A Performance-based Assessment of the Survival of Damaged Ships – Final Outcome of the EU Research Project HARDER

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SUMMARY
The paper presents the results of the EU Research Project HARDER with regard to the development of generalized formulations to predict the probability of survival of a damaged ship in a seaway. The methodology follows the procedures used to develop the survivability functions for the probabilistic damage stability regulations for passenger ships developed in the 1960's, but makes use of an extensive series of new model test carried out both as part of the HARDER Project and as part of independent external model tests. Simplified formulations based on static calculations have been proposed and correlated to the model test results. Two formulations are proposed, one to be applied to all types of ship, and an additional function based on the SEM methodology, which is suitable for RoRo ships (or any other ships with large un-subdivided horizontal spaces near the final damaged waterline). These formulae are currently under consideration by IMO for the new harmonized damaged stability regulations in the upcoming SOLAS 2006 revisions.

NOMENCLATURE

RoRo – Roll-on Roll-off type ships. From the standpoint of damage survivability the term generally refers to ships with large un-subdivided horizontal spaces.

IMO – The International Maritime Organization and it's various technical subcommittees such as the SLF (Sub-Committee on Subdivision, Loadlines and on Fishing Vessels.

A.265 – IMO Assembly Resolution 265, the first probabilistic regulations for damage survivability of passenger ship, an alternate to the traditional SOLAS deterministic standards, adopted in 1971.

s-factor – the probability of survival of a ship after a significant side collision.

$h_{1/3}$ – Significant wave height, the mean of the 1/3 highest wave in a seastate.

SEM – Static Equivalent Method, a static way of estimating the amount of dynamic flooding water that can cause the ship to capsize.

H_S – The survivable seastate, the highest significant wave height that a ship can survive.

1. INTRODUCTION

In March 2000 project HARDER was launched as a consortium of 19 organizations from industry and academia in Europe. This project aims to systematically investigate the validity, robustness, consistency and impact of harmonized probabilistic damage stability regulations on the safety of existing ships and on the design evolution of new ship concepts for various types of cargo and passenger ships. This paper presents the findings related to the development of the "s-factor" which accounts for the probability of survival after flooding. The proposed formulas indicated in this paper have recently been considered by the IMO Sub-committee on Stability Loadlines and Fishing Vessels (SLF) at their 45th session, and have been accepted for further evaluation as the basis for the proposed SOLAS 2006 regulations.

The overall objective of HARDER Work Package 3 (WP3) was to devise a generalised formulation of probability of survival addressing all relevant types of ships and damage scenarios deriving from studies of the dynamic behaviour of a damaged ship in realistic environments by means of model experiments and numerical simulations. Specific objectives included the following:

To address from first principles the probability of survival pertaining to all risks (including transient, intermediate stages of flooding and progressive flooding effects) and to develop a generalised expression applicable to all relevant ship types. To extend and generalise existing formulations pertaining to probability of ship survival with water accumulation on deck relevant to special category ships (having large undivided continuous spaces, such as Ro-Ro vessels), and to investigate the interdependence between the above component probabilities and develop a generalised expression applicable to all relevant ship types and risks relevant to side collision damage.

The HARDER consortium sought to develop a generalised expression of the probability of survival to reflect the dynamic wave effects on survivability for all types of damaged ships. The resulting proposals for the s-factor, which are suitable for incorporation in the harmonized damage stability requirements, are included in Section 5 of this paper.

2. HARDER MODEL TESTS

The HARDER model test programme was set up to addresses the key issues pertaining to water ingress/egress, water accumulation and capsize, including transient, intermediate and progressive flooding effects and attempt to qualify and quantify these phenomena as a function of design and operational parameters. The tests were also envisioned to provide the necessary benchmarking for validation of the numerical simulation tools.

The model-testing programme endeavoured to investigate all the known key aspects affecting ship survivability and included the following range of design and operational parameters:

- 7 different ship models representing a range of different types, sizes and forms of ships representative of the fleet. 3 Passenger ships (2 Ro-Ro's and one cruise liner) and 4 dry cargo ships (Ro-Ro Cargo Ship, Containership, Capesize Bulk Carrier, and a Panamax Bulk Carrier) were included in the testing program.

- 2 different spectral shapes: JONSWAP spectrum, a narrow band spectrum representing limited fetch undeveloped seas typical of the North Sea and Pierson-Moskowitz spectrum, a wide band spectrum representing fully developed seas typical of the North Atlantic

- a range of loading conditions addressing a range of permeability, trim, heel, draught, and vertical centre of gravity (KG)

- all known main risks in addition to water accumulation on large undivided spaces: cargo shift, heeling moments from passenger crowding, launching of life raft and wind, heel bias and effects related to intermediate stages of flooding, transient and progressive flooding.

