STABILITY CRITERIA EVALUATION AND PERFORMANCE BASED CRITERIA DEVELOPMENT FOR DAMAGED NAVAL VESSELS

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ABSTRACT

The current quasi-static damage stability criteria used by the UK MoD are largely based on the Sarchin and Goldberg work published in 1962. These criteria ensure a level of stability performance after damage. Like the intact stability criteria, the inherent level of safety in these criteria and the link to the dynamic performance of the vessel in waves is little known.

A methodology has been developed to evaluate the dynamic stability performance of naval vessels after damage. The evaluation of the current criteria has been performed using a large number of time-domain ship motion simulations using a computer program capable of simulating a damaged vessel with subsequent water ingress and flooding. This gives an insight into the level of safety inherent in the current damage stability standards.

A selection of damage cases were conducted using a frigate hullform with geometric variations made to the internal subdivision. A range of loading conditions from those passing the current criteria through to those failing in each of the geometric damage case variations were systematically assessed in a range of wave conditions representative of post-damage sea states. The results from the dynamic study were then compared to the current damage stability criteria terms to identify how the current criteria relate to the dynamic damage performance in waves.

1. 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 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.

The objective of this paper is to discuss the work that is currently being conducted to assess dynamic performance whilst damaged of naval type vessels in waves and wind. The first findings from this work are presented here.

The Royal Navy currently uses static and quasi-static stability criteria to ensure a level of stability performance after damage. Like the intact stability criteria, the inherent level of safety in these criteria and the link to the dynamic performance of the vessel in waves is little known.

A methodology has been developed to evaluate the dynamic stability performance of naval vessels after damage. In a similar manner to the probabilistic intact calculations previously conducted by McTaggart 2000, probabilistic calculations have been conducted to evaluate the level of safety inherent in the current damage stability standards.

A selection of damage cases based on a modern frigate hullform with geometric variations made to the internal subdivision was assessed. A range of loading conditions, from those passing the current criteria through to those failing in each of the geometric damage case variations was created.

2. DAMAGE STABILITY CRITERIA

As with many static-based stability criteria adopted around the world, the origins date back to data and information gathered over many years. This applies especially to the great Pacific Typhoon of December 1944, which struck vessels of USN Pacific Fleet causing the loss of 790 men and three destroyers (see Calhoun, 1981.). Following this incident a review of stability assessment was undertaken, which resulted in new stability criteria for U.S. Navy ships (Sarchin and Goldberg, 1962). This covers the intact and damaged stability criteria, which has been adopted by many Navies around the world including the UK MoD.

The current stability criteria and damage extents that UK naval vessels have to be able to survive are defined in DEFSTAN 02-109 (The Defence Standard). This document also states the minimum acceptable intact and damaged stability standards for the vessels for which the UK MoD is responsible. The current damage lengths are defined as follows:

- Vessels of waterline length less than 30m; any single main compartment.
- Vessels of waterline length between 30m and 92m; any two adjacent main compartments. A “main compartment” is to have a minimum length of 6m.
- Vessels of waterline length greater than 92m; damage anywhere along its length, extending 15% of the waterline length, or 21m whichever is greater.

Significant subdivision is common practice in naval ship design. These internal arrangements introduce the potential for both symmetric and asymmetric flooding when damaged. The current Royal Navy stability criteria are based largely upon the criteria originally suggested by Sarchin and Goldberg in 1962. This traditional damage stability analysis using quasi-static approximations cannot account for the behaviour in a seaway or for example, the head of water on a bulkhead bounding a damaged region. For this example of the V-line requirements for the Royal Navy, a dynamic allowance over and above the static damage waterline is included in order to account for vessel motions in a seaway. It has until recently not been possible to asses the suitability of these damage criteria for modern vessels.

3. DAMAGE CRITERIA ASSESSMENT CRITERIA

To investigate the inherent level of safety in the current damage stability criteria (DEFSTAN 02-109) a new methodology was required to systematically compare the dynamic performance of a damaged vessel to the current static damage criteria based on GZ parameters.

There are several degrees of increased complexity involved in damage dynamic stability investigations over conducting intact dynamic stability studies. In the intact studies, the variables which directly influence the intact stability criteria values, for a particular vessel, can be largely restricted to KG and displacement. With a damage stability investigation, there is the added complexity of the load condition (tank states) and the size and shape of the damage, all which significantly influence the damage stability criteria values. This results in a complex matrix of simulations to isolate parameters and investigate the influence on dynamic damage stability performance.

The high level methodology that has been used to assess the current damage stability criteria is similar to that used previously by the CRNAV group to investigate the intact stability criteria, based on the work by McTaggart (2000). Dynamic stability performance was systematically assessed in a range of wave conditions, with the vessel in carefully selected damage and loading conditions. Results from the dynamic study were then compared to the current damage stability criteria terms to identify trends and which criteria are most closely linked to the dynamic damage performance in waves.

4. NUMERICAL MODELLING

The FREDYN program was designed to enable the simulation of motion of an intact steered ship in wind and waves. Unlike currently available frequency-domain programs, FREDYN is able to take account of 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 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 and has been described by De Kat and Peters (2002). The latest version of this software (9.8) was used for this study and can model the influence of damaged compartments and cross-flooding ducts on the vessel’s behaviour in waves.

5. A RELATIVE DAMAGE LOSS INDEX

FREDYN allows multiple load and environmental conditions to be tested and the dynamic performance of the vessel to be evaluated. The output from FREDYN consists of motions and relative water heights and so a new measure was required which could provide an overall measure of the damage stability performance in waves.

