Structural Failure of Large Bulk Ships

Report

Although it is widely known that the risk of failure is high in old ships, old bulk ships continue to be used. One reason is that until mid 1992 it was financially viable to maintain an old ship in service rather than dispose of it for demolition. Even though after mid 1992 it did not pay to keep an old ship in service, it was even less attractive to purchase a new ship. The BTCE's statistical analysis of voyage data identified ship age, flag state, commodity carried and voyage route as important factors influencing the risk of failure. Using this information, the BTCE has developed a technique for predicting the risk of failure of individual ships.

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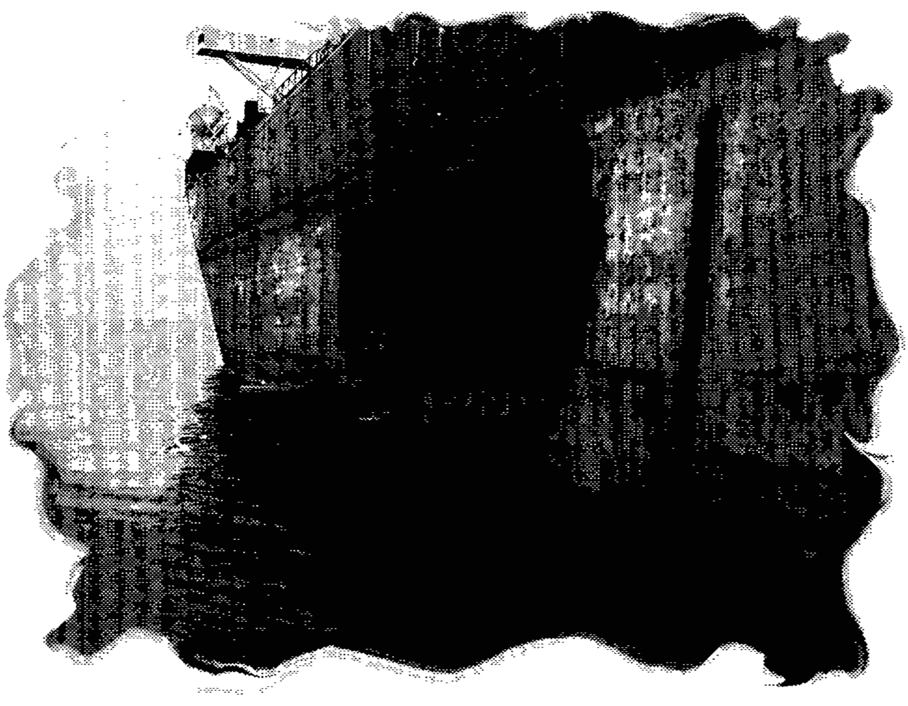
STRUCTURAL FAILURE OF LARGE BULK SHIPS

BUREAU OF TRANSPORT AND COMMUNICATIONS ECONOMICS

REPORT 85



Australian Government Publishing Service, Canberra

ISSN 1034-4152
ISBN 0 644 33027 9

Produced by The Australian Government Publishing Service

FOREWORD

The question of what to do about sub-standard bulk ships has become much more prominent in recent years. The number of bulk ships suffering major structural failures is more than is reasonably acceptable. Too many lives have been lost.

Several studies have been made in search of the reasons for ship losses. The most recent of Australian investigations was that of the House of Representatives Standing Committee on Transport, Communications and Infrastructure. This broad ranging study considered the commercial and regulatory environment in which bulk ships operate. It made an important contribution to understanding the main issues. Other investigations have focused on the technical aspects of ship failure.

The Department of Transport and Communications requested the Bureau of Transport and Communications Economics (BTCE) to undertake a statistical analysis to check if there were any factors unique to Australian bulk trades that might add to the risk of structural failure of ships carrying our exports. This study by the BTCE also takes a deeper look at the evidence in an attempt to uncover further insights into the issues.

The study team was lead by Neil Gentle assisted by Stephen Wheatstone and Josephine Salmi. Dr Trevor Breusch of the Department of Statistics at the Australian National University provided valuable advice to the team on statistical methods.

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Bureau of Transport and Communications Economics
Canberra
December 1993

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ABSTRACT

Between October 1989 and December 1991 50 dry bulk ships worldwide (including nine departing from Australia) suffered structural failure.

Currently, it is financially more attractive to operate old ships ready for scrapping than to invest in new ships. Although higher freight rates would be required to warrant investment in new ships, increased freight rates would also improve the attractiveness of maintaining old ships in service. Clearly, freight rate increases on their own cannot alter the balance in favour of improved ship safety.

One option to reduce the risk of structural failure is to improve inspections by port state surveyors. Australia and other countries are now more vigilant in their inspection programs. Evidence suggests these countries are being more successful at detecting unsound ships. However, port state surveyors have only limited time to assess a ship, and a thorough structural inspection is not normally possible.

The BTCE's statistical analysis of voyage data identified ship age, flag state, commodity carried and voyage route as important factors influencing the risk of failure. Using this information, the BTCE has developed a technique for predicting the risk of failure of individual ships.

If the BTCE's technique had been applied over the study period, 93 per cent of ships that failed would have been identified in an inspection of one in three ships. (This is the same proportion of ships as currently inspected by the Australian Maritime Safety Authority).

Insurance companies could use similar techniques to assist them to set premiums that more accurately reflect the risk of failure.

Insurance companies have a financial stake in reducing the risk of failure. They are already adjusting premiums to reflect the risk associated with different classes of ships. BTCE analysis suggests that premiums set on the basis of age, commodity carried, voyage route, current flag state, and history of ownership, flag state and classification society could be instrumental in reducing the number of bulk ships that suffer from structural damage. Potentially risky ships would then attract high premiums, making continued operation on risky voyages commercially unattractive.

SUMMARY

Between October 1989 and December 1991 nine dry bulk ships suffered structural failure after departing from Australian ports. During the same period 50 dry bulk ships (including the nine departing from Australia) failed throughout the world. Many of these ships sank and the evidence of the cause of failure was lost with them.

Although it is widely known that the risk of failure is high in old ships, old bulk ships continue to be used. One reason is that until mid 1992 it was financially viable to maintain an old ship in service rather than dispose of it for demolition. Even though after mid 1992 it did not pay to keep an old ship in service, it was even less attractive to purchase a new ship.

Some commentators have proposed that higher freight rates would improve the financial attractiveness of new ships, but, although this is indeed a necessary condition before a large-scale renewal of the bulk fleet can be expected, increased freight rates would also improve the attractiveness of maintaining old ships in service.

Clearly, freight rate increases on their own cannot reduce the number of bulk ship failures.

One option to reduce the risk of structural failure would be to improve port state control inspections. Improvements are being implemented in Australia and elsewhere. There is some evidence that this is having an effect in the detection of unsound ships. However, port state surveyors have only limited time to assess a ship, and a thorough structural inspection is not normally possible.

The BTCE has used statistical techniques to analyse voyage data to identify the most important factors associated with the risk of failure of dry bulk ships. The technique used (logit analysis) allows the relative importance of the possible factors to be estimated.

Ship age, flag state, commodity carried and voyage route were all found to be important factors in structural failure of bulk ships. Ships are most likely to fail where there is a combination of these factors. The route taken was found to be an especially important factor.

The flag state of the ship was found not to have as great an influence on risk of failure as frequently suggested. Nevertheless, a ship registered with a flag state with a high casualty rate was found to have the same risk of failure as a ship five years older registered with a flag state with a low casualty rate.

Of particular interest is whether there are unique factors associated with ships departing from Australian bulk ports that could increase the risk of failure. Statistical analysis showed that, although there were significant differences in age, size and flag state of ships between the various routes analysed, the differences did not indicate any particular factor likely to increase the risk of failure. When allowance was made for commodity carried and voyage route, no significant difference was found in the risk of failure between individual Australian ports of departure.

Can the results help identify the ships at risk?

The Australian Maritime Safety Authority currently inspects about 34 per cent of all ships visiting Australian ports. On the basis of a method developed by the BTCE, inspection of that proportion of bulk ships in the sample of voyages analysed would have identified for inspection 93 per cent of ships that subsequently failed. Even greater certainty could be achieved by inspecting more ships.

A recent change in ownership, flag or classification society is often considered to be a good indicator of poor ship condition. These factors could not be included in the BTCE analysis. However, the BTCE method used in conjunction with knowledge of recent change of ownership, flag or classification society could identify an even larger proportion of ships at risk of failure.

Similar techniques could assist insurance companies to set premiums that more accurately reflect the risk of failure.

Insurance companies have a financial stake in reducing the risk of failure. They are already taking a much more active role in adjusting premiums to reflect the risk associated with different classes of ships. The BTCE analysis suggests that premiums set on the basis of age, commodity carried, route, current flag state and history of ownership, flag state and classification society could be instrumental in reducing the number of bulk ships that suffer from structural damage. Potentially risky ships would attract high premiums, making continued operation on risky voyages commercially unattractive.

CHAPTER 1 INTRODUCTION

Six dry bulk ships carrying iron ore were lost at sea between October 1989 and December 1991 after loading at Western Australian ports (*Daily Commercial News* 1992; Lloyd's Register of Shipping 1992a). A further three ships suffered severe structural damage but were able to reach a port. Over the same period, another 41 dry bulk ships throughout the world suffered structural failure.[1] Although some were able to reach a port for repairs, many sank.

Classification societies,[2] such as Lloyd's (Lloyd's Register of Shipping 1992a), Nippon Kaiji Kyokai (NKK 1992) and the American Bureau of Shipping (ABS 1992), carried out technical investigations in response to losses of bulk ships, to establish the physical causes of failure.

Australia's House of Representatives Standing Committee on Transport, Communications and Infrastructure (HORSCOTCI) examination of ship safety took a much broader approach, including the commercial and regulatory environment of the industry (HORSCOTCI 1992a, p. x). HORSCOTCI considered that the underlying cause of the decline in the safety of bulk ships was the poor state of the bulk ship market. According to HORSCOTCI, low freight rates have meant that old ships cannot be replaced profitably, resulting in the ageing of the bulk ship fleet. Maintenance effort is reduced as owners seek to reduce costs, eventually contributing to a loss of structural integrity.

For example, Fearnleys (1992a) reported that the average age of dry bulk ships was 11.7 years in January 1992, compared with 11.4 years in July 1991. Over the same period, the average age of combination ships[3] increased from 14.1 to 14.3 years. The ageing of both of these fleets has aroused concern, as the majority of ships that have been lost since 1989 were over 15 years old (Lloyd's Register of Shipping 1992a).

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1. Throughout this report a ship is defined to have suffered a structural failure if the damage is of a severity that prevents the ship from completing a voyage. That is, the ship is either lost at sea or it must interrupt its voyage to undergo repairs.
2. Classification societies were originally developed to carry out surveys of ships' hulls on behalf of insurance underwriters. Their role has since expanded and they now carry out these responsibilities on behalf of owners and as agents for some flag states (HORSCOTCI 1992a, pp. 17–18).
3. Combination bulk ships are able to carry either dry or liquid bulk commodities.

HORSCOTCI also found that there was a general failure in regulatory arrangements: unsafe ships were being classified as structurally sound and allowed to continue operating. The standards were adequate; the problem lay in enforcing compliance with the standards.

Insurance companies were also seen as slow to react to increased bulk carrier losses (HORSCOTCI 1992a, p. xvii). The insurance industry has in the past relied solely on inspections by the classification societies to ensure that the ships they insured were safe. However, HORSCOTCI found that insurance companies are now taking a more active interest in the previous record of ships and their owners before agreeing to extend insurance.

HORSCOTCI concluded that international economic conditions and regulatory failure had been major factors in the loss of bulk ships in recent years.

Although HORSCOTCI's findings are relevant to bulk shipping as a whole, there still remains the possibility that other factors may have contributed to structural failure of ships departing from Western Australia. Of particular interest are the following questions:

- Why have ships carrying iron ore from Western Australia experienced more losses than ships carrying other commodities, such as coal and grain, from other Australian States?
- Are the risks to iron ore ships departing from Australia dependent on the trade route?
- Are the risks to iron ore ships departing from Australia greater than for those departing from other major exporting countries?

METHOD

The BTCE adopted a statistical approach to help isolate factors that may contribute to the risk of structural failure in bulk ships.

Reports of engineering studies of structural failure were used to identify major likely physical causes. The major problem in analysing structural failure is that ships frequently sink after suffering structural failure, so evidence of the physical causes of failures is limited. Where data were not available for variables that might be considered important to structural integrity (for example, quality of maintenance) proxy variables were used.

An especially difficult statistical problem involved the small number of failures compared with the overall number of voyages undertaken by bulk ships. For example, from mid 1989 to mid 1992, out of approximately 47 000 voyages by large bulk ships (over 30 000 deadweight tonnes) throughout the world, 50 ships were lost through structural failure; that is, one ship was lost for every 940 voyages. Because of the small number of failures, conventional statistical techniques can identify the factors that influence the risk of failure, but cannot estimate the relative strengths of the factors or the interactions between them. Logit analysis was used to overcome these problems.

The BTCE also found it useful to consider structural failures in the wider context of commercial pressures on bulk ship operators, particularly the continued operation of sub-standard ships.

THE DATA

The BTCE purchased Lloyd's voyage data for bulk ships departing from Australia and from the major bulk exporting countries of Brazil, India, South Africa and the United States of America, for voyages over the period from May 1990 to May 1992. These data allowed a detailed examination of route and ship characteristics relevant to the ship at the time of the voyage.

Voyage data were not purchased for the full period for which casualty data were obtained, or for all bulk ship movements. However, the voyage sample of, approximately 29 000 voyages was considered a reasonable compromise between costs and effectiveness of the analysis, and included 60 per cent of the known failures examined (see appendix I).

Changes to name, owner, flag or classification society are frequently suggested as strong indicators of a sub-standard ship, but information was not available on these variables. To this extent the analysis does not capture the full set of variables that help determine the risk of failure.

CHAPTER 2 FACTORS CONTRIBUTING TO STRUCTURAL FAILURE

Understanding the interaction between factors contributing to ship failure is clearly important in the development of an understanding of the failure mechanisms. For purposes of analysis, the likely factors influencing risk of failure can be classified into four broad categories: vessel condition, commodity, weather conditions, and operating conditions. These factors are examined below. Further details of aspects of structural failure are provided in appendix II.

VESSEL CONDITION

In nearly all structural failures of bulk ships, the failure was preceded by water being taken in one or more holds. Loss of side shell plating frequently features in ship failures (Lloyd's Register of Shipping 1992a; NKK 1992).

However, the events that are the immediate precursor to failure generally have a long gestation period. Lloyd's (Lloyd's Register of Shipping 1992a) and the American Bureau of Shipping (ABS 1992), among others, point to corrosion and metal fatigue as major causal factors leading to deterioration in the integrity of a ship's structure.

Corrosion

All ships corrode. Preventive systems are therefore normally included in the design and construction of ships to limit the onset and progression of corrosion. Common methods are the application of protective coatings and the use of cathodic protection systems. It is also common design practice to use thicker plates to allow for some wastage of metal through corrosion over the life of the vessel.

If protective coatings and other anti-corrosion systems are not maintained, corrosion is likely to weaken structures to the point where they are unable to withstand the stresses they were designed for.

Some cargoes, such as coal, may accelerate the deterioration of protective coatings and thus promote corrosion (ABS 1992; Lloyd's Register of Shipping

1992a; NKK 1992). Coal cargoes can become hot enough for sulphur compounds and moisture in the coal to form acid. The acid condensing on the inner surfaces of the hold attacks the structural components of the ship. Unchecked, the resultant corrosion can lead to serious wastage of metal in critical structural components of the ship.

Metal fatigue

Ships are designed so that stresses in the ship structures are below the metal fatigue endurance limit (that is, the level of stress at which the structure will fail after it has endured a history of cyclic stresses — see appendix II for further detail).[1] Because of this, fatigue failure is not normally a part of design considerations.

However, corrosion resulting in reduction of metal thickness at points of high stress loads will lead to an increase in stress within the structure. It may not require much loss of metal to increase stresses to a level which exceeds the endurance limit. Roughening of the surface of the metal, through corrosion or physical damage, also reduces the endurance limit.

Unloading procedures for bulk ships often require the use of heavy grabs, which can be as heavy as 35 tonnes when empty (Lloyd's Register of Shipping 1992a). The grabs, and bulldozers and pneumatic equipment used to remove adhering and inaccessible cargo, can easily damage the structure. If the damage is not repaired, it can act as points of stress concentration, thus creating conditions favourable to the initiation of fatigue cracks.

Age

With poor maintenance, the initial damage from corrosion and fatigue can spread until the structure is seriously weakened. The effects of corrosion and fatigue in combination with poor maintenance may build up over several years before the risk of failure becomes unacceptably high. Older ships may thus be at higher risk of failure than newer ships.

Figure 2.1 illustrates the influence of age on the risk of failure of bulk ships. 'Expected' failure rates were estimated under the assumption that age has no influence on the risk of failure, and that risk of failure is proportional to the exposure to risk as measured by the number of voyages.

The figure indicates that ships older than 14 years experienced many more failures than 'expected' and those less than 10 years old failed less often than 'expected'. Ships in the 10- to 14-year age group failed about as often as would

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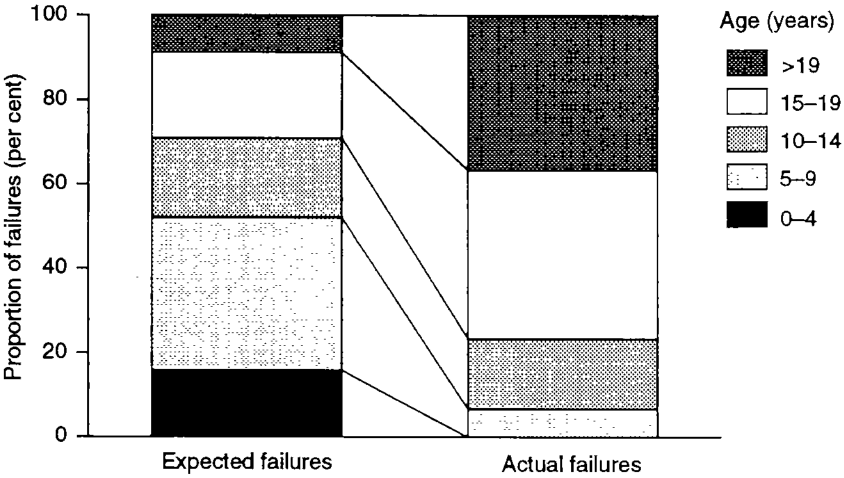
1. Cyclic stresses applied to steel can eventually result in the failure of the metal. For mild steel, if the cyclic stress is less than a specific value (the endurance limit) no failure will occur. Above this limit, failure usually occurs after 1 to 10 million stress cycles.



Note Expected failures are calculated by assuming that risk of failure is proportional to the number of voyages.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.1 Age and failure rate BTCE

be expected on the basis of voyage numbers.The analysis in appendix table III.1 shows that this is a statistically significant result; that is, age is in fact associated with failures.

Surprisingly, the number of actual failures of ships over 24 years old was not significantly higher than the 'expected' number of failures (appendix table III.1). The 'expected' number of failures was less than one, and in fact there were no actual failures. This result may be due to the relatively small number of ships in this age group in the data sample used. If ships in this age group do have an elevated risk of failure the actual number of failures would still be relatively small. The fact that there are none is not inconsistent with age being a factor. The relatively small size of these older ships may also be a factor.

Ships over 24 years old also have a fundamental difference in their structural design compared with newer ships. In the early 1970s the classification societies changed the method of determining the thickness of the steel components used to construct the ship's structure. Prior to this period sizes were determined by rules based on experience. These rules generally incorporated sizeable safety factors to reflect the lack of knowledge of the behaviour of ship structures. When sophisticated computer analysis became available in the early 1970s, shipbuilders could estimate stresses in ship structures more accurately. The improved accuracy of stress calculations reduced the need for allowances for unknowns, so structural redundancy could be reduced, leading to more economical designs with reduced plate thicknesses. However, the thinner plates have less tolerance to wastage through corrosion.

Flag state

Flag state[2] has attracted considerable attention as a possible indicator of the risk of ship failure (DCN 1992). Owners are considered likely to register their ships with flag states whose standards are compatible with the owner's approach to maintenance. If this is so, then it can be expected that ships registered with states with poor maintenance standards would be likely to exhibit greater than average failure rates.