Three HARDER partners participated in the testing programme:

- SSRC – Strathclyde University, Ship Stability Research Centre, Glasgow
- MARIN – Maritime Research Institute, Netherlands
- DMI – Danish Maritime Institute

Each partner was tasked to build two models at a scale of approximately 1:40. This means that each vessel type has been tested in two different tanks, thus providing some evidence of consistency in testing. DMI focused on the phenomena of ingress/egress and water accumulation, SSRC on defining boundary survival curves, and MARIN on the phenomena of transient, intermediate and progressive flooding. Again some duplication of effort was intended to ensure consistency and validity of the experimental results.

Test results that have been used to develop the generalized survival factors and survival boundaries were primarily from the SSRC's test of three HARDER vessels, the DMI test of a containership, as well as other test results for non-HARDER model test (another European Commission funded project, OPTIPOD RoRo, plus the results from 44 additional SSRC model test of RoRo passenger ships evaluated for compliance with the Stockholm Agreement), and the Bird tests, Ref. [1], from the 1960's were also used in the statistical correlations.

Specific details of the model test procedures, model design and construction, model testing programme, ship loading and damage conditions, wave conditions and spectra, instrumentation and calibration, and specific test results are contained in the main report of the model test results, Ref. [2], and the 12 associated reports and test appendices.

3. METHODOLOGY PRIOR TO HARDER

The vast majority of the previous work regarding testing of damaged ship models, and the establishment of generalized formulae for prediction of ship survival in waves after damage, occurred during two specific periods:

- During the late 1960's and early 1970's in connection with the development of the first probabilistic rules for passenger ships, IMO Assembly Resolution A.265.

- During the period from 1987, commencing shortly after the loss of the Herald of Free Enterprise, through the investigations of the Joint Northwest European Project, initiated after the loss of the Estonia, concluding in 1996.

A brief description of these two developments and outlines of their results follow.

3.1 A.265 METHODOLOGY

In preparation leading up to the final development and adoption of the first probabilistic damage survivability regulations for ships in 1971, IMO Resolution A.265, two sets of model experiments were conducted, one in the United Kingdom, Ref. [1], and one in the United States, Ref. [3]. These tests are believed to the very first of their kind and were instrumental in establishing the criterion and standards for damaged ship stability in the A.265 regulations and have been used as a basis for survival criteria in most other IMO instruments that remain in effect today. These test, for the first time, examined and systematically analysed the actual capsize mechanisms for damaged ships.

In general, the overall methodology and theory used in developing the survival criterion for Resolution A.265, were based primarily on the early work of Wendel, Ref. [4], and is still considered valid. Much of the work of the HARDER project is designed to update and validate the specific regulations, but no significant alternations in the overall methodology have been proposed.

Specifically regarding the development of the s-factor, the methodology of using model tests to develop a generalized methodology to predict the survival seastate for a damaged ship, followed by the application of the probability of seastate occurrence, is still considered appropriate, valid, and has been used once again in the recent HARDER development.

In consideration of development of a new survival factor it is useful to briefly review the methodology that was used in the development of the A.265 regulations. The explanatory notes to resolution A.265 give some outline of the methodology used in developing the s-factor for A.265, however the "Authors Reply" in Ref. [1] gives a far more comprehensive description of this methodology which is general described as follows:

Step 1 – The results of all of the model test first were generalized and presented in a format which showed the relationship between survival significant wave height ($h_{1/3}$), the flooded GM, and the damaged freeboard (FE).

Step 2 – The cumulative probability of survival for a single damaged GM was constructed by combining the damage tests results with the probability of wave height at the time of the casualty.

Step 3 – Step 2 was repeated for a range of damaged GM's to yield the family of survival curves, which represents the resulting probability of survival (s) as a function of damaged GM and damaged Freeboard (FE).

Step 4 – Approximate formulae for representing these s curves were proposed in for final adoption in resolution A.265.

3.2 RORO SHIP METHODOLOGY

During the period commencing shortly after the loss of the Herald of Free Enterprise, a number of model test of damaged RoRo models were conducted. A second period of very intense activity in this area was initiated after the loss of the Estonia in 1994. The Joint Northwest European Project, Ref. [5], calumniated in 1996 with the development of the Static Equivalent Method (SEM) for RoRo ships.

The Static Equivalent Method (SEM), which will be described in detail later in this paper, was initially developed from the observations of model tests and numeric simulations of damaged RoRo ships. The primary observation of the model test was that the capsize mechanism almost always appeared to be quasi-static in nature and dependent upon the volume of water elevated onto the vehicle deck due to wave action. The basis of the method is the derivation of two independent components, 1) the critical volume of water to cause the ship to capsize, and 2) the relationship between dynamic water head on the vehicle deck and the seastate which causes the head.

