COLLATING EVIDENCE FOR A UNIVERSAL METHOD OF STABILITY ASSESSMENT OR GUIDANCE

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SUMMARY

This paper reviews two related projects conducted for the Maritime and Coastguard Agency, and collates their findings with additional casualty data, in an attempt to promote a simple method of safety assessment. The method was developed by the author during research conducted for the Maritime and Coastguard Agency. It was evaluated in a subsequent research project, where the recommendations were that it was not worthy of adoption or further development for regulatory purposes.

Contrary to that evaluation, the method has received supportive comments from a number of naval architects, and this paper is offered as a means of presenting it more widely to the industry. Individuals may wish to use the method to assess their own designs, or to provide some simple safety guidance to operators.

1 INTRODUCTION

Much of the recent and current effort in stability research is striving to refine the calculation of ship motions and dynamics, to predict capsize of vessels in specific circumstances. This involves increasingly complex analysis using software developed by some brilliant minds. Whilst the value of such research in advancing our understanding of ship behaviour is undoubted, it is debatable whether the prediction of capsize is likely to become a precise science.

Despite the extensive investment in stability research during the last two decades, much assessment of stability still relies on criteria derived from Rahola's work, published in 1939. Things are changing now, as the IMO is committed to developing a revised Intact Stability Code, and considerable effort is being directed towards it. Whether the revised Code will provide a more reliable assessment of the level of safety remains to be seen, but it is unlikely to be as simple as the current criteria.

The method described here offers a very simple means of using the statical stability to estimate the safety of an intact or damaged vessel, while recognising that safety also depends on the size of the vessel in relation to the operational seastate.

2 DERIVATION OF THE METHOD

During revision of the IMO Code of Safety for High speed Craft, 2000, a number of research projects were commissioned by the MCA to inform the discussions at IMO. One of those, Research Project 509, was to assess the level of safety provided by the criteria for multihulls, and compare it with that provided by the criteria for monohulls, [1]. That work comprised extensive model tests in a towing tank to determine the minimum wave height that could capsize model ships. Six models, including monohulls and multihulls, were tested in a total of fifty three intact and damaged configurations. For each configuration the minimum wave height to capsize was determined by testing at a range of regular wave frequencies, bringing the number of test cases to over 800. Each of these was tested at all headings to the waves, so the overall number of test scenarios was unusually high. Furthermore, many of the configurations had an initial angle of list, due to offset loading or asymmetric flooding. These were tested heeling towards and away from the approaching waves. All tests were on models floating unrestrained in the "dead ship" condition, so the tests did not simulate scenarios that might occur when under power, such as broaching or parametric rolling. It is often assumed that beam seas represent the most vulnerable heading, but the tests proved that the most vulnerable heading was unpredictable, and 23% of the capsizes in the minimum wave heights occurred at other headings. Figure 1 illustrates a typical example of capsize data for one of the model cases tested, and the derivation of the minimum wave height to capsize; 0.8 metres in this case.

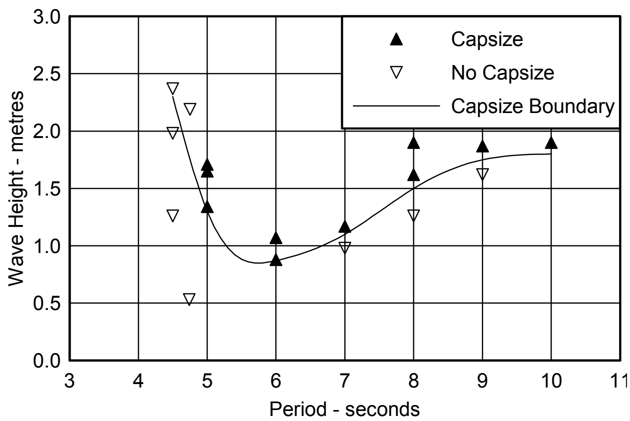

Figure 1 Derivation of minimum wave height to capsize, for one model configuration in Research Project 509.