To test this hypothesis, flags were ranked according to casualty experience of all ships in their fleets. Flags were then classified into four categories (A to D), so that each category contained approximately one-quarter of the world bulk fleet in terms of gross registered tonnage. The category containing flags with the largest loss rate was category D while category A contained the flags with the smallest loss rate. The categories were determined using loss ratios for each flag state calculated by the UK Institute of London Underwriters (Commission of European Communities 1993) for the period 1987 to 1991, as follows. The loss ratio is calculated as the ratio of the total gross tonnage of the losses for a year divided by total registered gross tonnage of the fleet, expressed as a percentage. Note that the loss ratio reflects the losses of all ships, not just bulk carriers, in the fleet of each flag state. The world average loss ratio for the period was reported as 0.29 per cent. The four groups were:

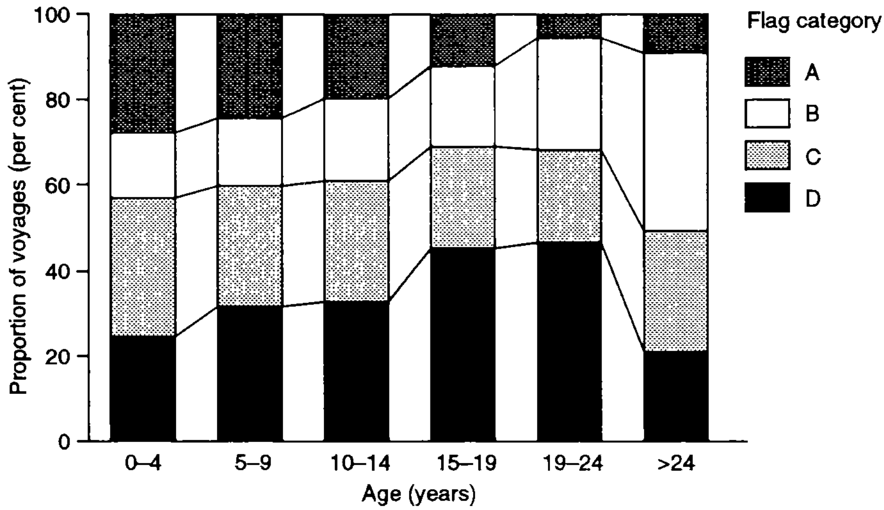
D >0.44 per cent
C >0.23 and ≤0.44 per cent
B >0.12 and ≤0.23 per cent
A ≤0.12 per cent

Figure 2.2 shows the proportion of bulk ship voyages in the BTCE database in each age group in each flag category. There appears to be a clear tendency for older ships (15 to 24 years) to be registered with flag states in the D category. Similarly older ships tend not to be registered with flag states in the A category.

There appears to be a contrary tendency for ships over 24 years old. A possible explanation is that ships older than 24 years and still in service are those most likely to have been well maintained throughout their lives. Poorly maintained ships registered with D flags are likely to have been scrapped before they reached 24 years old, so that the remaining ships over 24 years will be more likely to be those registered with the other flag categories. Unfortunately, the data to test this explanation were not available.

If flag is an indicator of risk of failure of bulk ships, then the proportion of bulk ship failures should be less for the A category than for the D category. This is in fact observed for the actual failures shown in figure 2.3. The D category had

2. The country in which a ship is registered and which undertakes the responsibility for the implementation of international conventions relating to that ship (HORSCOTCI 1992a, p. 13).

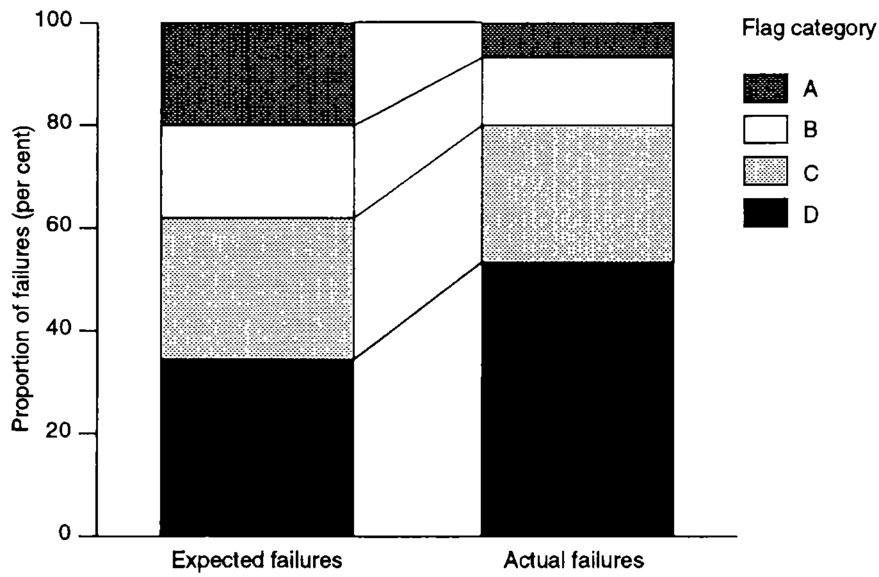


Note See text for definition of flag category.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.2 Flag and age

BTCE

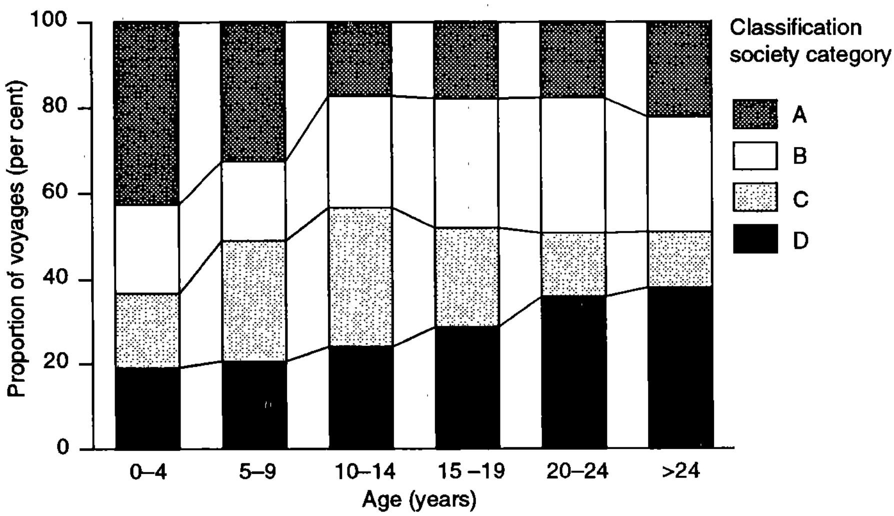


Notes 1. Expected failures are calculated by assuming that risk of failure is proportional to the number of voyages.
2. See text for definition of flag category.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.3 Flag and failure rate

BTCE

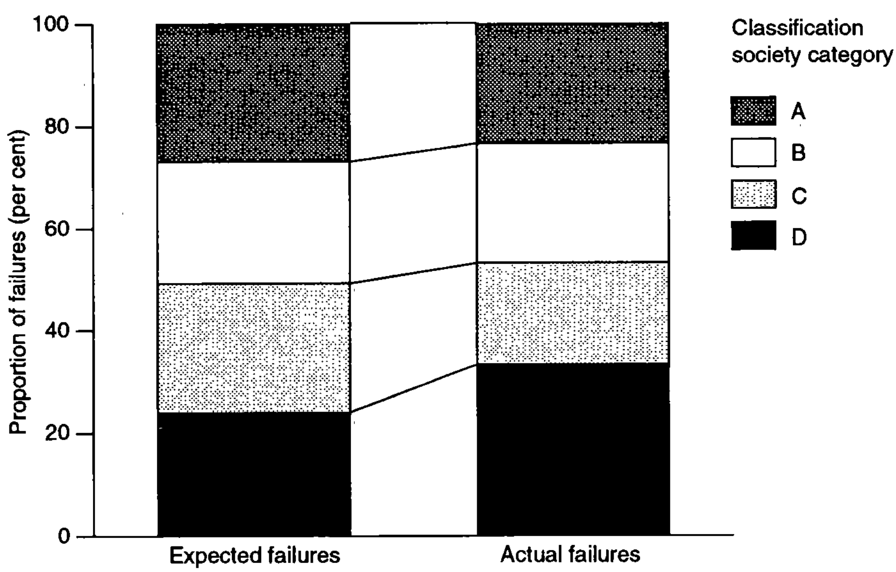


Note See text for definition of classification society category.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.4 Classification society and age

BTCE



Notes 1. Expected failures are calculated by assuming that risk of failure is proportional to the number of voyages.
2. See text for definition of classification society category.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.5 Classification society and failure rate

BTCE

more bulk ship failures than would be expected if flag had no influence on risk of failure. However, this association of flag with risk of failure is not statistically significant for the four-way classification shown in figure 2.3 (see appendix table III.2). When the A, B and C categories are combined into a single category, the effect of flag becomes marginally significant, but this effect of flag could also be related to the influence of age, as discussed above.

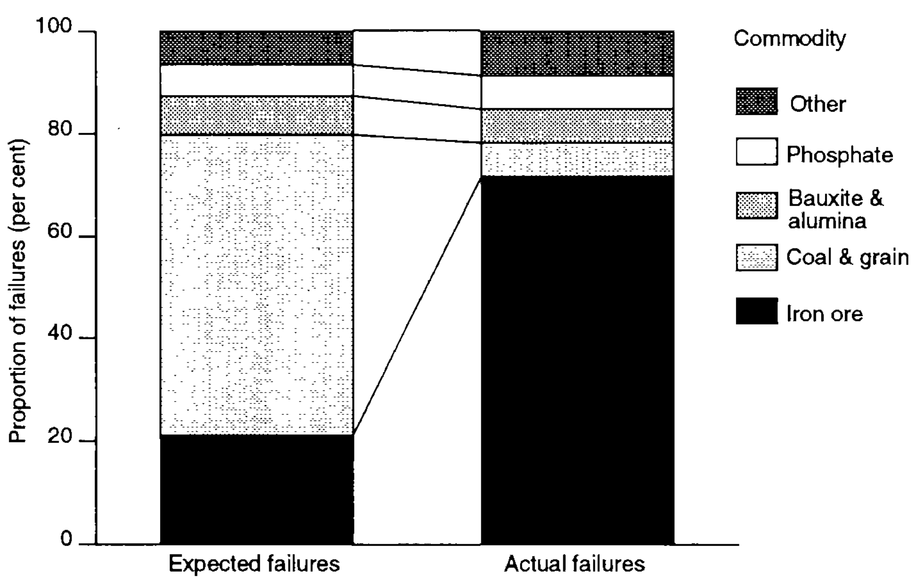
Classification society

Classification societies have also been criticised for not adequately inspecting ships classified by them (Stephens 1992).

Classification societies were categorised into four categories A to D using the same procedure as for flag. As with flag, older bulk ships are more likely to be inspected by D category societies compared with A category societies (see figure 2.4). However, figure 2.5 indicates that, in contrast to the flag analysis, there is little association between classification society and risk of failure of bulk ships. This is confirmed by the statistical analysis in appendix table III.3.

COMMODITY

Of the 50 bulk ship failures worldwide during the period October 1989 to December 1991, 33 were carrying iron ore. Figure 2.6 shows that ships carrying iron ore fail much more frequently than would be expected if commodity had no



Note Expected failures are calculated by assuming that risk of failure is proportional to the number of voyages.

Source BTCE estimates based on Fearnleys (1992a, 1992b).

Figure 2.6 Commodity and failure rate

BTCE

influence. The analysis in appendix table III.4 shows that the commodity carried is statistically significant in explaining ship failures.

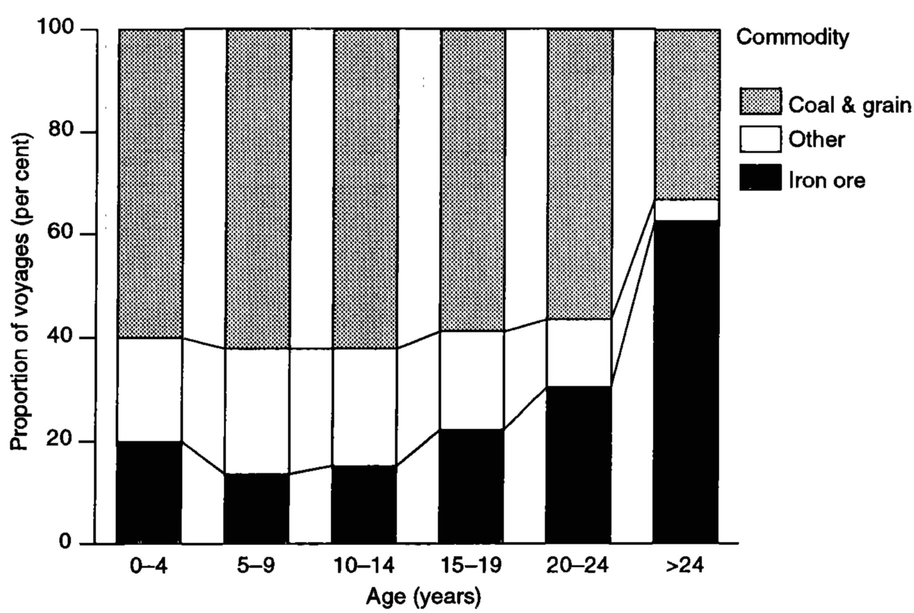
Iron ore has a stowage factor of 0.3 to 0.8 cubic metres per tonne, and iron ore pellets 0.5 cubic metres per tonne (ACA 1992). This is a much higher density than other major bulk commodities and can have a marked effect on the stresses imposed on a ship's structure. Appendix figure II.5 illustrates how stresses in the ship's structure are influenced by the commodity carried.

Figures 2.7 and 2.8 show that iron ore ships are likely to be older and larger than bulk ships carrying coal, grain or other commodities. The higher failure rate of ships carrying iron ore could therefore also be related to their age.

Commodity and size

Figure 2.9 indicates that bulk ships over 80 000 dwt failed more often than would have been expected if size had no effect on failure rates, whereas ships less than 50 000 dwt exhibited fewer failures than expected.

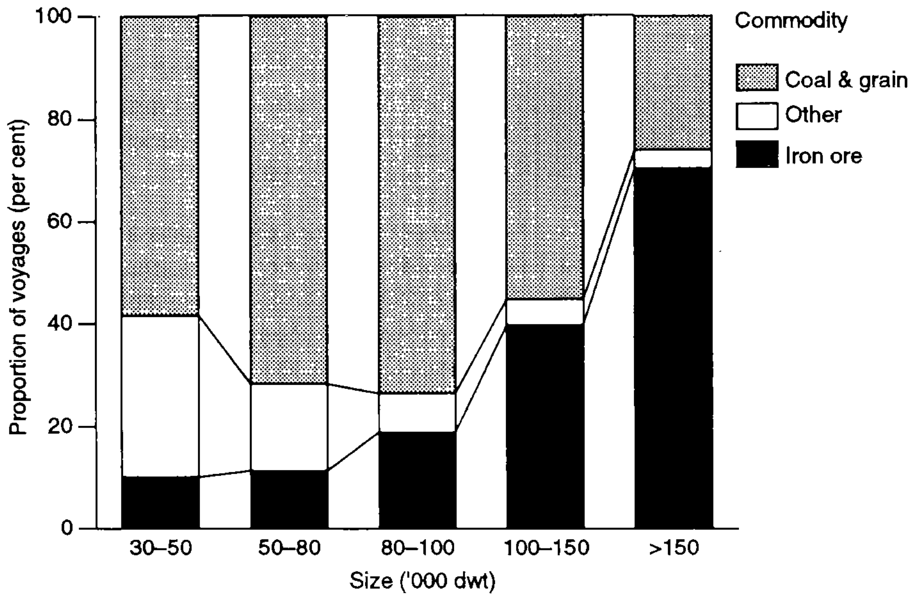
Because iron ore tends to be carried in larger ships, it is not clear which is the more important causal factor, size or type of commodity carried. However, consideration of the mechanisms of failure, as discussed in appendix II, suggests that commodity is undoubtedly important.



Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.7 Commodity and age

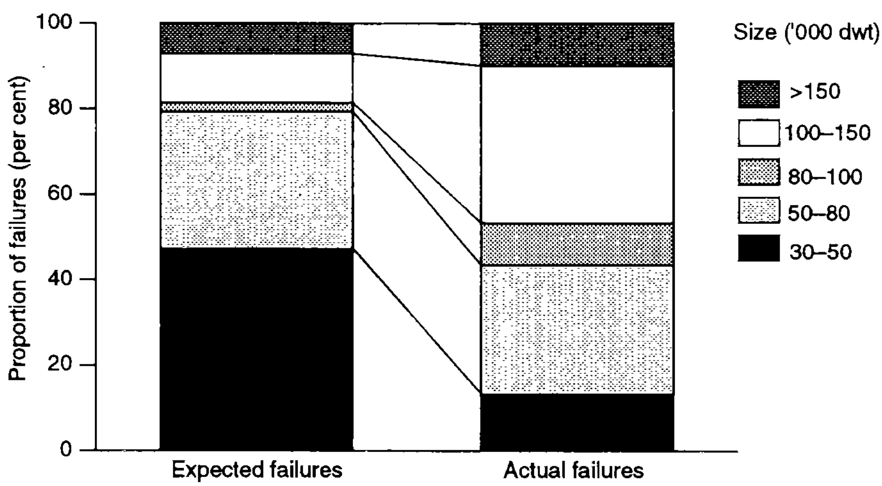
BTCE



Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.8 Commodity and size

BTCE



Note Expected failures are calculated by assuming that risk of failure is proportional to the number of voyages.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.9 Size and failure rate

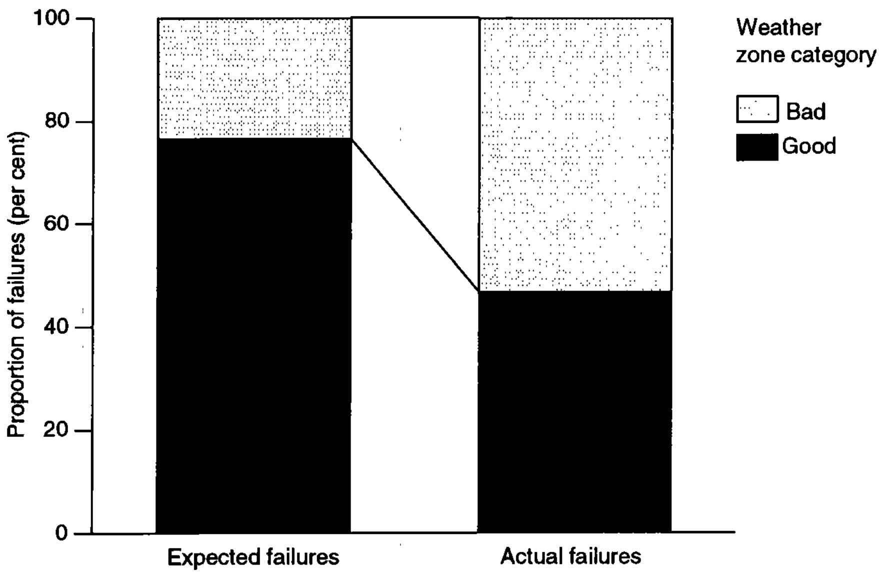
BTCE

WEATHER CONDITIONS

Structural failure occurs mostly during bad weather conditions. Of six ship failures discussed in the Department of Transport and Communications submission to the HORSCOTCI inquiry into ship safety, five experienced heavy seas and gale-force winds at the time of failure (DTC 1992).

Large waves pounding an already weakened structure can initiate a failure that might not have occurred under calmer conditions. Although information on the weather conditions at the time of the failures is generally available, data on weather conditions experienced during successful voyages are not available. For this reason, likely weather conditions in zones transited by ships in the database were used as a proxy for actual weather conditions. Bad weather zones were defined as those where at least 1 in 1000 waves exceeds 14 metres in height during the season in which the voyage was undertaken.

Figure 2.10 indicates that bulk ships traversing zones likely to have bad weather conditions fail more often than could be expected if weather conditions were irrelevant.



Note Expected failures are calculated by assuming that risk of failure is proportional to the number of voyages.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.10 Weather and failure rate

BTCE

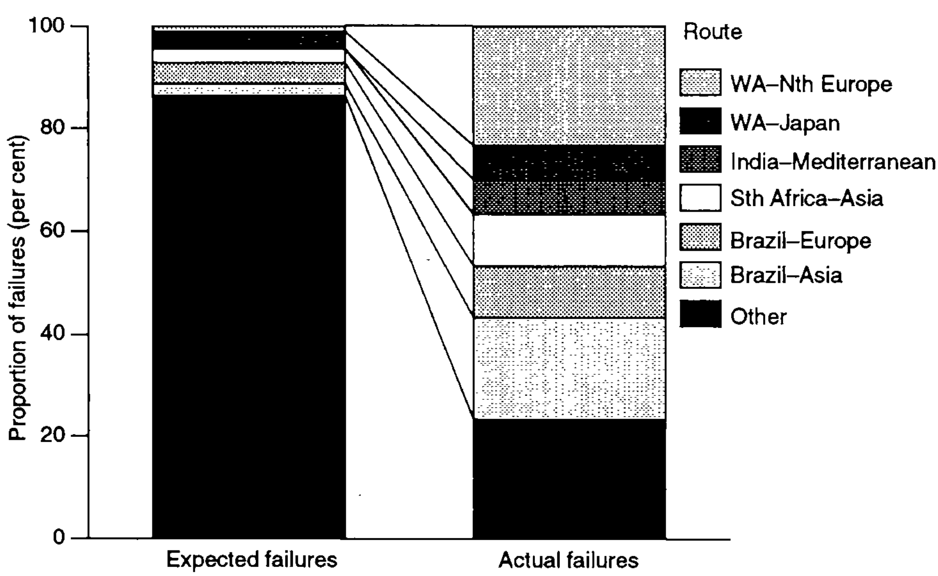
Route

Voyages are more easily classified according to route rather than the areas of the sea through which they pass. Because of this it is easier to test for an association between particular routes and risk of failure than between bad weather zones and risk of failure.

