DAMAGE SURVIVABILITY OF NON-RO/RO SHIPS

Robert Tagg*, Cantekin Tuzcu*, Maciej Pawlowski, Dracos Vassalos* and Andrzej Jasionowski***
*The Ship Stability Research Centre (SSRC), The Universities of Glasgow and Strathclyde, UK, ssrc@na-me.ac.uk
**SSRC Visiting Research Fellow, Technical University of Gdansk, Poland, mpawlow@pg.gda.pl

SUMMARY

The Static Equivalent Method (SEM) was developed in the wake of significant research into the capsizing of Ro/Ro vessels following the *Estonia* disaster. This method can predict with reasonable accuracy the survival sea state for specific Ro-Ro damaged conditions. Recent model tests of damaged non-Ro-Ro (or conventional) ships have indicated that the capsize mechanism has many similarities with the mechanism observed in Ro-Ro vessels' capsize, which formed the basis for the development of the SEM. On this basis, using the same idea as in the original research and the same methodology in analysing available experimental and numerical data, a new expression has been developed to account for geometric dissimilarities between Ro-Ro and non-Ro-Ro vessels. The predicted results from the new formulation are compared with the experimental results from recent model tests and the agreement was found to be satisfactory. Based on these preliminary findings, it is believed that this simple method could be applied to all ship types, and efforts to finalise this generalisation are underway at SSRC, as part of the EU project HARDER.

NOMENCLATURE

θ_{max}	Heel angle at which GZ is maximum.
h	Mean elevation of water on deck (the vehicle deck for a Ro-Ro ship or the weather deck for a conventional ship) above the mean sea surface.
H_s	Average significant wave height characterising the critical sea state.
H_{sr}	Reference wave height, where $H_{sr}=(H_s)^b$; a coefficient to be determined by physical and/or numerical experiments.
f	Freeboard to the deck edge at the PNR. For Ro-Ro vessels this is measured at the longitudinal centre of damage. A negative f implies the deck edge is immersed.
F	Residual freeboard in the traditional sense.
PNR	Point of no return, defined as the heel angle for the damaged ship, which when reached whilst progressive flooding is taking place, the ship will normally not recover and will proceed quickly to capsize.
s	The probability of the ship surviving a specific damage condition, in a given sea state.
SEM	Static Equivalent Method

1. INTRODUCTION

The tragic accidents of the *Herald of Free Enterprise* in 1987 and the *Estonia* in 1994 initiated a significant surge of research related to the capsizing of Ro-Ro type ships. This research effort culminated in significant developments that helped the ferry industry to raise safety levels to demanding new heights, in response to strict new regulations, cost-effectively. One of these developments, which is gaining wide acceptance is the Static Equivalent Method (SEM), [1]. The SEM is an empirical capsize model for Ro-Ro ships that can predict with reasonable accuracy the survival sea state for specific damage conditions. The SEM was developed and validated using several model experiments and a large number of numerical simulations.

The EC-funded project HARDER, started March 2000, was set up to systematically investigate the validity, robustness, consistency, and impact of all aspects of the probabilistic damage stability calculations for cargo and passenger ships. One significant aspect of the HARDER project is to devise a generalised formulation of the probability of damage survival for all types of ships and relevant damage scenarios. This plus other related research, includes model testing several aspects of the damage survivability of seven ships, covering a range of ship types and sizes. The model test programme provided additional material for testing the wider applicability of the SEM to other ship types as well as a basis for further refinements of the formulation pertinent to Ro-Ro vessels. This paper examines some of the initial results of the model tests for non-Ro-Ro ships and presents a new formulation that renders SEM applicable to these conventional types of ships.