The critical volume of water is calculated statically for any specific damage case, and is defined to be the volume of water required to reduce the damage GZ curve to neutral stability. This volume of water was then related to the static waterline to measure the dynamic head (h) at the critical heel angle.

The second component, the relationship between the dynamic head and seastate is derived from purely a statistical correlation of measured dynamic water heads and seatates for damaged model and numeric simulations at the critical heel angle (the observed heel angle after which the ship proceed rapidly to a full capsize). The resulting SEM formulation was simply the statistical relationship between "h" and the survival seastate "H_S" represented by the formula:

$$H_S = (h/0.085)^{1/1.3}$$

At the time of the initiation of the HARDER project, this SEM methodology was generally considered to be the most accurate and reliable method, short of a full model test programme, to determine the survival characteristics of a damaged RoRo ship.

4. HARDER PREDICTION OF SURVIVAL

As previously described, one of the objectives of the HARDER project was to develop the generalised expression of the probability of survival of the equilibrium seastate, considering the effects of dynamic wave action for all types of ships.

4.1 OBSERVED MECHANISMS OF CAPSIZE

As observed in the HARDER model test, and also noted from previous model tests, there are basically three common critical mechanisms of capsize in waves following in the final stage equilibrium condition after a damage, as indicated below. It should also be noted that in general damaged ships have very large inertia and very large damping, which results in ship motions that are dominated by heave and sway. Synchronous roll is not generally observed since the roll periods are much slower than the typical wave encounter periods.

High Freeboard Ships – Provided that there is some minimal positive righting lever and range of stability the ship will not capsize in moderate waves. Wave impacts on the side of the ship will induce some rolling in marginally stable cases, which can cause capsize at the larger seastates. Often the ship is more vulnerable with the damage and static heel to leeward, since the GZ levers are typically less in the damaged direction and the induced dynamic roll is typically somewhat greater in the leeward direction.

Low Freeboard RoRo Ships - This is almost always the mechanism of capsize for RoRo ships or any other ships with large un-subdivided horizontal spaces near the damaged waterline. The wave action gradually pumps water up onto the vehicle deck. The height of the water gradually increases until either a reasonably stable equilibrium level is reached where inflow is approximately equal to outflow for ships with sufficient reserve stability, or if stability is inadequate, the heeling moment of the water will cause a capsize to windward.

Low Freeboard Conventional Ships – This is the typical mechanism of capsize for ships that do not have large internal spaces with horizontal decks near the damaged waterline. The highest waves will form boarding seas and will pile-up on the windward side of the deck, inducing roll and capsize, usually to windward. The weather deck tends to drain quickly if there is no capsize, and there is typically no build-up or gradual accumulation of water as seem with enclosed RoRo decks. One or two high waves in close succession are often sufficient to cause capsize.

Of course, any damaged ship, in any of these configurations will capsize even in flat calm water unless there is some minimal level of positive GZ levers to both sides of the static damaged equilibrium position.

4.2 SURVIVAL OF HIGH FREEBOARD SHIPS

In such cases, the previous model experiments indicate that the damaged ships will be safe in all moderate wave conditions, usually up to significant wave heights (Hs) of about 4m, with only a nominally positive GZ curves. Suggested values, such as the minimum SOLAS values of minimum GZ lever of 0.05m and a minimum range of 7 degrees seem reasonably adequate. Since the relative motion of the ship at the damage opening has been observed to be roughly $H_S/2$ and seastates at the time of collisions (as will later be discussed in Section 5) are almost always under H_S=4m, static final stage damage freeboards of about 2m and higher can typically characterize the "High Freeboard" type, which will not be subjected to the other "water on deck" type capsize mechanisms.

4.3 SURVIVAL OF LOW FREEBOARD RORO'S

The HARDER model tests for RoRo ships were primarily based on one RoRo passenger ship (PRR01) and one cargo RoRo (DCRR01), however the passenger RoRo ship was tested over a very wide range of damage cases, initial draughts, and trims, each over a range of vertical centres of gravity (KG) to establish the survival boundaries. Two ships were also considered from a recent programme of tests as part of the OPTIPOD project, a modern RoPax design including a lower hold, which was tested by the SSRC under essentially the same experimental conditions as the HARDER tests. Also the survival seastate tests at SSRC for an additional 44 passenger RoRo ships tests have been considered.

Since test in conjunction with the A.265 criteria were instrumental in establishing the pervious s-factor criteria, some selected results from this test series, Ref. [1] above, were also included to extend the range of applicability of any new criteria. It was anticipated that methodology for the survival for RoRo type ships would be based on the SEM methodology or some modification of the originally proposed SEM method, Ref [5].