The routes in figure 2.11 are those on which more than one ship failed during the analysis period. The category 'other routes' combines all the routes on which no ships failed or only one ship failed. Figure 2.11 supports the hypothesis that structural failures may occur more often on some routes than can be attributed to chance alone.

Most of these routes where more than one ship failed are principally iron ore routes (South Africa to Asia and the 'other' category are the exceptions). This suggests that the combination of the carriage of iron ore and areas of rough sea can result in dangerously high stresses in ship structures.

A further analysis of Australian routes compared with other routes is given in appendix IV.



Notes 1. Expected failures are calculated by assuming that risk of failure is proportional to the number of voyages.
2. 'Other' routes are routes with zero or one failure.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 2.11 Route and failure rate

OPERATING CONDITIONS

How a ship is operated during the voyage can have an important influence on its failure risk. The HORSCOTCI (1992b) inquiry into ship safety identified crew training as an important factor in ship losses. The Australian Coal Association (ACA) in its submission to HORSCOTCI commented that 'insufficient training in seamanship and ship operation may result in vessels being held on course at dangerously high speeds in heavy seas. Investigations of several recent losses of bulk carriers would suggest that failure to reduce speed or to divert around bad weather may have been the principle cause of these disasters' (ACA 1992).

Although information is usually available about crew qualifications for ships that fail, similar information is not available for ships that successfully complete voyages. Nor are data available on the speed with which ships pass through rough seas. For this reason it was not possible to examine the influence of crew qualifications on the risk of ships failing.

Another important aspect of ship operations is that of loading and unloading. For the loading of iron ore, the important parameters are the number of passes made during the loading procedure and whether the ship is loaded in alternate holds or homogeneously (some cargo in each hold). Alternate hold loading is often preferred because it allows faster loading and raises the ship's centre of gravity, which moderates its roll motions (Lloyd's Register of Shipping 1992a). Appendix II has further details on loading methods.

Statistical analysis of port of loading (appendix II) showed no significant link between specific ports and the probability of a ship failing, after allowing for route and commodity. If poor loading practices are a problem, they appear to be a universal problem. An analysis of loading speed for iron ore ships failed to detect any significant link to ship failure. Data for actual average speed of loading or number of passes were not available for all the ships in the database.[3]

CONCLUSION

The analysis so far suggests that age, commodity, size, flag, weather and route can all contribute to the risk of failure. However, the analysis is complicated by apparent interactions between the factors. Factors such as size, age, route, commodity and flag may be important individually or in particular combinations. For example, iron ore tends to be carried in older ships and on routes that appear to present higher than average risk of failure.

3. Some information was available for the Western Australian iron ore ports for the last quarter of 1991. During that period approximately 50 per cent of bulk ships were loaded in alternate holds and the remainder were loaded homogeneously. The average number of passes was 2.8.

CHAPTER 3 RELATIVE IMPORTANCE OF THE DIFFERENT FACTORS

The analysis in chapter 2 and appendix III suggests that the major factors influencing the risk of failure are age, commodity, route, size and flag state. These results are generally well known, but little analysis appears to have been done on the relative strength of the different factors in contributing to the risk of structural failure in bulk ships. Nor have the interactions between different factors been fully investigated.

This chapter seeks to assess the importance of the different factors and their interactions in the failure of bulk ships.

Because of the small number of failures, conventional statistical analysis cannot be used to assess the interaction between these different factors, nor can it be used to measure their relative strengths. Logit analysis provides an appropriate method that allows the relative strength of the various factors to be measured and, in principle, the interaction between variables to be explored. The technique can be used to estimate the probability of failure. A brief discussion on logit techniques is presented in appendix V.

Using logit analysis, the effects of the different variables on risk of failure can be obtained by examining results for different combinations of variables. Variables that add little to the results can be progressively dropped until the most useful combination for the particular application remains.

Table 3.1 illustrates the most useful of the results obtained. The results confirm the significant role played by route, age and commodity in failure risk. The flag state is also significant, but has less of an effect on failure risk than commodity or route.

All of the variables listed in table 3.1, except for age, are dummy variables. That is, they can take a value of 1 if they are to be included in the estimation of failure probability or 0 if they are to be excluded. If all dummy variables are set to 0, the logit equation will estimate the probability of failure of a ship registered in a flag state with a good casualty record[1] carrying coal or grain on a route other than those listed in table 3.1.

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1. See chapter 2 for a discussion on the categorisation of flag states. In the logit equation represented by table 3.1, setting the flag dummy variable to 1 is equivalent to a flag state in category D as defined in chapter 2.

TABLE 3.1 RELATIVE IMPORTANCE OF DIFFERENT FACTORS IN STRUCTURAL FAILURE OF BULK SHIPS

Variable	*Parameter estimate*	*Standard error*
Intercept	–11.82	0.88
Iron ore	1.94	0.61
Other commoditiesa	1.31	0.72
Age	0.19	0.04
South Africa – Asia	2.54	0.66
Brazil – Asia	2.27	0.54
Western Australia – North Europe	3.46	0.54
Flag	0.92	0.4

Note Log likelihood ratio for intercept and covariates is 353.7; χ^2 value for covariates is 117.8.

a. Commodities other than iron ore, coal and grain. The probability of coal or grain voyages failing is estimated by setting the iron ore and 'other commodities' variables to zero.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

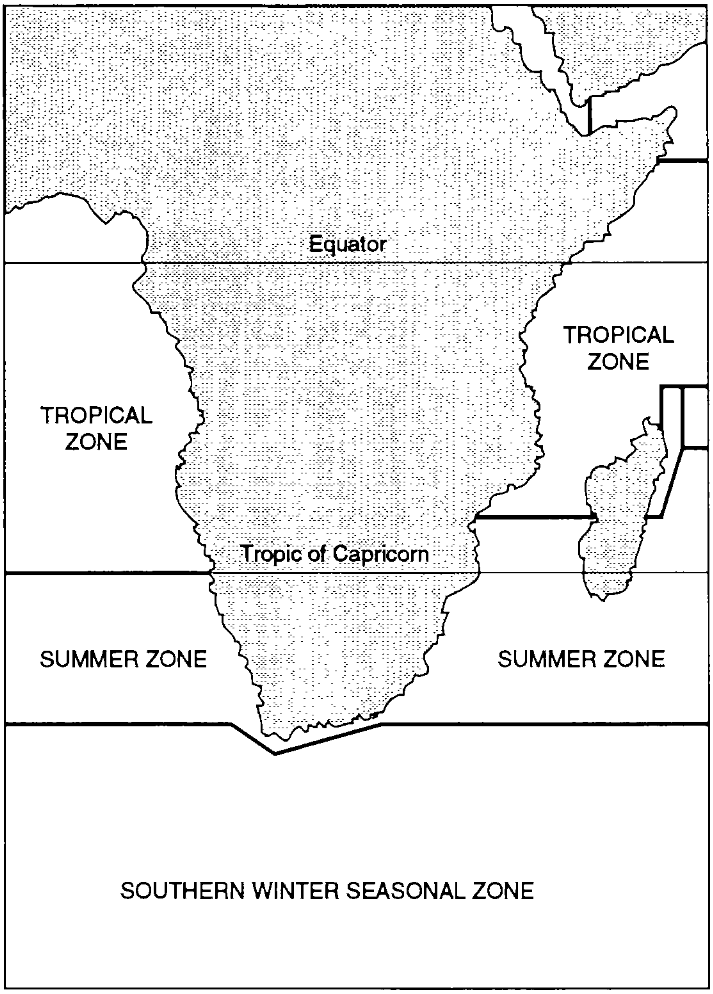
RESULTS

Iron ore is shown by the logit analysis to be less important as a factor influencing structural failure of bulk ships than the analysis in chapter 2 might suggest. This is because the routes included in the results are predominantly iron ore routes. This means that the effect of iron ore is represented to some extent by the route variables.

Although when ship size was examined on its own in chapter 2 and appendix III it appeared to have some significant association with risk of failure, when examined in combination with other variables in the logit analysis size was found to be unimportant. Iron ore ships tend to be larger than ships carrying other bulk commodities. The size effect detected in chapter 2 and appendix III may thus be related to the commodity or the route.

The analysis reveals that three routes — South Africa to Asia, Brazil to Asia, and Western Australia to North Europe — make large contributions to the probability of failure of bulk ships. Other routes were tested but they added little to the results. These three routes all involve a transit of the Cape of Good Hope. Of the 30 failures included in the database, 16 occurred on these three routes. Of these 16 failures, 13 were either in the vicinity of the Cape of Good Hope or in the Southern Indian Ocean (appendix figure II.7).

International Maritime Organisation (IMO) regulations limit the maximum load that the ship can carry (the summer load line); the winter load line and other load lines effectively reduce the load the ship is permitted to carry in recognition of additional weather hazards likely to be encountered. Figure 3.1 illustrates the load line regions defined by the IMO in the vicinity of the Cape



Source Hydrographer of the Navy (1987).

Figure 3.1 Load line zones around the Cape of Good Hope

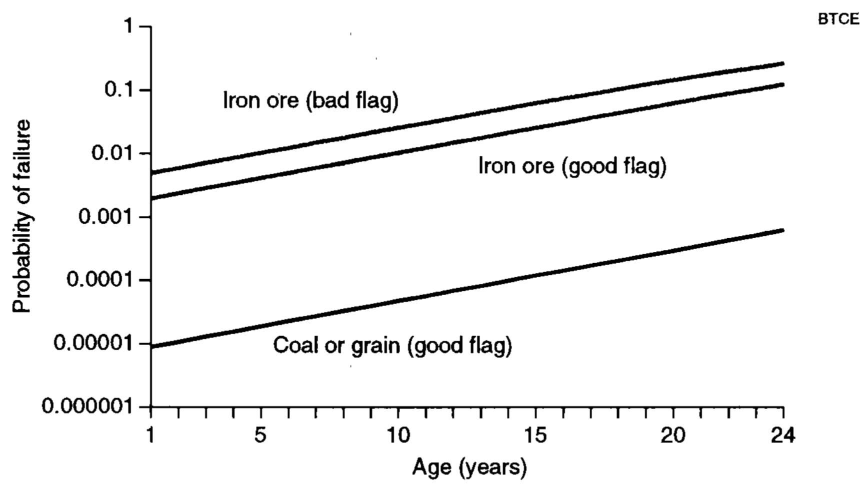
of Good Hope. The current regulations allow vessels rounding the Cape of Good Hope to load to the summer load line irrespective of the season. However, with the elevated risk of failure for bulk ships transiting the Cape of Good Hope identified by this analysis, the region boundaries shown in figure 3.1 may not be appropriate for large bulk vessels. The IMO is presently conducting a review of these regulations.[2]

2. *International Convention on Load Lines 1966* (IMO) — currently under review by IMO subcommittee on Stability, Load Lines and Fishing Vessels

Figure 3.2 illustrates the probability of failure for ships undertaking three types of voyages. The group with the highest failure probability are those ships registered with a flag state[3] with a poor casualty record, carrying iron ore from Western Australia to northern Europe. Voyages of bulk ships registered with a flag state with a good casualty record carrying coal or grain over routes that do not transit the Cape of Good Hope face the lowest risk of failure.

The two curves for iron ore voyages in figure 3.2 differ only in flag category. One way of interpreting figure 3.2 is that the probability of failure of an iron ore ship registered with a flag state with a poor casualty record is equivalent to an identical voyage of a ship five years older registered with a flag state with a good casualty record. That is, ships registered with a 'good' flag state are not as likely to fail as early in their lives as others.

An important issue is the likely error in the estimates. This can be measured by the confidence limits for the estimated probabilities. Figure 3.3 shows the 90 per cent confidence limits for the two iron ore voyage curves in figure 3.1.[4] The marginal separation of the two confidence intervals for ships older than 10 years indicates that the logit equation is better at predicting failure rates for

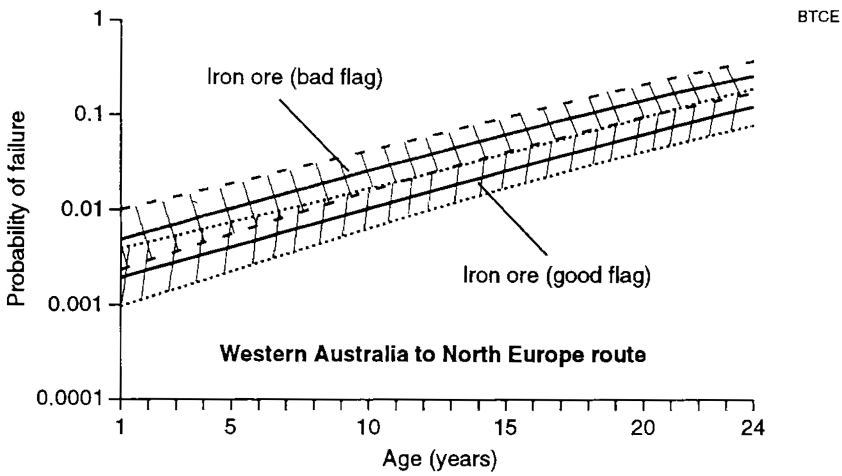


Note Iron ore voyages are on the Western Australia to northern Europe route. The 'coal or grain' voyages do not transit the southern Indian Ocean.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 3.2 Estimates of failure probability

3. The flag states with the bad casualty record are those in the D category in chapter 2. Those with a good casualty record are those in A, B and C categories.
4. The method used to calculate the confidence limits is shown in appendix V.



Source BTCE estimates based on Lloyd's Maritime Information Service data.

Figure 3.3 Confidence limits for effect of flag

these older ships. This is not surprising as most of the failures occur in the older ships. The separation of the two confidence intervals provides support for the view that the influence of flag is an important factor for the older ships that are most at risk of failing. The confidence intervals also indicate that as the ship ages the policies of the flag state on enforcing IMO regulations would become increasingly more important.

A different way of considering the effect of flag is to estimate the change in age required to exactly compensate for the effect of registering a ship with a flag state with a bad casualty record. This differs from an examination of confidence intervals because only two variables are changing (flag and age), all other variables being held constant. Appendix V gives details of how the confidence interval for the change in age required can be estimated. The mean effect for iron ore ships (see figure 3.2) is about five years. The estimated confidence interval is from 1.3 to about 9 years. Although the confidence interval is large, the change in age to compensate for the effect of flag is significantly different from zero.

QUALIFICATIONS REGARDING THE METHOD

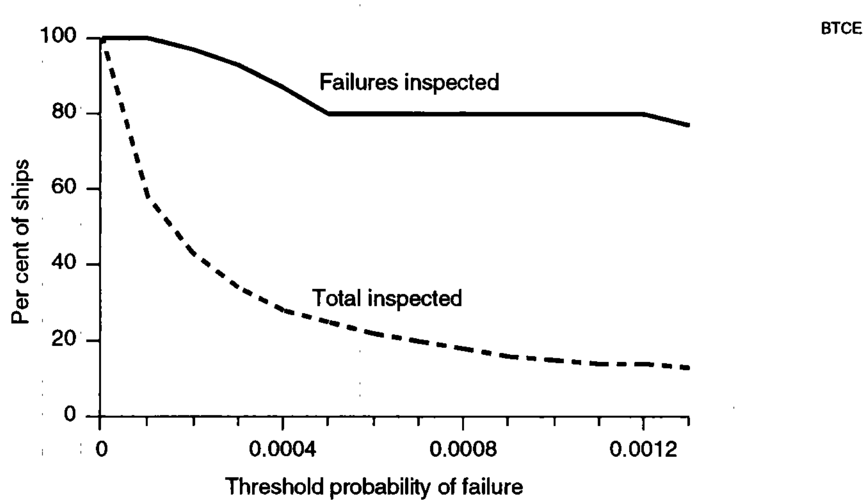
The logit procedure is based on the assumption that each observation is independent of all other observations. However, the almost 29 000 voyages in the database, were undertaken by approximately 3000 individual ships. That is, on average each ship completed about ten voyages during the two-year period covered by the database. This large number of repeated voyages by individual ships is likely to result in more optimistic confidence limits than might otherwise be the case. Appendix V contains more detail on this point.[5]

POLICY EXPERIMENT

Although the factors in table 3.1 were all shown to be statistically significant in ship failures, the essential issue is the ability of the logit model to correctly identify ships with a high probability of failure. One method of testing the model is to measure how well it can identify the ships that actually failed.

The test was based on setting a threshold probability of failure. Suppose that only ships with an estimated probability of failure in excess of a threshold level would be subject to inspection. The number of ships identified for inspection using this procedure can then be compared with the number of failed ships that would have been inspected. Figure 3.4 shows how the proportion of failed ships included in the inspection group declines as the threshold for inspection is raised.

The Australian Maritime Safety Authority currently inspects 34 per cent of all ships trading to Australia, compared with the internationally accepted



Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure 3.4 Proportion of ships that would be included in inspection, according to inspection threshold level

5. The qualifications in this section were suggested in a personal communication from Dr T. Breusch of the Australian National University Department of Statistics.

inspection target of 25 per cent (Stephens 1993). These are the proportions which would be inspected if thresholds of 0.0003 and 0.0005 probability of failure, respectively, were used to determine whether a ship would be inspected (see figure 3.4). At a threshold of 0.0003, 93 per cent of failed ships would have been included in the group of ships inspected. At the higher threshold of 0.0005, only 25 per cent of ships would have been inspected, including only 80 per cent of failed ships.

This approach on its own could therefore capture a large proportion of structurally deficient ships in the inspection net. But it would be better if used in conjunction with other information, such as recent change of ownership, that was not included in the analysis because of lack of data. Used in this way the results of the BTCE analysis could complement present methods of selecting ships for inspection.

Nevertheless, it is important to be aware that no inspection system is foolproof. Although a large proportion of ships that subsequently failed would have been included in an inspection system based on the BTCE approach, it is not certain that their potential for failure would have been detected. Thorough inspections that would be certain to detect structural deficiencies are time consuming and may not be possible under operating conditions faced by port control surveyors.

CHAPTER 4 ECONOMICS OF DEMOLITION AND PURCHASE OF NEW SHIPS

Age is clearly an important factor in the failure of bulk ships. Some old ships have been well maintained and are perfectly capable of safely undertaking long ocean voyages. However, conditions in the market in which bulk ships operate have not generally been conducive to expenditure on maintenance by shipowners. As a result, many old ships are likely to have suffered from a lack of maintenance or have been operated beyond their design life.

In order to gain some insight into the reasons for the continued operation of old and possibly sub-standard ships, the BTCE analysed some of the factors involved in scrappage and purchase decisions.

DEMOLITION OF OLD SHIPS

Owners of old ships are continually faced with the choice of disposing of a ship or of keeping it in service. The planning horizon for keeping the ship in service will depend on the prospects for finding employment for the ship, and on its condition. For convenience it is assumed that the decision period is one year. That is, at the beginning of the year the shipowner is faced with the choice of demolishing the ship or of committing the ship to as many voyages as possible for one more year and selling it for demolition at the end of the year. The present value of the cash flow under both of these choices can then be compared. (A 10 per cent discount rate is used to calculate the present value of all costs and revenues.)

For purposes of analysis a typical 120 000 dwt iron ore bulk carrier trading between Brazil and Europe was chosen as a representative ship (tables 4.1 and 4.2). The maximum number of voyages the representative ship could make in the twelve months at normal operating speeds and port times is eight, but the actual number could be less.

Major assumptions made were:

- All loan capital has been paid off.
- The ship is employed on a voyage charter basis.[1]

1. A voyage charter is a contract to carry a cargo on a single voyage between two specified ports or areas. The shipowner has to defray all operating expenses, such as crew costs, port charges, bunkers and agency fees, out of the freight (Packard 1986, p. 25).

