# Tolerable Capsize Risk of a Naval Vessel

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## ABSTRACT

Many of the operations and duties conducted by naval ships involve a degree of risk. This risk is somewhat unavoidable due to the nature of operating a warship at sea, where operational requirements can put the vessel and crew in harms way. One of the hazards that the crew are subjected to while on operations is that of the weather.

The objective of this paper is to discuss the tolerable risk associated with the loss of a naval vessel due to the weather conditions. A review of tolerable risk and potential methodologies of calculating an annual probability of loss of the vessel which uses time domain simulations and statistics of observed weather conditions aboard naval ships are presented.

## KEYWORDS

Tolerable risk, Damage ships, Vessel loss.

## INTRODUCTION

Many of the operations and duties conducted by navies involve a certain degree of risk. This risk is somewhat unavoidable due to the nature of operating a naval vessel at sea, where operational requirements can put the vessel and crew in harms way. One of the continual hazards that the crew are subjected to whilst on operations is that of the weather.

Many navies, such as the UK's Royal Navy, now have a duty of care to ensure the level of risk they expose the ship's company to is commensurate with the benefits gained. It is this basis which is the principle of tolerable risk [1]. Navy ships are exposed to many hazards when at sea, like most commercially operated ships, but unlike commercial ships they may not be able to avoid heavy weather conditions due to operational requirements.

By using the theory and application of risk tolerability principles, as used by the UK's Health and Safety Executive (HSE) and adopted in most industries, an assessment of tolerable risk can be made [2]. This methodology is available for any business that deals with risk to the workforce or to the general public, including the UK MoD. The UK MoD assess the tolerability of risks associated with all areas of military equipment and operations. These tolerability principles could be applied to provide a suitable tolerable risk for the annual capsize risk of a naval vessel.

In 1990, the Cooperative Research Navies (CRNAV) Dynamic Stability group was established with the aim of deriving dynamic stability criteria for naval vessels. To derive such criteria, the group needed to evaluate in-service and new ship designs in moderate to extreme seas, in terms of their relative safety and probability of capsize. This would ensure that new vessels continued to be safe, whilst avoiding high build and life-cycle costs associated with over-engineering.

To achieve these objectives, the numerical simulation program FREDYN was developed and continues to be applied extensively both to intact and damaged ships. This time-domain program is able to take account of nonlinearities associated with drag forces, wave excitation forces, large-angle rigid-body dynamics and motion control devices. The current CRNAV group comprises of representatives from UK MoD, Naval Sea Systems Command (NAVSEA), the Australian, Canadian, French and the Netherlands navies, as well as the U.S. Coast Guard, Defence Research & Development Canada, (DRDC), Maritime Research Institute in the Netherlands (MARIN), Naval Surface Warfare Center Carderock Division (NSWCCD) and QinetiQ.

The objective of this paper is to discuss the concept of tolerable risk, which is the willingness to live with a risk so as to secure greater benefits. Using an accepted framework known as the Tolerability of Risk (TOR), decisions as to whether risks from an activity are unacceptable, tolerable or broadly acceptable can be made. These principles of tolerable risk are examined in association with the loss of a naval vessel due to the weather conditions.

## BROAD PRINCIPLES OF RISK ASSESSEMNT

Some may argue that any risk is unacceptable, but in reality the risk of suffering harm is an unavoidable part of living in the modern world. However, some risks can indeed be deemed acceptable for the following reasons [3]

- Threshold condition: A risk is perceived to be so small that it can be ignored.
- Status quo condition: A risk is uncontrollable or unavoidable without major disruption in lifestyle.
- Regulatory condition: A credible organisation with responsibility for health and safety has established an acceptable level of risk.
- De Facto condition: An historic level of risk continues to be acceptable.
- Voluntary balance condition: The benefits are deemed worth the risk by the risk taker.

In recent times there is an expectation for a society free from involuntary risk. The concept of risk is often used in everyday discussions where people often describe taking a risk in relation to taking a chance of adverse consequences to gain some benefit. Risk, however, is defined as ‘the combination of the likelihood and consequence of an unplanned event leading to loss or harm’ [1,2]. The way in which society treats risk depends upon the individual perception of how the risk relates to them. There are many factors involved and it is down to how well the process giving rise to the risk is understood, how equally the danger is distributed and how individuals can control their exposure [1]. Studies have shown that hazards give rise to concerns which can be put into two categories:

*Individual Concerns:*

This is associated with how the hazard affects an individual and all things that they value personally. Individuals are more likely to happily accept higher risks of hazards that they choose to accept rather than any hazards imposed upon them, unless they are considered negligible. If the risks provide benefits they will want the risks to be kept low and be controlled [2].

*Societal Concerns:*

This is the impact of hazards on society and if they were to happen would result in a socio-political response with repercussions for those responsible for controlling the hazard. These concerns are often associated with hazards that if they were to occur would cause significant damage and multiple fatalities. Examples would include Nuclear Power stations, rail travel and genetic engineering. Concerns due to multiple fatalities from a single event/effect are known as societal risk [2].

