables is often referred to as *chance variables* (or *random variables*) and the second category as *decision variables*.

The structure, or topology, of the network should capture qualitative relationships between variables. A set of directed arcs (or links) connects pairs of nodes, representing the different kinds of relations among the variables and utility functions. Assuming discrete variables, the strength of the relationship between variables is quantified by conditional probability distributions associated with each node.

A variable X is said to be a direct cause of Y if setting the value of X by force, the value of Y may change and there is no other variable Z that is a direct cause of Y such that X is a direct cause of Z. To correctly represent the dependence and independence relations that exist among a set of variables of a problem domain it is useful to have the causal relations among the variables represented in terms of directed links from causes to effects. That is, if X is a direct cause of Y, we should make sure to add a directed link from X to Y. If done the other way around (i.e., Y → X), we may end up with a model that does not properly represent the dependence and independence relations of the problem domain. Figure B-2 shows a typical Bayesian Network with 6 nodes.

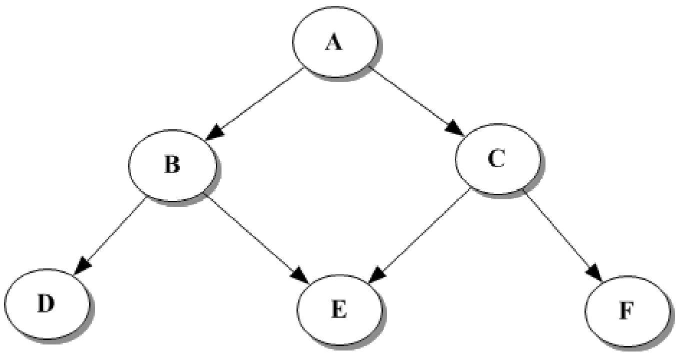


Figure B-2 Bayesian Network with 6 nodes

Common types of discrete nodes included in a Bayesian Network are as follows:

- **Boolean nodes**, which represent propositions, taking the binary values true (T) and false (F).

- In some situations, the nodes can take **ordered values** like; node *pollution* might represent a person's pollution exposure and take the values {*low, medium, high*}.
- The nodes can also represent random variables taking **Integral values** like a node called *Age* might represent a patient's age and have possible values from 1 to 100.

B.3.1.1 Terminology of the Bayesian Network structure

In talking about network structure it is useful to employ a standard nomenclature: a node is a parent of a child, if there is an arc from the former to the latter. If there is a directed chain of nodes, one node is an ancestor of another if it appears earlier in the chain, whereas a node is a descendant of another node if it comes later in the chain. In Figure B-2, the E node has two parents, B and C, while A is an ancestor of both D and F. Similarly, B is a child of A and parent of D and E. The set of parent nodes of a node E is given by Parents (E).

B.3.1.2 Types of Connections in the Network

There are basically three types of connections which we come across in a network, namely *serial connections, diverging connections* and *converging connections.* In Figure B-2, consider the connection $A \rightarrow B \rightarrow D \ or \ A \rightarrow B \rightarrow E$, is an example for a serial connection. In such type of a connection, Information may be transmitted through a serial connection X → Y ← Z unless the state of Y is known. The connection B ← A → C, is an example for a diverging connection. Here, Information may be transmitted through a diverging connection X ← Y →Z unless the state of Y is known. The connection B → E ← C, is an example for a converging connection where Information may only be transmitted through a converging connection X → Y ← Z if evidence on Y or one of its descendants is available. The property of converging connections, X → Y ← Z, that information about the state of X (Z) provides an explanation for an observed effect on Y, and hence confirms or disconfirms Z (X) as the cause of the effect, is often referred to as the *explaining away* effect or as *inter-causal inference*. The ability to perform inter-causal inference is unique for graphical models, and is one of the key differences between automatic reasoning systems based on probabilistic networks and systems based on, for example, production rules.

B.2.2 Bayesian Network - Quantitative Part

Once the topology of the Bayesian Network is specified, the next step is to quantify the relationships between connected nodes – this is done by specifying a conditional probability distribution for each node. In case we consider discrete variables, this takes the form of a *conditional probability table* (CPT). First, for each node we need to look at all the possible combinations of values of those parent nodes. Each such combination is called an instantiation of the parent set. For each distinct instantiation of parent node values, we need to specify the probability that the child will take each of its values.

After specifying topology, the Conditional Probability Tables (CPT) for each discrete node must be specified, such that

- Each row contains the conditional probability of each node value for each possible combination of values in its parent nodes
- Each row must sum to 1
- A CPT for a Boolean variable with n Boolean parents contains 2^{n+1} probabilities
- A node with no parents has one row (its prior probabilities).

Once a relationship has been discovered, the degree of the relationship is maintained in the conditional probability table (CPT). CPT represents the degree to which the sates of a child node are affected by all the states of its parents. This effect is calculated through a process known as *inference.* Unfortunately, this makes the size of the CPT grow exponentially with an increase in the number of possible parents. For instance a node with five states and two parents requires a CPT of 125 values, and that same node with 3 parents will require a CPT of 625 values. This exponential growth in the size of the CPT therefore limits the number of parents that a node can have. In response to this other storage mechanisms such as decision trees and decision graphs have been proposed to reduce the space requirement of the CPT.

In general, modelling with Bayesian networks requires the assumption of the Markov Property which asserts that there are no direct dependencies in the system being modelled which are not already explicitly shown via arcs.