2. SEM FOR RO-RO SHIPS

The SEM for Ro-Ro ships postulates that the ship capsizes quasi-statically, as a result of accumulation of a critical mass of water on the vehicle deck, the height of which above the mean sea surface uniquely characterises the ability of the ship to survive a given critical sea state. This method was developed following observations of the behaviour of damage ship models in waves. Among the most important observations from the model tests and subsequent investigations [1] are:

1. As the ship reaches the "point of no return" (PNR) it behaves quasi-statically, with subdued roll motion and marginal transverse stability.

2. The PNR generally occurs at an angle very close to θ_{max}.
3. The critical amount of water on the vehicle deck can be predicted from static stability calculations by filling the undamaged vehicle deck with water until the ship lolls at θ_{max}.
4. The unique measure of the ship's survival capability is the height (h) of the water elevated above the sea level at PNR, as shown in Figure 1 (Ro-Ro vessel) and Figure 5 (conventional ship).
5. The model tests and numerical simulations indicated that this elevation of water on deck, h, can be directly correlated to the critical sea state, characterised by H_s.
6. The higher the water elevation (h) at PNR, the higher the sea state needed to elevate the water to this level and capsize the ship.

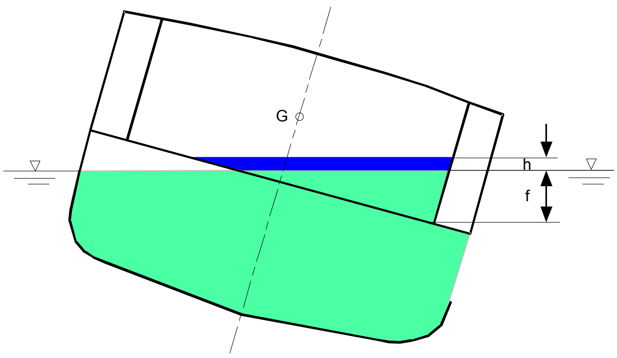

Figure 1: Damaged Ro-Ro vessel with water elevated on the car deck at PNR

3. MODEL TESTS FOR NON-RO-RO SHIPS

The model test programme of HARDER comprises seven ships to be tested in three model basins, as shown next.

1. PRR01 .... Large Ro/Ro Passenger Ship
2. PRR02 .... Medium sized Ro/Ro Passenger ship
3. PCLS .... Large Passenger vessel
4. DCCS .... Containership
5. DCRR......... Cargo Ro/Ro vessel
6. DCBC01 ..... Cape Size Bulk Carrier
7. DCBC02 ..... Panamax Bulk Carrier

This paper deals, in particular, with the initial findings from tests of ship 5, the Cargo Ro-Ro, and ship 7, the Panamax Bulk Carrier. The Cargo Ro-Ro involved tests in three configurations, two of which (wing tank damage and combined wing plus lower hold damage) can be considered as non-Ro-Ro configurations since the upper vehicle deck is undamaged. The two non-Ro-Ro configurations are shown in Figure 2 and Figure 3.

The Bulk Carrier tests also involve three configurations, all based on the same midship 2-hold damage scenario, but with three different ship depths to weather deck. The ship with the smallest depth is shown in Figure 4.

