An investigation into the V-line criteria for naval vessels

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1 ABSTRACT

The quasi-static damage stability criteria for the Royal Navy include a dynamic allowance for heave and roll. The values for the dynamic allowance incorporated in the Red Risk and V Line criteria are based on Sarchin and Goldberg's work published in 1962. A methodology has therefore been developed for the evaluation of these criteria for naval vessels, using a time-domain ship motion program capable of simulating a damaged vessel with subsequent water ingress and flooding. For this investigation, the probability of occurrence of the water heights on the bounding bulkheads for two damage cases on three ships have been calculated. This paper compares the performance of the different size vessels and discusses the suitability of the criteria for the three sizes of vessel.

2 INTRODUCTION

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, while 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 latest version of FREDYN permits investigations into the dynamics of damaged vessels operating in realistic environments, rather than simple pseudo-static analysis. The current CRNAV group comprises 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.

Significant subdivision is common practice in Naval ship design. These internal arrangements introduce both symmetric and asymmetric flooding when damaged. Traditional damage stability analysis using quasi-static approximations cannot predict in a seaway the head of water on a bulkhead bounding a damaged region. For ships of the Royal Navy, a dynamic allowance over and above the static damage waterline is included in order to account for heave and roll in a seaway (Red Risk and V Lines).

This dynamic allowance is based upon the criteria originally suggested by Sarchin and Goldberg in 1962. Using contemporary dynamic stability analysis the dynamic allowance within the Royal Navy's Stability Standard (DEFSTAN 02-109) has been investigated. The study was based on the water heights experienced on the bulkheads of three different sizes of damaged vessels. A mine-hunter size vessel (750 Tonnes), vessel A, a modern frigate design (4500 Tonnes), vessel B and a larger vessel (60,000 Tonnes), vessel C.

The objective of this paper is to discuss the work that is currently being conducted to assess suitability of the Royal Navy's Red Risk and V-lines criteria for modern vessel designs of differing size. The initial findings from the work are presented.

3 Dynamic stability Analysis

Static stability analysis of damage scenarios can be performed using standard static stability software, however, this does not take account of the vessel motions or the consequential progressive flooding that can occur as a vessel moves in waves. The use of a time-domain simulation program enables the water heights on the bounding bulkheads to be analysed in a seaway, thus allowing the probability of exceedance of the water heights to be calculated. The FREDYN dynamic stability software was used for this investigation.

4 DAMAGE STABILITY CRITERIA & V-LINES

As with many static-based stability criteria adopted around the world, the origins date back to data and information gathered over many years. Following the great Pacific Typhoon of December 1944, during which United States Navy Pacific Fleet lost 790 men and three destroyers (Calhoun, 1981.), a review of stability assessment was undertaken. This resulted in new stability criteria for U.S. Navy ships (Sarchin and Goldberg, 1962). The criteria proposed form the basis of the intact and damaged stability standards that have been adopted by many Navies around the world including the Royal Navy in the form of DEFSTAN 02-109.

Included with Sarchin and Goldberg's criteria under the "Reserve of buoyancy Requirements" is a means for calculating "Flooding Water Levels on Bulkheads". The dynamic allowance applied by the UK MoD (DEFSTAN 02-109) although similar differs slightly to that applied by Sarchin and Goldberg.

The importance of calculating the flooding level on bulkheads relates to:

The requirement to design a bulkhead to survive the head of water imposed following damage.

The need to define the extents of watertight integrity of subdivision boundaries.

The need to define which openings need to be readily shut following damage.

To account for roll motion, the current DEFSTAN 02-109 specifies a 15 degree angle to the calm water damage waterline to produce the Red Risk Line. For heave related motions, a 1.5m allowance is added to obtain the V Line. This is an increase on that from the original 1962 paper, Figure 3.