TABLE 4.1 DATA USED FOR DEMOLITION ANALYSIS

Year	*Quarter*	*Voyage charter rate (US$/tonne)*	*Demolition price (US$ million)*[a]	*Fuel price (US$/tonne)*[b]
1988	Q1	7.90	5.0	73
	Q2	6.20	5.2	79
	Q3	6.00	5.3	70
	Q4	7.20	5.3	59
1989	Q1	8.00	5.3	74
	Q2	8.00	5.6	95
	Q3	7.20	5.8	84
	Q4	7.80	5.6	101
1990	Q1	8.00	5.6	97
	Q2	7.00	5.8	72
	Q3	5.70	5.4	108
	Q4	7.00	4.4	138
1991	Q1	7.80	4.1	101
	Q2	7.40	3.9	71
	Q3	6.80	3.7	70
	Q4	6.70	4.0	81
1992	Q1	5.40	3.8	69
	Q2	4.40	3.3	82
	Q3	4.00	3.3	90
	Q4	4.23	3.3	92
1993	Q1	4.60	3.4	74

Note The representative ship is a 120 000 dwt dry bulk carrier.

a. Price for demolition in the Far East.
b. Price for high viscosity oil in Rotterdam.

Source Quarterly figures are averages of monthly figures published in *Lloyd's Shipping Economist* (1989a, 1989b).

- Operating cost, fuel costs, new building prices and demolition prices are those published in *Lloyd's Shipping Economist* (1989a, 1989b). The ship for which the *Lloyd's Shipping Economist* costs are estimated is manned under an open registry by Indian officers and Korean ratings. Operating costs include crew, technical (stores and supplies, running repairs and maintenance, and lubricating oils), management and miscellaneous (management fees, insurance and communication). *Lloyd's Shipping Economist* reports costs for a panamax[2] vessel but not for a 120 000 dwt ship. To convert the panamax ship costs to those appropriate to a 120 000 dwt ship, the technical and management and miscellaneous costs reported by Lloyd's were increased by 40 per cent. This increase was based on the results of a previous Bureau

2. A panamax ship is usually in the range 50 000 dwt to 80 000 dwt and is the largest size bulk ship able to pass through the Panama Canal.

TABLE 4.2 OPERATING COSTS FOR A PANAMAX DRY BULK CARRIER
(US$ '000)

Year	*Quarter*	*Crew*[a]	*Technical*[b]	*Management and miscellaneous*[c]	*Total*
1988	Q1	38.9	17.5	16.0	72.4
	Q2	38.8	17.0	22.0	77.8
	Q3	38.8	17.0	22.0	77.8
	Q4	38.8	17.0	22.0	77.8
1989	Q1	42.4	17.8	22.8	83.0
	Q2	42.4	17.8	22.8	83.0
	Q3	42.4	18.5	23.5	84.4
	Q4	42.4	18.5	23.5	84.4
1990	Q1	46.4	20.0	25.0	91.4
	Q2	46.4	20.0	25.0	91.4
	Q3	46.4	20.6	25.0	92.0
	Q4	46.4	22.0	25.0	93.4
1991	Q1	49.0	25.5	28.0	102.5
	Q2	49.3	26.3	28.5	104.1
	Q3	49.3	27.6	28.7	105.6
	Q4	49.3	27.6	28.7	105.6
1992	Q1	53.8	28.1	30.8	112.7
	Q2	54.2	28.9	31.4	114.5
	Q3	54.2	30.4	31.7	116.3
	Q4	55.0	33.0	33.0	121.0
1993	Q1	57.7	33.6	34.7	126.0

a. Ship manned under an open registry with Indian officers and Korean ratings.
b. Technical costs are for stores, supplies, lubricating oil, running repairs and maintenance.
c. Management and miscellaneous costs are for management fees, insurance and communication.

Source Quarterly figures are averages of monthly figures published in *Lloyd's Shipping Economist* (1989a).

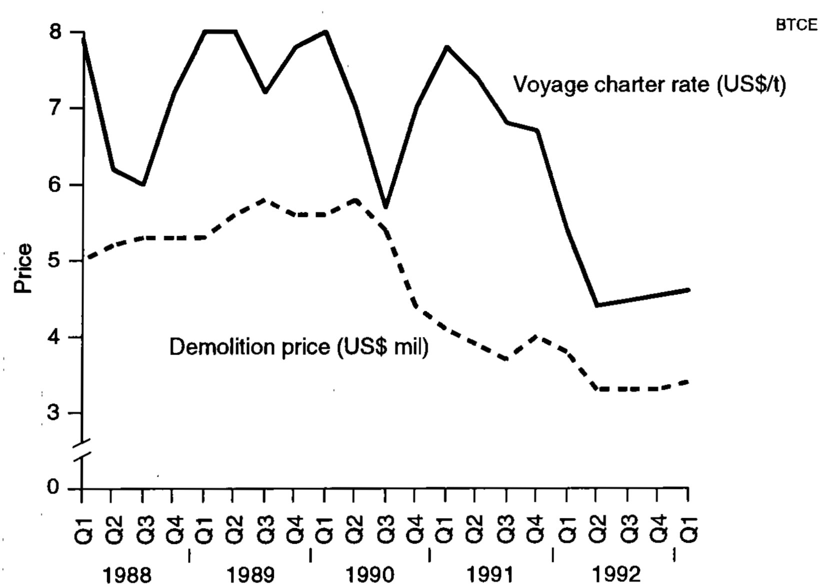
study of bulk ship costs (BTCE 1988). Crew costs tend to be independent of ship size, so the crew costs for the 120 000 dwt ship were assumed to be the same as those reported for the panamax ship.

- Revenue is received in twelve equal payments throughout the year. Costs are also spread evenly throughout the year. This assumption may not exactly represent the actual receipt of revenue but would be a reasonable approximation for the payment of costs.
- Operating costs are incurred for the full year even if the ship is not earning revenue. This is probably an unrealistic assumption and would overstate the costs for ships undertaking few voyages during the year. The more voyages undertaken during the year the less is the overstatement in costs.
- The ship is demolished in Asia. The costs of sailing the ship to the breaker's yard is deducted from the demolition price.

The operating costs reported by *Lloyd's Shipping Economist* (1989a) are for a 10-year-old ship. The ship on which this analysis is based is likely to be considerably older, but no allowance is made for the higher maintenance and insurance costs which could be expected on an old ship, if the market and regulatory systems operated adequately. That is, the following additional assumptions are made:

- Maintenance costs are assumed to be no different than for a 10-year-old vessel. Even though an old ship can be expected to require additional maintenance, the owner is assumed to keep maintenance costs down so as to maximise the short-term benefits of retaining the ship for an extra year of trading.
- Insurance costs are assumed to be the same as for a 10-year-old vessel. This is consistent with the HORSCOTCI (1992a) report, which indicated that it is only recently that insurance companies have begun to arrange their own inspections of ships and to adjust premiums to reflect risk.

The results in figure 4.1 indicate that there is some correlation between demolition prices and voyage charter rates. One possible explanation is that if demolition prices decline in response to conditions in the scrap steel market, the alternative option of retaining old ships in service becomes more attractive. As fewer ships are demolished, there is downward pressure on charter rates.



Source Lloyd's Shipping Economist (1989b).

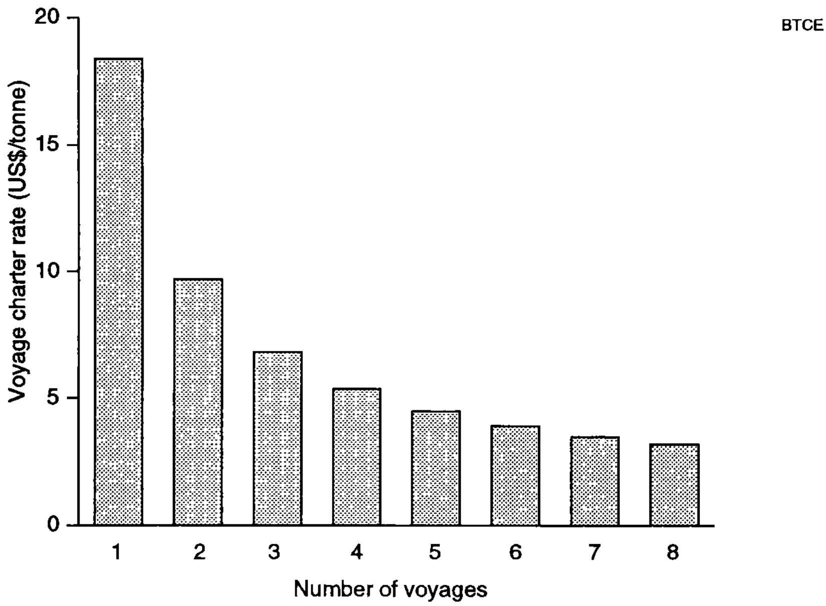
Figure 4.1 Voyage charter rates and demolition price for a 120 000 dwt bulk carrier

An alternative explanation could be that as charter rates decline due to conditions in the freight market, there is an increased supply of ships available to breakers with a resultant downward pressure on demolition prices.

Both explanations are probably partially correct. Irrespective of which explanation better describes causality in the market, individual shipowners will take into account both sets of prices in making their decisions.

The number of voyages expected to be undertaken in the forthcoming 12 months is a key parameter in deciding the best course of action. The charter rates required for the representative bulk ship to break even for up to eight voyages completed during the year were estimated, for each quarter from the first quarter in 1988 to the first quarter in 1993. A typical result of this analysis is shown in figure 4.2 for the second quarter of 1990.

The voyage charter rate for carrying iron ore between Brazil and North West Europe averaged US$7.00 per tonne for the second quarter of 1990 (*Lloyd's Shipping Economist* 1990). The break-even charter rate for the representative bulk ship for three voyages during the following twelve months was estimated to be US$6.80 per tonne (figure 4.2). Thus, if the shipowner could be sure of three or more voyages it would pay to retain the ship in service.



Source BTCE estimates based on *Lloyd's Shipping Economist* (1989a, 1989b).

Figure 4.2 Break-even charter rate for a 120 000 dwt bulk carrier, Brazil to North Europe, as a function of the number of voyages, second quarter 1990

TABLE 4.3 DATA FOR ANALYSIS OF NEW SHIP PURCHASE

Year	Quarter	Time charter rate (US$'000/day)	Second-hand price (US$ million)[a]	Dry dock (US$'000)[b]
1988	Q1	14.50	21.8	196.0
	Q2	14.40	23.7	280.0
	Q3	13.80	24.5	280.0
	Q4	15.00	27.3	280.0
1989	Q1	16.20	29.5	308.0
	Q2	17.10	30.7	308.0
	Q3	17.30	32.6	329.0
	Q4	17.80	32.8	329.0
1990	Q1	17.30	32.2	350.0
	Q2	15.40	30.7	350.0
	Q3	13.60	28.2	367.5
	Q4	12.20	27.0	378.0
1991	Q1	11.8	28.3	399.0
	Q2	13.9	33.7	413.0
	Q3	15.0	36.2	424.0
	Q4	16.0	35.8	424.0
1992	Q1	13.6	34.7	439.0
	Q2	10.5	32.3	454.0
	Q3	9.7	29.7	466.5
	Q4	9.5	28.0	469.0
1993	Q1	10.0	28.0	492.5

Note The representative ship is a 120 000 dwt dry bulk carrier.

a. Five years old.
b. Required at intervals of 30 months. Price estimated from costs reported by *Lloyd's Shipping Economist* (1989) for a panamax bulk carrier.

Source Quarterly figures are averages of monthly figures published in *Lloyd's Shipping Economist* (1989a, 1989b).

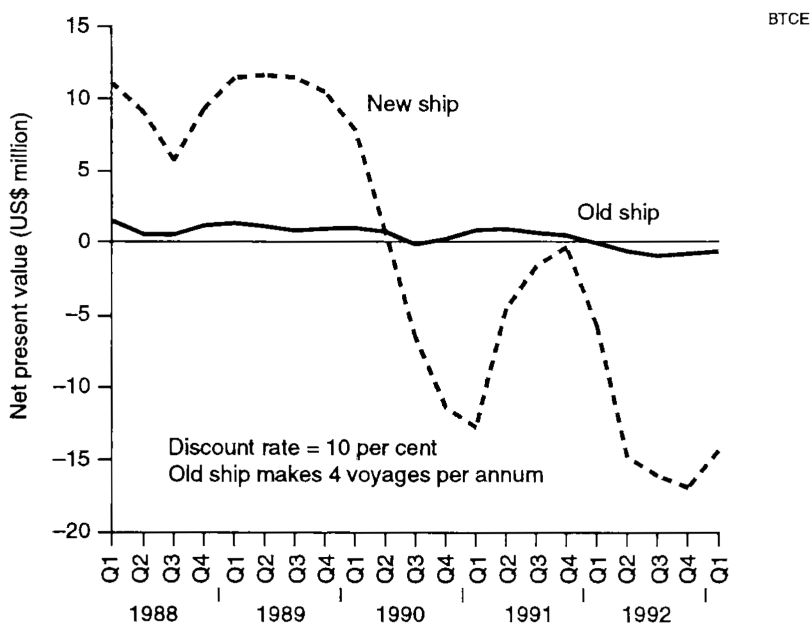
- Any money left over after paying for operating costs and interest payments is used to reduce the principal of the loan.
- Operating costs and time charter rates were assumed not to change over the period of the analysis. This assumes a degree of optimism on the part of the shipowner, as the data in figure 4.4 and in *Lloyd's Shipping Economist* (1989a, 1989b) indicate that time charter rates have trended downwards and operating costs have tended to increase.
- The ship is dry-docked at intervals of 30 months at prices reported in *Lloyd's Shipping Economist* (1989a).

For most of the period from 1988 to early 1992 it was profitable to retain an old ship, provided that more than three voyage charters could be arranged during the 12-month analysis period. The net present value estimated at a discount rate of 10 per cent is compared for the old ship (with four voyage charters) and the new ship in figure 4.5 and similarly the internal rates of return are compared in figure 4.6.

Figure 4.5 shows that until early 1990 the net present value of purchasing a new ship was far higher than that obtained by retaining an old ship. After early 1990 the net present value at a 10 per cent discount rate for the new ship became negative. Although the net present value of the old ship was not large (negative in late 1992), it was superior to that of the new ship. Figure 4.6 shows that the internal rate of return for the old ship with four voyage charters is higher than that of the new ship for almost all of the period analysed. The retention of an old ship gave a positive return until early 1992. It is not surprising, in these circumstances, that there were so many old ships offered for charter contracts.

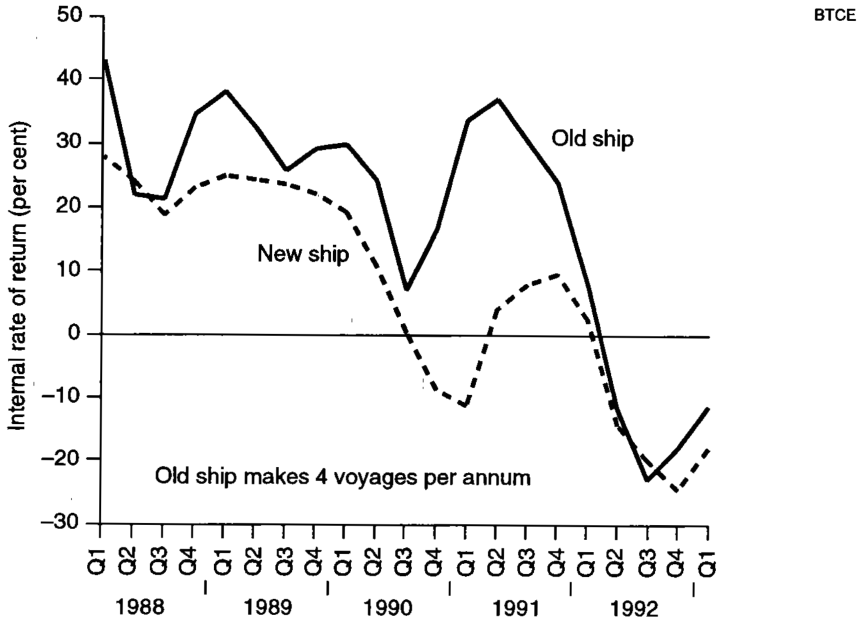
The results suggest that in late 1992 it was not profitable to retain an old vessel, nor to purchase a new one. *Lloyd's Shipping Economist* (1990, p. 8) made the following observation at a time when the prospects for new bulk carriers began to become doubtful:

> [E]xamples such as these are always artificial because they look at single vessels as isolated entities rather than part of a fleet. In practice, it is very common for the purchase of new buildings and modern second-hand vessels to produce negative



Source BTCE estimates based on *Lloyd's Shipping Economist* (1989a,1989b).

Figure 4.5 Net present value of retaining an old 120 000 dwt ship and purchasing a new 120 000 dwt ship



Source BTCE estimates based on *Lloyd's Shipping Economist* (1989a,1989b).

Figure 4.6 Internal rate of return of retaining an old 120 000 dwt ship and purchasing a new 120 000 dwt ship

> cash flow after debt service in the early years. In a fleet with a well spread age profile, these ships are initially subsidised by the strong net cash flow produced by older vessels on which the debt has been largely or totally paid down. This is a situation to which the industry has become habituated over the years, but in fact is most unhealthy, since it encourages shipping companies to be content with a level of remuneration which is too low to support the renewal and growth of their business.

Market conditions have clearly worsened since 1990. The results in figures 4.5 and 4.6 suggest that it is not currently worthwhile considering the purchase of a new ship. Sanderson (1993) commented in the *Daily Commercial News* that '[w]ith steadily depressed freight rates and sharply rising carrier costs the necessity for a substantial rise in freight rates is the biggest single issue facing the shipping industry. A 400 per cent increase over 1992 rates is necessary to provide a proper reward to shipping companies to replace aging tonnage ... .'

The results in this chapter indicate that the increase in freight rates required to make it attractive to replace aging ships, although less than that estimated by Sanderson, was substantial, probably in the order of 80 per cent. However, an increase in freight rates also makes retention of aged vessels more attractive. In the last quarter of 1992 an increase of 80 per cent in freight rates would have improved the internal rate of return of retaining an old ship, from –20 per cent to

32 per cent. Clearly, more than an increase in freight rates is required to remove old tonnage from the world fleet.

Increased regulatory control of ship standards is one approach that has been implemented in Australia and in other countries to try to reduce the number of unsafe ships. Sanderson (1993) reports that improvements in control by the port state are having an effect on which countries sub-standard ships are prepared to call at. He reports that some ships are now sailing in ballast from the Pacific to South Africa and the Atlantic, rather than coming to Australia where they would be subjected to a higher level of inspection.

Now that insurance companies have suffered large losses from marine insurance, greater attention is being focused on the level of premiums and risk. Companies now seem to be charging premiums that better reflect the risk (HORSCOTCI 1992a), and this is likely to assist in removing sub-standard ships from the world fleet, but the results in chapter 3 suggest that it may be possible to be more effective. It is feasible to set premiums according to the risk associated with particular voyages. This would add to the costs of employing old ships on risky voyages, such as carrying iron ore around the Cape of Good Hope. Old ships could then become uncompetitive on risky voyages, leaving them to those ships better suited to the potentially hazardous conditions.

Full consideration of better insurance and regulatory arrangements is beyond the scope of this paper. However, the results in this and the previous chapter suggest that a close alignment of insurance premiums with risk would assist in discouraging continued operation of unsafe ships.

CHAPTER 5 CONCLUSIONS

The statistical analysis of Lloyd's voyage records indicates that age, route, and commodity (especially iron ore) are major indicators of increased risk of structural failure.

Although flag state is frequently mentioned as a significant indicator of high failure probability, the analysis suggests that flag is not as important as other factors. The results suggest that a ship registered with a flag with a bad casualty record has the same probability of failure as a ship from a 'good' flag that is five years older.

Classification societies have been frequently criticised for failing to inspect bulk ships adequately, resulting in the continued operation of sub-standard ships. However, the analysis of voyage records failed to establish any statistical link between failure risk and classification societies. This does not mean that classification societies are providing an adequate standard of inspection. What it does suggest is that the classification societies in the database have been equally successful (or unsuccessful) at detecting sub-standard ships.

The route on which bulk ships travel was found to be of much greater statistical importance to the risk of structural failure than previously suspected, and more important than flag state. In particular, for Australian exports of iron ore, the route to North Europe via South Africa poses especially high failure risks. Ships carrying iron ore on routes from South Africa and Brazil to Asia also face above-average risks of structural failure.

These routes all transit the same region in the Southern Ocean. Of the 30 bulk ship failures included in the database, 13 occurred in this region. Weather conditions in the Southern Ocean can be very severe. International load line regulations allow ships to travel around the Cape of Good Hope loaded to summer load lines, but, given the enhanced risk of failure associated with this area of the ocean, it may be appropriate for the current IMO review of load lines to consider changes for this region.

Although ships departing from some specific ports appeared to have a higher than average probability of failure, the failures tended to be associated with the routes identified as having high failure rates. When corrected for the effect of route, ports, including Australian ports, had no statistical link with structural failures.

Although the analysis focused on dry bulk ships, an interesting question is whether the results would carry over into other ship types. Tankers and container ships have different types of structure, but there are some similarities. The best that can be said is that the cargoes carried by tankers and container ships tend to be low density cargoes compared with iron ore, so they may be more likely to have similar risks to dry bulk carriers employed in the carriage of coal and grain.