In order to assess the minimum criteria, it was possible to assume that a model represented a vessel at a particular scale, and ballast it such that it just complied with one or more of the criteria. The minimum wave height in which it capsized could then be scaled to determine the critical wave height or seastate for the ship. The problem with model tests of criteria, rather than specific ships, is that the model equally could represent a ship of a different size, at a different scale. Indeed it could represent a ship of any size. Only at one scale would the test represent a ship that just complies with the minimum criteria. Smaller ships would fail the criteria and larger ships would have stability in excess of the minimum criteria because, although regulatory criteria do not vary with ship size, the GZ values are not non-dimensional. This highlighted the fact that the level of safety provided by the criteria is dependent on the size of the vessel and the seastate in which it operates. Criteria based on the positive range of stability are the exception to this, because range is a non-dimensional parameter, unlike GZ or the area under the GZ curve.

The objective of the study proved difficult to satisfy for a number of reasons:

- In order to compare the levels of safety given by the differing criteria it is necessary to compare vessels of the same size, and there is not a simple definition of equivalent size of a multihull compared with a monohull. It could be length, displacement or passenger numbers for example.
- The criteria address specific values of GZ or areas under the curves, and these could be satisfied with different shaped curves. It soon became clear that the critical seastate is highly dependent on the range of positive stability, which is not regulated.
- Some of the criteria do not address the residual stability with passenger crowding moments applied, and to compare them with minimum requirements of residual stability was meaningless.

The outcome of the work was a recommendation for a new criterion, or method of estimating the minimum level of safety of a vessel, given its size and stability. Following extensive analysis of the minimum wave heights to capsize, together with various measures of stability, it was recognised that vulnerability to capsize depended largely on the residual range of stability and, to a lesser extent, on the maximum righting moment. A strong relationship was found between the critical wave height and the following combination of residual stability characteristics:

$$\frac{\mathrm{Range}\sqrt{\mathrm{RMmax}}}{\mathrm{B}}$$

Where range is the range of positive residual stability, RMmax is the maximum residual righting moment, and B is the beam of the vessel. This differs from the parameters used in most conventional stability criteria because it includes displacement in the righting moment term, which is beneficial, and beam, which is not. Although wide beam provides good initial stability, if two vessels of different beams have similar stability characteristics, the one with the wider beam generally will be more vulnerable to capsize.

Naval architects are very familiar with the concept that the area under the GZ curve represents the energy to resist capsize, and with its use as a measure of safety. It is tempting therefore, to try to relate it, or the product of the range of stability and GZmax, to this formula. Research Project 509 demonstrated, however, that those parameters are less reliable measures of capsize resistance. The formula does not represent a simple physical characteristic, but relates to the capsize resistance which is dominated by the range of residual stability, supported to a lesser extent by the maximum righting moment.

The expression is not dimensionless, but effectively has the same dimension as the critical wave height. A purist might prefer to express the range in radians, replace the maximum righting moment with the product of the volume of displacement and GZ and incorporate a constant to maintain the correct relationship. The author takes a pragmatic view however, and prefers the use of more familiar engineering quantities for the sake of simplicity.

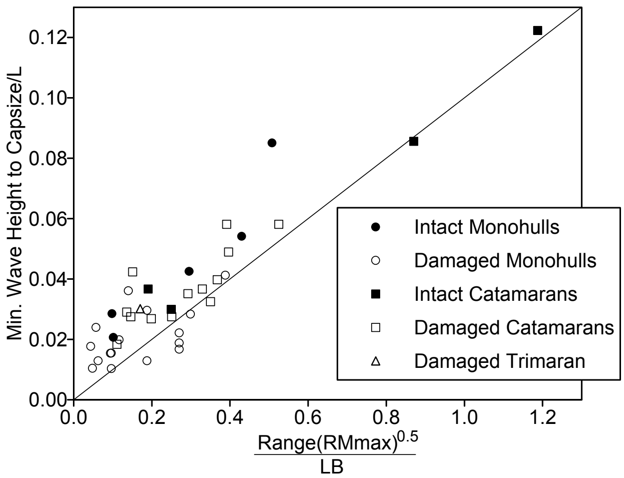

Figure 2 Relationship between stability and the minimum wave height to capsize from research Project 509.