## CHARACTERISING THE ISSUES IN TERMS OF RISK

To examine the risk associated with the loss of a naval vessel the first stage must involve framing the issues relating to the risk. This will result in characterising the risk both quantitatively and qualitatively to look at how it may occur and what effect it will have on those involved and society at large.

A risk assessment is normally conducted when characterising the issues affecting the risk, which includes identifying the hazards which would lead to harm, what the likelihood of it occurring would be and what harm and consequences would be experienced if it was to happen.

This stage of the assessment often assesses the individual risk and then moves to look at the effect on societal concerns to first identify if the hazards should be considered at all or could be regulated sufficiently.

The analysis of this for the loss of a naval vessel in heavy weather can be, in some cases, simplified in certain aspects. The outcome of a vessel capsizing in bad weather will inevitably result in the fatalities or extreme harm to the majority of the crew onboard and would result in the material loss of the platform. An event of this type leads towards examining the societal risk aspects due to the outcome resulting in multiple deaths and loss of a naval asset. The additional repercussions that the navy and government would have to deal with are also associated with societal risk.

## TOLERABILITY PRINCIPLES

Once a risk has been assessed it must be examined to identify if the level of the risk is broadly acceptable, tolerable or unacceptable and whether the hazard should be even considered. It is therefore not surprising that a lot of work in determining criteria for these acceptability levels has been conducted [2].

Criteria used by regulators in the health and safety field have shown that the criteria can fall into three ‘pure’ criteria [2]:

*Equity based criteria*

These have the premise that individuals have the unconditional right to a certain level of protection, i.e. which is usually acceptable in normal life. This often results in a level of risk that can not be exceeded. If the risk level after analysis is above this level and suitable control measures can not be introduced to lower the risk, the risk is deemed unacceptable. For naval vessels these criteria will be relevant.

*Utility based criteria*

These criteria apply to the comparison between incremental benefits of the measures to reduce the risk, the risk of injury and the costs of the benefit. These criteria therefore look at comparing, in monetary terms, the cost of the benefits (statistical lives saved) of the preventative measure compared to the cost of implementing it.

*Technology based criteria*

These criteria essentially reflect that a satisfactory level of risk is obtained when ‘state of the art’ measures are employed to control the risks. For a naval vessel this could include advanced heavy weather training or onboard operator guidance systems.

## TOLERABILITY OF RISK

These criteria described above can be used on their own although a combination is often a better approach. The HSE have incorporated them in a framework known as the Tolerability Of Risk. This methodology breaks the level of risk down into three regions. These are described in figure 1 with the ‘ALARP triangle’ and are described in detail as follows :

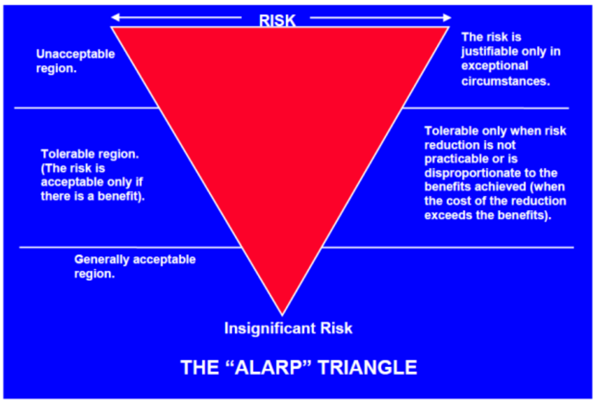

*Figure 1 – ALARP triangle*

### *Broadly acceptable risk region*

Risks that fall into the broadly acceptable risk region are deemed insignificant. Regulators would not require any additional measures to reduce the risks further than they already are. Further actions would only be required if lowering the risk was practical or where there is a legal requirement to lower it further. Regulators are required to regularly monitor the risk to ensure that it remains in this region. The level of risk at this level is comparable to what people regard as insignificant or trivial in their day to day lives [2].

### *Tolerable risk region (As Low As Reasonably Possible - ALARP)*

This region lies between the broadly acceptable and intolerable regions. Risks in this region relate to those risks that people are willing to tolerate in order to gain from the benefits. This means that the risk is deemed tolerable where society desires the benefits of the activity and only if further risk reduction is impracticable or the penalties are grossly disproportionate to the improvement gained. The levels of the risks must be assessed and the results used correctly to determine control measures. The assessment method must use the best available scientific knowledge [2].

### *Intolerable risk region*

The risk in this region cannot be justified except in extraordinary circumstances. Control measures are required to drive the risk downwards into one of the lower risk regions.

The aim for any activity would be to have the risks fall into the broadly acceptable region. However, the practicability of achieving this, for example with a naval vessel operating in open ocean conditions, may be difficult to achieve without unacceptable restrictions on the ship and operation. Therefore as the intolerable region by its nature can not be acceptable in anything but extraordinary circumstances, the As Low As Reasonably Possible (ALARP) region is realistic for naval vessels, with measures such as training and heavy weather guidance to assist in controlling the risk of capsize.

