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Model Experiments to Determine the Survivability Limits of Damaged RO-RO Ferries in Waves

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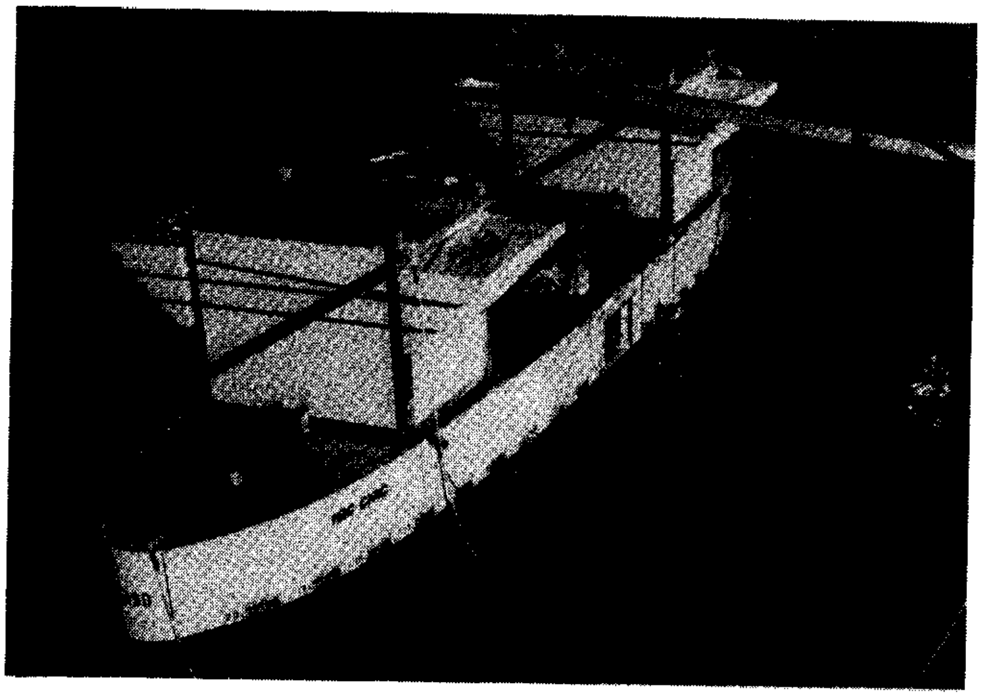


ABSTRACT

The sinkings of the European Gateway, the Herald of Free Enterprise and the Estonia have highlighted the potential for tragedy when water floods the car deck of RO-RO ferries. Transport Canada, through the Marine Safety Directorate and the Transportation Development Centre, sponsored model experiments to evaluate the effectiveness of the current SOLAS regulations and to determine if they can be safely relaxed when applied to domestic ships operating in sheltered waters. The first model tested was a prismatic hull, with the overall dimensions and stability characteristics of a 160 m ferry.

The subject of this paper is the results for the second model tested which was a simplified ship shaped hull with a waterline length of approximately 87 metres. The basic hull form was derived from smaller ferries, but was modified to be symmetrical about midships. The program of experiments was carried out over ranges of residual freeboard, vertical centre of gravity and area of freeing ports (fitted with flaps). The estimated maximum significant waveheight that the ship will survive is presented against various stability parameters and freeing port areas.

The limits of survivability are evaluated against the current SOLAS requirements. and are also compared with the findings from the Joint North West European R&D Project 'Safety of Passenger/RO-RO Vessels'. These results were developed from ships with fully enclosed car decks, rather than typical North American designs.

NOMENCLATURE

A	Total area of freeing ports per side, sq. m.
B	Beam, m.
C	Constant depending on direction of waves relative to damage
D	Depth of water on deck, m.
Δ	Displacement of ship at flooded waterline, tonnes.
Fb	Residual freeboard after damage, with dry deck, m.
GMf	Metacentric height of ship, after flooding, m.
GMn	Non-dimensional GMf.
g	Acceleration due to gravity, 9.81 m/s^2.
h	Static head of water on deck, above calm waterlevel, m.
Hs	Significant waveheight, m.
Hn	Non-dimensional significant waveheight.
KG	Vertical centre of gravity, above keel, m.
Tm	modal, or peak period, sec.
Lpp	Length of ship between perpendiculars, m.
ω	Wave frequency, $2\pi/Tm$, s^{-1}.

INTRODUCTION

The sinking of the 'European Gateway', the 'Herald of Free Enterprise' and the 'Estonia', with the tragic loss of many lives, served to highlight the potential for disaster when water floods the car deck of RO-RO ferries. While human error was determined to be an important component in all these casualties, there are conceivable scenarios when water accumulation on the car deck is unavoidable. One of these cases is when the ferry is damaged during a collision. The stability requirements for the ferry in this situation are regulated through the Safety of Life at Sea (SOLAS) Conventions under the auspices of the International Maritime Organization (IMO, 1986).

