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**AN INVESTIGATION INTO THE FEASIBILITY OF  
CONSTRUCTING A MATHEMATICAL MODEL OF  
SHIP SAFETY**

A THESIS IN PARTIAL FULFILMENT FOR  
THE DEGREE OF MASTER OF SCIENCE IN  
MATHEMATICS AT  
MASSEY UNIVERSITY

Ian Murray James Clarke

1996

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### **Abstract**

This thesis investigates the feasibility of developing a mathematical model to provide quantitative measures of total ship safety. Safety is an intuitive concept and is a subset of economic utility. There is economic pressure to transport goods at minimum cost and, without regulation, the frequency of shipping casualties could be unacceptably high.

Mathematical methods associated with elements that influence ship safety are reviewed. Techniques for analysing ships' structures, stability, motions and engineering reliability are well established, but those for assessing the effect of human involvement, and operational and organisational influences on safety are less developed. Data are available for winds, waves, currents and tidal movements, and their variability suggests that probabilistic models are appropriate.

Given the complexity of the international shipping industry, a simple computer model is developed in which 50 ships serve four ports. This allows safety to be assessed when input variables are adjusted. Obstacles to developing a mathematical model of ship safety are identified, and it is concluded that the feasibility of such a model depends on its required inclusiveness and utility.



## **Acknowledgement**

I thank Dr. Robert McKibbin, Senior Lecturer with the Department of Mathematics, Massey University, for his helpful supervision of this thesis, and for his valuable advice.



## Glossary of terms and abbreviations

**Bilges:** Wells or channels for drainage, located near the bottom of cargo holds or the engine room. Bilges also refer to the rounded part of a ship's hull between bottom and side plating.

**Block coefficient ( $C_B$ ):** The volume of displacement divided by the volume of a rectangular block with dimensions equal to the ship's length, the waterline breadth and draught.

**Bridge:** The navigational control station of a ship, comprising the wheelhouse, chart room and lookout decks.

**Bulkhead:** A vertical partition that divides a ship into compartments.

**Classification societies:** Independent societies that make rules for the construction of ships, approve plans and materials used in their construction, and carry out surveys on ships. Classification societies carry out statutory surveys on behalf of some national maritime administrations. See also IACS.

**Constructive total loss:** When a ship is damaged so that the cost of repair is greater or equal to the value of the ship.

**Cost benefit analysis (CBA):** A technique that attempts to evaluate the social costs and social benefits of an investment project.

**Deadweight (DWT):** The mass of cargo, water, fuel, stores and anything else that a ship carries.

**Depth (D):** The vertical distance from the bottom of the keel to the side of deck, measured at mid-length.

**Displacement (W):** The total mass of a ship and anything that it carries.

$$\text{Displacement} = \text{Lightweight} + \text{Deadweight}$$

**Draught (d):** The vertical distance from the underside of the keel to the waterline.

**Dynamic loading approach (DLA):** A computer based method for assessing stresses acting on a structure.

**Externality:** The effect the actions of one party have on the welfare of others who may have no direct financial interest in such actions.

**Failure mode and effect analysis (FMEA):** A formal method for analysing the effect of different types of failures.

**Finite element method (FEM):** A method in which a structure is divided into small elements for analysis.

**Freeboard (Fbd):** The vertical distance between a waterline and the side of the deck, measured at the mid-length of a ship.

**Founder:** To take in water and sink as a consequence of heavy weather or structural failure.

**Global positioning system (GPS):** An all-weather navigation system that can derive accurate positions from signals received from satellites.

**Global Maritime Distress and Safety System (GMDSS):** A distress and safety communication system that uses satellite communications as well as terrestrial radio to provide 24 hour coverage on a world-wide basis.

**Gross tonnage (GRT):** A measure of the size of a ship given by the formula specified in the International Tonnage Convention (1966):

$$\text{GRT} = (0.2 + 0.02 \cdot \text{Log}_{10} V) \cdot V,$$

where V is the total volume of enclosed spaces of a ship.