The sizes and ages of the ships employed on routes departing from Western Australia differ from those employed on routes from Eastern Australia. The differences do not indicate that any specific factor unique to Australian conditions increases risk of structural failure. But the differences support the conclusions regarding the riskiness of the Southern Ocean routes.

Recent change of ownership, of flag, or of classification society are said to be pointers to the possibility of a ship being sub-standard. It would have been useful to examine this statistically. Unfortunately the data available to the Bureau did not include these variables.

The larger the number of ships inspected, the more likely a sub-standard structurally deficient ship will be caught in the inspection net. A logit model developed from the data provides a tool that could be used to assist in the selection of ships for inspection. The model can be used to estimate the probability of failure for each ship in terms of its characteristics and route. A ship on a particular voyage that has a probability of failure above a pre-determined threshold would be inspected. In practice, some simple decision rules could be developed, which in conjunction with information not able to be modelled (such as recent change of ownership), would allow inspections to be directed towards the ships most at risk.

Although an inspection plan may ensure almost all ships that have a high probability of failure are inspected, in practice the limited time available for inspections by port state surveyors means that there can still be no certainty that sub-standard ships will be prevented from sailing.

Improvements to inspections by the port state are part of the solution to the problem of sub-standard ships, but they are not the total solution. The economic environment in which bulk shipping operates does not favour the building of new ships. Freight rates need to be higher than they are at present before ship operators are likely to commit themselves to a substantial number of new orders. However, an increase in freight rates would also make the continued use of older sub-standard ships more attractive. Clearly an increase in freight rates would not provide a solution to the problem of sub-standard ships.

Insurance companies can play an important role in the control of ship quality. There is evidence that insurers are now taking a more active role in monitoring the quality of vessels they insure. Knowing that old ships are more at risk, and that old ships carrying iron ore on specific routes face elevated risks, insurers should adjust their premiums to more accurately reflect these factors (O'Brien 1992).

For example, old ships could have premiums set on a voyage by voyage basis, unless it could be shown that their condition was of a high standard. If the voyage was intended to carry iron ore through the Southern Ocean then the premiums could be increased significantly, whereas if the voyage was to carry grain on a safer route then the premium would be lower.

Continuing this scenario, freight rates would ultimately reflect the premiums charged. Ships facing high failure risk would be much less competitive and would therefore tend to be used on routes for which they are better suited. For example very old ships could be used to carry iron ore on known safe routes. Better quality ships would become more competitive on the more risky routes.

It might be thought that an insurance company adopting this policy would lose business to a less discriminating company. But a company charging high premiums for old ships carrying iron ore on dangerous routes would be able to provide lower premiums for good quality ships than the less discriminating insurer. The better quality and lower risk ships would be attracted to the company that discriminated against risky ships. The other companies would soon find they were carrying a greater proportion of risk. Market forces would then provide incentive for all companies to adopt similar practices.

In summary, the major conclusions that can be drawn from the analysis are:

- High risk ships are those that are over 15 years old, carry iron ore, and are registered with flag states with high casualty rates. If they also transit the Southern Ocean they face an even higher level of risk.
- Consideration should be given to amending load line regulations for the area in the vicinity of the Cape of Good Hope, to reflect the high level of risk faced by ships transiting this region while carrying iron ore.
- Enhanced port state inspections would help to decrease the risk of structural failure. A more effective means of reducing failures would be for insurance premiums to closely reflect the degree of risk to individual ships and possibly voyages.

APPENDIX I DATA ON STRUCTURALLY FAILED SHIPS

TABLE I.1 BULK SHIPS EXPERIENCING STRUCTURAL FAILURE, OCTOBER 1989 TO DECEMBER 1991

Name	*Lloyd's no.*	*GRT*	*Type*	*Failure date*	*Year built*	*Flag*	*Departure port*	*Destination port*	*Cargo*	*Size* (dwt)
Ademontasa	6807747	26 271	BC	Apr-90	1968	Lib	Zhenjiang	New Orleans	Barytes[a]	55 118
Al Taludi	7041041	24 956	BC	Feb-90	1970	Mta	Ningbo	San Nicolas	Ballast	41 300
Alexandre P	6803222	54 566	OC	15-Mar-90	1967	Pan	Dampier	Gijon	Iron ore	94 532
Alexita	7227229	60 846	BC	Dec-90	1972	Nor	Port Cartier	Europoort	Iron ore	122 544
Algarrobo	7327665	89 178	OC	18-Sep-90	1973	Lib	Huasco	Kawasaki	Iron ore	135 466
Amazon	8010453	74 729	BC	Aug-90	1981	Nor	Tubarao	Chiba	Iron ore	140 832
Atlas Pride	7315911	112 306	OBO	Aug-91	1973	Lib	Ras Tanura	Angra dos Reis	Oil	248 604
Azalea	6916366	44 276	OC	22-Mar-90	1969	Krs	Narvik	Bremerhaven	Iron ore	78 571
Berlisa	7343011	80 174	BC	May-91	1975	Nor	Tubarao	SE Asia	Iron ore	154 489
Blooming Orchard	7027435	70 872	BC	Aug-91	1970	Cht	Tubarao	SE Asia	Iron ore	140 440
Cape North	7117084	41 565	OBO	Jan-90	1971	Cyp	Ponta do Ubu	Bremerhaven	Iron ore	85 180
Continental Lotus	6717899	29 966	BC	21-Jan-91	1967	Ind	Mormugao	Geno	Iron ore	53 346
Elounda Day	7328542	20 966	BC	23-Dec-90	1973	Pan	Vancouver	SE Asia	Potash	38 250
Entrust Faith	7329596	35 104	BC	27-Nov-91	1973	Grc	Puerto Ordaz	Bremen	Iron ore	65 533
Gallant Dragon	7389637	64 967	BC	23-Oct-90	1976	Pan	Tubarao	Kakogawa	Iron ore	123 126
Juliana	7037155	32 521	BC	Nov-90	1971	Cyp	Inchon	Dutch Harbour	Ballast	65 455
Kashee	7372892	71 739	OBO	May-91	1973	Cyp	Port Hedland	Rotterdam	Iron ore	138 673
King William	7330234	42 236	BC	Aug-91	1974	Gbi	Setubal	Hampton Roads	Ballast	79 304
Kiwi Arrow	7909865	26 191	BC	30-Apr-91	1981	Bah	Cape Town	Taichung	Steel	38 695
Manila Transporter	7533018	67 624	BC	7-Jul-91	1976	Phi	Dampier	Port Talbot	Iron ore	115 960
Marmara S	7021302	58 785	BC	Dec-91	1970	Trk	Sepetiba Terminal	Las Palmas	Iron ore	121 552
Mel Gui Hai	7002306	21 508	BC	Nov-90	1969	Chr	Zhenjiang	New Orleans	Bauxite	37 326
Melete	7343059	35 516	BC	24-Aug-91	1975	Grc	Dampier	Port Talbot	Iron ore	72 063
Mineral Diamond	8015726	75 330	BC	17-Apr-91	1982	HKg	Dampier	Ymuiden	Iron ore	141 028
Mineral Star	7233723	36 330	BC	25-Jan-90	1973	Cyp	Hampton Roads	Belem	Coal	66 350
Orient Pioneer	7039452	51 506	BC	7-Jan-90	1971	Lib	Tubarao	Kaohsiung	Iron ore	108 504
Pacific S	7117474	55 084	OBO	Jun-90	1971	Trk	United Emirates	Japan	Oil	103 480
Pan Dynasty	6902951	21 567	BC	4-Oct-89	1968	Krs	Tampa	Kwangyang	Phosphate	36 650
Pankar Indomitable	7205740	39 219	BC	Jan-91	1971	Grc	Port Cartier	Oxelosund	Iron ore	77 996
Pasithea	7045607	80 225	OC	4-Aug-90	1971	Grc	Port Walcott	Wakayama	Iron ore	155 407

TABLE I.1 BULK SHIPS EXPERIENCING STRUCTURAL FAILURE, OCTOBER 1989 TO DECEMBER 1991 (CONT.)

Name	*Lloyd's no.*	*GRT*	*Type*	*Failure date*	*Year built*	*Flag*	*Departure port*	*Destination port*	*Cargo*	*Size* (dwt)
Petingo	6702662	38 997	BC	9-Jul-90	1967	Van	Saldanha Bay	China	Iron ore	80 580
Protektor	6704957	43 218	BC	11-Jan-91	1967	Sng	Port Cartier	Oxelosund	Iron ore	80 185
Pythia	7235343	64 355	BC	Oct-90	1973	Cyp	Port Walcott	Dunkirk	Iron ore	120 143
Rokko San	7118753	71 877	OBO	15-Jun-90	1971	Pan	Unknown	Richards Bay	Ballast	150 900
Rollon	7301764	38 611	BC	Jan-91	1972	Grc	Tubarao	Las Palmas	Iron ore	67 826
Salvia	7027386	82 014	OBO	9-Feb-91	1970	Krs	Huasco	Pohang	Iron ore	153 256
Scandinavian Pine	7409023	34 157	Wood	Jan-90	1976	Nor	Unknown	Unknown	Unknown	41 203
Shensi	7522320	88 675	BC	15-May-90	1977	Pan	Dampier	Yokohama	Iron ore	169 999
Shou An Hai	7340980	62 811	BC	Mar-91	1974	Chr	Hampton Roads	St Michael's	Grain	119 500
Silimna	7525944	32 508	BC	12-May-90	1978	Lib	Mormugao	Italy	Iron ore	69 165
Snestad	7124180	28 656	BC	Sep-90	1972	Nor	Cape Town	Barcelona	Grain	62 503
Sonata	6829719	25 597	BC	13-Nov-91	1969	Pan	Kirkenes	Bremerhaven	Iron ore	79 681
Starfish	7007100	28 147	BC	8-Apr-91	1970	Pan	Port Walcott	Swinoujscie	Iron ore	56 277
Tao Yuan Hai	7389675	64 920	BC	23-May-90	1977	Chr	Puerto Ordaz	Port Kembla	Iron ore	122 734
Theanoula	7341336	35 100	BC	Apr-91	1974	Cyp	Trombetas	New Orleans	Bauxite	72 063
Tribulus	7917850	68 619	BC	Feb-90	1981	IoM	Seven Islands	Rotterdam	Iron ore	127 907
Vallabhbai Patel	7391563	62 563	CBO	Jan-90	1977	Ind	Tubarao	Mizushima	Iron ore	113 925
Vasso	6801705	34 591	BC	4-Apr-91	1967	Bah	Saldanha Bay	China	Iron ore	57 181
Vulca	6814049	19 699	BC	31-Dec-89	1968	SVC	New York	Busan	Scrap steel	42 245
Walter Leonhardt	6608725	23 570	BC	18-Feb-90	1966	Cyp	Tampa	Antwerp	Phosphate	42 805

Note Flag abbreviations are explained in table I.2.

BC Bulk carrier
dwt Deadweight tonnes
GRT Gross registered tonnage
OBO Oil or bulk ore carrier
OC Ore carrier
Wood Woodchip carrier

a. Sulphate of barium.

Sources ABS (1992); AMSA (1992); DTC (1990, 1991a, 1991b, 1991c, 1991d); Lloyd's of London (1992a, 1992b, 1992c, 1993b); Lloyd's Register of Shipping (1992b, 1992c); NKK (1992).

TABLE I.2 FLAG ABBREVIATIONS

Flag code	*Country*
Bah	Bahamas
Chr	China Peoples Republic
Sng	Singapore
Cht	Taiwan
Cyp	Cyprus
Gbi	United Kingdom
Grc	Greece
IoM	Isle of Man
Ind	India
HKg	Hong Kong
Krs	South Korea
Lib	Liberia
Mta	Malta
Nor	Norway
Pan	Panama
Phi	Philippines
SVC	St Vincent
Trk	Turkey
Van	Vanuatu

Source Lloyd's Register of Shipping (1992b).

APPENDIX II ASPECTS OF STRUCTURAL FAILURE

Bulk ship failures are normally the culmination of a long slow process involving a combination of events and circumstances throughout a ship's working life. The events that started the failure process may have occurred years earlier.

Figure II.1 shows the major factors which can contribute to ship structural failure.

MODES OF FAILURE

Ferguson (1991, pp. 7–9) and Nippon Kaiji Kyokai (NKK 1992, p. I) both agree that, in the majority of reported ship losses due to structural failures, the final stages started with 'the loss of side shell plating[1] in the cargo holds' (Ferguson 1991, appendix 1). Over 50 per cent of the ship structural failures analysed in these studies were lost. Survivors reported that their ships broke in two and sank rapidly.

Most engineers agree that beam failure is the most likely mechanism causing ships to break in two. The only alternative mechanism is shear failure.

Beam failure occurs to a ship when it fails through bending, normally in heavy seas when the ship is in an extreme hogging or sagging condition. Figure II.2 shows extreme hogging and sagging conditions, when the length of wave is roughly equivalent to the ship's length. Beam failure often involves some torsional stresses due to twisting. A ship which is missing large areas of side plating, or has large cracks in the side shell, is particularly vulnerable to torsional stresses caused by crossing seas.

Shear failure normally occurs at bulkheads[2] when one hold becomes overloaded through flooding or poorly distributed cargo with the adjacent hold nearly empty. The difference between the upward buoyancy forces on the empty hold and downward forces on the full hold acts like scissors slicing the ship in two, close to the bulkhead (see figure II.3).

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1. Shell plating is the steel plating forming the outer side and bottom of the hull.
2. Bulkheads are 'the vertical partition walls which subdivide the interior of a ship into compartments' (D'Arcangelo 1969, p. 594).

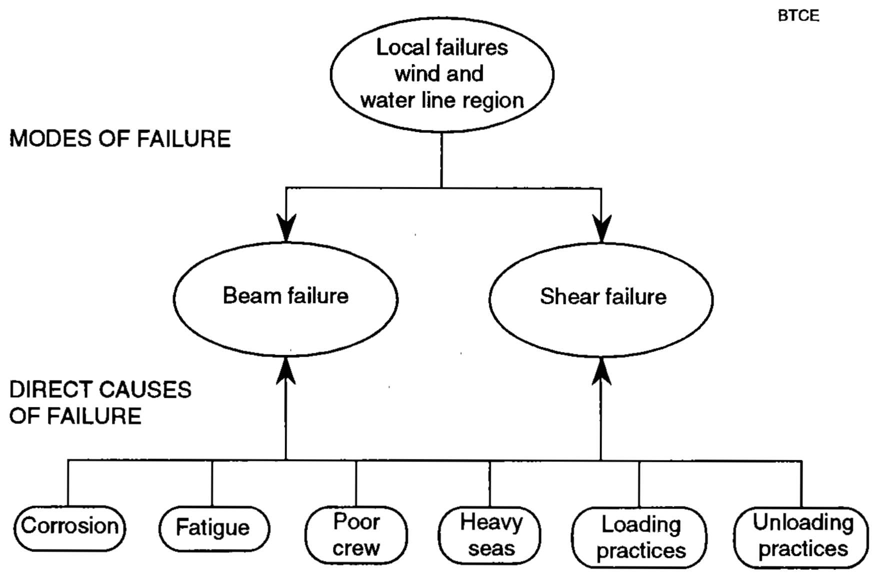

Figure II.1 Flow chart of the factors contributing to ship failure

Shear failure is likely to occur when the hull beam[3] cross-sectional area has been reduced by severe corrosion. Damage to the hold structure, such as cracking, can also increase shear stresses. Failure is usually sudden, and would probably occur with extreme overloading due to green water[4] on the weather deck or major flooding of the holds.

However, such high overload forces usually cause localised failures such as loss of side shell plating, which will in turn lead to beam failure (AMSA 1993).

CORROSION

Corrosion occurs when a structure reacts chemically with its surrounding environment resulting in a deterioration of the structure.

Traditionally ships were designed with extra thickness to allow for 0.07 to 0.15 mm per year to be lost to corrosion on all steel surfaces over the life of the vessel. However, pitting and abrasion can lead to much higher rates of corrosion, particularly in the wind and waterline[5] region (D'Arcangelo 1969). NKK (1992) has documented corrosion of 2.8 mm over a two-year period, which is well over traditional expectations.

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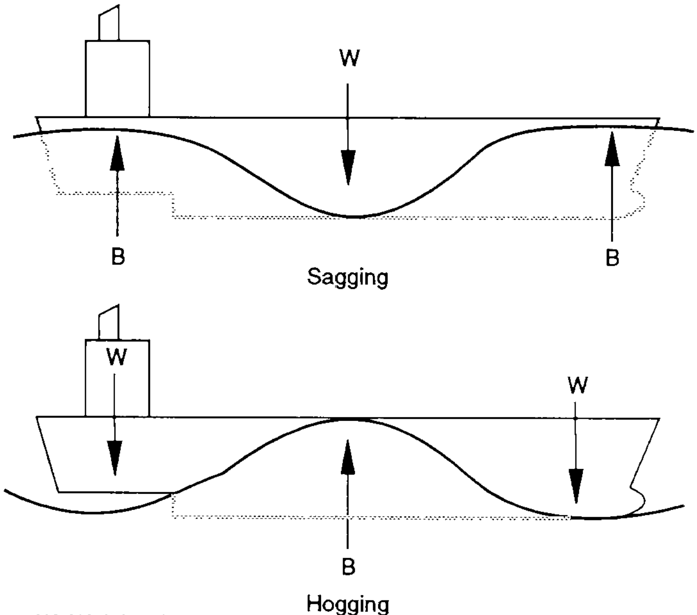
3. The hull beam is the structural body of the ship (including shell plating, frames, decks and bulkheads) which is considered in its entirety as a beam.
4. Solid unbroken waves on deck, not 'frothy' white water.
5. The wind and waterline region is the area of the hull between the lightship waterline and the loaded waterline.

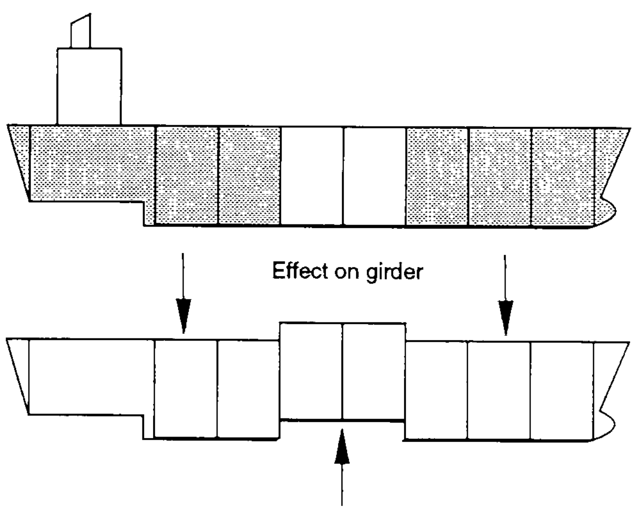
BTCE



W Weight of vessel
B Bouyancy forces

Figure II.2 Hogging and sagging

BTCE



Source Bendall (1993).

Figure II.3 Shear stress

Present design rules do not include a corrosion rate. Instead, classification societies require scantlings[6] of new ships to allow for about 20 per cent corrosion. Steel is required to be replaced when this allowance has been used up (AMSA 1993; Parker 1992).

The speed and degree of deterioration depend on:

- ship maintenance and corrosion protection;
- type of cargo carried; and
- methods and procedures used in loading and unloading cargo.

The available data that can best represent these factors are age, commodity carried, classification society, flag state and type of cargo carried in the past.

Age

A ship starts to corrode from the time the steel is created in the steel mill, and continues to corrode throughout its entire life. Ships are designed and built to counter corrosion.

A ship's corrosion prevention system includes control systems such as paint schemes and cathodic protection, as well as design allowances for wastage over the ship's life. If the corrosion prevention system is not maintained, then the rate of corrosion can increase considerably. In particular, where barrier systems such as paint are employed, any damaged area of the barrier will result in corrosion.

Most corrosion prevention systems are designed at the time of building the ship. They are based on the likely interval between scheduled maintenance dockings expected at the time of construction. However, as underwater paint schemes have improved, the interval between regular planned dockings has tended to increase. Docking every two years was once the norm but every four years is now common. Protection systems on older ships were designed for the shorter periods between docking and many have not been updated. As a result many older ships' original protection systems are unlikely to be functioning properly towards the end of the periods between dockings.

Because corrosion occurs progressively over time, age is the best available variable to represent the possible extent of corrosion.

Commodity

The type of commodity and the way a cargo is shipped can also result in structural failure.