To measure the performance of the vessel after damage the initial focus was on the safety of the vessel and crew following a damage incident rather than on residual mission capability. A number of measures were developed to establish a relative probability of effective loss of the vessel in each damage simulation. These measures of damage performance relate directly to the fundamental modes of loss of the vessel after sustaining damage. These measures provide an indication of the inherent safety of the vessel when damaged, and are as follows:

- Roll angle, related to the likelihood of capsize;
- Pitch angle, related to plunging and the ease of movement (for evacuation) longitudinally along the vessel;
- Reserve of buoyancy, related to sinking (vertical stability); and
- Gunwale submergence, related to loss of weather deck area and the ability to evacuate effectively.

For each damage simulation the time spent and the number of excursions over a range of roll and pitch angles was calculated. The reserve of buoyancy in the hull was also evaluated throughout the simulation. For the evaluation of the gunwale submergence, six water height points were positioned at 0.25 length between perpendiculars (LBP), 0.5 LBP and 0.75LBP on each side of the vessel on the gunwale. During each simulation, the amount of time each water height point was submerged was calculated. Post analysis of the output was conducted to identify when adjacent pairs of water height points were submerged at the same time indicating significant submergence of a large portion of the weather deck.

Together with each of these four performance measures, an acceptable limit was required to define the point where the vessel was deemed to have been “effectively lost”, i.e. no longer safe for the crew to be onboard and the complete catastrophic loss of the vessel imminent. The selection of these limits has an element of subjectivity to it. In this study the limits chosen were identical in all of the test cases, so the relative performance difference between the test cases could be evaluated.

The roll angle limit was set at 85% of the range of positive stability of the GZ curve in the damage condition for each case. This provides a 15% margin for exceeding the range of positive stability and a complete capsize occurring. The time spent over this roll angle limit is assumed analogous to the probability of loss due to roll for the damage case, load and wave condition tested. If the vessel actually capsized during one of the runs the probability of capsize of the run was taken as 100% in the analysis.

The pitch angle limit was set to 15 degrees. This was selected based on discussions with operators at the Royal Navy damage control school (DRIU) and naval officers, which suggested that at 15 degrees pitch angle, moving along the decks becomes very difficult and moving damage control equipment becomes very restricted. The 15 degree pitch limit indicates where evacuation becomes difficult and therefore was selected as a suitable limit to use for the relative performance measure. The time spent over this pitch angle therefore is analogous to the probability of loss due to pitch for the damage, load and wave condition.

The reserve of buoyancy output from FREDYN is defined by the buoyancy remaining in the hull up to the weather deck. A limit was selected as 2000 Tonnes of equivalent buoyancy, as this relates to approximately half of the original displacement of the vessel in the intact condition. This reserve of buoyancy was considered necessary to keep the crew inside the vessel and allow for the possibility of escape. It was not envisaged that the reserve of buoyancy would be one of the limiting factors due to the relatively short floodable damage length used in this study.

The deck edge water height points were used to capture excessive immersion of the gunwale and weather deck. Regularly immersing pairs of points on the gunwales indicates that there is significantly reduced area of the weather deck and that safe crew evacuation would become very difficult with the gunwales deeply submerged and the weather deck awash. Following discussion within CRNAV it was concluded that if two of the adjacent water height points were simultaneously submerged by more than 0.2m, the vessel was considered to be effectively lost. Therefore the percentage of time spent with two adjacent water height points submerged above 0.2m indicates the probability of effective loss of the vessel.

In order to produce a measure for the probability of the effective loss of the vessel in the damage case, load and wave condition, each one hour simulation was conducted five times with different wave realisations at the same wave height and modal period. The five hours of simulation in each wave and heading combination is believed to provide sufficient time and wave encounters to evaluate the performance of the vessel.

By analysing these four measures for ‘effective loss’ of the vessel, the limiting measure in each case was identified and used as the relative probability of loss for that damage, heading and sea condition. Using global wave statistics (Bales 1982) in combination with the probability of Royal Naval vessels being in the waves (Haywood 2006), a relative probability for the vessel being in a particular wave condition was calculated. Multiplying the relative probability of loss for each wave condition by the probability of the ship encountering the wave conditions, produces a relative risk of loss of the vessel after damage. These relative risks of loss for each wave and heading can then be summed together for all wave conditions to provide an overall relative risk of loss measure.

The Relative Damage Loss Index (RDLI) term provides a measure of the dynamic damage stability performance of the vessel in a particular damage scenario and load condition for a 99.9% probability [Haywood 2006] of the waves the vessel is likely to experience after becoming damaged. Using these RDLI values calculated from a range of loading and transverse damage extent cases allowed the performance to be compared to the static damage stability criteria. This allows relationships between the static criteria and the dynamic damage performance to be derived.

6. VESSEL DAMAGE CASES AND LOAD CONDITION SELECTION

Computer models of a modern frigate were required to perform simulations; the basic static stability model and the FREDYN dynamic stability model. A static stability model was required to provide the basic hydrostatic inputs for FREDYN; it also serves as a benchmark test to validate the FREDYN model.

PARAMARINE was chosen as the software for which the static stability model would be produced. Graphics Research Corporation (GRC) develops PARAMARINE with specific funding from the UK MoD. QinetiQ has rigorously tested and validated PARAMARINE against pure mathematical models on the behalf of the UK MoD.

6.1 Damage Length

It was decided that the damage length that would be used for the vessel would remain fixed in all cases in the study. The damage length and shape that was used related to a 'significant damage' event previously defined [Peters 2007] as the 95th percentile of the damage data for this size of vessel, based on commercial damage statistics using the data from the HARDER project (HARDER 2003, Lutzen 2001). This damage length is similar to that required in the current DEFSTAN 02-109 criteria. The location of the damage opening was fixed, giving flooding into three compartments.