Figure 2 presents a summary of the model test capsize data, and demonstrates that the critical wave height appears to be independent of hull shape or damage configuration. The data have been rendered non-dimensional using the overall length to normalise both axes. The stability parameters which are frequently regulated, such as GZ values and GZ curve areas, were studied on their own and in various combinations, but none collapsed the data as effectively as that shown here. These results, together with observations of the models' behaviour, led us to the belief that the vulnerability to capsize is not dependent on the form of the vessel, the number of hulls or the existence or extent of damage. All configurations may be considered as simple floating bodies characterised by their residual stability curves.

The line on the graph represents the simplest formula that provides an effective fit to the data, and might be used as a method of estimating the critical wave height. It is defined as:

$$\text{Critical Wave Height} = \frac{\text{Range}\sqrt{\text{RMmax}}}{10\text{B}}$$

Because the tests defined the minimum possible wave height to capsize, this line presents a conservative estimate of the critical wave height in most cases, although a few of the test results lie slightly below it. It could be adjusted to provide a greater, or indeed lower, level of safety, by the simple subtraction or addition of a constant factor of the length. A lower line was also suggested for consideration as a more conservative option but, for simplicity, has not been included here.

Given a particular critical wave height value, it is reasonable to suggest that the critical seastate will be somewhat less than that. In research Project 509 it was recommended that the critical seastate can be related to the critical wave height by the factor 0.5. For example, if the critical wave height is predicted to be 2 metres, the critical seastate will be 1 metre, on the basis that one should expect to encounter waves of twice the significant height every few hours. This gives the alternative expression:

$$\text{Critical Seastate} = \frac{\text{Range}\sqrt{\text{RMmax}}}{20\text{B}}$$

3 INDEPENDENT EVALUATION

The work was submitted to the IMO in 2005, [2], and there seemed to be a view that further validation of the findings was justified. In response to this, in January 2008, the MCA commissioned BVT Surface Fleet to conduct Research Project 583. The aim of the project was to compare the proposed method of estimating the minimum wave height to capsize with other model test results and full scale casualties or service history. The project was completed a year later and the report published on the MCA website, [3].

4 CRITICAL REVIEW OF THE EVALUATION

4.1 SHIP CASUALTIES

For that project the consultants collected well documented reports of capsizes in heavy seas from a number of sources, and compared the proposed formula with the wave heights believed to be present at the time. They identified only six suitable casualties and concluded that reliable ship capsize data are scarce. This is partly due to the fact that most ships operate well in excess of the minimum criteria and, unless disabled, actively avoid vulnerable headings to large waves. They excluded small craft and fishing vessels under 20 metres, and thereby excluded a large number of casualties. They also identified five cases of ships surviving heavy seas. Their data are presented in Figure 3.

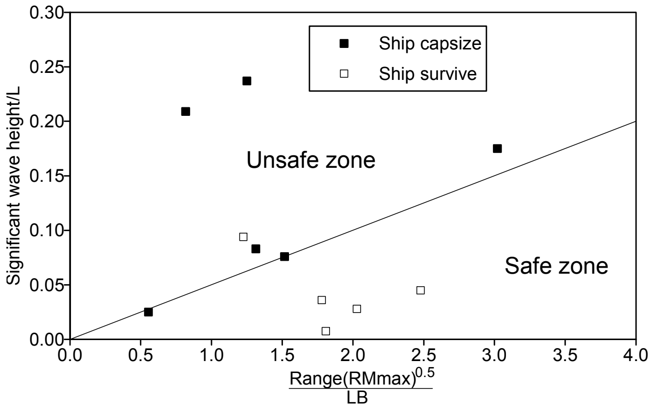

Figure 3 Real ship data gathered in Research Project 583, plotted in relation to the Wolfson formula.