**Grounding:** Contact with the sea bed during the operation of a ship, for example by misjudgement of the limits of a channel.

**Heel:** Inclination of a ship about its longitudinal axis caused by an external force.

**Hogging:** Longitudinal bending of a ship caused by a resultant upward force at the mid-length and resultant downward forces near the ends. Opposite to sagging.

**Hydroelasticity:** The interaction between inertial, hydrodynamic and mechanical forces.

**International Association of Classification Societies (IACS):** An association of the major classification societies.

**International Convention for the Safety of Life at Sea (SOLAS):** Conventions agreed to by the maritime nations at international conferences held in 1914, 1929, 1948, 1960 and 1974. The conventions deal with many aspects of ship safety.

**International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW convention) 1978.**

**International Maritime Dangerous Goods Code (IMDG code):** A reference manual published by IMO giving details of dangerous goods (explosive, flammable, corrosive, etc.) and precautions for their carriage in ships.

**International Maritime Organisation (IMO):** The United Nations agency formed to promote co-operation among government in technical matters affecting shipping. The IMO has a responsibility for the safety of life at sea.

**Length (L):** Various definitions of ship's length are used: Overall length ( $L_{OA}$ ) is measured from the forepart of the stem to the aftermost part of the stern. Other lengths are: register length ( $L_R$ ), subdivision length ( $L_S$ ), waterline length ( $L_{WL}$ ) and length between perpendiculars ( $L_{PP}$ ).

**Lightweight (LWT):** The mass of an empty ship.

**Lifesaving appliances (LSA):** Lifeboats, davits, liferafts, lifejackets, buoyant apparatus and rescue boats.

**List:** A steady inclination of a ship about its longitudinal axis caused by an unsymmetrical distribution of mass.

**Load lines:** Marks indicating several maximum depths to which a ship may load in various circumstances.

**Margin line:** A reference line used in subdivision calculations, 75 mm below, and parallel to, a deck to which bulkheads form watertight compartments.

**Master:** The person in command of a merchant vessel.

**Metacentric height (GM):** The vertical distance between the centre of gravity and the transverse or longitudinal metacentre.

**Periodical survey:** Survey of hull, machinery and equipment at intervals (not exceeding five years) specified by a ship's national maritime administration.

**Pilot:** A person with local knowledge and ship-handling skills who navigates a ship in harbour or coastal waters. The master remains responsible for navigation and safety, but is usually obliged to follow the pilot's instructions. The word pilot also means a reference book for coastal navigation (eg. New Zealand Pilot).

**Principal dimensions:** Length (L), breadth (B) and depth (D), etc. of a ship.

**Response amplitude operator (RAO):** The ratio of reaction amplitude to excitation amplitude of forced harmonic motion in a linear system, as a function of frequency.

**Sagging:** Longitudinal bending caused by a resultant downwards force at the mid-length and resultant upward forces near the ends. Opposite to hogging.

**Scantlings:** The dimensions of components of a ship's hull structure, for example the thickness of plates, frames and girders. Originally the term applied to timber, but its use is extended to include steel components.

**Seakeeping:** The behaviour and movement of a ship in a seaway.

**Significant wave height:** The average height of the 1/3 highest waves.

Still water bending moments (SWBM): Longitudinal bending moments acting on a ship floating in still water. See also WBM.

Stranding: Driven ashore by force of weather.

Tactical diameter: The diameter of a ship's turning circle for a given speed and condition of loading.

Trim: The difference between the forward draught and the aft draught. When the keel is parallel to the water surface, a ship is on an even keel, otherwise the ship is trimmed by the head or by the stern, depending on which draught is greater

Twenty-foot Equivalent Unit (TEU): A measure of the capacity of a container ship, given by the number of ISO twenty-foot containers the ship can carry.