With the damage length fixed for the study, the variables that could influence the stability criteria parameters were restricted to those that define the transverse extent of damage flooding, such as the position of the longitudinal subdivision. The other major parameters that influence the damage stability criteria are the vessel's intact displacement and load condition.

To set the boundaries for the study a modern frigate hull hullform was used; taking a typical DEFSTAN 02-109 asymmetric damage case as the baseline. A PARAMARINE model of a modern frigate design was used to generate the test cases for the investigation. A typical DEFSTAN 02-109 three compartment damage case for the vessel was selected as the start point for the investigation. This arises from the current DEFSTAN 02-109 damage length of 15% LBP which equates to the 'significant' damage length for this vessel in the study. This damage case incorporates flooding into zones including large machinery spaces as well as two pairs of Dieso wing tanks. A typical light loading condition was used to set the displacement and fluid levels in the tanks to be the same for all the cases tested.

6.2 Loading Condition

At the light loading displacement, the limiting KG value was calculated for the current DEFSTAN 02-109 stability criteria in this initial damage case. The values of all the damage stability parameters were calculated at this limiting KG condition to identify which was the limiting criterion.

Varying the vessel's KG at the fixed displacement allowed three loading conditions to be set which provided a pass, marginal and fail condition against the current DEFSTAN 02-109 damage stability criteria. Each criteria term was calculated at the three load conditions. KG values at the pass and fail conditions were set equal to the limiting KG values for the more asymmetric and less asymmetric damage cases discussed below to give common load conditions between the damage cases.

The second variable investigated in the study was the transverse damage extent i.e. the longitudinal subdivision. The transverse damage extent and transverse subdivision were systematically varied to change the amount of damage and flooding of the vessel. These changes to the transverse damage extent affect the damage stability criteria and so allow for variation of the criterion for a fixed displacement and KG load condition. The three damage cases are presented in Figure 1.

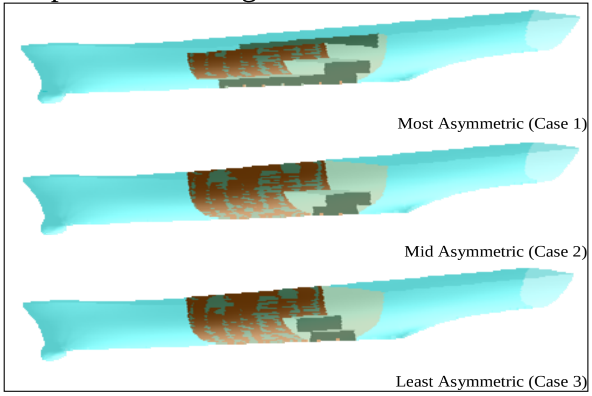

Figure 1. Damage cases.

The transverse damage extent was increased and decreased to create two further damage cases with differing transverse flooding extents. At each of these new damage cases the limiting KG value was calculated. Each of the criteria terms was calculated at the limiting KG condition to identify the limiting criterion. The KG was then varied to create a pass and fail load case against the current stability criteria for the three damage cases. This is shown pictorially in Figure 2 where the limiting KG cases for each of the three damage scenarios are indicated by the markers with black centres.

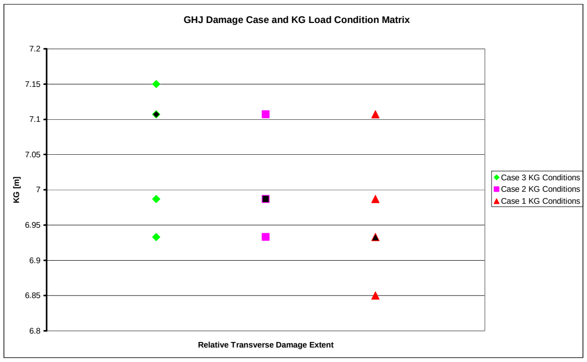

Figure 2. KG load matrix for the 3 damage cases.

For each the limiting KG condition in each of the three damage cases, the limiting criteria term is different. This allowed the effect of each criteria parameter and the current DEFSTAN02-109 criteria limit to be investigated in comparison to the dynamic stability performance.

FREDYN simulations

Each of the load cases and damage scenarios were set up in FREDYN V9.8 using QinetiQ’s current standard practice for creating FREDYN models, by exporting the geometry and compartment definitions from the PARAMARINE model in the format for use with FREDYN.

Each case was set up to examine the vessel at two beam seas headings. At the 90 degree heading the vessel is in beam seas with the damage opening towards the waves. At the 270 degree heading the vessel is in beam seas with the damage opening away from the waves.

In each case a total of 32 different wave height and period combinations were used to cover the range of waves that the vessel would likely encounter if damaged (Bales 1982). The wave height was set to a maximum of 6m significant wave height, as it has been shown that the probability of a Royal Navy vessel being in a sea state 6 or less is 99.9% based on data from the past 40 years [Haywood 2006]. The simulations were set up using QinetiQ’s computer clusters to allow multiple simulations to be conducted simultaneously.

Following each simulation the roll, pitch, reserve of buoyancy and water height data were automatically analysed and the statistics of the motions collected. The motion and water height data were averaged over the five different realisations for each run. The relative probability of loss for roll, pitch, reserve of buoyancy and the water height combinations were then calculated, based upon the pre-defined limits. The largest and hence limiting relative probability of loss was selected as the probability of loss for that damage scenario, heading and wave condition.