If the formula is reliable in predicting the minimum wave height to capsize, the casualties should lie on or above the line that was derived in Figure 2. Note that the vertical axis in Figure 3 is the significant wave height of the seastate, rather than wave height to capsize, and so the line has been adjusted accordingly. The Research Project 583 consultants stated in their report “While the data conforms to the broad trend, it does not clearly support the positioning of the line defining the safe limit to be applied as a criterion.”

4.2 OTHER MODEL DATA

The consultants also collected results of other model tests where capsizes had been studied, and some data from numerical simulations of capsize. Care must be taken with these data though, because model tests are not usually designed to determine the minimum wave height to capsize. The requirement to test at a range of frequencies at all headings is not normally included in a model test programme because other aspects of the capsize behaviour are being studied. Some data therefore can be expected to lie significantly above the lower boundary of the envelope of Wolfson Unit capsize data, and in that respect are similar to the ship casualty data.

4.2 (a) HARDER Project

The EU research project HARDER (Harmonisation of Rules and Design Rationale) was particularly useful in providing a substantial amount of model test data. A number of papers have been published which present selected data or findings, for example [4]. It is interesting to note that one of the findings of that project was that the stability parameter that correlated most closely with wave height to cause capsize was the range of residual stability after damage. The GZmax values also showed reasonable correlation, although they varied with vessel type, and they concluded that the most useful measure of survivability is a criterion based on the product of the two. This finding correlates very well with the outcome of Research Project 509. Their recommended formula for a survivability factor was submitted to IMO and has been adopted as a basis for the probabilistic damage stability regulations; SOLAS 2009 (MSC.216(82) – Annex 2):

$$s = K\left[\frac{GZmax}{0.12} \times \frac{Range}{16}\right]^{\frac{1}{4}}$$

Where K is a constant, depending on ship type.

Reference 4 does not report whether the HARDER researchers considered the inclusion of displacement or other ship dimensions to relate ship size to wave height, and thereby make their formula truly non-dimensional. The project concentrated on large ships, and their aim was to develop a method of assessment for certain types of ship, not a method that might be applied to vessels of any size. Notwithstanding that, the authors of that paper apparently believed the formula to be non-dimensional as they state "…..since all factors in the equation are already non-dimensionalized."

The values 0.12 and 16 in their formula were empirically derived values of GZ and range, and the formula therefore appears non-dimensional. The use of a constant value to replace GZ in this way, however, returns the formula to a dimensional form. In practice, for a limited range of vessel sizes and types, GZ curve characteristics tend to be similar because of regulatory or practical design constraints. The formula may be effective, therefore, in the same way as conventional criteria that apply constant minima for all vessels, but it is no more non-dimensional than they are. If very small vessels had been considered it is likely that different constants, or perhaps a different formula might have been required to fit their test results. Indeed, different values have been recommended to replace the constant 0.12 for ships of different types, such as Ro-Pax ships, where the value 0.25 is more appropriate.

This aspect is discussed with particular reference to the 2009 Solas regulations in [5], where it is noted that these new "harmonized" probabilistic regulations require different formulae for different ship types. It is common for regulations to have different approaches or formulae for different sizes or types of ships, but it presents problems if design trends take new vessels outside the range of those used in the rule development. It would be preferable for truly harmonised standards to be non-dimensional and capable of assessing all vessels with a common formula.

Models of six ships were tested in the HARDER project, and the results of four of these were used in Research Project 583. Figure 4 presents these selected HARDER model test data in a similar way to [3], and again using significant wave height as the vertical scale. The conclusion drawn in Research Project 583 was that "These model test plots do not convincingly support the Wolfson Criterion." because some capsizes fall below the line, and "Many survive cases are well above the line and in general the data do not exhibit a trend that follows the Wolfson line even vaguely." It is the case that the capsize cases appear widely distributed on this graph, and the suggested combination of stability parameters has not collapsed the data into a convincing narrow envelope. It should be appreciated that for each model configuration tested by the Wolfson Unit in project 509 there were many capsizes at higher wave heights than those plotted in Figure 2. If all of those were presented together they would not fall into a narrow envelope. It is only by plotting the minimum wave heights at which capsize occurred for each case that this trend may be found.