Red Risk Line	Static angle of heel + 15^{o}
V Line	Damaged waterline height at centre line+1.5m +35^{o}

Figure 1 Summary of Current DEFSTAN 02-109 Criteria

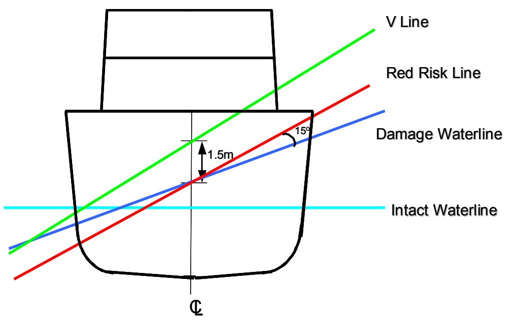

Figure 2 Red Risk and V-line

Allowance	Sarchin and Goldberg 1962	UK MOD (DEFSTAN 02-109)
Angle of Heel	15 degrees static heel assumed following asymmetric damage	Worst case damage angle of heel (limited by 20 degree list/loll criteria)
Angle of Roll	Related to displacement as per graph in published paper	15 degrees above static damaged angle of heel
Heave	4 foot heave allowance	1.5m heave allowance

Figure 3 Sarchin and Goldberg dynamic allowance as compared to DEFSTAN 02-109

5 NUMERICAL MODELLING

The FREDYN program was designed to enable the simulation of motion of an intact steered ship in wind and waves. Unlike the currently available frequency-domain programs, FREDYN is able to take account of the non-linearities associated with the drag forces, excitation forces and rigid-body dynamics. The approach is a physical one, where all factors are considered. Non-linearities have to be considered as they arise from:

- Effect of large angles on excitation forces,
- Rigid-body dynamics with large angles,
- Drag forces associated with hull motions, wave orbital velocities and wind, or
- Integration of wave induced pressure up to free surface.

The latest version of FREDYN can model vessels with damaged compartments and progressive flooding, and can predict the vessel's behavior in waves. A new option is now included to give the water heights at specified points in the compartments at each time step in the simulation.

5.1 Extreme Motions of Damaged Ship

The theory for predicting the large amplitude motions with FREDYN has been described by McTaggart and De Kat (2000) and by Van 't Veer and De Kat (2000). The derivation of the equations of motions for a ship subjected to flooding through one or more damage openings is based on the conservation of linear and angular momentum for six coupled degrees of freedom (De Kat and Peters, 2002).

5.2 Model Generation for the Current Study

Two computer models for each of the three test vessels were required to perform simulations; the static stability model and the FREDYN dynamic stability model. The static stability model provides the V lines and the basic hydrostatic inputs for FREDYN; it also serves as a benchmark against which to validate the FREDYN model.

The static stability model on which the FREDYN models were based, was provided by the UK MoD in the form of a PARAMARINE design. PARAMARINE is a conventional static stability software program available from the Graphics Research Corporation (GRC).

The internal arrangement of the 3 vessels were set-up in FREDYN based on the PARAMARINE damage cases. The tanks containing fluid required individual definition to set-up the model correctly to ensure accurate flooding and free surface effects. Including every tank can create an over complex model so only additional tanks with significant free-surface effects are modelled.

The damage region was created using a damage scenario that was based on a simplified weapon effect as shown in Figure 4.

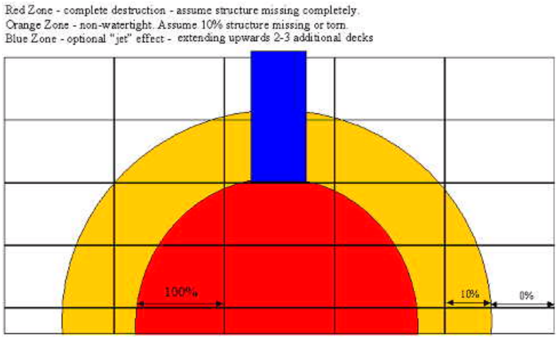

Figure 4 Damage Effect

For the three vessels that were tested, this damage was scaled so that it resulted in the DEFSTAN 02-109 assumed extent of damage. The geometry was modelled as follows:

- The structure in the middle zone was removed by having 100% free flow patches in the immediate damage region
- Openings between decks and bulkheads were made with 10% area of the deck to represent flooding due to perforations from an explosion
- The exterior shell was removed in its entirety in the centre zone across the keel of the ship as a square patch.

5.3 Water Height Modeling in FREDYN

New water height points were incorporated into FREDYN program. These points were positioned across the decks of the ships at the base of the bulkheads bounding the damage region. These points produce a time history of the water height at the points in ship fixed axes. Analysis can be conducted on this time history file to provide the amount of time the water height was above a certain level. In order to ensure that the results were statistically reliable, for each speed, heading, and Sea State combination, the simulations were run for a total of three hours, in different wave realisations. Although the transient flooding was calculated in FREDYN this initial part of the simulation was not used in the analysis.