7. COMPARISON BETWEEN DEFSTAN 02-019 DAMAGE CRITERIA AND THE DYNAMIC STABILITY PERFORMANCE

The RDLI calculated for each of the eleven combinations of damage extent and load condition were plotted in a number of ways to identify how the dynamic damage performance compares to the current stability criteria. The load condition, the transverse damage extent and wave height were also examined to identify the effect on the dynamic stability performance.

The current damage stability criteria values were plotted for the eleven cases on a linear and logarithmic scale to identify relationships between the criteria and the dynamic performance of the vessel. Linear and logarithmic scales were used for the plots as they were previously found to highlight trends during studies on intact stability criteria performance [Peters 2007]. Linear, log and power fit trend lines were then used to fit to the data in order to rank the criteria.

Figure 3 shows the relationship between the damage list angle and the RDLI. It is clear that the damage list angle stability criterion gives a poor relationship (based on the best R2 fit of 0.71) with the RDLI. This is of particular interest as this damage stability criterion is often a dominating factor in the certification of naval ships due to their inherent asymmetry in the internal subdivision. This figure shows that in isolation, it is not a particularly strong measure of the damage performance of this vessel. The current 20 degree limit from DEFSTAN 02-109 relates to a 28% RDLI value for this vessel when using the derived trend line, but the results show a variation in RDLI between 12% and 58%.

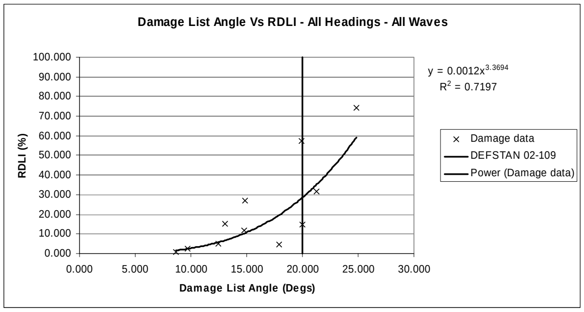

Figure 3. Damage list angle criteria vs. RDLI all headings and waves.

Figure 4 shows the Area A1 criteria versus the RDLI. This criterion shows a slightly improved relationship compared to the static list angle, with an exponential curve R^2 fit of 0.85. The current DEFSTAN 02-109 stability criteria again relates to an RDLI of close to 28%, which is very close to that given by the current damage list angle criteria.

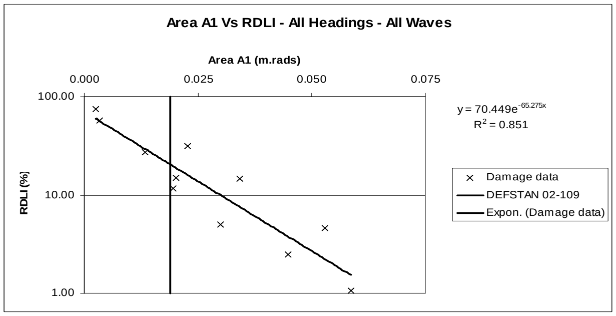

Figure 4. GZ Area A1 criteria vs. RDLI all headings and waves.

Figure 5 shows the results of the GZc/GZmax criteria in comparison with the RDLI data. This criterion shows improvement over the two previous criteria (list angle and A1 area criteria), with a R^2 fit of 0.93 using a linear data fit. It is interesting to note that the data is predominately below the current DEFSTAN 02-109 stability criteria (all but one case), giving an RDLI of 62% for this criterion at its present value. This suggests that this criterion is not particularly good in these cases if used in isolation, even with the good data fit (R^2=0.93).

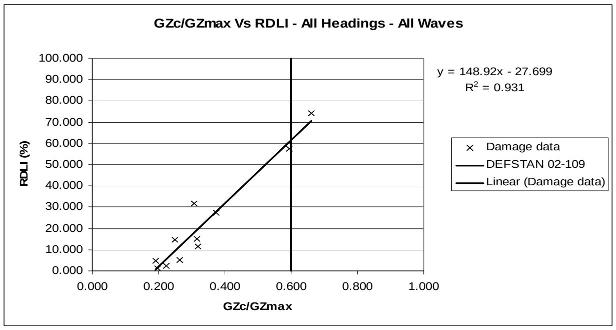

Figure 5. GZc/GZmax damage criteria vs. RDLI all headings and waves.

Figure 6 shows the A1/A2 damage criteria versus the RDLI. An exponential fit to the data from the eleven test cases produced an R^2 fit of 0.992 and is the best fit of all the current damage criteria. This criterion appears to show an excellent (R^2 = 0.992) relationship to the dynamic performance of the vessel in waves after damage. The A1/A2 criterion provides a relationship between the restoring and disturbing energy on the vessel after damage. This is based on the wind heeling curve and a fixed 15 degree roll back angle. No wind effects were included in the FREDYN calculations and so the only disturbance was from the waves in the simulations, which has been shown to be the dominating disturbing effect.

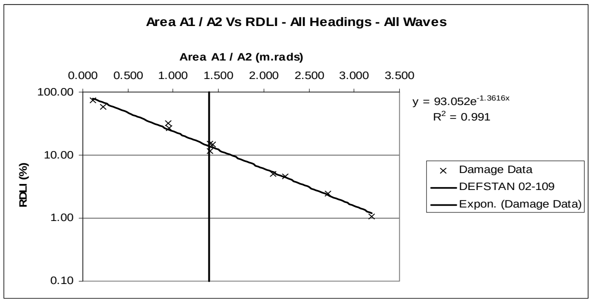

Figure 6. A1/A2 damage criteria vs. RDLI all headings and waves.