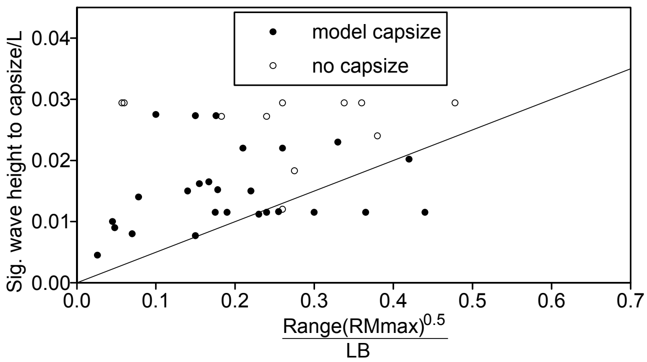

Figure 4 Results of tests on 4 models in the HARDER project, plotted in relation to the Wolfson formula.

The use of seastates rather than regular waves may introduce greater scatter into model test results because the models encounter waves of varying height, and may be capsized by a particularly large wave. Conversely, in regular waves, some capsizes may be influenced by the resonant nature of the roll motion, which will only occur in a seastate if a group of relatively regular waves is encountered. These different test methods should be borne in mind when comparing data. It appears that several of the HARDER models capsized in the same seastate, with a significant height/L of just over 0.01on the graph, and some of these are the cases that fall on the "safe" side of the line. The actual waves that caused the capsizes may have been of different heights and, if recorded, might have been plotted in different locations relative to each other using critical wave height as an axis, as in Figure 2. Whilst this horizontal stratification on the graph may have given rise to the perception that the data do not follow the trend of the line, it is unlikely to account for the fact that one of the models capsized in a significant wave height about half that predicted by the Wolfson line. There are a number of other factors that might account for this.

The definition of capsize in the HARDER project was a capsize in each of 5 runs in a particular seastate, so one would expect the data to be statistically sound. The two models which have test points on the safe side of the line were both tested in the same facility, where the experimenters reported: “It was also noted that the first wave was decisive for the survival. In many runs the vessel capsized by being hit by the first wave. In these set of runs, the vessel survived the remaining run, if the first wave was successfully passed.” [6] & [7]. This phenomenon was noted during preliminary tests at the Wolfson Unit, and was due to the fact that the models were more vulnerable before the down-wave drift was established. During subsequent tests the model was supported until the natural drift was established. Failure to do this in the HARDER tests might have caused some of the results to be a little pessimistic.

The same experimenters also reported that, for these two models, some of the internal ballast was moved to one side to obtain an initial list of 1 – 2.5 degrees to the damage side. Such a shift is significant in terms of the residual GZ and range of stability in the damage case. It appears not to have been accounted for in the analysis, although the details of this are not reported, and so it is possible that these points should be plotted at a lower value on the x-axis; further to the left on the graph.

The models tested in the HARDER project were restrained by light lines or soft springs in order to maintain the desired orientation to beam seas. Whilst minimal restraint is always the aim, it is inevitable that the tethers must apply some forces to the model, or they would not be required. This was the method used initially by the Wolfson Unit in Research Project 509, but it soon became clear that even the slightest restraint could initiate a capsize if the model was close to a critical point, so the models were tested totally unrestrained. If they became misaligned or too close to the tank wall their position was corrected manually, and the tests continued. This was possible because the tests were conducted in regular waves but perhaps would not be practical in tests of long duration in a seastate, as was the case in the HARDER project. It is possible, therefore, that some of the capsizes might have been influenced by the restraint method.