Unattended machinery space (UMS): Machinery space fitted with a control system and alarms, and with bridge control of propulsion machinery so that it does not require continuous manning by a duty engineer. Machinery space may be classed as UMS.

Wave bending moments (WBM): Longitudinal bending moments acting on a ship in a system of waves, usually considered for a wave system in the direction of the ship's longitudinal axis, with trough or crest amidships. See also SWBM.

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# Chapter 1

## A mathematical model of ship safety

This investigation was motivated by proposals that a scientific approach should be used for the assessment of total ship safety. Analytical methods are used in several areas of ship design and operation, but the techniques in use apply to particular problems, and not to the much wider concept of total ship safety. Safety involves technical processes such as designing, building and outfitting a ship, as well as the on-going management, operations and maintenance necessary to fulfil its commercial purpose. External hazards such as bad weather and vessel traffic need also to be considered. A scientific approach requires assessment on the basis of objective evidence and, given the nature of the problem, this raises doubts about whether such an approach is possible. Objective evidence implies quantitative measures, and it is the aim of this study to investigate the feasibility of developing a mathematical model that will enable the evaluation of relative levels of ship safety.

The concept of a scientific approach to total ship safety is not new, and in his book "The Safe Sea", Abell (1932) said:

*"If there is needed any guide to international understanding it is to be found in the agreements made in 1929 and 1930, by all maritime countries, to work to one code of conduct for all that makes for safety of life on their ships - the ships of the seven seas. These sea laws have been built up in a scientific way - first from the simple experiment, then the considered result, followed by another trial and perhaps error, repeated again and again, until the twentieth century sees the result of 120 centuries of sea adventure."*

Present day writers do not appear to share this view that safety should be allowed to evolve through trial and error, and advocate a more active approach to the assessment of total ship safety, including the development of mathematical models:

*"So the assessment of the 'fitness for purpose' of a ship must include not only a realistic analysis of the strength of the component parts but also an appraisal of the reliability of the safety of the ship as a single entity ... The latter necessitates the use of probabilistic techniques and mathematical modelling to include the effect of component interaction and of random occurrences such as human or material failure. Acceptable risk levels for possible hazardous events must be determined so that the performance of a ship, in terms of reliability and safety, can be rationally assessed and quantified for comparison purposes."*

(Aldwinckle and Pomeroy, 1982)

*"Safety does not depend only on the structural integrity of a vessel. Safety is commonly associated with the total integrity of a vessel. There is no doubt that the operational aspects have to be considered in addition to structural and seakeeping practice..."*

(Kwon, 1994)

The above statements, made twelve years apart, indicate that the need for assessment of total ship safety is well established, but that the methods and general approach are still under discussion. Casualty records show that during this twelve year period, 3206 ships with a total gross tonnage of more than 16.8 million were lost (Curry, 1995). The records are for ships with gross tonnage 100 and over, but do not include ships that were repaired after damage, nor do they indicate deaths, injuries, third party damage and damage to the environment as a consequence of ship casualties.

Casualties may result from material or equipment failure, incorrect judgement or action by mariners, poor organisation, a hostile environment, or from a combination of several factors. There is usually a significant element of chance in any accident, and ship owners are generally aware of the risks associated with operating ships. Known risks can be reduced by taking precautions, but this usually incurs an economic penalty, and while ship owners bear the full cost of safety precautions, they may not have to bear the full cost of accidents. The international safety conventions and national shipping safety regulations prescribe minimum standards for ship construction, equipment, and the qualification of seafarers. These regulations are introduced to improve particular aspects of safety, often as a reaction to particular types of casualties. However there are disadvantages to prescriptive regulations; attempts to minimise compliance costs can make the final outcome of a regulation uncertain, and can result in a poor reallocation of resources which may provide a lower overall standard of safety.