As briefly introduced in Section 3, an estimate of the volume and height of water accumulated on deck for RoRo ships, or other ships with large un-subdivided spaces that have horizontal boundaries near the damaged waterline, can be made using the SEM procedure. In principle, the method statically develops the volume of water that will reduce the damage GZ curve to exactly zero, see Figure 1. From this neutral stability position, any less water volume will be survivable and any more water will cause capsize. For the re-analysis of the SEM method, at this critical heel angle two parameters **h** – the dynamic water head, and **f** – the freeboard at the θ critical angle are calculated, see Figure 2.

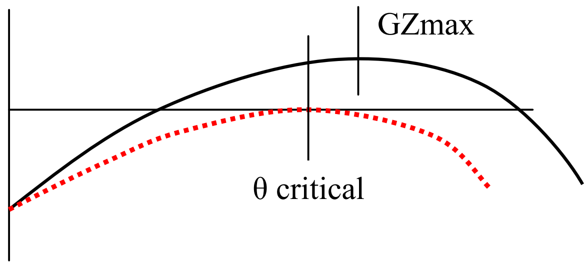

Figure 1 – Reduction of GZ Cruve

These values of h and f are then statistically correlated with the survival seastate boundary from the damage survivability model tests.

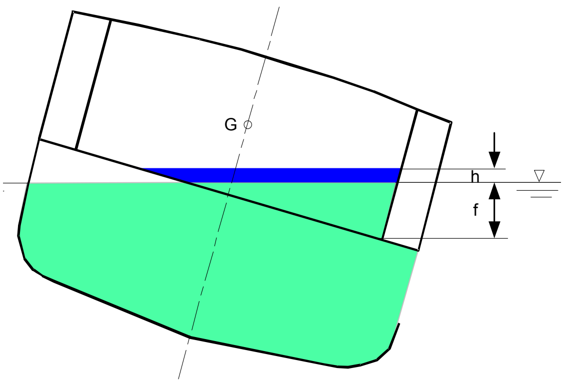

Figure 2 – SEM Parameters "h" and "f"

Three items should be noted about the static calculation required to determine the SEM parameters. First, the damaged compartments above the internal deck (typically the vehicle space and any damaged wing spaces) are considered free flooding as in a standard damage stability calculation, with buoyancy being contributed to by intact wings or casings. Second, the development of the reduced GZ lever curves should typically be-based on either constant volume of added water over the range of heel angles or a constant dynamic head (h). And three, it should be noted that the critical angle (θ critical) is generally solved for iteratively, and is typically only slightly less than the GZmax angle when calculating the lever curves without the dynamic water.

In a manner similar to the original formulation of the SEM, the statistical relationship between dynamic water head (h), the freeboard (f) at the θ critical, and the mean significant survival wave height (H_S) was re-examined. This statistical relationship has been modelled with a three dimensional regression.

Observations of the data set showed that regression fit to a flat plane slightly over estimates survivability for the lower end of the data set. Therefore it was intuitively clear that a curved surface would better fit the data set.

The accuracy in obtaining the survivability level of a ship at model test basin is limited with the maximum and minimum wave height that the wave makers can generate at given model scale. Because of this reasoning and our emphasis on seastates of 4m and less, the sample data was limited H_S of 5m and less.

Several sample curved surface functions were tested to obtain the best fit, while still keeping it relatively easy to implement within the probabilistic calculation procedure. The following surface was found to be a statically good fit and relatively simple to implement:

$$H_S = 2.221 \text{ Log}(h) - 0.635f + 4.676 \quad (1)$$

The statistical data for the fit is as follows:

- Residual Sum of Squares = 12.27
- Standard Error of the Estimate = 0.476
- Coef. of Multiple Determination (R^2) = 0.8245
- Highest Overestimate = 0.904m
- Lowest Underestimate = -1.064m
- Mean Error = 0.378m

The above function (1) is produced in Figure 3, together with the sampling data points. The prediction of the lower sea states are slightly better while keeping the over all accuracy of the fitness satisfactory.

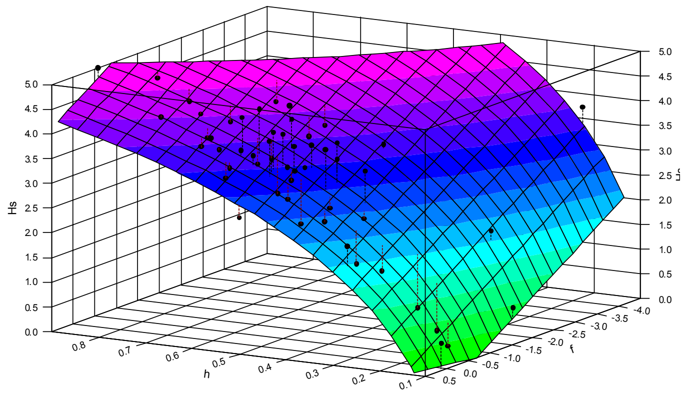

Figure 3 –Regression for H_S as a function of "h" and "f" by curve surface

Previous international and national damage stability criteria have traditionally used other common stability characteristics to measure the survival characteristics for damaged ships. Damage GM and damaged Freeboard were used as the measure of stability in A. 265 and most traditional damage stability criteria employ the use of properties of the GZ lever curves, such as GZmax, GZ Range, or GZ Area. The SEM methodology was developed in recognition that these traditional measures cannot adequately be used to predict the survivability of damaged RoRo ships.