The effects of the following parameters on the head of water on the bulkheads were investigated :-

- Sea State
- Heading
- Speed

5.4 Run Selection

To conduct the entire run set through all combinations of the initial selected variables would have resulted in an unreasonably large number of simulations. Instead, a rational parametric search was planned such that the effects of each significant change in the variables could be determined. Each set of runs in the table below concentrates on a particular part of the matrix with the number of runs set so data trends can be deduced.

Sea State	Speed (kts)	Headings
3	0	8
	4	4
	8	4
4	0	8
	4	4
	8	4
5	0	8
	4	4
	8	4

Table 1 Matrix of conditions investigated

Given that the original Sarchin and Goldberg V line criteria was developed for a frigate at zero speed in Sea State 4, the baseline case for this study was therefore Vessel B. Although a modern frigate form, Vessel B most closely resembled the original types of ship.

5.5 Damage cases

For each ship, two damage cases were chosen. This was done in such a way that a full combination of aft, forwards, amidships, symmetric and asymmetric damage cases were modeled. In each case, the damage extents reflected those required within DEFSTAN 02-109.

5.6 Ship Condition

As DEFSTAN 02-109 stipulates that the V line is to be calculated in the deep end of life condition, the vessels were therefore run in FREDYN in correspondingly realistic deep conditions.

5.7 V Line Heights

The V Lines for the ships investigated were previously calculated for these vessels according to DEFSTAN 02-109 and supplied for the purposes of this investigation.

6 RESULTS AND DISCUSSION

6.1 Vessel B - Frigate

For vessel B in the Sea State 3 there are low motions due to the size of the vessel. In the stern sea case, the water height maximum reached 0.25m below the V-line locus point. In the beam seas, the mid point was lower by 0.5m, with the side points only measuring a maximum of 0.25m greater. In the head sea case the water heights were not as high as the stern seas.

At 4Kts forward speed there was very little difference in the results across the heading, but when this is increased to 8Kts then there was a significant rise in the water heights at certain headings. In the head seas, Figure 5 and 6, the maximum water height is increased with the water height distribution stretched in the x-direction. In the beam seas, the mid height did not change significantly but the height at the side points increased by 0.2m.

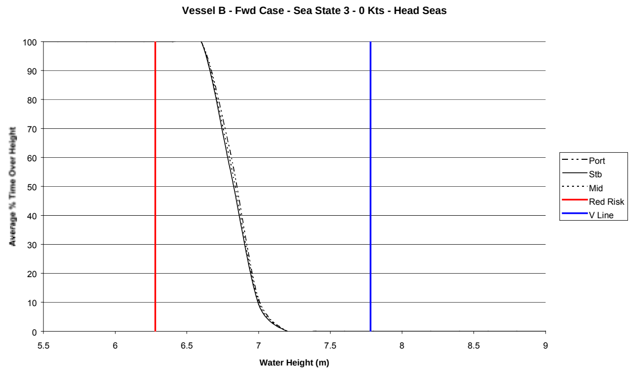

Figure 5 Vessel B – Sea State 4 - Head seas – 0Kts

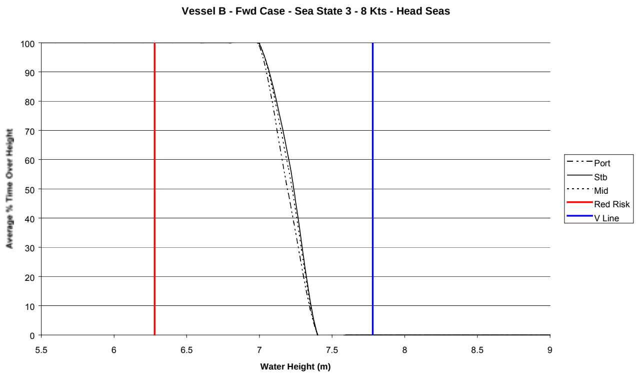

Figure 6 Vessel B – Sea State 4 - Head seas – 8Kts

Plots were also produced showing the probability of exceedance shown on the bounding bulkheads. Figures 6 and 7 show the bounding bulkhead with the probability of exceedance ploted on it as a set of curves. These curves result from a 21m DEFSTAN 02-109 damage aft from the forward perpendicular.