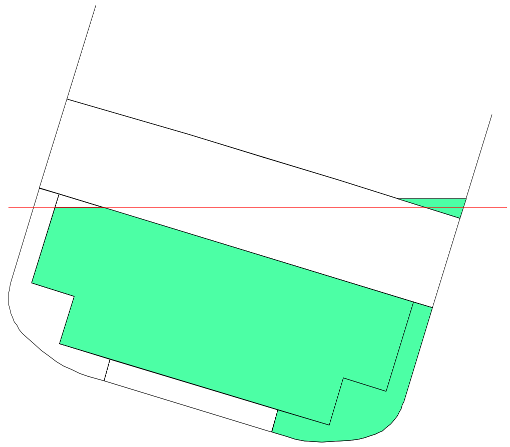

Figure 2: Cargo Ro-Ro with combined wing plus lower hold damage

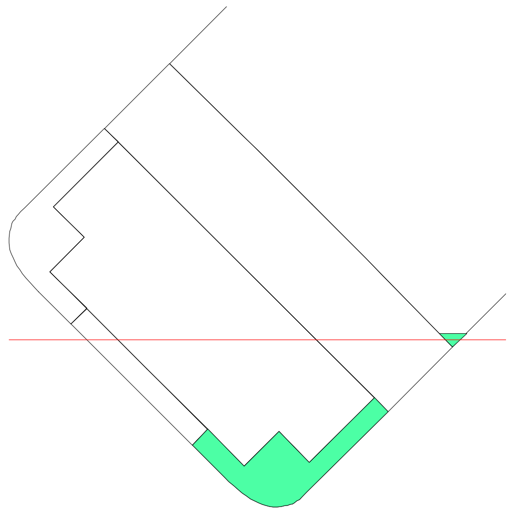

Figure 3: Cargo Ro-Ro with wing tank damage below the car deck

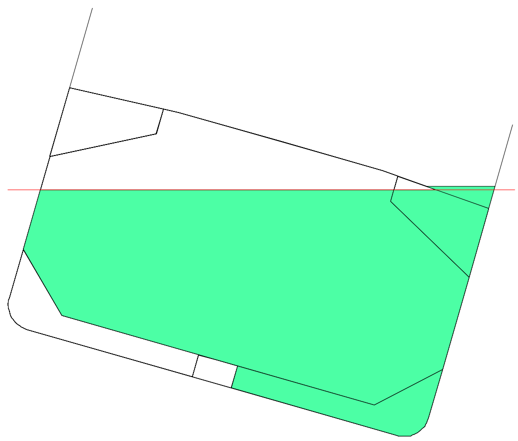

Figure 4: Panamax Bulk Carrier – Configuration 1

These five ship/damage configurations were tested over a range of KGs and sea states to establish the survival boundary. The model tests were performed at Denny

Tank, the University of Strathclyde model testing facility in Dumbarton. The Denny Tank is a conventional towing/wave-making tank measuring 100mx7mx2.7m. Unidirectional random waves were modelled using JONSWAP wave energy spectra with the model placed in the tank, free to drift, beam-on to the oncoming waves. Survivability was tested in a number of sea states, each repeated at least five times, so that a clear distinction between capsize and the survival cases could be ascertained and a survival band defined.

From observations of these model tests it became apparent that the ship behaviour near the capsize region is very similar to that seen with Ro-Ro ships. While the mechanics of water ingress and egress to and from an open deck are different than Ro-Ro ships, the mechanics of capsize appeared to be the same. In fact, the quasi-static nature of ship capsize at PNR is even more apparent with conventional ships because of generally smaller metacentric heights and deeper draughts.

4. GENERALISATION OF SEM

The SEM calculation procedure to determine both h can obviously be applied to conventional ships, if the effect of water shipping on the weather deck, unprotected by the ship's sides, is regarded as equivalent to that of water accumulated on the vehicle deck due to large-scale flooding. Essentially the same calculation method can be applied to the ship as if her sides were extended vertically above the open deck, as shown in Figure 5.

This suggestion does not come without a precedence considering that a rise of water on the weather deck has been previously proposed in [2] and subsequently adopted by the US Navy. In the said case the dynamic effects of wave action were represented by a rise 1.2m of water on the weather deck, irrespective of the ship size and freeboard. Subsequent experience has shown that this suggestion is overly conservative for commercial ships considering the typical sea states at the time of a casualty.