4.4 SURVIVAL OF LOW FREEBOARD CONVENTIONAL SHIPS

The HARDER model tests for conventional (non-RoRo) ships were primarily based on the limited data set of two non-RoRo deck damage configurations of the cargo RoRo (DCRR01), the containership tested at DMI (DCCS01), and the three alternate depth configurations of the Panamax bulk carrier (DCBC02). In these ships represent a range of ship sizes and configurations and they were tested over a wide range of damage locations, initial draughts, and trims, each over a range of vertical centres of gravity (KG) to establish the survival boundaries.

The model tests in general confirmed the observations from the modest number of previous model test for non-RoRo ships in the 1960's. Some of these observations are repeated here:

- The ships were highly damped in roll and the predominant motions were in heave and sway.
- The dominant capsize mechanism was from heel toward the approaching waves initiated by waves boarding onto the main deck.
- There was no steady build-up or accumulation of water as seen in the RoRo ships test since the water it is free to flow off the weather deck. Capsize was often initiated by one or two large waves that occur within a short period of time.
- Ships with sufficient freeboard to stop most of the waves from boarding on the main deck showed considerable resistance to capsize even with quite marginal stability characterises.

4.4.1 SEM Methodology for non-RoRo Ships

Many of these common characteristics observed between the capsize of RoRo and conventional non-RoRo ships suggested the application of the SEM methodology to conventional ships. It was anticipated that the methodology for the survival for non-RoRo ships could be based on the same or similar SEM methodology used for RoRo ships. Essentially the same static SEM calculation to determine "h" and "f" can be made on conventional ships by assuming the ships sides were extended vertically above the open deck, as shown in Figure 4.

The same methodology as used for RoRo ships can be used for the SEM development and correlation. At the critical heel angle, the two parameters, "h" the dynamic water head, and "f" the freeboard at the θ critical angle were calculated.

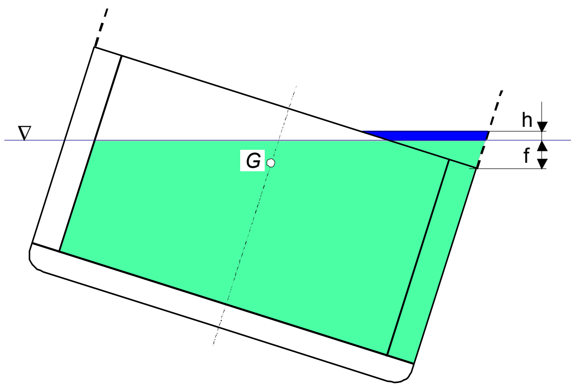

Figure 4 – SEM Parameters for Conventional Ships

Then also in a manner similar to the original formulation of the RoRo SEM, the statistical relationship between dynamic water head (h), the freeboard (f) at the θ critical, and the mean significant survival wave height (H_S) was re-examined. A three dimensional regression was carried out to fit a 3D function through the data. The resulting best-fit plane surface is shown in Figure 5.

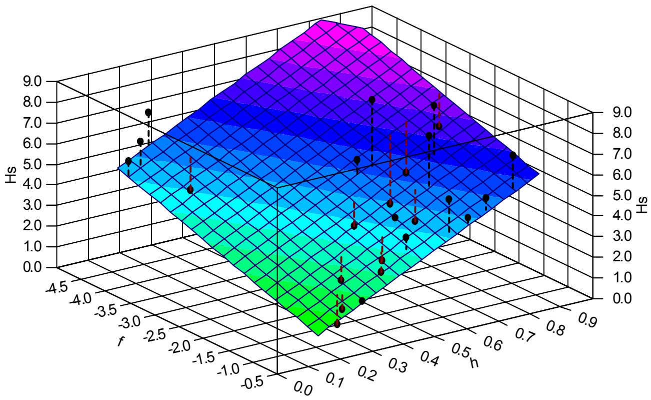

Figure 5 – New Regression for H_S as a function of "h" and "f"

There is significant statistical scatter in the data however and it was found that a simple plane surface fit the data as well as other more complicated surfaces.