## TOLERABILITY LIMITS – INDIVIDUAL RISK BOUNDARIES

The term 'Individual risk' is used to describe the level of risk of fatality of an individual that is exposed to a particular activity. UK HSE guidelines state that an annual 1 in a million probability of fatality is a very low level of risk and should be used to define the boundary between the broadly acceptable and the Tolerable regions of risk [2].

The UK HSE guidelines [2] for a hypothetical person exposed to hazards in the workplace have defined the maximum tolerable risk of fatality as 1 in 1000 per year ($10^{-3}$) and 1 in 10000 ($10^{-4}$) for the risk of fatality to a member of the general public. This is referred to as the basic safety limit and is the cumulative value of risk an individual is exposed to. This measure is applied to investigate the risk to a hypothetical worker working in a particular industry, such as offshore for example, and used to compare to levels in other industries. It provides a base line for comparison and assessment of changes to the level of risk.

Individual risk however can not be used on its own for larger events which, if they occur, will result in higher numbers of fatalities. Group risk or societal risk as it is commonly known is used to describe the relationship between the probability of an unplanned event and the number of people affected by the event. It applies to those activities which present major implications for society such as a high number of fatalities, the loss of a major asset, environmental and political damage. Societal risk is not just calculated by taking the individual risk and multiplying it by the total number of fatalities from a single event, but is often complex and has many influences on its level.

## TOLERABILITY LIMITS – SOCIETAL RISK BOUNDARIES

For large events which impact on society as a whole, the societal risk will be the dominating factor rather than individual risks. Events which involve multiple fatalities will attract wide social interest and the societal risk encompasses both societal risk and society's reaction to an event.

When considering what society considers tolerable, there are several aspects which influence the response of society to the event and hence certain events are considered more tolerable than others. For example:

1. Acts by God or nature are considered more tolerable than those of human error.
2. Risks are more tolerable if we have control or have had participation in the decision leading to the risk e.g. car accidents are deemed more tolerable than aircraft accidents.
3. Risks are not tolerable if we cannot see the benefit for ourselves.
4. Familiarity makes a risk more tolerable. For example, a car accident is more tolerable than a nuclear radiation accident.
5. A large number of accidents spread over a fairly long period of time is more tolerable than a large number of incidents in close succession.
6. Less tolerable with risk towards the innocent and vulnerable.
7. Personal experience.

These and many other factors come into the society's response to an incident; particularly the knowledge of the hazard, whether the hazard was man made or natural and whether the potential victims are particularly vulnerable, e.g. children and the elderly [1].

Media coverage can significantly influence society's level of tolerability to a risk. For example, there are few car crashes reported in the press. However, aeroplane crashes or passenger ship accidents always are, when there are far fewer of these incidents. This makes society much more wary of ships and aeroplanes than driving a car.

The loss of a naval vessel due to capsizing in heavy weather would be classed as a significant event, due to the loss of a high proportion of the crew, the naval asset and the political damage associated with it. However, the hazard in this case is from nature and it is understood by society that naval personnel are exposed to greater risks whilst on operations, such as a search and rescue mission in heavy weather, and may accept a higher risk as being tolerable in that case.

The complexity of developing tolerable limits for events that would raise societal concerns is complex, so a way of conveying this information has been accepted. It uses the concept of FN curves, where the F denotes frequency and the N denotes the number of fatalities. These diagrams provide relationship data on the frequency of the fatal accident (plotted on the y axis) and the number of fatalities resulting from it (plotted on the x-axis). These curves can be used to graphically describe limits of risk acceptance. The curves can be generated by defining different combinations of consequence (i.e. fatalities) and the related frequency that gives negligible, acceptable and unacceptable risk respectively.

The UK HSE [2] have realised the complexity involved in analysing societal risk and have produced guidelines to define the acceptable borders between the tolerable and intolerable regions. This guidance is based on a FN criteria point for a single accident which occurs with a frequency of $2x10^{-4}$ events per year (1 in 5000) which results in 50 fatalities. This result is then extended on the FN diagram by applying a line with a slope of -1, using logarithmic scales on both axes, which is then defined as the risk neutral line i.e. a linear relationship between frequency and consequence. The broadly accepted region is taken as 2 orders of magnitude below this criteria (<1 in 500,000). These zones of tolerability are shown pictorially in figure 2. This FN diagram provides a framework in which to assess the risk tolerability of society of a particular event.

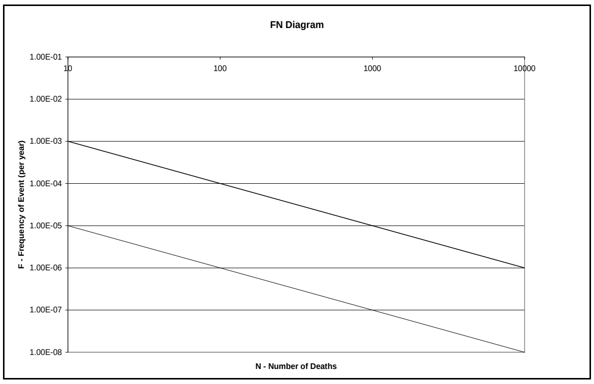

*Figure 2 - FN diagram*

In assessing an event such as the capsizing of a naval vessel, both the individual and societal risks need to be evaluated as they incorporate different concepts.