B.4 Reasoning and Evidence in Bayesian Network

A Bayesian Network can very well represent domain and its uncertainty and hence can be used to reason about the domain. In particular, when we observe the value of some variable, we would like to condition upon the new information. The process of conditioning (also called probability propagation or inference or belief updating) is performed via a "flow of information" through the network. Note that this information flow is *not* limited to the directions of the arcs. In our probabilistic system, this becomes the task of com- putting the posterior probability distribution for a set of query nodes, given values for some evidence (or observation) nodes. Basic task for any probabilistic inference system is to compute the posterior probability distribution for a set of *query variables,* given new information about some *evidence variable* called *conditioning* or *belief updating* or *inference*

B.4.1 Types of Reasoning in Bayesian Network

Bayesian networks provide full representations of probability distributions over their variables. That implies that they can be conditioned upon any subset of their variables, supporting any direction of reasoning. One can perform diagnostic reasoning, i.e., reasoning from symptoms to cause which occurs in the *opposite* direction to the network arcs. One can perform predictive reasoning, reasoning from new information about causes to new beliefs about effects, following the directions of the network arcs. A further form of reasoning involves reasoning about the mutual causes of a common effect; this has been called inter-causal reasoning. A particular type called explaining away is of some interest. Suppose that there are exactly two possible causes of a particular effect, represented by a v-structure in the Bayesian Network. Also, the combination of diagnostic and predictive reasoning gives the combined reasoning. Figure B-3 shows the different types of reasoning.

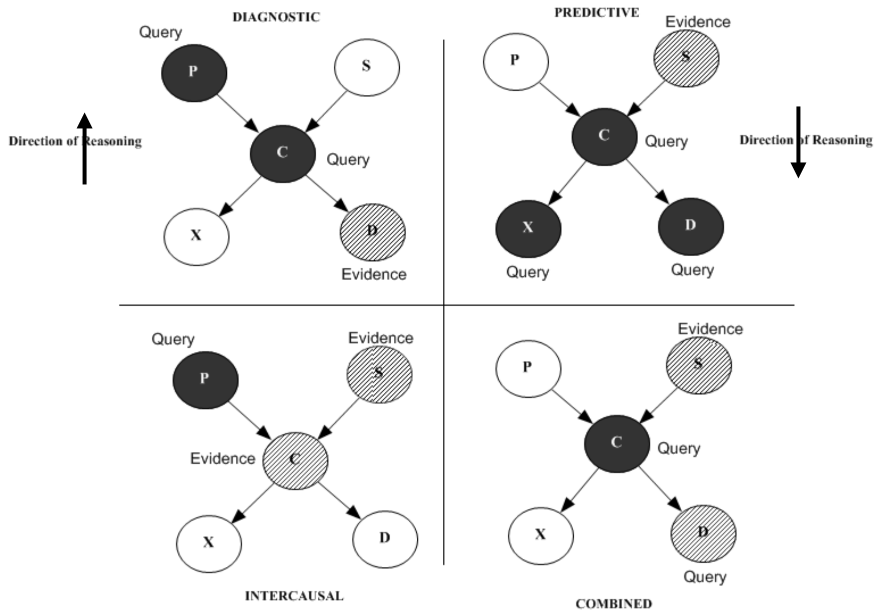


Figure B-3 Types of reasoning

B.5 Understanding Bayesian Network

Most commonly, Bayesian Networks are considered to be representations of joint probability distributions. There is a fundamental assumption that there is a useful underlying structure to the problem being modelled that can be captured with a Bayesian Network, i.e., not every node is connected to every other node. If such domain structure exists, a Bayesian Network gives a more compact representation than simply describing the probability of every joint instantiation of all variables.

Consider a Bayesian Network containing the n nodes X_1 to X_n, taken in that order. A particular value in the joint distribution is represented by $P(X_1 =$

$x_1, X_2 = x_2, \dots, X_n = x_n$) or more compactly, $P(x_1, x_2, \dots, x_n)$. The chain rule of probability theory allows us to factorize joint probabilities so:

$$P(x_1, x_2, \dots, x_n) = P(x_1) \times P(x_2|x_1) \times \dots \times P(x_n|x_1, \dots, x_{n-1})$$
$$= \prod_i P(x_i|x_1, \dots, x_{i-1})$$

Also, the structure of a Bayesian Network implies that the value of a particular node is conditional *only* on the values of its parent nodes, this reduces to

$$P(x_1, x_2, \dots, x_n) = \prod_i P(x_i|parents(X_i)),$$

provided $parents(X_i) \subseteq \{x_1, x_2, \dots, x_{i-1}\}$

B.6 Inference in Bayesian Network

The basic task for any probabilistic inference system is to compute the posterior probability distribution for a set of query nodes, given values for some evidence nodes. This task is called belief updating or probabilistic inference. Inference in Bayesian networks is very flexible, as evidence can be entered about any node while beliefs in any other nodes are updated. Different inference algorithms are suited to different network structures and performance requirements. Networks that are simple chains merely require repeated application of Bayes' Theorem. Inference in simple tree structures can be done using local computations and message passing between nodes. When pairs of nodes in the Bayesian Network are connected by multiple paths the inference algorithms become more complex. For some networks, exact inference becomes computationally infeasible, in which case approximate inference algorithms must be used. In general, both exact and approximate inferences are theoretically computationally complex. In practice, the speed of inference depends on factors such as the structure of the network, including how highly connected it is, how many undirected loops there are and the locations of evidence and query nodes.