The best-fit planar regression is:

$$H_S = 7.4975h - 0.838f - 1.380 \qquad (2)$$

The statistical data for the fit is as follows:

Residual Sum of Squares = 65.41
Standard Error of the Estimate = 1.72
Coef. of Multiple Determination (R^2) = 0.4410
Proportion of Variance = 44.11%
Highest Overestimate = 3.30m
Lowest Underestimate = -3.38m
Mean Error = 1.37m

In comparing the results of this statistical correlation to that seen for RoRo ships it can be observed that the fit for this limited sample of non-RoRo ships is not nearly as good. Numerous attempts were made in re-examining the data, the most notable were varying the longitudinal location along the ship where "f" was measured (the best correlation was to measure at the centre of mass of the added water), and to iterate the SEM calculations at some marginally positive GZ lever rather than the neutral point. None of these attempts improved the correlation of the data to any reasonably shaped surface. Perhaps additional attests future research will yield improvements in the methodology to give a better correlation between the theoretical and experimental data.

4.5 CONVENTIONAL METHODOLOGY FOR NON-RORO SHIPS

Previous international and national damage stability criteria have traditionally used other common intact stability characteristics to measure the survival characteristics for damaged ships. Most traditional damage stability criteria employ the use of properties of the GZ lever curves, such as GZmax, GZ Range, or GZ Area. The SEM methodology was developed with the recognition that these traditional measures could not adequately be used to predict the survivability of damaged RoRo ships. Since the correlation between the SEM prediction was not a good as was hoped for, the following plots, Figure 6, Figure 7, and Figure 8, review the correlation of these three traditional parameters with the observed survival seastate from the no-RoRo model tests.

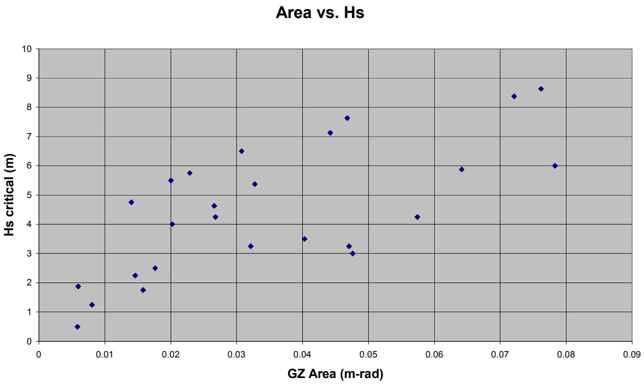

Figure 6 – GZ Area

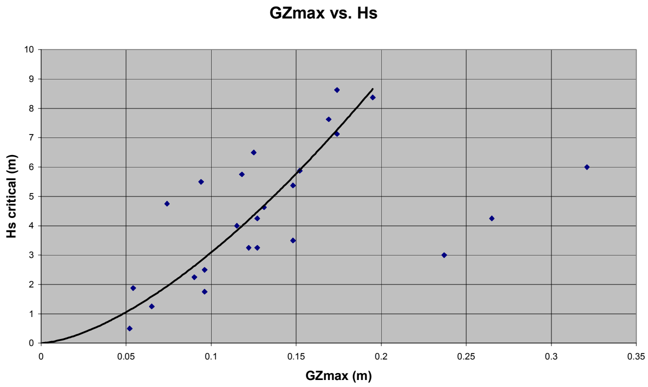

Figure 7 - GZmax

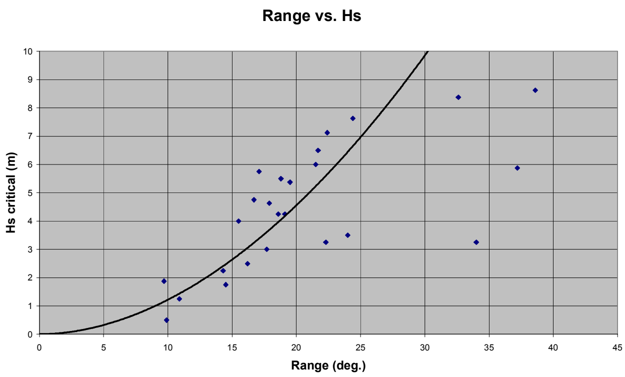

Figure 8 – GZ Range

While the correlation is quite poor for Area, with the exception of a relatively few points widely scattered points to the right side of the plots, the correlations for GZmax and GZ Range are reasonably adequate. The trend lines were then developed, excluding the wildly scattered points. When focusing on the GZmax and Range plots it was also seen that the widely scattered points on the GZmax plots (the points with large GZmax values yet relatively small H_S), had fairly small ranges and plotted quite near the regression line for the Range. Similarly, when focusing on the Range plots, the widely scattered points (those with large Ranges but relatively small Hs) had fairly small GZmax values.