Excluding the other hazards that the crew onboard Royal Navy warships are exposed to in this study, the HSE guidelines can be used to assess what could be used as the tolerable risk of loss of a naval vessel.

## RISK ASSOCIATED WITH TRANSPORTATION

Examining various forms of transport, identifying how these industries deal with risk and what society deems acceptable allows direct comparison for what could be deemed acceptable to society for the maritime industry and naval vessels.

The risks involved in the air transportation industry are those which most people are aware of and accept when they fly. An accident survey of 1,843 aircraft accidents from 1950 through 2006 determined the causes of the accidents to be as follows:

- 53%: Pilot error
- 21%: Mechanical failure
- 11%: Weather
- 8%: Other human error (air traffic controller error, improper loading of aircraft, improper maintenance, fuel contamination, language miscommunication etc.)
- 6%: Sabotage (bombs, hijackings, shoot-downs)
- 1%: Other cause

(The survey excluded military, private, and charter aircraft.)

However, the risk of being involved in a crash on a single flight is, on average, 1 in 6 million [4,5], depending upon airline, in comparison to the likelihood of dying in a car journey of 1 in 5000. This means that for anyone flying, the individual is much more likely to die on the journey to the airport rather than during the flight itself. Fear of flying is common, mainly due to lack of personal control, understanding and the general concept of being at high altitude. People are perfectly happy to drive cars frequently, as they are in control and are happy to disregard the fact that there are 50,000 fatalities on highways every year. To put this into perspective, statistically a person would have to fly once a day every day for over 15,000 years in order to be involved in an aircraft accident.

When discussing modes of transport, there are a number of ways in which to define a fatality risk measure. The potential loss of life (PLL) measure is a basic measure of risk of fatality per year that is often used to define accident rates. However, this criterion has the short coming of not incorporating any exposure time into the measure. It is also important to make the distinction between individual and societal risk. The most common risk measures for individual risk are the Average Individual Risk (AIR) and Fatal Accident Rate (FAR). The AIR measure is calculated by dividing the PLL measure by the number of people exposed e.g. the number of crew on a naval ship. The FAR measure is calculated by dividing the PLL value by the total number of man hours of exposure and multiplying by a $10^8$ scaling factor. This gives the number of fatalities per $10^8$ hours of exposure to the hazard.

These measures provide a good means of comparing risks from travelling by various modes of transport, as shown in table 1.

**Table 1 - Individual risk of fatality for transport modes**

| **Travel Mode** | **Fatalities per $10^8$ passenger KM** | **Fatalities per $10^8$ passenger hour (FAR)** |
|---|---|---|
| Motorcycle | 9.7 | 300 |
| Bicycle | 4.3 | 60 |
| Foot | 5.3 | 20 |
| Car | 0.4 | 15 |
| Van | 0.2 | 6.6 |
| Bus/coach | 0.04 | 0.1 |
| Rail | 0.1 | 4.8 |
| Water | 0.6 | 12 |
| Air | 0.03 | 15 |

As can be seen from table 1, travelling by sea is one of the least risky modes of transport. The FAR value can be calculated for travelling on UK ferries and is 8.8 fatalities per $10^8$ hours of exposure [6]. Compared to the other modes of transport, UK ferries can be seen to be one of the safest forms of transport.

Regarding the risk of capsize of a navy vessel, consideration should be made to the exposure time and particularly the exposure to the heavy weather conditions where capsize is more likely to occur.

Other areas of the marine industry and other wider industries can be used to provide further comparison of the level of risk a person working in that industry is exposed to during their working life. These results for wider industry provide an indication to what society generally regards as acceptable.

The UK HSE [7] provides statistics comparing the risk of fatalities in various UK industries, table 2:

**Table 2 - Individual risk of fatality in UK Industries**

| **Industry** | **Annual Individual Risk of Fatality** |
|---|---|
| Agriculture | $8.10 \times 10^{-5}$ |
| Construction | $3.70 \times 10^{-5}$ |
| Offshore | $4.00 \times 10^{-5}$ |
| Services | $0.35 \times 10^{-5}$ |

These UK statistics are lower when compared with statistics from other parts of the world, table 3 [6].

**Table 3 - Individual risk of fatality in industries worldwide**

| Industrial Activity | Fatalities per 1000 worker-years |
|---|---|
| Mining | 0.9 - 1.4 |
| Construction | 0.3 |
| Industry | 0.15 |
| Shipping | 1.9 – 2.1 |
| Fishing on the Continental self | 2.3 |
| Fishing | 1.5 |

These statistics illustrate that the highest individual risks in UK industry are generally around $10^{-5}$ - $10^{-4}$ fatalities per year, compared to the $10^{-3}$ to $10^{-4}$ level for industries worldwide which are at the tolerable limit defined by the UK HSE.

Over the last few decades, extensive resources have been used to reduce the risks involved with the shipping industry. The long term trend of loss frequency has been studied [8] and it was concluded that the annual loss rate had been reduced by a factor of 10 in the twentieth century, from more than 3% in 1900 down to 0.3% in 1990. However, the greatest level of reduction was early in the century and the level of reduction has levelled off in recent years.