Dense cargoes (such as iron ore). The carriage of iron ore is the 'most severe cargo in terms of loading on the ship' (Ferguson 1991). Irrespective of the

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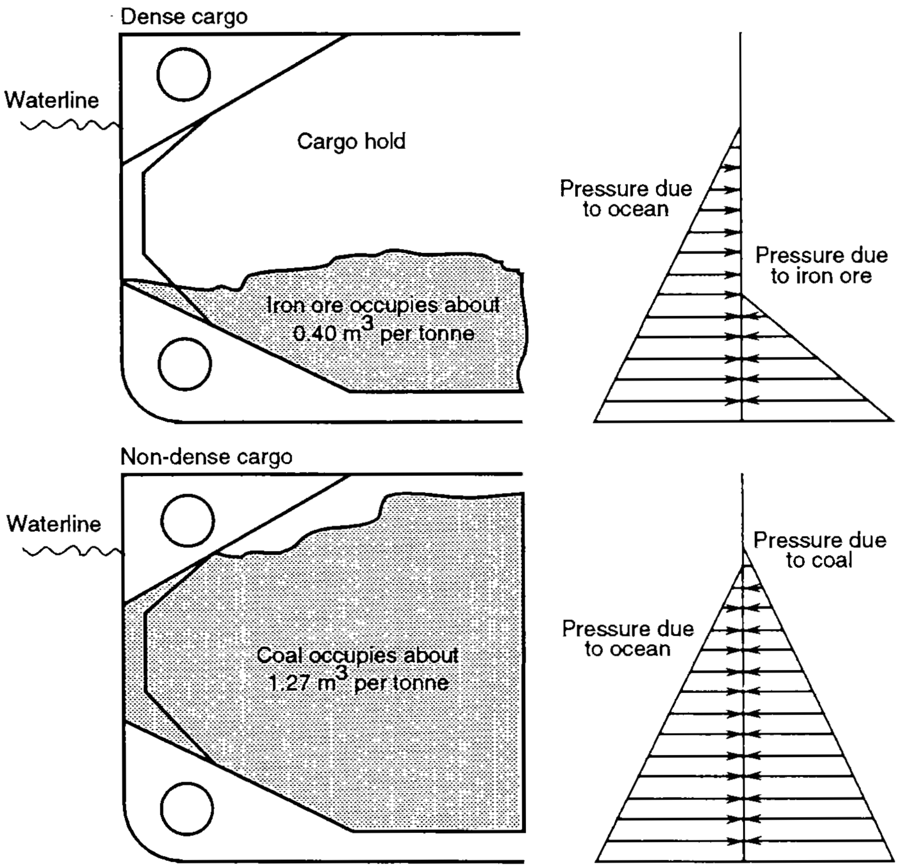
6. Scantlings are the dimensions of a ships frames, girders, plating etc.

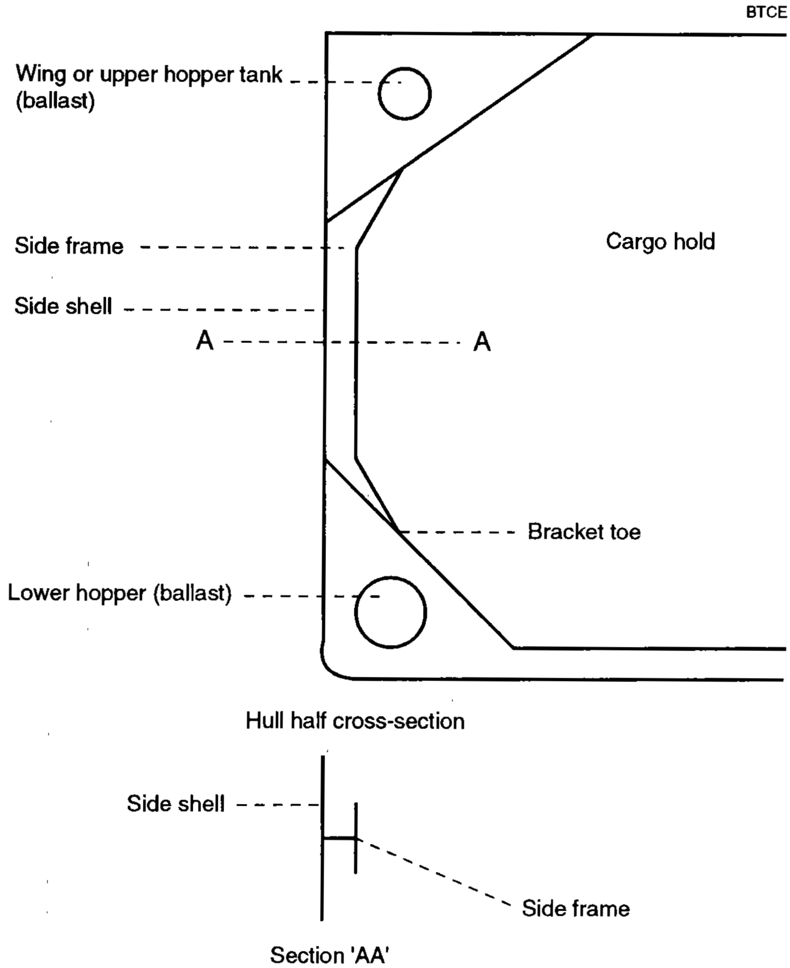


Source NKK (1992).

Figure II.4 Side shell forces exerted by dense and non-dense cargo

loading method used, iron ore cargoes do not occupy a large volume of the hull, hence the cargo does not exert any direct loads on to the side shell. This increases the hull stresses since there is no force, other than that provided by the structure itself, to counteract the external hydrostatic pressures (figure II.4).

Temperature. Cargo loaded at a high temperature can cause damage to the hull structure by affecting the metallurgical properties of the steel. In certain pelletised ore and coal cargoes, high temperatures can lead to hull degradation. Davies (1988) notes the effect of ores coming straight out of furnaces and being loaded at well above the recommended temperature of 65°C.



Source NKK (1992).

Figure II.5 Structural cross-section of a typical bulk carrier

Coal. Studies by both NKK (1992) and Lloyd's Register of Shipping (1992a) indicate that high sulphur coals can initiate corrosion, with cracks appearing within six months of carrying coal. Sulphur compounds from the coal and water vapour combine to form acid which condenses on the internal surface of the side shell structures, which are cooled by the lower temperature of the sea water outside the hull. The acid then trickles down the side shell frames causing localised corrosion where the frame is welded to the side shell (figure II.5).

Abrasion. Cargo abrasion also promotes corrosion. If the paint system is breached, corrosion sets in. When a ship is loaded with lighter cargoes such as coal or grain, the side shell and side frames are in direct contact with the cargo (see figure II.4). An abrasive cargo can remove both the paint and any evidence of corrosion. Ironically iron ore rarely causes any mechanical damage to the protective coating because it normally does not reach the side frames (NKK 1992) (figure II.4).

Classification societies and flag states

Flag states and classification societies, through their respective regulations, influence a ship's seaworthiness and structural integrity, although ultimately the owner is responsible for the condition of the ship.

Unfortunately it was not possible to study the effect of different owners in ship failures. Of the approximately 3000 ships in the database there were 762 different owners, owning from 1 to 44 ships each. There is no statistically satisfactory method to analyse such a large, diverse group given the relatively small number of failures. Data on past owners, or the number of past owners of a ship, were also not available. To some degree flag state and classification society provide an alternative measure of owners' approach to maintenance.

Classification societies and flag states are both subject to market forces since within each group there is competition for ship registrations. It has been claimed that poor quality ships migrate from traditional flag states and classification societies to 'flags of convenience' and to second-rate registers, because owners are able to select societies with safety and maintenance inspection standards that match their approach to maintenance and the condition of their ships (HORSCOTCI 1992a).

FATIGUE

Fatigue is a phenomenon that leads to failure under conditions of repeated, fluctuating or interrupted loads. As the number of cycles or fluctuations increases, the critical stress level at which fatigue failure is likely to occur is reduced. Fatigue failure occurs well below the stress levels at which failure would occur under monotonic[7] loading.

Stress cycles for ships vary from the long-period cycles caused by ship loading and unloading to the very rapid cycles caused by machinery vibration. The rate at which fatigue normally develops depends upon the type and magnitude of these various stress cycles.

The most common stress cycles affecting the ship's hull are those due to passing waves. These cycles occur approximately every 12 to 24 seconds depending on the sea conditions (British Maritime Technology 1986). In the space of a year, a ship could experience up to 3 million cycles, depending on the time at sea and the wavelength of the seas it operates in. Since most waves

7. Unvaried, non-changing load.

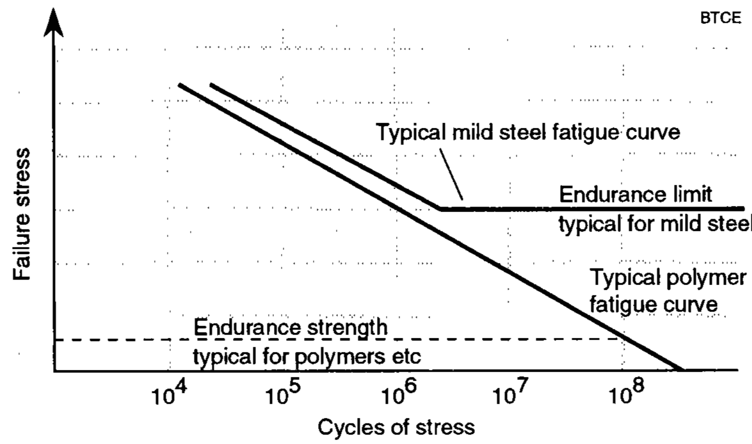


Figure II.6 Typical fatigue curves

encountered are not large and their wavelengths do not correspond to the ship's length, the magnitude of the stress cycles will be small. However, because of the large number of cycles, their effect cannot be ignored.

Fatigue failure usually starts with micro-cracks which grow over time until the stresses within the structure increase to such an extent that the structure fails (Blodgett 1975, pp. 2.1–5, 2.9–1).

It is very hard to separate corrosion failure and fatigue failure because they usually occur together. Mild steel[8] members with low stresses will experience fatigue failure once they have corroded sufficiently to increase the stress endured during cyclic fluctuations to levels at which fatigue failure becomes probable. Likewise, fatigue cracks provide an excellent environment for corrosion to develop.

In some materials, particularly ferrous[9] and titanium alloys, the stress at which fatigue failure occurs reaches a minimum at 10^6 cycles and falls no further. This stress is called the fatigue or endurance limit (see figure II.6).

There is no fatigue limit for most other metals, polymers and composites. The allowable stress for these materials continues to fall beyond 10^8 cycles, gradually getting lower and lower. For design purposes, the stress that allows failure-free operation for 10^7 cr 10^8 cycles is often called the fatigue strength to distinguish it from endurance limit. (Often, in expressing the data the terms

8. The steel most commonly used in structure.
9. For steels where the uts is less than or equal to 1.4 GPa.

endurance limit and fatigue strength[10] are interchanged and it is left to the reader to determine which is appropriate.)

Figure II.6 shows failure stresses according to the number of load cycles for various materials.

Historically, ships were considered not to suffer from fatigue since they were primarily constructed out of mild steels, and the mild steel structures were designed so the stress did not exceed 210 MPa (30 000 psi), which is the same level of stress as the fatigue strength (in this case the endurance limit) at 10^6 cycles for bending loads (Blodgett 1975, p. 2.1–5). But in reality the endurance limit of mild steel ship structures is actually a lot lower.

In designing structures to withstand fatigue, there are three major types of fluctuating loads to consider: axial, bending and torsional. All three act upon a ship. The endurance limits or fatigue strengths quoted for axial and torsional loads are lower than for bending loads:

- 85 per cent of the bending endurance limit, for axial loads, and
- 58 per cent of the bending endurance limit, for torsional loads.

Fatigue strength is also reduced by:

- *Surface condition.* The normal endurance limit quoted is for a polished steel round bar. The endurance limit for hot rolled mild steel is approximately 80 per cent of the endurance limit for a polished mild steel bar. For corroded steels in salt water, the endurance limit is further reduced, from 50 per cent of the endurance limit for mild steel, down to 10 per cent for the strongest high tensile steels (Sharpe 1989, pp. B3/55–B3/56).
- *Notches and stress concentrations.* These can occur in places such as frames, brackets, repairs, cracks and tears (Sharpe 1989, p. B3/56).

All these influences reduce the strength of the ship's structure. The extent of the reduction can be sufficient for fatigue to be a major problem for structures which were considered to be fatigue-free. For example, the fatigue endurance limit for corroded steel structures in old ships is not the 210 MPa for which they were designed but may actually be less than 60 MPa.[11]

For ships built in mild steel, fatigue failure becomes a real possibility as they age.

Fatigue can be delayed by maintenance activity to reduce the detrimental effect of poor surface condition, but every ship's structure will eventually fail. Thus, as with corrosion, age is a reasonable proxy to measure the fatigue process.

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10. The endurance limit or fatigue strength quoted for commercial steels is usually for bending using a polished steel round bar (Sharpe 1989, p. B3/55).
11. Normal bending endurance limit × 0.58 (change for torsional load) × 0.5 (corroded surface) × corrections for notches etc.

High tensile steels

Although traditionally only small quantities of high tensile steels were used in ship building, primarily around the bottom and weather deck plating and the row of side plating adjoining these regions (that is, the bilge and shear strakes[12]), increasingly they are being used for the more highly stressed members of the hull in large ships to keep down weight and to reduce the use of extremely thick members (D'Arcangelo 1969). New buildings today have up to 90 per cent of their hull constructed in high tensile steels (Parker 1992).

High tensile steels do not have a fatigue endurance limit (Sharpe 1989, p. B3/55). Ship designers presumably were well aware that ships constructed from high tensile steels would eventually be at high risk of fatigue failure and so have a finite life.

CREW TRAINING

Poorly trained crews and lack of a common language between crew, officers and land based workers may result in inefficient ship operations (HORSCOTCI 1992b). It has been argued that poorly trained crews lose ships while good crews save ships (HORSCOTCI 1992a). Other things being equal, there is a good deal of merit in this argument. During a crisis, such as a ship encountering bad weather or beginning to break up, crew training and communication may well be critical to the safety of a ship.

Since there were no data on crew nationality or training standards, the only available proxy was flag state. But this is a poor proxy since crew nationality is not necessarily related to flag.

Further work may be warranted to determine the importance of training in helping save ships that suffer structural damage during a voyage.

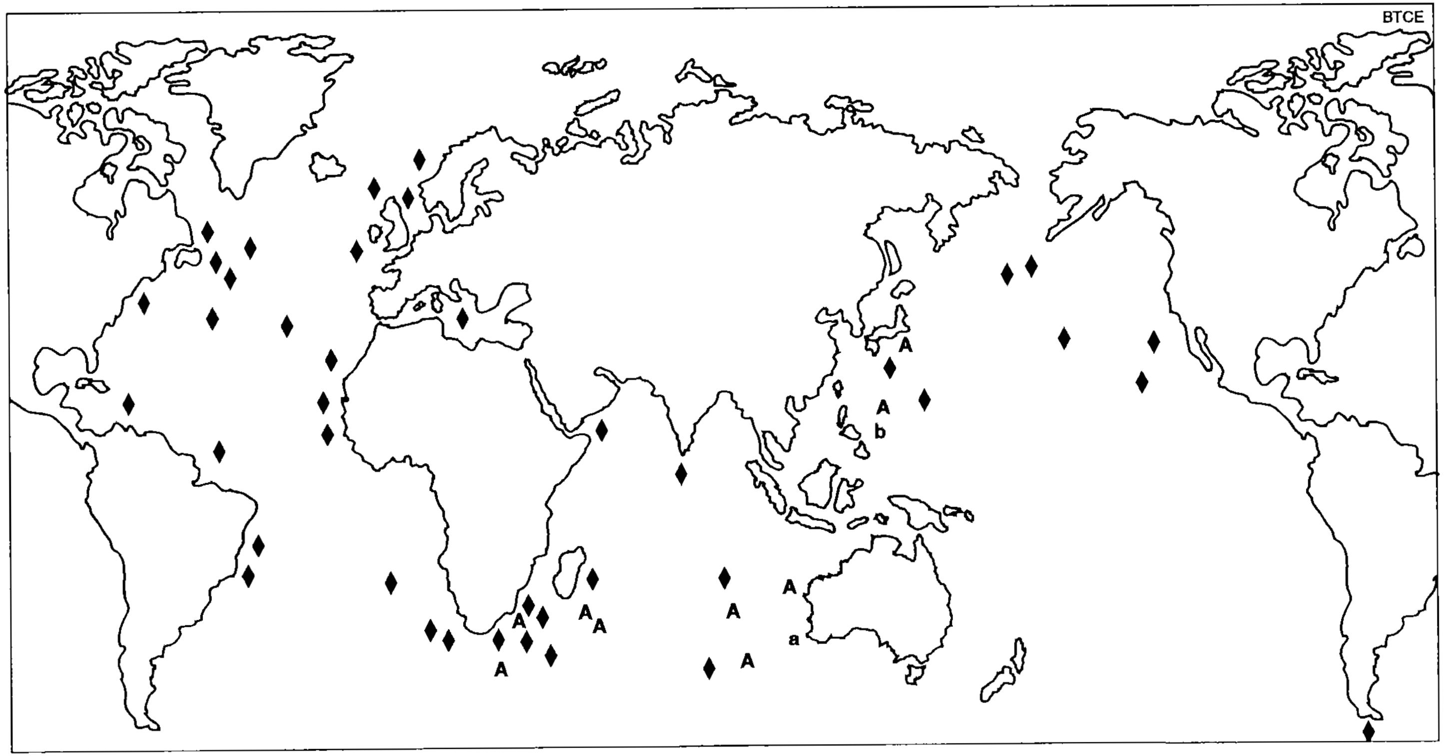
HEAVY SEAS

Heavy seas can act as a catalyst for failure. Both Lloyd's and NKK note the concurrence of heavy seas and failure (Lloyd's Register of Shipping 1992a; NKK 1992). The stresses imposed by waves are discussed in the fatigue section above.

Proxies that may be used to measure extreme heavy seas are route, bad sea areas, season, and wavelength relationships.

Of the 50 world fleet failures examined, many experienced heavy weather before and during failure (NKK 1992; Ferguson 1991; Beresford & Dobson

12. A strake is a course or row of shell, deck, bulkhead or other plating (D'Arcangelo 1969, p. 600).



A Failures after departing Australia

♦ Other world failures

a *Singa Sea* sank on 4 July 1988

b *Daeyang Honey* sank on 24 October 1992

Note *Scandinavan Pine* is not indicated on this figure. The location of its failure was unknown.

Sources ABS (1992); AMSA (1992); Crisp (1992); DTC (1988, 1990, 1991a, 1991b, 1991c, 1991d); Lloyd's Maritime Information Services (1993); NKK 1992.

Figure II.7 World bulk ship failures, 1989 to 1992

1989; DTC 1990, 1991a, 1991b, 1991c, 1991d). The majority of the ships failed in well known bad weather zones (figure II.7). For example, the loss of the *Daeyang Honey* in late 1992 occurred during a typhoon 300 nautical miles east of the Philippines. Most of the Australian departure failures occurred in the Southern Indian Ocean, where storms are prevalent. Of the ships which sank, four experienced gale-force winds with rough seas and swell prior to failure.

Bad weather can place extra stress on areas already weakened by corrosion and fatigue. Wave-induced load and hammering in rough seas can trigger cracks and detachments of hold frames, especially those weakened by corrosion and wastage (Lloyd's Register of Shipping 1992a; NKK 1992).

As discussed above, under modes of failure, the risk of beam failure is high in heavy seas when a ship is in extreme hogging or sagging conditions, when the length of wave is roughly equivalent to the ship's length (see figure II.2). If beam failure is the primary failure mechanism it could be expected that there would be a strong correlation between the size of failed ships and route.

Alternatively, if shear failure is the primary cause then size would not be important, and there should be a strong correlation with alternate hold loading (see figure II.3), but not with size of the ship.

Although ships in the size ranges 80 000 to 100 000 dwt and 100 000 to 150 000 dwt[13] were found to have failure rates significantly higher than expected (appendix table III.5), there is also a strong correlation between ship size and route. The statistical evidence is thus consistent with beam failure but is not conclusive.

LOADING AND UNLOADING

Recent research into structural failure has focused on the condition of the ship. In the past, many papers on structural failure placed a heavy emphasis on ship loading and unloading practices. According to the NSW Coal Association (1992), IMO research during the 1980s into causes of ship losses concentrated on cargo characteristics, loading and unloading, and trimming procedures.

Cargo loading and unloading procedures can affect ship structures, both in the loads exerted on the hull and in damage caused to the hull. Ferguson (1991) and NKK (1992) both detail the ways the cargo can overload the hull structure and cause damage.