The range of values from the eleven test cases provided an even spread of data for the A1/A2 criteria and did not show clustering of data on the chart like the GZc/GZmax criteria. The criteria provides a good fit to the data and a good spread of results, meaning this criterion is potentially a very good indicator of the dynamic damage stability performance after a damage incident.

The current DEFSTAN 02-109 A1/A2 criteria limit is shown on the plot, Figure 6. The current criterion limit value relates to an RDLI of 12% which is significantly lower than the 28% of the next two closest fitting criteria. Like the list angle criteria, this criterion is often the limiting damage criteria for Frigates.

8. COMPARISON BETWEEN OTHER POTENTIAL DAMAGE STABILITY CRITERIA AND THE DYNAMIC STABILITY PERFORMANCE

Together with the current static damage stability criteria analysis, additional potential alternative criteria measures were calculated for each of the eleven test cases. These potential measures were plotted against the RDLI in a number of ways to identify if an alternative measure could be used to relate to the dynamic performance of the vessel after damage.

The damaged GM was the first alternative measure investigated, as this is a measure that is often used to give an indication of residual damage stability performance both by naval architects and naval staff. Damage GM versus the RDLI for all waves and headings is shown in Figure 7.

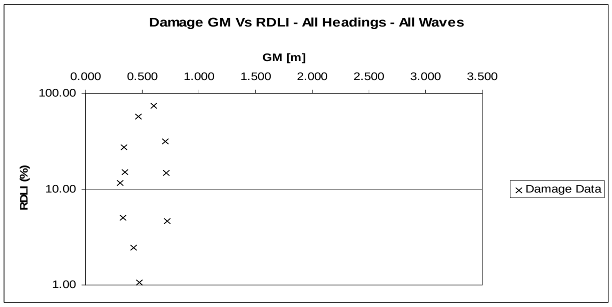

Figure 7. Damage GM alternative criteria vs. RDLI all headings and waves.

From Figure 7, it can be seen that the damage GM does not show a close relationship with the RDLI in the cases tested. This suggests that the damaged GM is not a good indicator of the dynamic damage stability performance.

The area under the GZ curve has been shown to be a good measure of the intact dynamic stability performance [Peters 2007]. It was therefore hypothesised that the area under the GZ curve from the angle of list to the range of positive stability (RPS) would provide good indication of the dynamic damage performance in waves.

In each of the eleven cases tested, the area under the GZ curve was calculated and plotted against the RDLI using a log scale. Figure 8 shows the relationship between the area under the damaged GZ curve and the RDLI.

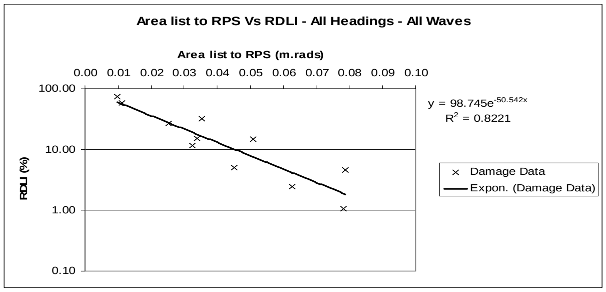

Figure 8. Area under GZ from list angle to RPS alternative criteria vs. RDLI all headings and waves.

As can be seen in Figure 8, the damaged GZ curve area provides an indication of the dynamic stability performance with a reasonable spread of the data points, but the R2 data fit is 0.822, which is not as good as the top three ranked current damage stability criteria.

In order to improve on this criterion another alternative measure was considered. This investigated the relationship between the areas under the GZ curve prior to damage divided by the area under the damaged GZ curve from the angle of list to the range of positive stability. This is shown in Figure 9 below plotted on a log scale.

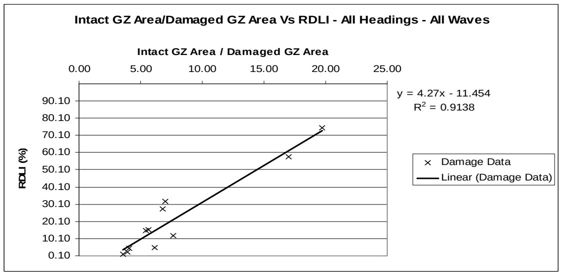

Figure 9. Intact area under GZ / Area under GZ from list angle to RPS alternative criteria vs. RDLI all headings and waves.

Figure 9 shows the data fit with the inclusion of the intact GZ area term. With an R^2 value of 0.913, it shows an improvement in comparison to the damaged GZ area in isolation. Unfortunately this criterion does not provide a reasonable spread of data as the data are predominantly clustered at the left hand side of the chart.

Using this hypothesis the area from the angle of list to 30 degrees and then to 40 degrees was calculated and plotted against the RDLI using a log scale. Figure 10 shows the area from the angle of list to 30 degrees, which shows an improvement (R^2 = 0.894) compared to the full GZ area from the angle of list to the range of positive stability. There is also a greater spread of data.

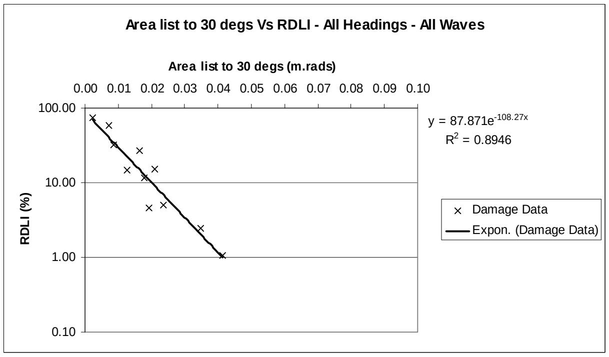

Figure 10. Area from list angle to 30 degrees alternative criteria vs. RDLI all headings and waves.