Investigations into the risk of loss of merchant vessels using Lloyd’s world casualty statistics has been conducted [9]. In that study, the total loss rate for different types of merchant ships are analysed, table 4.

**Table 4 – Commercial vessel annual risk of vessel loss**

| Vessel Type | Total loss rate (per 1000 ship years) | Annual probability of ship loss |
|---|---|---|
| General Cargo | 5.4 | $5.4 \times 10^{-3}$ |
| Bulk Dry | 3.3 | $3.3 \times 10^{-3}$ |
| Oil Tanker | 1.5 | $1.5 \times 10^{-3}$ |

On examination of fatalities from the loss of these different vessel types, it was found that there were 170 fatalities per year on general cargo ships that were lost. This relates to 1.8 deaths for every complete vessel loss. Taking the typical number of crew on this type of vessel, the individual risk of death for a general cargo ship crew member is calculated as $3.7 \times 10^{-4}$ [9]. This is the highest of the vessel types, with many of the other vessel types having a probability of individual risk of death close to the $1 \times 10^{-4}$ level. RoRo passenger vessels were found to have a individual death risk of $7 \times 10^{-5}$. The relatively large public focus on marine accidents reflects society’s considerable awareness of these fatalities.

As described above, regarding multiple fatalities and societal risk, an FN diagram is often used to convey acceptable risk levels for events with multiple fatalities. However, the FN diagram can be used to describe both required and the prescribed risk levels.

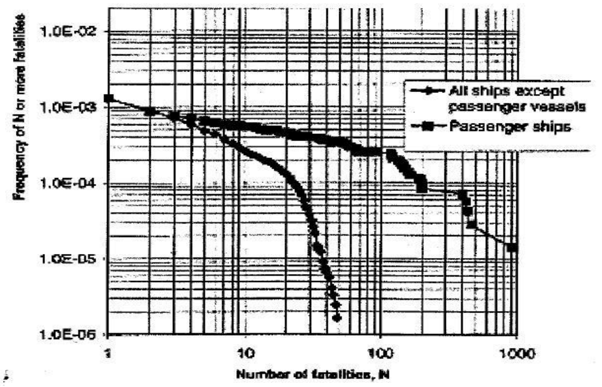

*Figure 3 – Frequency of accidents involving N or more fatalities DNV 1998 [10]*

Figure 3 is based on data from DNV in 1998, which shows the observed FN values for passenger ship accidents (upper curve) and cargo ships accidents (lower curve). For the passenger ships, it can be seen that small single fatality incidents occur with a frequency of approximately $10^{-3}$ per year, whereas an extreme casualty event (approximately 1000 casualties) occur with a frequency of $10^{-5}$ per year.

## TOLERABLE CAPSIZE RISK OF A NAVAL VESSEL

It cannot be assumed that the loss of a frigate from capsize would result in an approximate 10% fatality rate among the crew onboard, as found in the commercial vessels statistics. As the duty stations of the crew on naval ships are distributed throughout the vessel, many are below the weather deck which is quite different to commercial vessels where the majority of the crew will be in the vessel’s superstructures. It therefore can be assumed that the loss of at least 50% of the crew would be a more realistic value, as the crew stationed below 2 deck on a frigate would be unlikely to escape if the vessel capsized.

From the commercial vessel statistics, the probability of loss of the vessel is in the order of $10^{-3}$, table 1. This is just within the tolerable region, with up to 10 fatalities from any incident. From the loss of the general cargo vessels, the average fatality rate has been found to be 1.8 deaths per vessel loss. For the capsize of a naval vessel the number of fatalities would be significantly higher.

The FN diagram statistics for passenger ships, figure 3, show a probability of 8.5 x $10^{-3}$ for 100 fatalities and 1 x $10^{-4}$ for 200 fatalities per year. A passenger ship could be considered to be similar to a naval vessel, as there are a high number of personnel onboard compared to a cargo ship. As this is the observed level of probability, it could be taken that this is acceptable to society, as it is a historically accepted level of risk.

From the risk analysis, it is clear that the capsize of a naval vessel will result in a significant number of fatalities, as a medium sized vessel (such as a frigate) could have approximately 200 crew members. Based on the HSE tolerability limits, this would require the probability of the loss of the ship to be 6 x $10^{-5}$ per year to be within the tolerable region. This is slightly higher than the credible failure risk assumed for submarines, which is taken as a minimum of $10^{-6}$ for a 90 day patrol, where a failure event will also likely result in the fatalities of the entire crew [11]. This $10^{-6}$ value is on the tolerable and generally acceptable regions boundary of the UK HSE FN diagram.

Having around 100 fatalities (50% of a frigate crew) in the tolerable risk region would require an annual probability vessel loss of less then $1 \times 10^{-4}$. The generally acceptable region would require annual probability of loss of less than $1 \times 10^{-6}$. This would also result in an individual risk to the crew members at a similar magnitude as other areas of the marine and wider UK industry.