4.2 (b) Model Data from Other Sources

Figure 5 presents the other model test data collected for comparison with the formula. Two of these points are worthy of note. Point A represents a model which capsized twice at this wave height, at different headings and speeds, and with different mechanisms. The Research Project 583 report states that “This vessel had an unusually large range of stability but water was trapped on deck.” This highlights a potential problem with the formula. Because it relates to the residual stability at the time of capsize, account needs to be taken of all heeling moments and factors that reduce the stability at the time. Water trapped on deck is likely to reduce the GZ substantially and, if taken into account in this case, would move the point to the left on the graph. Such a scenario may not be predictable though, and this suggests that a greater margin of safety might be justified. The alternative view is that this particular vessel was more vulnerable because water could not be cleared efficiently from the deck, and perhaps its water freeing arrangements were inadequate. Point B on the graph was not a model test, but a non-linear mathematical model reconstruction of a real ship incident.

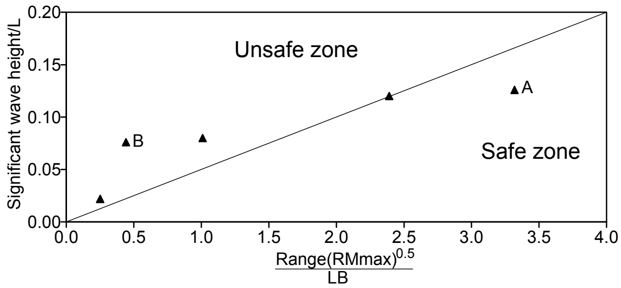

Figure 5 Other model test data collected in Research Project 583.

4.3 SHIP NON-CASUALTIES

As requested by the MCA, the consultants engaged in Research Project 583 also collected reports of vessels operating without incident in heavy seas. Their reasoning is given in their report as: “Examples of ships that survived waves were important to test out the Wolfson Formula, so as not to preclude any cases where it might predict capsize.” Unfortunately it appears that the basis of the formula was not clearly understood here. It is not a formula that predicts capsize, rather a formula that estimates the *minimum possible* wave height that *could* cause capsize. There were many cases during the Wolfson tests when models did not capsize in waves much higher than the critical height, because the waves were not of the critical frequency or because the model was not at the critical heading. In most of these cases, the models showed no signs of vulnerability. For the same reasons, there will be many instances where a ship will survive waves larger than the critical wave height estimated by the formula, and it is understandable that the crew might have no indication that their vessel would be vulnerable should they change their heading or encounter frequency. Additional reasons for survival of ships in larger waves are that a vessel under way is likely to be safer than in the dead ship condition, and its level of safety may be greater than that given by the formula which was designed to be on the conservative side of the envelope of data. The examples they considered are included in Figure 3 as the “Ship survive” data points.

The consultants in Project 583 considered that “The available real ship data and published model results identified in this study do not provide sufficient validation, nor indicate that this would be achieved by further development.”

5 COLLATION OF DATA

To put all of these ship and model data into perspective, a combined graph is presented in Figure 6. Twelve fishing vessel casualties, which have been well documented, have been collected by the Wolfson Unit and added to the data already discussed. It should be understood that, although they are plotted as points for the sake of clarity, the wave heights for real vessel capsizes cannot be known precisely and a vertical error bar might be more appropriate. Only capsize data are presented, because the survival of a vessel is not a reliable measure of the formula unless, by some means, one could be certain that the vessel had encountered waves at the most vulnerable heading and wave period.

It is apparent from this graph that the HARDER model test data fall into a similar envelope to the capsize data derived by the Wolfson Unit in Research Project 509. The HARDER data represent vessels with extremely low residual stability. At the other extreme, some of the other model capsizes and ship casualties have very high stability and lie well outside the range of stability values tested in Research Project 509. Correlation with the Wolfson model test data requires considerable extrapolation by the proposed formula, from x-axis values of less than 1.2 in the model test database to values of 3 or more for some ships.