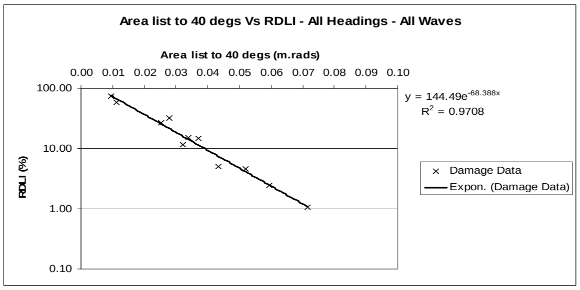

Figure 11. Area from list angle to 40 degrees alternative criteria vs. RDLI all headings and waves.

Figure 11 shows the area from the angle of list to 40 degrees compared to the RDLI. This shows a much improved R^2 data fit of 0.97 compared to that from Figure 8 and 9. This criterion shows the greatest potential as an alternative criterion that could be used in conjunction with the higher ranked current criteria such as GZc/GZmax and the A1/A2 criteria.

A suitable criteria limit for the area from the angle of list to 40 degrees would be 0.04 mrads, which equates to a 10% RDLI. This 10% RDLI is in close alignment with the level associated with the current A1/A2 damage criteria for the cases tested. Further investigation is required to extend the data set to cover other geometries and conditions.

9. GM AND WAVE HEIGHT EFFECT ON RELATIVE DAMAGE LOSS INDEX

Figures A1-A6 (Appendix A) shows the plots of the RDLI against significant wave height to examine how the RDLI changes as the sea state increases. The values presented are calculated by averaging the results from each of the wave periods at the specific significant wave height. Figures A1-A6 show the RDLI versus the significant wave height for each of the three transverse damage extents, showing curves for each of the GM conditions tested at 90 degree (damage opening towards the waves) and 270 degree (damage opening away from the waves) headings respectively.

Figures A1 and A7 show the data for the most asymmetric of the three damage extents tested, at 90 and 270 degree headings. On comparing the largest GM load condition data it can be seen there are very similar results for the RDLI at both the 90 and 270 degree headings.

Figures A2 and A5 show the mid asymmetric damage case at the 90 and 270 degree headings respectively. For the largest GM case, the RDLI value increases steadily to 20% at 90 degree heading and 11% at 270 degree heading at the 4m significant wave height. The RDLI then increases rapidly reaching 85% and 66% at the 6m significant wave height at the 90 and 270 degree headings respectively. This shows that the 270 degree heading (damage opening away) provides a lower RDLI across the wave height range.

Examining the limiting GM curve for this damage case (GM=0.73m at A1/A2 criteria limit), there is a similar pattern with a steady increase in RDLI to the 3m wave height at both headings. Above the 3m significant wave height, the RDLI at the 90 degree heading increases rapidly to 100% in the 5m waves. At the 270 degree heading the rate of increase in RDLI is much lower with the RDLI reaching 40% at the 5m significant wave height.

The GM case which is outside the current criteria limit starts with an RDLI of over 40% at both headings and both rapidly increase with wave height. The RDLI value at the 270 degree heading then levels off at around the 85% level. The 90 degree heading reaches an RDLI of 100% level at the 4m significant wave height and remains at that level. This shows that the 270 degree (opening away) heading has a better survival probability than the 90 degree (opening towards) in this low GM condition.

10. RESULTS AND CONCLUSIONS

Performance based measure of the damage performance of a vessel for assessment of the strengths of static and quasi-static based damage stability criteria has been conducted.

The RDLI is a measure of the probability of the vessel no longer being viable for the crew to remain onboard safely for an hour after damage, considering all waves up to sea state 6. This is used to compare the current static damage stability criteria with a measure of the dynamic stability performance in waves.

When the current DEFSTAN 02-109 damage criteria and current levels of criteria are examined in comparison with the RDLI, the GZc/GZmax and A1/A2 are the two current measures that show a good logarithmic relationship with the dynamic performance of the vessel after damage. However, it is only the A1/A2 criteria ($R^2 = 0.99$) which shows a suitable current level for the criteria, with the current DEFSTAN 02-109 criteria level equivalent to an RDLI of 12%.

This indicates that this criteria level provides an 88% possibility of survival for 1 hour after damage, considering both beam sea headings and all waves up to sea state 6.

The alternative criteria measures that were examined highlighted two key points. The first shows that the damaged GM value, which is often used as rule of thumb for damage stability performance was shown to have a poor relationship to the dynamic performance in all of the cases tested. The second point was that the area under the GZ curve from the angle of list to 40 degrees was shown to be a good alternative measure for the dynamic performance of the vessel after damage. A value of 0.04 mrads for this criterion would provide an RDLI value of 10%, which is in line with that from the current A1/A2 criteria.

The cases tested during the study have shown interesting relationships between the static stability criteria and dynamic damage performance. The addition of results from further damage cases for this and other vessel types are required to identify if the conclusions regarding the criteria with the strong relationships to dynamic performance are still valid.

It is clear from the study that the significant wave height has a great influence on the survivability of the vessel after damage. Using a 10% RDLI value as an acceptable level of risk of loss of the vessel in a seaway, it is clear from the current criteria limiting cases that the current stability criteria reach the 10% RDLI at or just above the significant wave height of 2m, which equates to a sea state 4. When the significant wave height reaches 3m there is often a considerable increase in the probability of the effective loss of the vessel. This indicates that if the vessel was damaged with a significant damage length and the significant wave height was above 2m, then the general guidance would be to consider evacuation of the crew or to prepare for rapid evacuation.