Considering all these points, it is suggested that a tolerable region boundary of 1 x $10^{-4}$ would be a suitable level for the annual risk of loss of a navy vessel in heavy weather and would be comparable to other areas of the marine industry and other major events. A value of 1 x $10^{-4}$ annual capsize risk was therefore found to be a suitable level for the tolerable risk boundary for the loss of a naval frigate at sea.

However, the manner in which extremely rare independent events are combined adds a final additional complexity to the problem, as probability theory has the combined probability of different independent events defined as the sum of the independent risks. This suggests that the other potential risks of loss of the ship and crew at sea should therefore be considered and subtracted from the 1 x $10^{-4}$ risk level to produce the tolerable limit of annual loss of the frigate and crew due to capsize. If these other potential risks have a probability of occurrence that is several orders of magnitude lower than the vessel capsizing, then tolerable risk value presented could still be closely related to that of the vessel capsizing. In a similar way to capsizing, naval vessels have almost never been known to be totally lost to fire, for example, while at sea (in peace time in recent years). Further investigation is required to identify the other potential risks of loss for a warship while at sea to identify how these risks realistically combine to produce an overall capsize risk that compares with other areas of industry.

## ASSESSING THE RISK OF CAPSIZE OF A NAVAL VESSEL

Assessment of the probability of a vessel capsizing is a significant aspect of assessing the risk. Calculating the probability of the vessel capsizing can be conducted with modern computational tools, such as FREDYN, which can model a vessel in extreme wind and waves. However, there are many areas of uncertainty that are inherent in the calculations that require careful consideration.

In order to accurately calculate the capsize probability of a naval vessel, a simulation tool is required to examine all possibilities of sea state and operational loading conditions to provide assessment of all realistic operational scenarios. The numerical simulation program FREDYN was developed by the Maritime Research Institute Netherlands (MARIN) for the Cooperative Research Navies working group and continues to be applied extensively to both intact and damaged ships. This time-domain program is able to take account of nonlinearities associated with drag forces, wave excitation forces, large-angle rigid-body dynamics and motion control devices. The FREDYN program permits investigations into the dynamics of intact and damaged vessels operating in realistic environments.

## CALCULATION OF ANNUAL CAPSIZE RISK PROBABILITY

FREDYN simulations can be used to evaluate the critical roll (capsize) behaviour of a vessel in a range of realistic operating load conditions. This procedure was developed by McTaggart [12] in 2002 and is described further in his paper [13]. The method, adopted by the CRN working group, is largely based upon the method described fully in his report [12] and is used for evaluating capsize risk of intact ships in random seas. This approach for predicting ship capsize risk combines the time domain simulation program FREDYN with probabilistic input data for wave conditions and ship operations (speed and heading). For a ship in a seaway of duration D (e.g. 1 hour) the probability of capsize $P(C_D)$ is:

$$P(C_D) = \sum_{i=1}^{N_{V_s}} \sum_{j=1}^{N_\beta} \sum_{k=1}^{N_{H_s}} \sum_{l=1}^{N_{T_p}} P_{v_s}(v_{s,i}) P_\beta(\beta_j) P_{H_s,T_p}(H_{s,k}T_{p,l}) P(C_D \mid V_s, \beta, H_s, T_p) \tag{1}$$

Where: $V_s$ = ship speed, β = wave heading relative to ship, $H_s$= wave significant height, $T_p$ = wave modal period.

The last term is a conditional probability of capsize in a given wave condition and ship heading relative to the waves.

Limited Gumbel distributions are used to fit to the maximum roll angles recorded in each of the seaway conditions, in order to calculate the capsize probabilities. A second, distribution free method, is also possible and was investigated with a new set of data calculated in a recent study. However, the limited Gumbel distributions have been shown by members of the CRN group to provide the best data fit and better predictions at the higher roll angles, which is the area of most interest for capsize prediction [12]. The Gumbel fit uses the upper 30 degree range of the simulation and fits to a minimum of 10 data points. This work was validated on large numbers of simulations (400+) by McTaggert [12]. However this number of runs was not feasible for any routine calculations, as the time to compute would be very lengthy. Realistically, the number of simulations has to be between 10-50. The sensitivity of using this number of runs was also investigated by McTaggert and was shown to give very good results [12]. Recent studies with the CRN group have shown that for other frigate types there may be a need for a greater number of simulations to produce statistically reliable results. Current investigations by CRN members are onward to identify if using the peaks over threshold methodology produces better fidelity of results, as the roll motion peaks during the whole simulation are used in the calculation of the capsize probability rather than just the maximum roll angle in each simulation.

The probability of capsize is calculated based on a time period of 1 hour and can be computed using equation 1. The associated annual probability of capsize can be calculated from the following equation, using the 1 hour capsize risk [7]:

$$P(C_{annual}) = 1 - \left[1 - P(C_D)\right]^{\alpha \times 1\,year/D} \tag{2}$$

Where α is the fraction of time spent at sea and D is duration (hours).