Loading practices

Three loading issues that may affect the risk of failure are:

---

13. Deadweight was used as a proxy for size.

TABLE II.1 χ^2 ANALYSIS OF IRON ORE VOYAGES ROUNDING THE CAPE OF GOOD HOPE, BY PORT OF DEPARTURE

Port	*Expected failures*	*Actual failures*	χ^2
Dampier, Australia	2.2	4	1.5
Port Hedland, Australia	1.2	1	0.0
Port Walcott, Australia	1.3	2	0.4
Saldanha Bay, South Africa	1.8	2	0.0
Sepetiba, Brazil	1.7	1	0.3
Tubarao, Brazil	3.7	4	0.0
Other	3.0	1	1.3
Total	15.0	15	3.6[a]

Notes 1. Expected failures are calculated by assuming that risk of failure is proportional to the number of voyages.
2. Figures may not add to totals due to rounding.
3. Significant χ^2 for 6 degrees of freedom is 12.5 at the 0.05 level of significance

a. Includes χ^2 for successful voyages.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

- bad loading practices, including trimming, and poor adherence to loading procedures;
- loading speed; and
- homogeneous versus alternate hold loading.

Bad loading practice. If bad loading practices (for example, cargo loaded too fast for ballast pumps to keep up, and not keeping to loading plans) at the port of loading are a major cause of failure then there should be a statistical link between ships that fail and a few particular ports of loading. However, although a χ^2 analysis of the Lloyd's voyage data showed a strong statistical relationship between port of departure[14] and failures, the relationship became marginal when the analysis was extended to allow for the effect of commodity carried. When route as well as commodity were used, as in table II.1, for example, the relationship was found to be insignificant. Table II.1 results show that, for iron ore voyages which round the Cape of Good Hope, if bad loading practices are a problem, then it is a universal problem, and not one that can be attributed to particular ports.

Loading or unloading operations can cause damage or weakening of the hull structure which is not apparent and can go unnoticed. This damage may only become apparent when the vessel is undertaking a voyage when it is fully

14. In the absence of data on port of loading, port of departure was used for port of loading.

loaded, particularly with dense cargoes, and encounters bad weather. Hence damage from *past* ports of call could be the true culprit, but there were no data available to analyse this effect.

Some proponents of loading practices as a cause of structural failure note the practice of dropping cargo from heights in excess of 20 metres onto the hold floor. Although this practice may cause some localised high stresses on the hold floor for a short period until the floor is covered by cargo, hold floors are specifically reinforced to accommodate the high stress produced by falling cargo.

Loading speed. Another hypothesis relates ship failures to high speed of loading. Iron ore loading rates are typically in the range 6000 to 16 000 tonnes per hour (Lloyd's of London 1993a). A χ^2 analysis did not demonstrate any statistically significant link between rated speed of loader and ship failure.

Homogeneous versus alternate loading. A third hypothesis is that the order of loading the holds and the amount placed in each hold are important determinants of structural damage. Cargo may be loaded in several ways (Lloyd's Register of Shipping 1992a):

- homogeneously (evenly distributed over all the holds);
- alternate holds (distributed over odd-numbered holds); or
- combinations or variations of the above.

Not all ships are designed to be operated using all of the above methods. The ship may not be strong enough for some loading practices (Lloyd's Register of Shipping 1992a). A mismatch between design and loading practice may therefore result in unwarranted stresses.

Very little information is available to analyse loading practices. Low density cargoes such as grains and coal are usually loaded homogeneously to maximise the use of the ship's volume capacity. Iron ore has a very high specific gravity, and a ship loaded with iron ore will reach its mass capacity long before it reaches its volume capacity. It is for dense cargoes such as iron ore that alternate hold loading and its variants are often used (Lloyd's Register of Shipping 1992a).

AMSA (1992) collected some load configuration data on ships leaving Western Australian iron ore ports for three months in 1991. Both homogeneous and alternate hold loading methods were used (49 per cent homogeneous, 51 per cent alternate) during the three months. Department of Transport and Communications ship failure reports have found that both types of cargo distribution have been used amongst ships which have failed.

Unloading practices

Poor unloading practices have been hypothesised as being among the reasons why ships suffer structural damage. If this were the only reason for failure then there should be some correlation with particular previous types of cargo carried, or ports visited. Unfortunately, the data available did not allow the effect of previous ports or cargoes to be tested.

PROXIES FOR FACTORS CAUSING FAILURE

Table II.2 summarises the proxies used in the BTCE analysis.

TABLE II.2 CAUSES OF FAILURE AND PROXIES USED IN THE ANALYSIS

Causes of failure	*Proxy*
Corrosion and poor maintenance	Age, commodity, flag and classification society
Fatigue	Age
Crew	Flag and classification society
Heavy seas	Route, deadweight, and sea regions
Loading	Commodity, ports
Unloading	Previous commodities and ports

APPENDIX III RELATIONSHIPS BETWEEN VARIABLES AFFECTING SHIP FAILURE

Although a relationship between bulk ship failures and various ship and voyage characteristics may be suspected, it is important to establish if the relationship has statistical significance. A chi-square (χ^2) analysis is used in this appendix to test for this significance.

As an illustrative example, in table III.1 we examine the hypothesis that a relationship exists between ship age and ship structural failures. First, the factor being analysed (ship age) is assumed to have no influence on the risk of failure (the null hypothesis). On this basis the expected number of failures in each age group is assumed to be proportional to the number of voyages the ships in this age group have undertaken. That is, in table III.1 we assume that a 25-year-old ship is just as likely to fail during a voyage as a new ship on its maiden voyage (age has no influence). In the χ^2 analysis we compare the number of failures expected where no relationship exists (the null hypothesis) with the actual

TABLE III.1 SHIP AGE

Age (years)	*Voyages*	*Expected failures*	*Actual failures*	χ^2
0–4	4 554	4.8	0	4.8
5–9	10 335	10.8	2	7.2
10–14	5 413	5.7	5	0.1
15–19	5 781	6.1	12	5.8
20–24	2 079	2.2	11	35.7
>24	435	0.5	0	0.5
Total	28 597	30.0	30	54.3[a]

Notes 1. Numbers may not add to totals due to rounding.

2. Significant χ^2 value for 5 degrees of freedom and 5 per cent level of significance is 11.07.

a. Includes contribution from successful voyages (see text).

Source BTCE estimates based on Lloyd's Maritime Information Services data.

number of failures recorded. The χ^2 score is a measure of the difference between the expected and actual failures.

If the pattern of actual failures is similar to the pattern of expected failures, then the total sum of the χ^2 will be less than the significant χ^2 value and we have proved that no significant relationship exists. Table III.2 is an example of this result (6.1 is less than the significant value of 7.81).

If the total sum of the χ^2 exceeds the significant χ^2 value then we are satisfied that a significant relationship exists. Table III.1 is an example of this result (54.3 is greater than the significant value of 11.07).

The tables in this appendix (usually referred to as contingency tables) are limited to one-way classifications. The number of failures are too few to allow valid results to be obtained from two-way classifications. Multi-variate classifications are effectively carried out through use of logit analysis in (chapter 3). Logit methodology is discussed in appendix V.

In calculating the χ^2 score in a contingency table, the number of actual and expected successful voyages should be compared as well as the actual and expected unsuccessful voyages. However, in this analysis the comparison of actual and expected successful voyages generally added little to the χ^2 score.

TABLE III.2 FLAG

Flag	*Voyages*	*Expected failures*	*Actual failures*	χ^2
Four-way flag classification				
D	9 860	10.3	16	3.1
C	7 853	8.2	8	0.0
B	5 161	5.4	4	0.4
A	5 723	6.0	2	2.7
Total	28 597	30.0	30	6.1 [a]
Two-way flag classification				
D	9 860	10.34	16	3.1
A, B, C	18 737	19.66	14	1.6
Total	28 597	30.0	30	4.7 [a]

Notes 1. Numbers may not add to totals due to rounding.

2. Significant χ^2 value for 3 degrees of freedom and 5 per cent level of significance is 7.81 and for 1 degree of freedom is 3.84.

a. Includes contribution from successful voyages (see text).

Source BTCE estimates based on Lloyd's Maritime Information Services data.

TABLE III.3 CLASSIFICATION SOCIETY

Society category	*Voyages*	*Expected failures*	*Actual failures*	χ^2
D	6 850	7.2	10	1.1
C	7 239	7.6	6	0.3
B	6 808	7.1	7	0.0
A	7 700	8.1	7	0.1
Total	28 597	30.0	30	1.6[a]

Notes 1. Numbers may not add to totals due to rounding.

2. Significant χ^2 value for 3 degrees of freedom and 5 per cent level of significance is 7.81.

a. Includes contribution from successful voyages (see text).

Source BTCE estimates based on Lloyd's Maritime Information Services data.

TABLE III.4 COMMODITY CARRIED

Commodity	*Average voyages*	*Expected failures*	*Actual failures*	χ^2
Iron ore	3 373	9.8	33	55.4
Coal and grain	9 332	27.0	3	21.3
Bauxite and alumina	1 193	3.5	3	0.1
Phosphate	974	2.8	3	0.0
Other	1 039	3.0	4	0.3
Total	15 911	46.0	46	77.4[a]

Notes 1. Numbers may not add to totals due to rounding.

2. Significant χ^2 value for 4 degrees of freedom and 5 per cent level of significance is 9.49.

a. Includes contribution from successful voyages (see text).

Sources Fearnleys (1992a, 1992b); Lloyd's Register of Shipping (1992b).

For this reason, only the calculations for the unsuccessful voyages have been shown in the tables.

All but one of the tables are based on voyage and ship data purchased from Lloyd's Maritime Information Services. The one exception is table III.4, which is based on Fearnleys (1992a, 1992b) data, which allows a more disaggregated analysis of commodities.

TABLE III.5 SIZE OF SHIP

Size ('000 dwt)	*Voyages*	*Expected failures*	*Actual failures*	χ^2
30–50	13 520	14.2	4	7.3
50–80	9 174	9.6	9	0.0
80–100	589	0.6	3	9.2
100–150	3 256	3.4	11	16.8
>150	2 058	2.2	3	0.3
Total	28 597	30.0	30	33.7[a]

Notes 1. Numbers may not add to totals due to rounding.

2. Significant χ^2 value for 4 degrees of freedom and 5 per cent level of significance is 9.49.

a. Includes contribution from successful voyages (see text).

Source BTCE estimates based on Lloyd's Maritime Information Services data.

TABLE III.6 VOYAGE WEATHER CONDITIONS

Weather	*Voyages*	*Expected failures*	*Actual failures*	χ^2
Good	21 913	23	14	3.5
Bad	6 684	7	16	11.5
Total	28 597	30	30	15.1[a]

Notes 1. Numbers may not add to totals due to rounding.

2. Significant χ^2 value for 1 degrees of freedom and 5 per cent level of significance is 3.84.

a. Includes contribution from successful voyages (see text).

Source BTCE estimates based on Lloyd's Maritime Information Services data.

TABLE III.7 ROUTE

Route	*Voyages*	*Expected failures*	*Actual failures*	χ^2
Brazil–Asia	646	0.7	6	41.8
Brazil–Europe	1 172	1.2	3	2.6
South Africa–Asia	771	0.8	3	5.9
India–Mediterranean	78	0.1	2	45.0
WA–Japan	901	1.0	2	1.2
WA–North Europe	289	0.3	7	147.9
Other	24 740	25.9	7	13.8
Total	28 597	30	30	258.5[a]

Notes 1. Numbers may not add to totals due to rounding.

2. Significant χ^2 value for 6 degrees of freedom and 5 per cent level of significance is 12.59.

a. Includes contribution from successful voyages (see text).

Source BTCE estimates based on Lloyd's Maritime Information Services data.

APPENDIX IV CHARACTERISTICS OF SHIPS DEPARTING FROM AUSTRALIAN BULK PORTS

There is a substantial difference in the number of structural failures of bulk ships departing from the eastern Australian seaboard and those departing from the western seaboard. Between October 1989 and December 1991 there were nine failures of ships departing from Western Australian ports but no failures of ships departing from eastern Australian ports.

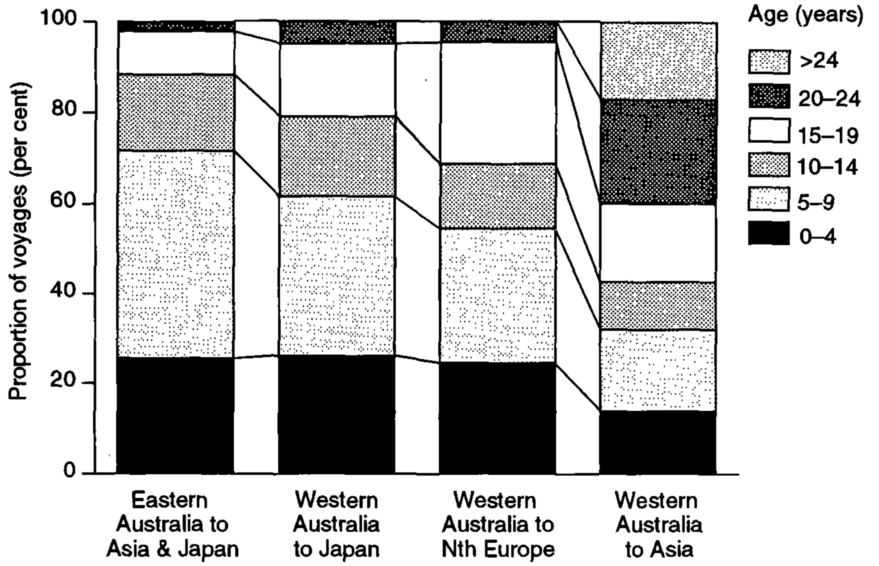
The larger number of failures of bulk ships departing from Western Australian ports raises the question of whether differences in the ships serving the two coasts might explain the divergence in failure rates. Also of interest is whether bulk ships serving Australian ports differ from those serving ports in other bulk exporting countries.

Chapter 3 suggests that route, commodity, flag and age of the ship are the major factors influencing the risk of structural failure. The analysis here therefore focuses on these characteristics as well as examining ship size in the context of the Australian routes.

AGE

Figure IV.1 illustrates the age distribution of bulk ships departing from Australia on major routes. The age distributions are significantly different between the different routes (table IV.1). It is clear that the Western Australia to North Europe route (which has a higher failure rate) involves older ships (31 per cent are older than 15 years) than the eastern Australia to Japan and Asia route (12 per cent are older than 15 years). The age difference would partly explain the difference in failure rates. However, the Western Australia to Asia route (mainly Chinese destinations) has an even higher proportion of old ships (57 per cent) but recorded no failures during the study period.

The routes from South Africa to Asia and Brazil to Asia (not shown in figure IV.1 and table IV.1) have comparable proportions of ships older than 15 years to the Western Australia to Japan and Western Australia to North Europe routes, namely 24 and 33 per cent, respectively. Figure 2.11 shows that these routes also have comparable elevated failure patterns.



Note Asia excludes Japan.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure IV.1 Australian routes and ship age

BTCE

TABLE IV.1 AUSTRALIAN ROUTES AND SHIP AGE

(voyages)

	Age						
	0–4	*5–9*	*10–14*	*15–19*	*20–24*	*> 24*	*Total*
Eastern Australia to Asia including Japan							
Actual	837	1 511	545	311	67	5	3 276
Western Australia to Japan							
Actual	236	320	157	145	42	1	901
Expected	230	416	150	86	18	1	901
χ^2	0.1	22.0	0.3	41.3	30.2	0.1	94.1
Western Australia to North Europe							
Actual	71	87	41	77	13	0	289
Expected	74	133	48	27	6	0	289
χ^2	0.1	16.1	1.0	89.6	8.5	0.4	115.7
Western Australia to Asia excluding Japan							
Actual	140	183	107	175	229	172	1 006
Expected	257	464	167	96	21	1	1 006
χ^2	53.3	170.2	21.8	66.2	2 111	18 925	21 348

Notes 1. 'Expected' number of voyages is calculated on the basis that the number of voyages by each age group would be proportional to the number of voyages by ships in that age group on the Eastern Australia to Asia and Japan route.
2. Figures may not add to totals due to rounding.
3. See appendix III for an explanation of χ^2.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

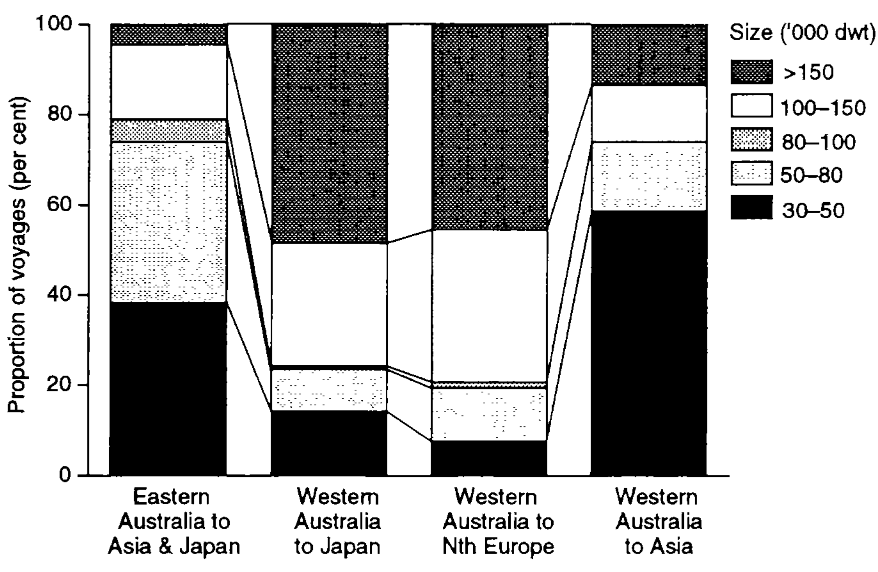
SIZE

Figure IV.2 illustrates the sizes of bulk ships on the major Australian routes. Ships departing from Western Australia to Japan and to North Europe are significantly larger than ships departing on the other routes (table IV.2). These ships are mainly large ships carrying iron ore.

The route from Western Australia to Asia has a high proportion of small ships, which also tend to be older ships.

The eastern Australia to Japan route is used by both coal and grain ships. Grain ships on Australian trade routes rarely exceed panamax size.[1] Coal ships are more likely to be larger than panamax size. The combined size distributions of the ships carrying grain and coal from eastern Australian ports would tend to be more balanced compared with the distribution of ship sizes on the other routes.

In appendix III, ships in the size range 80 000 to 150 000 dwt were found to be overrepresented in structural failures. The proportion of ships in this size range on the Western Australia to North Europe route (35 per cent) was considerably larger than on any of the other routes, the next largest being the South Africa to Asia route with 29 per cent. However, the relationship between size and failure risk is inconclusive (see appendix III).



Note Asia excludes Japan.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure IV.2 Australian routes and ship size

BTCE

1. Panamax size refers to ships between 50 000 and 80 000 dwt. They are the maximum sized bulk ships that can transit the Panama Canal.

TABLE IV.2 AUSTRALIAN ROUTES AND SHIP SIZE
(voyages)

	Size ('000)					
	30–50	50–80	80–100	100–150	> 150	Total
Eastern Australia to Asia including Japan						
Actual	1 258	1 164	165	544	145	3 276
Western Australia to Japan						
Actual	128	84	7	247	435	901
Expected	346	320	45	150	40	901
χ^2	137.3	174.2	32.5	63.4	3 914.8	4 322.2
Western Australia to North Europe						
Actual	22	34	4	98	131	289
Expected	111	103	15	48	13	289
χ^2	71.3	45.9	7.7	52.1	1 092.4	1 269.4
Western Australia to Asia[a]						
Actual	592	153	0	127	134	1 006
Expected	386	357	51	167	45	1 006
χ^2	109.5	116.9	50.7	9.6	179.8	466.5

Notes 1. 'Expected' number of voyages is calculated on the basis that the number of voyages by each age group would be proportional to the number of voyages by ships in that age group on the Eastern Australia to Asia and Japan route.
2. Figures may not add to totals due to rounding.
3. See appendix III for an explanation of χ^2.

a. Excluding Japan.

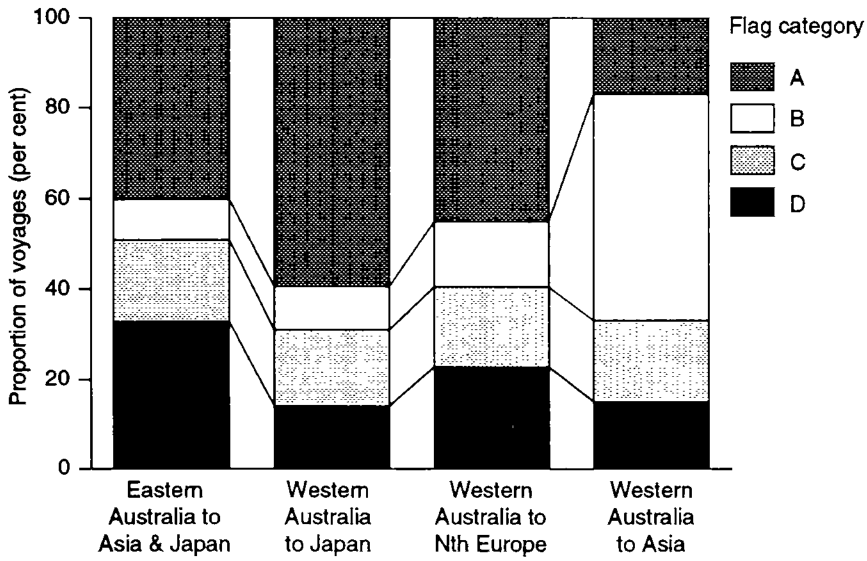
Source BTCE estimates based on Lloyd's Maritime Information Services data.