During the study the 270 degree (damage opening away from waves) heading was shown to be the safer of the two headings with a lower RDLI, in all of the waves. This was particularly evident in waves above 2m where the difference in performance was larger. This suggests that if the vessel suffers asymmetric damage and if it is possible to influence the vessels heading, then the damage opening should be positioned away from the waves.

11. ACKNOWLEDGEMENTS

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13. APPENDIX A

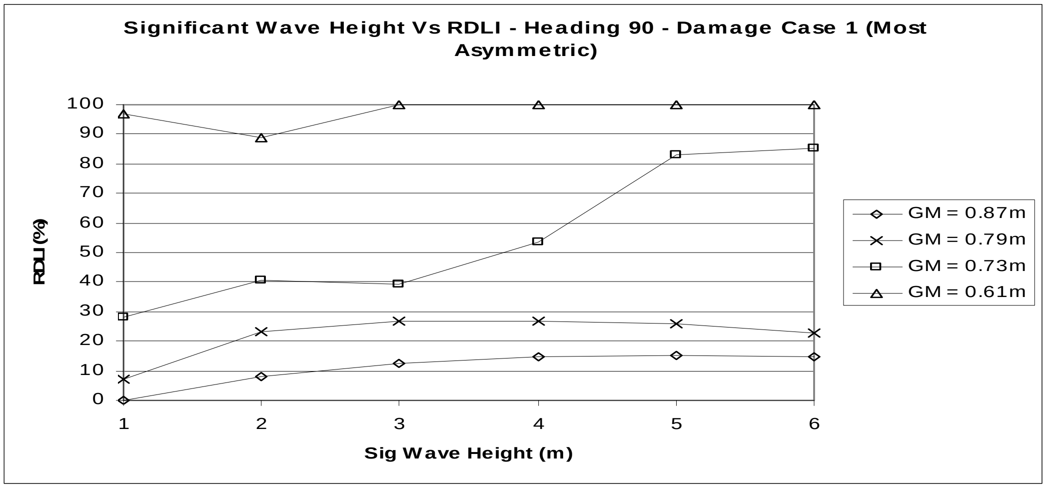

Figure A1.

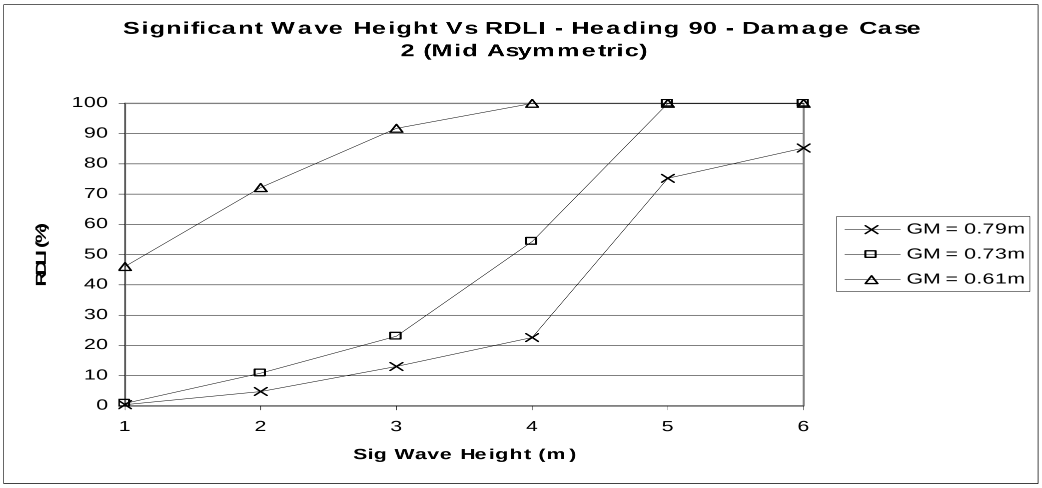

Figure A2.

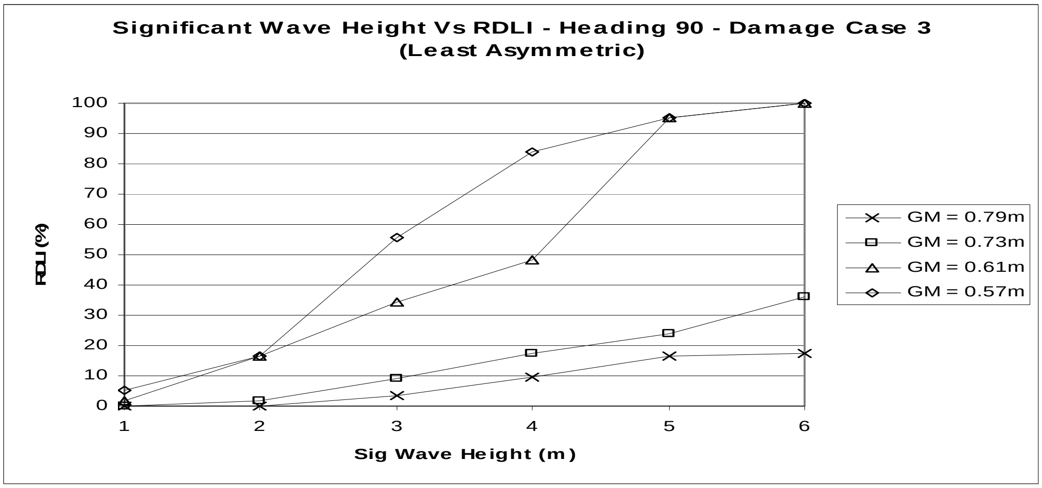

Figure A3.