## UNCERTAINTY IN RISK CALCULATION

In the assessment of uncertainty and the application of safety factors to areas of uncertainty, HSE recommends making use of sensitivity analysis and comparative risk assessments for novel hazards that have a similarity to the case under investigation [2]. In the engineering world, safety factors are calculated to take into account the uncertainties in materials, calculation methods, etc. This principle is particularly exploited in the world of ship structures. In general engineering, safety factors between 1.25 and 5 are often used, dependant on the level of knowledge and uncertainty of the material and the environment, stress and load a structure is to be subjected to. The aerospace and automotive industry use factors in the region of 1.15 and 1.25, due to the costs associated with structural weight. The testing and quality control is also higher in these industries, with significant modelling (computationally and physically) of the material stresses involved.

The submarine world uses safety factors of a similar magnitude to the aerospace world, with significant physical and computational models used to ensure accurate understanding of the influences.

When assessing risks, it is usually required for uncertainty in the calculations to be taken into account when there is lack of, or incomplete data [2].

When examining the risk of loss of a naval vessel, the uncertainty in the outcome of the event i.e. what would happen if the vessel was to capsize, is actually very low due to the fact that it would result in the inevitable total loss of the vessel and a large number of the crew onboard. However, the uncertainty associated with the calculation of the probability of the event occurring is greater and must be adequately handled in order to calculate realistic values of risk for the vessel.

Knowledge uncertainty is one of the areas that must be dealt with [2]. This occurs when there are sparse statistics or random errors; for example, in experiment data used to define the probability of the event occurring [2]. Although many commercial vessels are lost each year and the statistics are available, in the case of the loss of a naval vessel in heavy weather, the statistics are very sparse and mainly representative of outdated designs of hullforms.

Modelling uncertainty is the term given to the uncertainties in the mathematical terms used in a numerical model used to assess risks. This is also closely linked with limited predictability associated with an outcome that is sensitive to the assumed initial conditions of the system under investigation and affects the final state i.e. the initial conditions of the ship affecting whether it capsizes in a certain wave condition or not.

It is clear that there are potential levels of uncertainty in the modelling of the risk of loss of a naval vessel using simulation tools such as FREDYN. Some of the main areas of uncertainty are related to the following:

- The probability of the vessel being in the waves and level of exposure.
- The probability of the speed and heading combinations in heavy weather.
- The simulation time i.e. the length of time the ship is in the waves.
- The number of simulations used in the prediction of the capsize event.
- The vessel loading condition.
- The angle used to define the capsize event.
- The autopilot in the simulations.
- Roll damping characteristics.

Techniques have been developed under what is defined as the ‘precautionary principle’ to handle uncertainty when dealing with calculating risk [2]. Uncertainty can be overcome by constructing the most credible scenarios of how the hazards might be realised.

### *Sensitivity of the annual capsize risk calculation*

The variables listed above, which are input parameters into the FREDYN capsize simulations, can be investigated using standard sensitivity type approach to assess the sensitivity of the inputs on the output probability of the capsize event. This would allow scenarios from the most likely to the worst case to be established and allow suitable safety factors to be derived and accounted for in the assessments.

The probability of the vessel being in the waves can cause unrealistically high probabilities of capsize by using the equation 2. A Bales wave climate statistics table [14] for the North Atlantic is often used to provide the probability of the waves occurring during the year, which is multiplied by the probability of the capsize event in those conditions. This can cause an unrealistically high annual probability of loss of the vessel, as the probability of the largest waves occurring with a high probability of loss of the vessel have a large influence on the overall annual capsize risk.

The capsize risk associated with the current calculations suggests that the probability of the vessel actually encountering the worst sea conditions is over estimated in the scenarios. A more realistic probability of the vessel encountering the waves is required.

A study was made for the UK MoD [15] which analysed the wave condition records made by the RN bridge teams in the 6 hourly records, which are kept by all Royal Navy ships whilst at sea. This data was collected for 78 Royal Navy vessels from 1968 to the present day. The data was also analysed from 1985 to the present day, to reflect the change in conditions encountered following the end of the cold war. This equates to over 168 years of Royal Naval ships at sea, which provides a substantial data set of more realistic wave statistics for the calculation of an annual capsize risk.

Using this wave height data and the Bales wave scatter table to provide the distribution of wave periods at each wave height condition resulted in a factored wave scatter table with a more realistic probability distribution for the vessel encountering the waves in a year. The change in probability distribution of wave height from the new data compared to the standard Bales scatter table is shown in figure 4 below:-

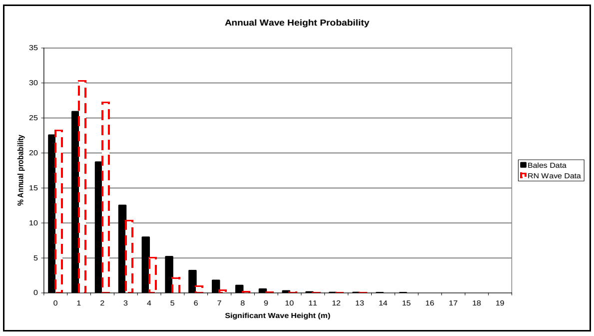

*Figure 4 – Wave Height Probability of Encounter*

It is clear from figure 4 that there is a distinct difference in the distribution of the wave height data that vessels have historically encountered compared to the annual probability of the waves occurring. The main significant factor is that the Royal Navy ships do not historically experience the larger waves as the standard annual wave statistics would suggest. This could be partly due to avoiding storms in certain cases, but not completely.