Recognising these disadvantages, the International Maritime Organisation (IMO) and other organisations involved with ship safety have considered alternatives to prescriptive regulations. The aim of most proposed alternatives is to provide means of showing that a ship achieves a level of safety performance that is at least equivalent to some standard. The following extract notes the desirability of defining and setting levels of safety (Cleary, 1989):

*"There has never been an actual equating of levels of safety in international regulations, in spite of equivalency statements included in each maritime convention requiring the Administration to maintain equal safety approaches to the published rules. It would be highly desirable for the nations gathered at IMO to state the target safety levels for each major safety function in the load line, SOLAS, MARPOL, and other IMO agreements and also to state the expected interactions between the main safety functions."*

Ship safety performance involves a complex interaction between many different factors, and the problem of defining, setting and measuring levels of safety has not been solved. This is evident in the following statement made by the House of Lords (1992) Select Committee on Science and Technology in its report: "Safety Aspects of Ship Design and Technology":

*"If ship regulation is to move from 'rule of thumb' to a more scientific basis, ship science must provide the regulators with the analytical tools to do the job"*

Total ship safety is a difficult concept to put into practice because its components are assessed in different ways, by different specialists, who may have different objectives from one another.

Tools that can be used in the definition and assessment of total ship safety still need to be developed and evaluated, and a mathematical model of ship safety could be one such tool.

It is necessary to question why a mathematical model should be of any help in assessing ship safety. Safety is a subjective quality, while mathematics deals with objective quantities. Safety arises from a complex and subtle interaction between materials, situations and objectives, while a mathematical model is an abstract, simplified view of reality, developed with a particular purpose in mind. There are great contrasts between the practice of safety and the discipline of mathematics, but the precision and clarity of mathematics may be utilised to make safety concepts more objective. Having said that, it is recognised that mathematical modelling is only one of a number of possible approaches to the improvement of safety assessment, and there have been developments in areas such as non-destructive testing, training of surveyors and the documentation and recording of inspections.

Mathematical methods are used in several areas that are important to ship safety. The finite element method is used extensively in structural evaluations, ship motions are derived from model tests using dimensional analysis and differential equations, and measures of equipment reliability are based on probability theory. These techniques are useful in the evaluation of parameters critical to ship safety, and it may be possible to combine such parameters with others so as to determine a measure of safety as a whole, rather than restrict the examination to whether a ship will fail under load, or how it will respond to a particular wave spectrum. Integrating safety elements is possible only when there is a suitable model, and without a mathematical model there may be no objective definition of total ship safety.

The process of building and evaluating models may promote improvement in ship safety. Concise expression of a problem in mathematical terms enables manipulation of the elements and encourages experiments. Standard mathematical theorems may simplify complex situations that are otherwise too difficult to solve, and isomorphisms can provide ready made solutions to difficult problems; for example the standard frequency distributions are used to model sea spectra, variable loads in a ship, navigational errors and the incidence of failure. Model building is in itself an iterative process in which objectives and attempted solutions are progressively refined. The development and use of mathematical models may thus focus and improve general ideas about ship safety.

The aim of this study is not to promote the advantages of a mathematical model of ship safety, but to evaluate its feasibility. The feasibility of a model depends on what it is expected to achieve, and while it may be entirely feasible to create models that will reflect safety in some way, this may not be particularly useful. A model in which the level of safety is calculated simply by entering measurable ship variables into a formula would obviously be useful, but given the complexities and uncertainties of individual safety elements, it seems unlikely that such a model could be developed. The evaluation must therefore recognise the trade-off between utility and feasibility in models.

In this study, Chapter 2 examines the concept of total ship safety, and looks at ways in which it can be measured or expressed in mathematical terms. Chapter 3 discusses safety in the context of the international shipping industry, and reviews the possible safety objectives of shipping companies and institutions associated with shipping. Chapter 4 focuses on the elements that affect safety and examines the mathematical methods that are available for their detailed analysis. Some of the approaches discussed are incorporated into a simple computer model of ship safety which is described in Chapter 5. In Chapter 6 the findings are reviewed and the feasibility of a mathematical model of ship safety is discussed.