Figure 7 shows the beam sea case, where the water height on the center-line does not get near the V-line locus. The outside points are higher than the mid point due to the roll motion in the beam seas. The angle of the 0.01% exceedance line, due to the roll motion is less than the 15 degree red risk line angle. The statistics for the beam sea runs show a RMS roll of 4.4 degrees and a maximum recorded of 15.6 degrees.

The head sea case, Figure 8 shows a set of exceedance lines intersecting with the V-line locus with only the 0.01% line above the current limit.

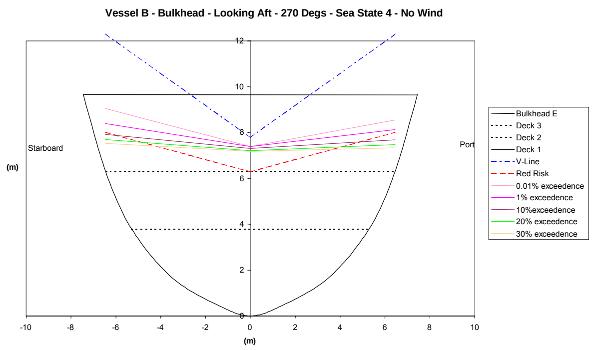

Figure 7 Vessel B – Sea State 4 - Beam seas

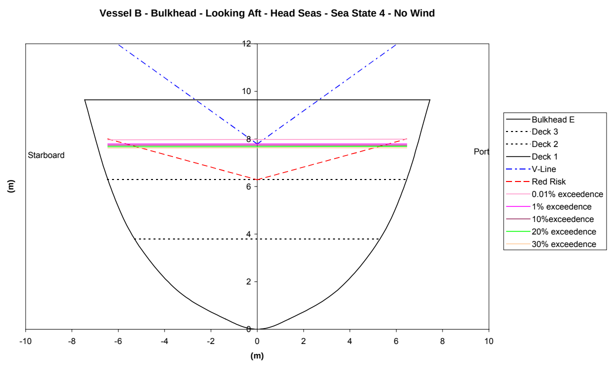

Figure 8 Vessel B – Sea State 4 - Head seas

The Vessel B frigate forward damage case demonstrated that even in the worst heading the current V-line value was only exceeded for short periods in the mid Sea State 4. This demonstrates that in the damage cases tested the current Sarchin and Goldberg based criteria are still suitable limits for a modern frigate design. In the aft damage case the aft of the bulkheads was starting to exceed the V-lines in the worst headings, where the forward bulkhead rarely did. The RMS roll for the forward case was 4.4 degrees with a maximum of 15.7 degrees measured close to the 15 degrees allowed in the criteria. The aft damage case had a RMS roll of 2.95 degrees and a maximum roll of 9.7 degrees. This is again within the 15 degrees that is given in the current criteria.

6.2 Vessel A – Smaller Vessel

The smaller vessel A was shown to have a satisfactory dynamic performance in comparison to the V-Lines criteria as long as the worst heading (stern seas) was not selected. The performance in the Sea State 4 was better than that seen for the Frigate in relation to the criteria. This is due to the fact that the smaller vessel A, didn’t have the sinkage as seen in the frigate case and still had a high reserve of buoyancy. This meant the smaller vessel contoured the waves better than the Frigate. The roll in the Sea State 4 for Vessel A had a maximum standard deviation of 4.8 degrees with a maximum roll recorded of 15 degrees, in the aft damage case. In the forward damage case the standard deviation was 4.45 degrees with a maximum roll measured of 12.5 degrees which is within the 15 degrees criteria.

Sarchin and Goldberg show a plot in the 1962 paper of different expected roll motion based on displacement, with smaller vessels rolling up to 14 degrees. The DEFSTAN 02-109 selected 15 degrees as the limit for all ship types.

6.3 Vessel C – Larger Vessel

For the Larger Vessel C, Figures 9 and 10 show plots of the bounding bulkheads in the forward damage case with the lines showing probability of exceedance in a Sea State 4. As expected with a vessel of this size very little heave and roll is noted in Sea State 4. This corresponds with the Sarchin and Goldberg 1962 paper, where a vessel of this size is predicted to have a dynamic roll of less than 5 degrees.

In head seas it can be seen in Figure 9 and 10 that the water level is well below the V-line locus point with 0.8m clearance. On the aft bulkhead, Figure 10, the water height was well below the V-line with 1m clearance.