In equation 2 above for the calculation of the annual capsize risk, the hourly capsize risk that is generated from the simulations is effectively extrapolated up for each hour the vessel spends at sea. In the moderate wave heights, the maximum roll angles that are recorded are used to predict the probability of exceeding the 70 degree capsize angle. The wave height conditions recorded on the navy ships are made every 6 hours, which is also a realistic time frame for a large storm sea to remain relatively constant. Calculating results for the probability of capsize over 6 hours simulations may provide better results, which would equal the time between measurements made onboard. With a naval ship at sea approximately 30% of the year this equates to 440 6hr time periods.

To evaluate the effect of the simulation time, a number of calculations have been performed with different simulation run lengths, from 30 minutes to 6 hours, as well as different numbers of realisations between 10 and 50. The results show that the effects on the annual capsize risk are very small after 2 hours of simulation and increasing the number of simulations makes little difference to the annual capsize risk at this run length, figure 3. This shows that this has little effect on the probability of the capsize event for this vessel. A wider study is required to identify if this is the same for other vessels and load conditions.

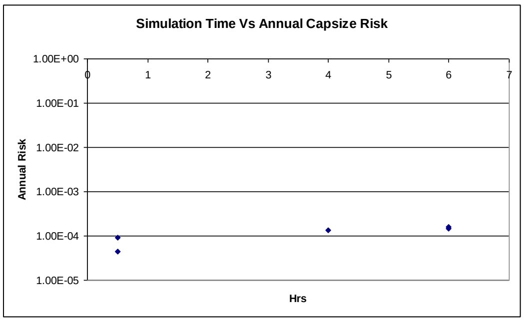

Figure 3 – Effect of simulation time on annual capsize risk

The selection of the ship speeds can have a large effect on the capsize risk and unrealistic speeds should be avoided in the simulations. To achieve the most realistic annual capsize probability, the actual operation of the ship in heavy weather is required to be accounted for in the calculations. Standard heavy weather seamanship training instructs operators to not go faster than 60% wave speed in heavy weather. This means that the vessel speed selection should be made as realistic as possible. Selecting speeds above 90% wave speed (30% safety factor for the operator) is unrealistic and will result in unrealistic capsize probabilities.

An even probability of heading is also usually assumed for the simulations. This could be considered to be precautionary, as in the very worst conditions the operator would avoid stern sea condition based on their experience, which is difficult to account for. Variation in the risk should be reviewed by removing certain headings, such as stern seas in the worst wave conditions. Selecting the accurate point this decision is made will require further discussion with operator training schools.

The roll damping characteristics of the model in the simulation will require investigation as to how it effects the risk calculation. The damping characteristics will be required to be set up as close as possible to the real vessel by comparing roll decay and roll period information. A systematic variation of the damping input parameters would provide the influence of the results to a specified variation of the damping characteristics. A suitable safety factor could then be derived to account for the variation on the modelling of the roll damping.

The autopilot control in the simulation will have an effect on the survival of the vessel. Using a systematic variation of the autopilot control parameters, the variation in risk could be derived based on those changes to the autopilot. A factor could then be derived based on the variation of the autopilot parameters.

The load condition of the vessel also needs to be considered in the annual capsize probability, as a vessel in a deep loading condition will often be inherently safer than in a light seagoing condition. It is therefore important to calculate at least two load conditions and use the typical operational profile to define the time the vessel would spend at each loading condition. This can then be realistically accounted for in the annual capsize probability. Operational procedures to ballast down with the forecast of heavy weather should also be accounted for in the calculations.

## CONCLUSIONS

In reviewing current Health and Safety guidelines, along with comparison with other modes of transport, other industries and the commercial marine industry guidelines for individual and societal risk have been described and can be used to examine the acceptable level of risk for capsize in heavy weather for the loss of a naval vessel. A value of $1 \times 10^{-4}$ annual capsize risk was found to be a suitable level for the tolerable risk boundary for the loss of a naval frigate at sea. The magnitudes and method of combining other very low risks of loss of the ship and crew at sea, needs to be further investigated and considered in defining the tolerable limit of annual capsize loss. If the other potential risks of vessel loss are found to be several orders of magnitude lower probability of occurring than the vessel capsizing, then the tolerable risk value presented will still relate predominantly to that of the vessel capsizing. Therefore, this could provide an overall capsize risk that can be compared with other areas of industry.

In order to calculate suitable levels of capsize risk, sensitivity analysis is required to assess the input parameters to identify the most realistic scenarios and the potential variation in the capsize risk due to realistic variation of the input parameters. By undertaking this analysis, realistic risk levels and safety factors can be calculated to evaluate the annual capsize risk of a naval vessel for comparison with the tolerable risk level deduced.

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