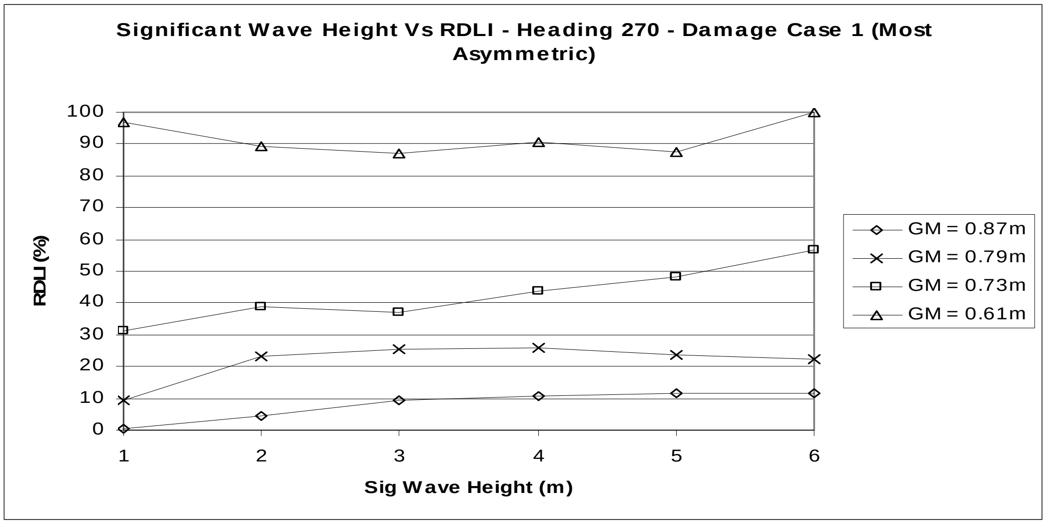

Figure A4.

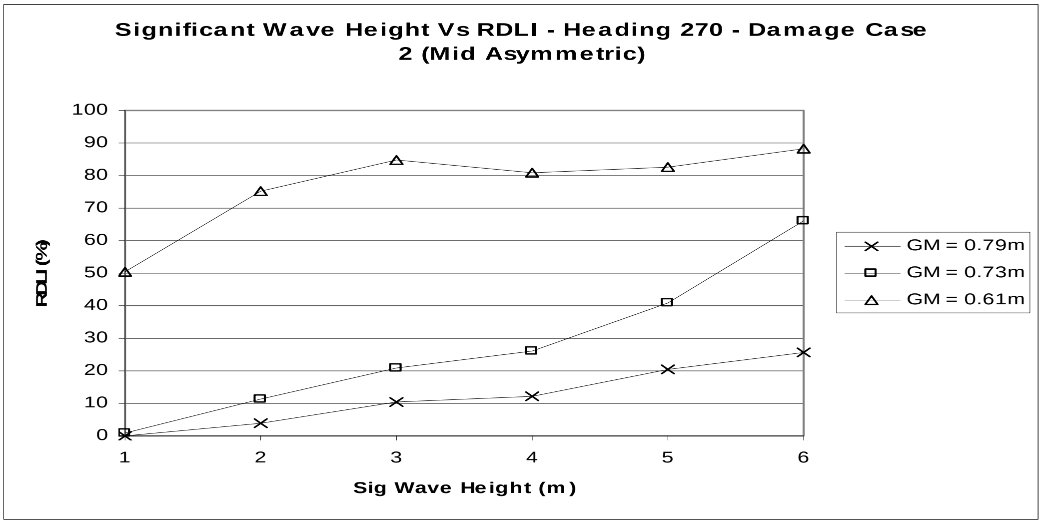

Figure A5

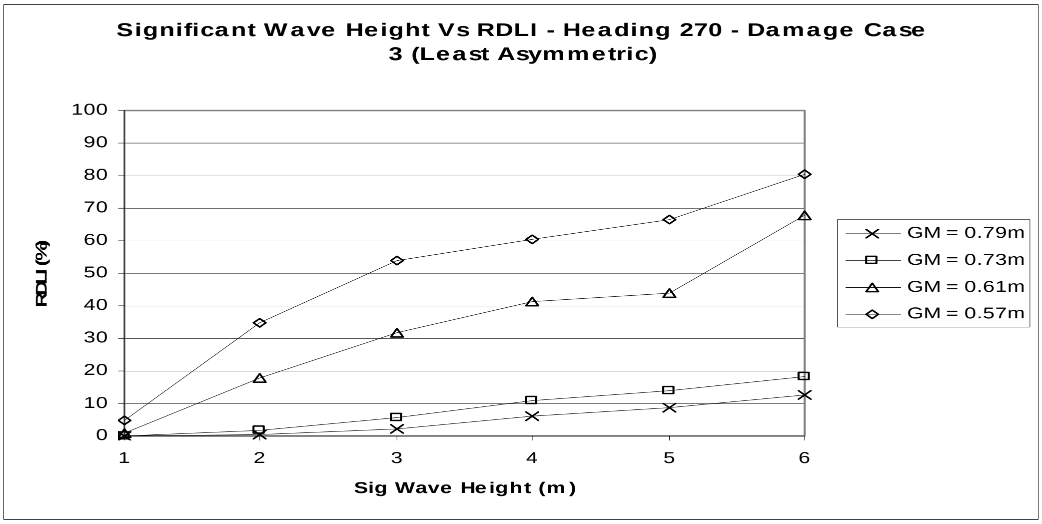

Figure A6.