In the beam sea conditions, the bounding bulkheads, Figure 11 and 12, show little heave effects. Instead, roll can be seen to be having an effect. It is noted that the angle of the probability of exceedance line, is well below the 15 degree Red Risk limit line. The statistics also show an RMS roll of 0.82 degrees with a maximum roll of 3.1 degrees. This is lower than the 5 degrees defined by Sarchin and Goldberg.

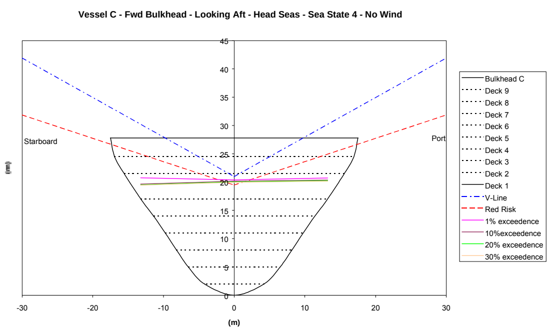

Figure 9 Vessel C – Sea State 4 - Head seas – fwd bulkhead

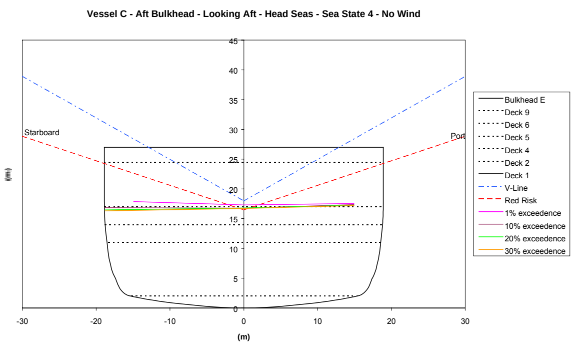

Figure 10 Vessel C – Sea State 4 - Head seas – aft Bulkhead

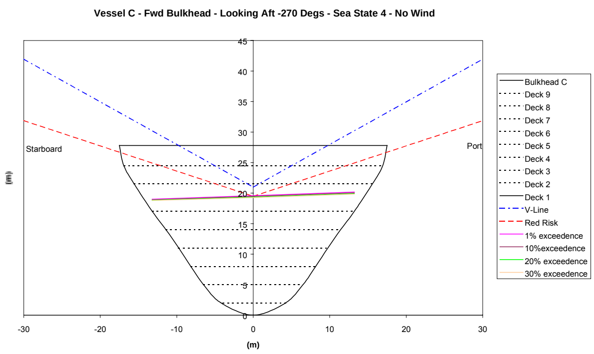

Figure 11 Vessel C – Sea State 4 - Beam seas – fwd bulkhead

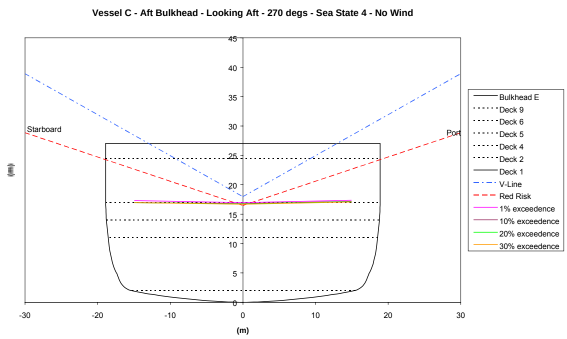

Figure 12 Vessel C – Sea State 4 - Beam seas – aft Bulkhead

7 CONCLUSIONS

It has been shown that following this methodology and using a suitable time-domain code that the Red Risk and V-lines criteria can be evaluated for different sized vessels. Information can also be provided to the operators on speed/heading.

For the damage cases tested it has been shown that the criteria based on the Sarchin and Goldberg V Line criteria which were based on World War II hull forms are still applicable to modern frigate damage cases.

It is apparent from this work that the DEFSTAN 02-109 criteria are suitable for different sized modern vessel designs in a Sea State 4 and not just frigate forms. Where the dynamic allowance for roll and heave were exceeded it was for only seconds during the hour-long simulations.

It should be noted that increasing the Sea State significantly affects the probability of the V lines and Red Risk Lines being exceeded for the two smaller vessels. For the larger vessel the probability of exceedance was similar to the frigate form in a Sea State 4.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the permission granted by QinetiQ and the UKMoD for publishing some of the findings from the investigation.

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