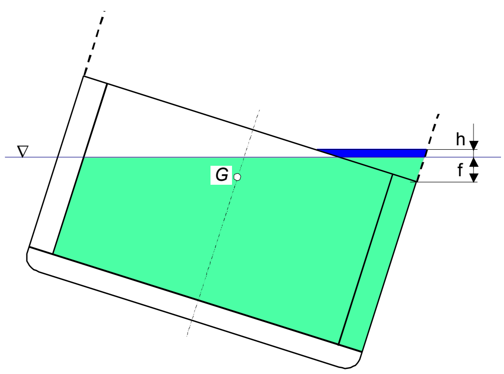

Figure 5: Conventional ship with water elevated on the weather deck at PNR

In view of the foregoing considerations, it would seem appropriate to pursue the same approach with conventional ships as that followed for Ro-Ro vessels by expressing the survival boundary in the non-dimensional form

$$h/H_{sr} = \mathrm{f}(f/H_{sr}),$$

with H_{sr}, h and f to be found with the aid of physical or numerical experiments for damage cases with marginal stability. As a first step, h and f were obtained by static calculations according to the SEM procedure and combined with H_s critical derived from model experiments in an attempt to derive a new formulation pertinent to conventional ships. The results of this effort are shown in Figure 6, the smallest scatter of points in obtained with $H_{sr} = H_s^{0.3}$, in contrast with the value of b of 1.3 derived from Ro-Ro vessel data.

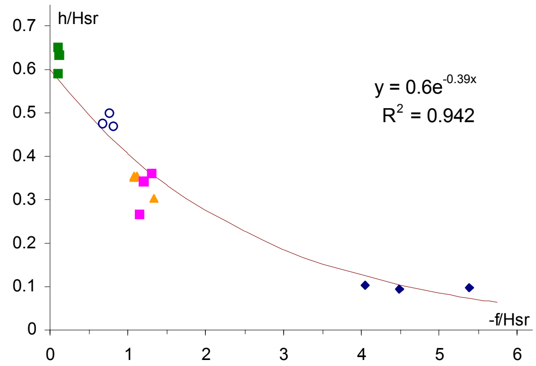

Figure 6: Boundary survivability curve for non-Ro-Ro ships with a modified $b = 0.3$ (total 16 cases)

The reason why the exponent b is different can be attributed to the different modes of water accumulation on deck as well as the geometrical differences between the two ship types (e.g., for conventional ships the non-dimensional freeboard varies in a much wider range than that for Ro-Ro ships). The regression in Figure 6 also shows a strong dependence between the non-dimensional values of h and f, contrary to the case of Ro-Ro vessels where a weak dependence led to the proposal of the formulation h/H_{sr} = 0.085, where h/H_{sr} was assumed to be independent of f/H_{sr} or

$$h \approx 0.085(H)^{1.3} \qquad (1)$$

Approximating the exponential in the regression equation of Figure 6 with the first two terms of a series and following some manipulations, the following expression may be derived

$$h \approx 0.6(H)^{0.3} + 0.24f \qquad (2)$$

Considering equations (1) and (2), a generalisation of SEM could be considered in the form

$$h = a(H_s)^b + cf \qquad (3)$$

with ship type dependent coefficients a, b and c.

Awaiting for proper analysis of the available experimental and numerical results, the interim expression (2) was used to compare SEM predictions of survival sea states with those measured from the model test programme of project HARDER and the agreement was found to be satisfactory, as demonstrated in Figures 7-11.