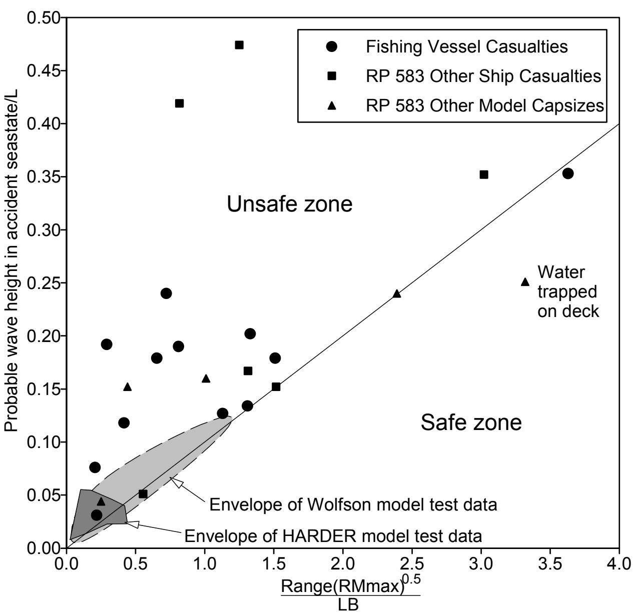

Figure 6 Correlation of casualty and model data with the proposed formula

The casualty with the greatest stability by this measure was Meridian, a 22.6 metre UK registered fishing vessel. It had very good stability characteristics, well in excess of the minimum requirements and therefore considered safe by all current methods of assessment. It was on guard duty in storm force 10 conditions and apparently capsized undamaged. Another vessel nearby reported the wave conditions and the Marine Accident Investigation Branch considered it most likely that Meridian, which had a relatively high GM, suffered as a result of synchronous rolling in beam seas that had a mean period close to the vessel’s natural roll period. [8]. This hypothesis correlates well with the model test findings, and represents an extrapolation to much higher stability values although, of course, the capsize wave height is an estimate.

With the exception of the model which capsized as a result of water trapped on deck, and therefore had less stability than that presented, all of these model and ship casualties are close to the line or to the unsafe side of it.

6 POTENTIAL APPLICATIONS

Figure 6 can be considered as truly non-dimensional, and the fact that model and full scale data can be presented together is evidence of this. It also appears to be applicable to all types of vessel, whether intact or damaged, upright or heeled. Whilst it is not claimed to give an accurate or even reliable prediction of capsize, it does offer an extremely simple means of estimating the minimum level of safety of a vessel, assuming that the external or internal heeling moments can be anticipated. It might be useful in a regulatory environment, but it may be more valuable if used as the basis of safety guidance, to inform masters whether a proposed operation has a reasonable level of safety. It could be used, for example, to assess a heavy lift over the side, or the carriage of an unusual cargo, and set an appropriate maximum seastate for the operation. This is not something that conventional criteria address very well, because they are limited to a pass or fail judgement, regardless of the vessel size or seastate. An operation that should not be contemplated in bad weather might be safe to undertake in calm conditions, and the definition of bad weather is very different for a 300 metre cargo vessel compared to a 12 metre fishing vessel. On most vessels, the master will have no such guidance on his level of safety on a day to day basis.

Casualty statistics indicate that the vessels most at risk from capsize are fishing vessels. There is no requirement for UK registered fishing vessels to assess the stability when lifting their catch, or indeed their gear, over the side. Many capsizes have occurred as a result of very heavy lifts, or in attempting to free gear fastened on a seabed obstruction, because fishermen have no information on when a particular operation might become hazardous in the prevailing conditions. With safety guidance based on this method, related to information from a load cell to monitor the lift, or an inclinometer to monitor the heel angle, the crew could be made aware of the level of hazard and take appropriate precautions, or abandon the lift. This philosophy was followed in MCA Research Project 560, [9], to develop a simplified presentation of stability information for fishing vessels. It was welcomed by industry representatives and well received by delegates in the IMO Working Group for Fishing Vessel Safety, but has not been implemented by the MCA.

7 CONCLUSION

The conclusions of research project 583 suggested that there was insufficient evidence to support application or development of the method for regulatory purposes, although it has some potential as an advisory guide to designers and mariners. It has been demonstrated here that their rather negative evaluation of the method was not necessarily a fully informed view. This paper presents a revised correlation of the data; with some additional vessel capsize data, which provides solid support for the proposed formula as a means of estimating the minimum wave height or seastate to capsize. It is hoped that this re-assessment will encourage others to consider its potential applications.

8 REFERENCES

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