The above observation lead to the assumption that survival in a seastate might be estimated by establishing both a GZmax and a Range criterion. Since it appears that both criterion need to be simultaneously met and excess of one criterion only did not seem to enhance survivability, H_S was presumed to be the minimum value obtained from the correlation functions of GZmax and Range.

$$H_S = \text{MIN} \begin{vmatrix} 0.153 \text{ Range } 1.9012 \\ 108.42 \text{ GZmax } 1.544 \end{vmatrix} \quad (3)$$

The statistical correlation over all of the data points for this function is

Sum of Squares = 43.53
Highest Overestimate = 2.10m
Lowest Underestimate = -2.80m
Mean Error = 1.05m

Therefore, this estimation based on the conventional methodology has at least as good a correlation with survival seastate than the SEM for non-RoRo ships.

On a more optimistic note, both this conventional methodology and the SEM methodology will result in mean errors of slightly under 0.4m when they are limited to the lower survival seastates of 4m or less. As will be shown in Section 5, it is the prediction of survival seastates up to the 4m range that is the most important for accurately formulating the probabilistic s-factor.

An alternate conventional GZ based criteria for the prediction of the survival seastate can also be proposed using the GZmax and GZ Range only based on the format used in the current SLF proposal. In order to match the methodology used for RoRo ships the following format is proposed, in the same way as the SEM formulation was used to correlate the mean survival seastate to the stability parameters, with H_S limited to 4m:

$$H_S = 4\text{m}*[(\text{GZmax}/\text{TGZmax})*(\text{Range}/\text{TRange})] \quad (4)$$

Based on an examination of the best correlation with the model test results the following values of TGZmax and TRange are proposed which are slightly more conservative than the existing SLF proposal:

TGZmax = 0.12m

TRange = 16 degrees

The statistical correlation for this function with data limited to H_S less than 4m is

Sum of Squares = 8.6
Highest Overestimate = 1.15m
Lowest Underestimate = -1.53m
Mean Error = 0.38m

At least within the 0 to 4m seastate range of interest, this formulation is reasonably accurate for the prediction of the survival seastate, with mean errors an improvement from the SEM methodology and at approximately equivalent accuracy to the SEM predications for RoRo ships.

5. PROBABILITY OF SEASTATE AT THE TIME OF A CASUALTY

Both the SEM and GZ based methodologies developed give results in terms of the significant wave height of the critical survivable seastate. In order to produce the probability of survival, the likelihood that the survivable seastate will be exceeded at the time of the casualty is required to predict the overall survival probability.

The statistical analysis of the observed seastates at the time of casualties was previously developed in Ref.[6] . A plot of this data and a proposed function to fit the data, which reaches 100% at just under 5 meters, is shown in Fig. 16. This data reinforces the previous data, developed as part of A.265, that practically all casualties (over 97%) occur in seastates of H_S=4m or less.

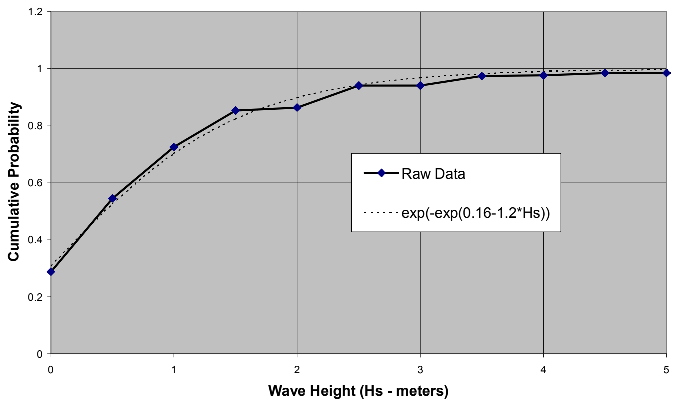

Figure 9 – Cumulative Probability of Wave Height at time of collision

The HARDER data was also examined to determine whether there were any possible correlations of the severity of casualties (damage size, ship losses, or human casualties) with the probability of seastate. There was insufficient data to examine the relationship of seastate probability to the loss of life. The data shows very little correlation the size of damage and seastate, and again, there was no discernable correlation found with the probability of seastate occurrence and ship survival.

6 SURVIVAL FACTOR "s"

Following the procedure established in Resolution A.265, the s-factor can be established by basing it directly on the probability of occurrence of the wave height that the ship will survive. "s" is then based on the survivable wave height, and probability of occurrence of that wave height, then "s" can be formulated from a single function for RoRo ship types and a single function for conventional ships.

Note that Fig. 9 indicates that there is approximately a 30% probability that the seas will be dead calm, it does not follow that a H_S of zero has a 30% probability of survival. A zero survivable wave height implies no residual righting energy and is considered non-survivable even in calm seas, however "s" will always be zero unless the minimum GZ properties are meet, and if they are meet the 30% survivability is still believed to be conservative.