FLAG STATE

Figure IV.3 shows the flag state of bulk ships employed on the major routes. There is a significant difference between the flag distributions on the different routes (see table IV.3). The eastern Australian routes have a higher proportion of voyages of ships registered with flags with poor casualty records (category D). The Western Australian routes to Japan and North Europe both have higher proportions of voyages of ships registered with flags with low casualty rates (category A).

Because the two routes with the highest failure rates — Western Australia to Japan and to North Europe — have relatively low proportions of ships registered with flags with high casualty rates, it appears that flag is not as important a factor indicating risk of failure as is often suggested. The evidence here suggests that route might be a much more important factor than flag.

The routes from Brazil and South Africa have a much higher proportion of voyages by ships registered with flags with high casualty rates (category D) than the Australian routes. The proportions for the South Africa to Asia and Brazil to Asia routes are both 34 per cent and the Brazil to Europe route is 37 per cent,



Notes 1. Asia excludes Japan.
2. Flag category A has the lowest casualty rate and category D has the highest casualty rate. See chapter 2 for the method of allocating flags to categories.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

Figure IV.3 Australian routes and flag BTCE

compared with 14 and 23 per cent, respectively, on the Western Australia to Japan and North Europe routes, although they have similar proportions of older ships, as noted above.

CONCLUSION

Although there are significant differences between the ships serving the various routes departing from Australian bulk ports, the differences do not suggest that there are any factors unique to Australian ports that contribute to failure. The difference in failure rates between ships departing from eastern and western seaboards can be explained by differences in age of the ships and the commodities carried. The Australian iron ore routes are serviced by ships with a similar proportion of old ships to other comparable international iron ore routes, and the flag distribution favours the Australian routes. The analysis discussed in appendix III found no port effect. The larger size of ships on one of the Western Australian routes was the only factor where an Australian route showed a significant difference that might influence risk of failure. However, the statistical evidence relating size to risk of failure is not conclusive.

TABLE IV.3 AUSTRALIAN ROUTES AND FLAG

(voyages)

	Flag category[a]				
	D	C	B	A	Total
Eastern Australia to Asia including Japan					
Actual	1 080	590	294	1 312	3 276
Western Australia to Japan					
Actual	126	154	86	535	901
Expected	297	162	81	361	901
χ^2	98.5	0.4	0.3	84.1	183.3
Western Australia to North Europe					
Actual	66	51	42	130	289
Expected	95	52	26	116	289
χ^2	9.0	0.0	9.9	1.8	20.7
Western Australia to Asia[b]					
Actual	150	183	503	170	1006
Expected	332	181	90	403	1006
χ^2	*99.5*	*0.0*	*1 886.7*	*134.6*	*2 120.8*

a. Flag category A has the lowest casualty rate and category D has the highest casualty rate. See chapter 2 for the method of allocating flag states to categories.
b. Excluding Japan.

Notes 1. 'Expected' number of voyages is calculated on the basis that the number of voyages by each age group would be proportional to the number of voyages by ships in that age group on the Eastern Australia to Asia and Japan route.
2. Figures may not add to totals due to rounding.
3. See appendix III for an explanation of χ^2.

Source BTCE estimates based on Lloyd's Maritime Information Services data.

The evidence supports the conclusion in chapter 3 that weather conditions on particular routes play a major role in structural failure of bulk ships, in conjunction with commodity carried, and the condition of the ship as measured by age and flag state.

APPENDIX V LOGIT ANALYSIS

The analysis of structural failures of bulk ships is essentially an analysis of voyages that have one of two outcomes: the voyage is either completed successfully or it is unsuccessful (that is, it fails). Chapter 2 highlights the main factors influencing ship failure. To understand the factors better and their interrelationship with each other, a technique which reflects the binary response is needed. Also needed is a tool that allows surveyors to predict which ships are more likely to fail.

The logit technique is well suited to the analysis of binary response data. It is a statistical tool which permits estimation of the probability of an event occurring. If a ship that fails is coded as 1 and a ship that successfully completes a voyage is coded 0, then the model represents the probability of failure.

The logistic curve used in the analysis has the form:

$$\text{Pr (Ship fails)} = 1/(1+e^{-\beta\tilde{x}})$$

where β is a vector of coefficients to be estimated and $\tilde{x}$ is a vector of explanatory variables.

Figure V.1 illustrates a typical logistic curve.

The vector β is estimated by maximum likelihood methods. The theory of logit analysis is described in several books such as Collett (1991).

One method of examining the usefulness of the model is to calculate the confidence limits for the predicted logistics curve. However, the confidence limits may be affected by an inherent characteristic of the data.

The logit procedure, and regression analysis in general, is based on the assumption that each observation is independent of all other observations. However, the approximately 29 000 voyages in the database were undertaken by about 3000 ships. That is, each of the ships, on average, completed about 10 voyages departing from the five origin countries in the database. There is very

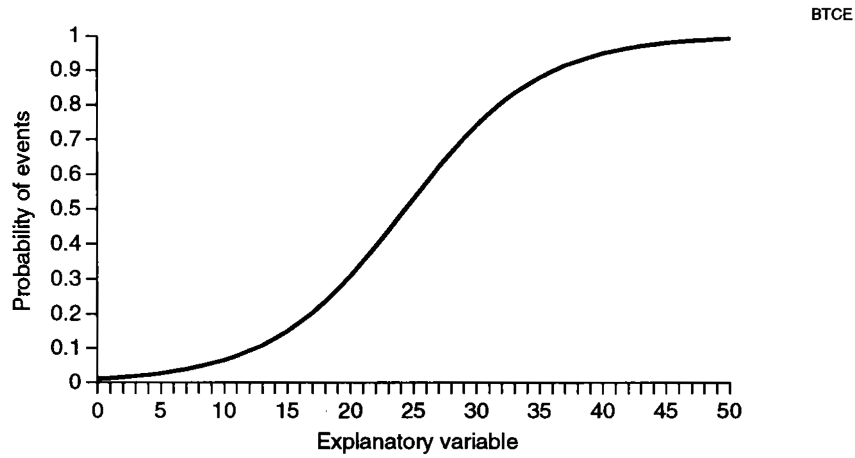


Figure V.1 Typical logistic curve

likely to be some correlation between repeated voyages undertaken by the same ship on the same route but at different dates. The assumption of independence between observations is, therefore, at least questionable.

The logit procedure does not allow for the possible correlation between repeated voyages, although its existence can affect the accuracy of the computed standard errors. In theory, the effect of correlation between voyages can either increase or decrease the magnitude of the standard errors. In practice, it is more likely to lead to standard errors that are smaller than those calculated taking account of the correlation. Unfortunately it is not possible to estimate the magnitude of the effect or to confirm its direction.

Although the standard errors are affected, there is no bias in the estimation of the coefficients.

CONFIDENCE LIMITS

Confidence limits for the main parameters can be calculated (SAS Institute 1989, p. 1091) as follows.

The linear predictor, $\eta = \beta'\tilde{x}$, is estimated by $\hat{\eta} = \hat{\beta}'\tilde{x}$. The standard deviation, $\hat{\sigma}(\hat{\eta})$, can be computed as the square root of $\tilde{x}'V_b\tilde{x}$ where V_b is the estimated covariance matrix of the parameter estimates $\hat{\beta}$.

The confidence interval around $\hat{\eta}$ is given by $\hat{\eta} \pm z_{\alpha/2}\hat{\sigma}(\hat{\eta})$, where $z_{\alpha/2}$ is the $100(1-\alpha/2)$ percentile point of the normal distribution. The upper and lower confidence limits are then given by:

$$1/\{1+\exp[-(\hat{\eta}+z_{\alpha/2}\hat{\sigma}(\hat{\eta}))]\} \quad \text{and} \quad 1/\{1+\exp[-(\hat{\eta}-z_{\alpha/2}\hat{\sigma}(\hat{\eta}))]\}$$

Confidence interval for change in age that implies same risk as a different flag

The results in chapter 3 indicate that ships registered with a flag with high casualty rates are subject to the same risk of failure as ships registered with flags with low casualty rates but which are 5 years older. The confidence limit for the difference in age that is equivalent to a change in flag is not the same as the confidence limits for $\hat{\eta}$. In the previous section, the confidence limits were calculated on the assumption that all variables can change. The full covariance matrix is therefore used in the calculation.

The problem examined here concerns only two variables, with all other variables held constant. Only the variance of the two variables and the covariance between them are needed in the calculation of the confidence limits. The following is from notes on logit model predictions supplied by Dr T. S. Breusch of the Department of Statistics, Australian National University (pers. comm. 1993).

The model is given by:

$$\Pr\text{ (Ship fails)} = f(X_1\beta_2 + \ldots) \quad \text{where} \quad f(\tilde{x}) = 1/1(1+e^{-\tilde{x}})$$

The aim is to find a confidence interval for a change in X_2 that exactly compensates for a one unit change in X_1 leaving $X_1\beta_1 + X_2\beta_2$ unchanged. That is, a confidence interval for $\theta = -\beta_1/\beta_2$. There are two methods that can be used.

Method 1 — Linear Approximation

Let $\hat{\theta} = -\frac{\hat{\beta}_1}{\hat{\beta}_2}$. Then:

$$\hat{\theta} - \theta = (-\frac{\hat{\beta}_1}{\hat{\beta}_2} - \theta) = -\frac{1}{\hat{\beta}_2}(\hat{\beta}_1 + \theta\hat{\beta}_2)$$

The variance is approximately:

$$\operatorname{var}(\hat{\theta}) = \frac{1}{\hat{\beta}_2^2}(v_{11} + 2\theta v_{12} + \theta^2 v_{22})$$

where v_{ij} is the covariance between $\hat{\beta}_i$ and $\hat{\beta}_j$ obtained from v_b.

The standard error $\hat{\sigma}(\theta)$ is $[\operatorname{var}(\hat{\theta})]^{1/2}$.

A symmetric $100(1-\alpha/2)$ per cent confidence interval can then be formed with end points $\hat{\theta} \pm z_{\alpha/2}\hat{\sigma}(\hat{\theta})$.

Method 2 — Fieller's Method

The following statement has probablity content $100(1-\alpha/2)$:

$$\left(\hat{\beta}_1+\theta\hat{\beta}_2\right)^2 \le z^2_{\alpha/2}\ \mathrm{var}\left(\hat{\beta}_1+\theta\hat{\beta}_2\right) = z^2_{\alpha/2}\left(v_{11}+2\theta v_{12}+\theta^2 v_{22}\right)$$

The end points of the confidence interval for the θ values are defined by the roots of the quadratic equation:

$$0=\left(\hat{\beta}_1+\theta\hat{\beta}_2\right)^2 - z^2_{\alpha/2}\left(v_{11}+2\theta v_{12}+\theta^2 v_{22}\right)$$

$$=\left(\hat{\beta}_1^2 - z^2_{\alpha/2}v_{11}\right)+2\theta\left(\hat{\beta}_1\hat{\beta}_2 + z^2_{\alpha/2}v_{12}\right)+\theta^2\left(\hat{\beta}_2^2 - z^2_{\alpha/2}v_{22}\right)$$

The confidence interval will generally not be symmetric about the point estimate $\hat{\theta}=-\hat{\beta}_1/\hat{\beta}_2$.

Method 2 is preferred by many users because it is exact if the coefficient estimates are exactly normally distributed, although they are only approximately normal here. Neither approach is to be trusted if the results are not roughly similar. Both methods are discussed by Collett (1991, pp. 96–101).

The confidence limits for the change in age to compensate for a change in flag category is 1.2 to 8.7 years using method 1, and 1.6 to 9.7 years using method 2. The results using the two methods are sufficiently similar to allow some trust to be placed in them.

The two methods could be used in a similar way to estimate confidence intervals for changes in age to compensate for changes in route or commodity.

REFERENCES

ABS	American Bureau Of Shipping
ACA	Australian Coal Association
AGPS	Australian Government Publishing Service
AMSA	Australian Maritime Safety Authority
BTCE	Bureau of Transport and Communications Economics
DTC	Department of Transport and Communications
HORSCOTCI	House of Representatives Standing Committee on Transport, Communications and Infrastructure
NKK	Nippon Kaiji Kyokai
NSW	New South Wales
UK	United Kingdom

ABS 1992, *Submission by the American Bureau of Shipping to the House of Representatives Standing Committee on Transport, Communications and Infrastructure Inquiry into Ship Safety*, HORSCOTCI Submission no. 39, HORSCOTCI, Canberra.

ACA 1992, *Submission by the Australian Coal Association to the House of Representatives Standing Committee on Transport, Communications and Infrastructure Inquiry into Ship Safety*, HORSCOTCI Submission no. 27, HORSCOTCI, Canberra.

AMSA 1992, *Submission by Australian Maritime Safety Authority to the House of Representatives Standing Committee on Transport, Communications and Infrastructure Inquiry into Ship Safety*, HORSCOTCI Submission no.18, HORSCOTCI, Canberra.

—— 1993, Data on bulk ships loading at Western Australia ports, AMSA, Canberra, unpublished.

Bendall, H. 1993, 'The aging international bulk fleet: implications for Australia', in *Papers of the Australasian Transport Research Forum 1993*, vol. 18, part 2, Graduate School of Management, University of Queensland, Brisbane, pp. 665–81.

Beresford, A. & Dobson H. (eds) 1989, *Lloyd's Maritime Atlas of World Ports and Shipping Places*, 16th edn, Lloyd's of London Press, Colchester, UK.

Blodgett, O. W. 1975, *Design of Welded Structures*, James F. Lincoln Arc Welding Foundation, Cleveland, Ohio.

British Maritime Technology (ed.) 1986, *Global Wave Statistics*, British Maritime Technology, Feltham, Middlesex.

BTCE 1988, *Characteristics and Cost Structure of the Bulk Shipping Fleet*, BTCE Occasional Paper no. 93, AGPS, Canberra.

Collett, D. 1991, *Modelling Binary Data*, Chapman & Hall, London.

Commission of the European Communities 1993, *A Common Policy on Safe Seas*, Communication from the Commission, COM(93)66 final, 24 February, Commission of the European Communities, Brussels.

Crisp, D. 1992, 'Liferaft discovery suggests bulker was lost in typhoon', *Daily Commercial News*, 28 October, p. 1.

D'Arcangelo, A. M. 1969, *Ship Design and Construction*, Society of Naval Architects and Marine Engineers, New York.

Daily Commercial News 1992, 'Governments to blame for "quality gap", says O'Neil', *Daily Commercial News*, 27 October, p. 6.

Davies 1988, *Arctic Carrier, 1985 — A Contributory Cause of Loss?*, cited in Ferguson (1991).

DTC 1988, *Report on the Preliminary Investigation into Certain Aspects of the Loss of the Philippine Flag Ship* Singa Sea *in the South Indian Ocean*, Maritime Operations, DTC, Canberra.

—— 1990, *Report on the Preliminary Investigation into Certain Aspects of the Loss of the Panamanian Flag Ship* Alexandre-P *in the South Indian Ocean, 14 March 1990*, P.I. 24, DTC, Canberra.

—— 1991a, *Departmental Investigation into Certain Aspects Concerning the Loss of the Bulk Carrier* Starfish *in the South Indian Ocean on 8 April 1991*, Report 28, DTC, Canberra.

—— 1991b, *Departmental Investigation into Certain Aspects Concerning the Loss of the Bulk Carrier* Mineral Diamond *in the South Indian Ocean on 17/18 April 1991*, Report 29, DTC, Canberra.

—— 1991c, *Departmental Investigation into Certain Aspects Concerning the Loss of the Bulk Carrier* Manila Transporter *in the South Indian Ocean on 7 August 1991*, Report 32, DTC, Canberra.

—— 1991d, *Departmental Investigation into Certain Aspects Concerning the Loss of the Bulk Carrier* Melete *in the South Indian Ocean on 24 August 1991*, Report 34, DTC, Canberra.

—— 1992, *Submission by the Department of Transport and Communications, Maritime Policy Division, to the House of Representatives Standing Committee on Transport, Communications and Infrastructure Inquiry into Ship Safety* HORSCOTCI Submission no 34, HORSCOTCI, Canberra.

Fearnleys 1992a, *World Bulk Fleet January 1991*, Fearnresearch, Oslo, Norway (and earlier issues, 6-monthly).

—— 1992b, *World Bulk Trades 1991*, Fearnresearch, Oslo, Norway (and earlier issues, annual).

Ferguson J. M. 1991, 'Bulk carriers — the challenge', in *Bulk Carriers — The Safety Issues*, Lloyd's Register of Shipping, London, 1992.

Gehling, R. 1992, 'Technology relating to bulk carrier safety', in *Maritime Technology 21st Century Conference, 25–27 November 1992,* University of Melbourne, Melbourne, section VI-3.

HORSCOTCI 1992a, *Ships of Shame, Inquiry into Ship Safety,* AGPS, Canberra.

—— 1992b, Reference: *Ship Safety 4 September 1992*, Official Hansard, Canberra.

Hydrographer of the Navy 1987, *Ocean Passages for the World,* 4th edn, Ministry of Defence, Taunton, UK.

Lloyd's Maritime Information Services 1993, Unpublished data provided from *Lloyd's Register* and *Lloyd's Voyage Record* databases, Lloyd's Maritime Information Services, Colchester, UK.

Lloyd's of London 1992a, *Lloyd's Shipping Index*, Lloyd's of London Press, Colchester, UK, 1992, 1991, 1990 issues.

—— 1992b, *Lloyd's List Daily*, Lloyd's of London Press, Colchester, UK (various issues).

—— 1992c, *Lloyd's Nautical Year Book 1992,* Lloyd's of London Press, Colchester, UK.

—— 1993a, *Lloyd's Ports of the World,* Lloyd's of London Press, Colchester, UK.

—— 1993b, *Lloyd's Nautical Year Book 1993,* Lloyd's of London Press, Colchester, UK.

Lloyd's Register of Shipping 1992a, *Bulk Carriers — The Safety Issues,* Lloyd's Register of Shipping, Ship Division, Colchester, UK.

—— 1992b, *Casualty Return,* 1992, 1991, 1990 & 1989 annual issues.

—— 1992c, *Casualty Weekly,* 1992, 1991 & 1990 weekly issues.

—— 1992d, *Lloyd's Register of Shipping,* 1992.

Lloyd's Shipping Economist 1989a, 'Costs', *Lloyd's Shipping Economist,* vol. 11, no. 2, p. 13 (and later issues).

—— 1989b, 'Rates and Prices', *Lloyd's Shipping Economist,* vol. 11, no. 2, p. 21 (and later issues).

—— 1990, 'Financial Gearing: Shipping Industry Remains Vulnerable' vol. 12, no. 6, June, pp. 6–8, Colchester.

NKK 1992, *Study Report on Bulk Carriers Loss,* NKK, Japan.

NSW Coal Association 1992, *Newsletter June 1992,* p. 4, Australia

O'Brien, D. 1992, 'P & I insurance: its current dilemma and future role', in *Maritime Technology 21st Century Conference, 25–27 November 1992,* section VII-6, University of Melbourne, Melbourne.

Packard, W. V. 1986, *Sea-trading,* vol. 3, *Trading,* Fairplay, London.

Parker, T. J. 1992, 'Do we really need new ships?', Paper presented to 'International Shipping Seminar', 15–17 March 1992, Oslo (cited in Gehling 1992).

Sanderson, V. 1993, 'Rates rise a must to improve shipping', *Daily Commercial News,* 18 March, p. 12.

SAS Institute 1989, *SAS/STAT User' s Guide, Version 6,* 4th edn, vol. 2, SAS Institute, Cary, North Carolina.

Sharpe, C. (ed.) 1989, *Kempe's Engineer Year-Book 1989,* Morgan-Grampian Book Publishing, London.

Stephens, B. 1992,'Classification societies the big losers', *Daily Commercial News,* 17 August, p. 32.

—— 1993, 'Collins pledges govt to "Ships of Shame" fight', *Daily Commercial News,* 7 September, p. 1.

ABBREVIATIONS

ABS	American Bureau of Shipping
ACA	Australian Coal Association
AMSA	Australian Maritime Safety Authority
BTCE	Bureau of Transport and Communications Economics
DTC	Department of Transport and Communications
dwt	Deadweight tonnage
GPa	Gigapascals
GRT	Gross registered tonnage
HORSCOTCI	House of Representatives Standing Committee on Transport, Communications and Infrastructure
IMO	International Maritime Organisation
MPa	Megapascals
NSW	New South Wales
NKK	Nippon Kaiji Kyokai
OECD	Organisation for Economic Co-operation and Development
psi	Pounds per square inch
uts	Ultimate tensile stress