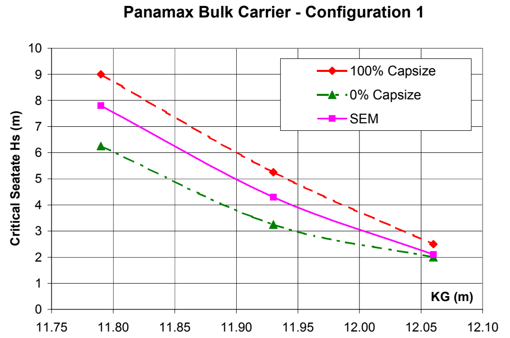

Figure 7: KG vs. Survival Sea State

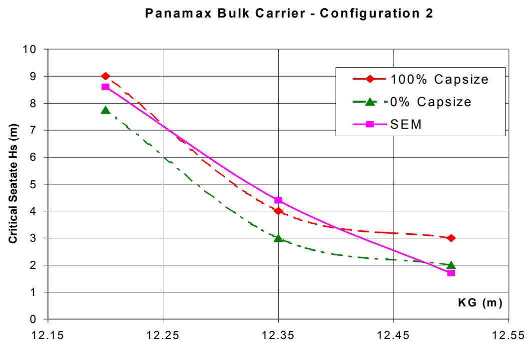

Figure 8: KG vs. Survival Sea State

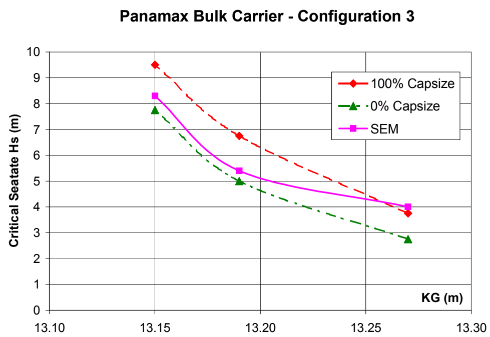

Figure 9: KG vs. Survival Sea State

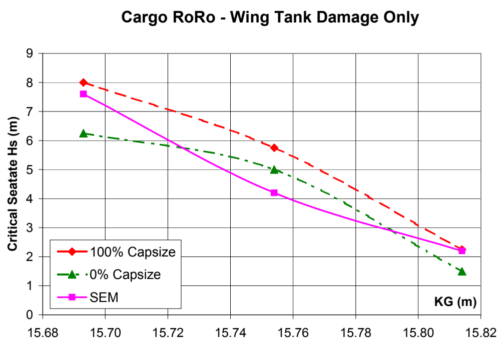

Figure 10: KG vs. Survival Sea State

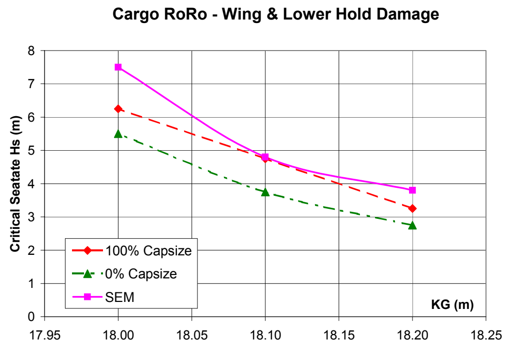

Figure 11: KG vs. Survival Sea State
(Large trim by bow)

5. CONCLUSIONS

At this stage of development, the following conclusions are noteworthy:

- A new formulation for predicting the critical survival sea state for conventional (non-Ro-Ro) ship configurations has been presented using the same procedure as proposed for Ro-Ro vessels, simply by by considering the ship sides to extend vertically upwards above the weather deck in the calculation of h and f.
- Based on the above a generalised formulation of SEM has been proposed where any differences between Ro-Ro and conventional ships are represented by different coefficients to be determined by physical and numerical capsize experiemtns.
- Comparisons of the predicted survival sea states between SEM predicted and experimentally measured values show satisfactory agreement.
- Further investigation is required for flooding cases with trim in order to verify the relationships between h, f, and H_{sr} at large trim, as well as where to measure f on a ship with significant trim.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the European Commission DG Research of the work presented in this paper, which forms part of Project HARDER, Contract No. **G3RD-CT-1999-00028** and to express their gratitude and sincere thanks.

7. REFERENCES

1. Vassalos, D., Pawłowski, M., and Turan, O.,"A Theoretical Investigation on the Capsizal Resistance of Passenger/Ro-Ro Vessels and Proposal of Survival Criteria", Final Report, Task 5, The North West European R&D Project, March 1996.
2. Sarchin, T. H., and Goldberg, L. L.: Stability and buoyancy criteria for U. S. Naval Ships, SNAME *Transactions*, Vol. 59, 1962, pp. 418–458.