For Conventional Ships:

A combined formulae for "s" can be derived by using the individual model test survival seastate results multiplied by the probability of seastate occurrence from Figure 9, and then to solve for the best fit correlation for a formulae similar to equation (4) for the survival seastate. Using this method the best fit is obtained from the following equation based on GZ based formulation can be used as a correlation to the probability of survival from the model tests. A format similar to the current proposal in the harmonized regulations is possible (See Figure 10):

$$s = [(GZmax/TGZmax)*(Range/TRange)]^{1/4} \qquad (5)$$

Where, TGZmax = 0.12m
and GZmax not to exceed TGZmax
TRange = 16 degrees
and Range not to exceed Trange

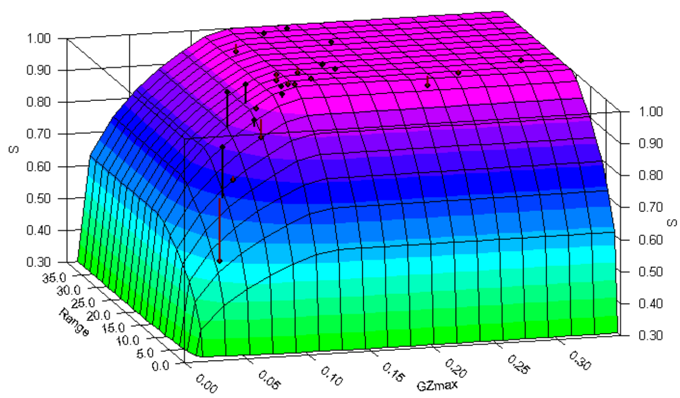

Figure 10 – GZ Based s-factor for Conventional Ships

This equation results in a mean error of .024 on “s”, the sum of the squares of the errors is 0.1620, with the lowest underestimate of 0.18 and the highest overestimate of 0.17.

Consideration was also given to a formula as close as possible to the current SLF proposal, which also includes the GZ Area parameter. However it was found that there was no improvement in the correlation with the addition of the Area component. Additionally it was observed that none of the model test indicated that were practical cases with adequate GZmax and Range parameters, which did not have adequate Areas.

It is worth highlighting that the ¼ exponent was selected purely from the regression point of view. It provides the best-fit regression to the data, and was not forced to be ½ for dimensional consistency since all factors in the equation are already non-dimensionalized.

For RoRo Ships:
Using the same methodology the s-factor formulations can be developed for RoRo type ships using the SEM methodology. The resulting function from regression analysis is given below formula (6) provides a satisfactory fit to data (See Figure 11). It is suggested that the results of this equation can be rounded to 2 decimal places.

$$S = \exp(-\exp(0.5f - 8h + 0.7)) \qquad (6)$$

The statistical data for the fit is as follows:

Residual Sum of Squares = 0.1490
Standard Error of the Estimate = 0.0498
Coef. of Multiple Determination (R^2) = 0.8236
Highest Overestimate = 0.1893
Lowest Underestimate = -0.1225
Mean Error = 0.0289

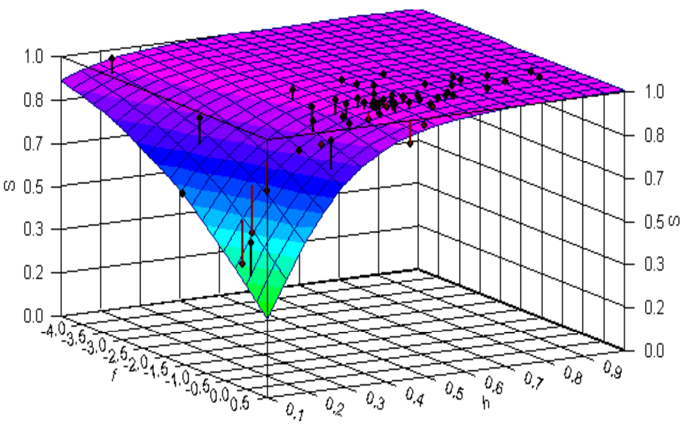

Figure 11 - SEM Based S-Factor for RoRo Ships

7. CONCLUSIONS

An extensive series of model tests have been utilized to provide a greater understand of the generalized mechanics of the capsizing of a damaged ship. Observations of these tests have led to proposals of relatively straightforward static principles that can be used to correlate with model tests results and predict the survival capability of damaged ships in specific seaways. The combination of the mean survivable seastate and the probability of seastate occurrence can be combined to formulate functions of the probability of survival for a damage ship. These formulations are suitable for incorporation into the overall framework of probabilistic assessment or regulation of ship damage survivability.

8. ACKNOWLEDGEMENTS

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