Transport Canada, through the Marine Safety Directorate and the Transportation Development Centre, sponsored a research project to investigate the parameters influencing the capsizing of RO-RO ferries after the hull is ruptured at midships, and to evaluate the effectiveness of the relevant SOLAS regulations in a Canadian context. This project was started in 1993 and has involved numerical methods and physical model experiments. It was divided into three phases. The first phase was designed to develop a fundamental understanding of the factors preventing the capsizing of a damaged RO-RO ship with the enclosed deck flooded. The hull studied had a constant cross section and it was designed to emulate the stability characteristics of a ferry approximately 160m long. The basic purpose of the experiments was to establish the effect of ship stability parameters on the limiting significant waveheight to cause a capsize. In addition, the potential for improving survivability by draining the car deck was investigated. Freeing ports with outward opening flaps allowed water to drain off the car deck, but prevented wave action from flooding it.

The second phase extended the research based on the same simplified hull form. It was directly influenced by the requirements of the Panel of Experts established by the Maritime Safety Committee at its sixty-fourth session in December 1994, to review all aspects of RO-RO ferry safety. The Canadian representative on the Panel of Experts was very interested in the safety of open shelter deck ferries operating on the west coast of Canada and the United States. These ferries do not operate in exposed waters, and typically have a centreline casing and freeing ports. The original model was modified to include an enclosed deck with an open stern, and a car deck protected only by bulwarks. Some questions were raised in the Panel of Experts discussion over the long term utility of flapped freeing ports, so permanently open freeing ports were included in the study.

The data collected during the first two phases was very useful in understanding the fundamental problem, but the results and the derived relations needed further validation against the tests with other hull forms. The third phase was to develop a more realistically shaped hull and to consider some of the same parameters studied in the first two phases. The results of the third phase are the subject of this paper. As with the first two phases, experiments were carried out over a range of residual freeboards, static stability conditions, and freeing port areas on a model with and without a centreline casing. The objective of the research was to define the limiting significant waveheight to cause a capsize for a range of stability parameters and freeing ports areas. The results are compared with the published data from similar experiment programs carried out on

European designs. These data will eventually be used to assess typical Canadian ferries against the SOLAS regulations, and to develop a relaxation scheme for those operating in protected, low traffic areas.

SUMMARY OF PREVIOUS CANADIAN RESEARCH INTO RO-RO FERRY CAPSIZING

The 1:20 scale model used for the first phase of the research included realistic decks, superstructure, double bottom tanks, bilge keels and a removable centerline casing. Measurements were made of model motions, waveheight and the instantaneous depth of water at 14 locations on the car deck. The results from these experiments have been published by Stubbs et al [1996] as limiting waveheight against stability parameters (GMf and GZ-area). Also given are limiting values of water on deck as a function of GMf. Detailed descriptions of the model and the test procedures are given by Molyneux & Cumming [1995]. The depth of water on deck data was also used by Hutchison et al [1996] as part of the North American contribution to the IMO Panel of Experts.

The most important findings can be summarized as follows:

- capsizing occurs after a critical volume of water has accumulated on the RO-RO deck;
- the critical volume of water on deck depends mainly on the GM after flooding
- the accumulation of water on deck is a function of the vessel's relative motion at the damage opening.

It was also observed that permanently open freeing ports were of no benefit to the survivability of the vessel, and in some cases they had a detrimental impact. The ability of the freeing ports to drain the deck is severely compromised by the water flooding the deck through the permanently open ports. Flapped ports however, do not allow the ingress of water to the vehicle deck but do permit drainage. Their effect was to introduce a progressive increase in vessel survivability as freeing port area was increased. The increase in limiting waveheight due to freeing ports was most at residual freeboards of 1 metre or more. At lower freeboards, the external wave action tended to keep the freeing ports shut and reduced their effectiveness.

When the casing was fitted, the water tended to drain off only through the ports facing the waves. When the casing was removed, the water on the deck could drain through the ports on both sides and a substantial increase in the limiting significant waveheight was observed. When permanently open freeing ports were used, the casing did not influence the survivability. Water flowing in through the ports caused a heel towards the damage and the water on deck tended not to flow the full width of the deck.

With permanently open freeing ports at an A/L ratio of 0.3, the vessel required 2 metres of residual freeboard to survive a significant wave height of 4 metres. With flapped freeing ports of the same area, the vessel survived the same waveheight with 1 metre of residual freeboard.

EXTENSION OF THE RESEARCH TO A SHIP SHAPED HULL FORM

The first two phases of the Canadian research had provided valuable insights into the capsizing mechanism and on the benefits of draining the car deck to prevent a capsize. However, the prismatic model was a simplification of the real flooding and capsizing situation. Also, the resulting geometry of the hull, whilst representative of the extreme flare on some Canadian west coast vessels, was not typical of the North American fleet. The simplified hull shape also meant that the flooded portion of the hull was approximately 36 percent longer than the equivalent value for a ship shaped hull. As such, the application of the results obtained from the first two phases was limited to the theoretical studies and secondary effects, such as improvements in survivability due to freeing port configuration. From the onset of the program, the research team realized that further experimental validation with more realistic ship forms was necessary to support the credibility of the initial results.

The main advantage of the prismatic hull was its simple geometry, which reduced the range of variables and simplified the mathematical description of the hull. In keeping with this philosophy, it was decided that the third

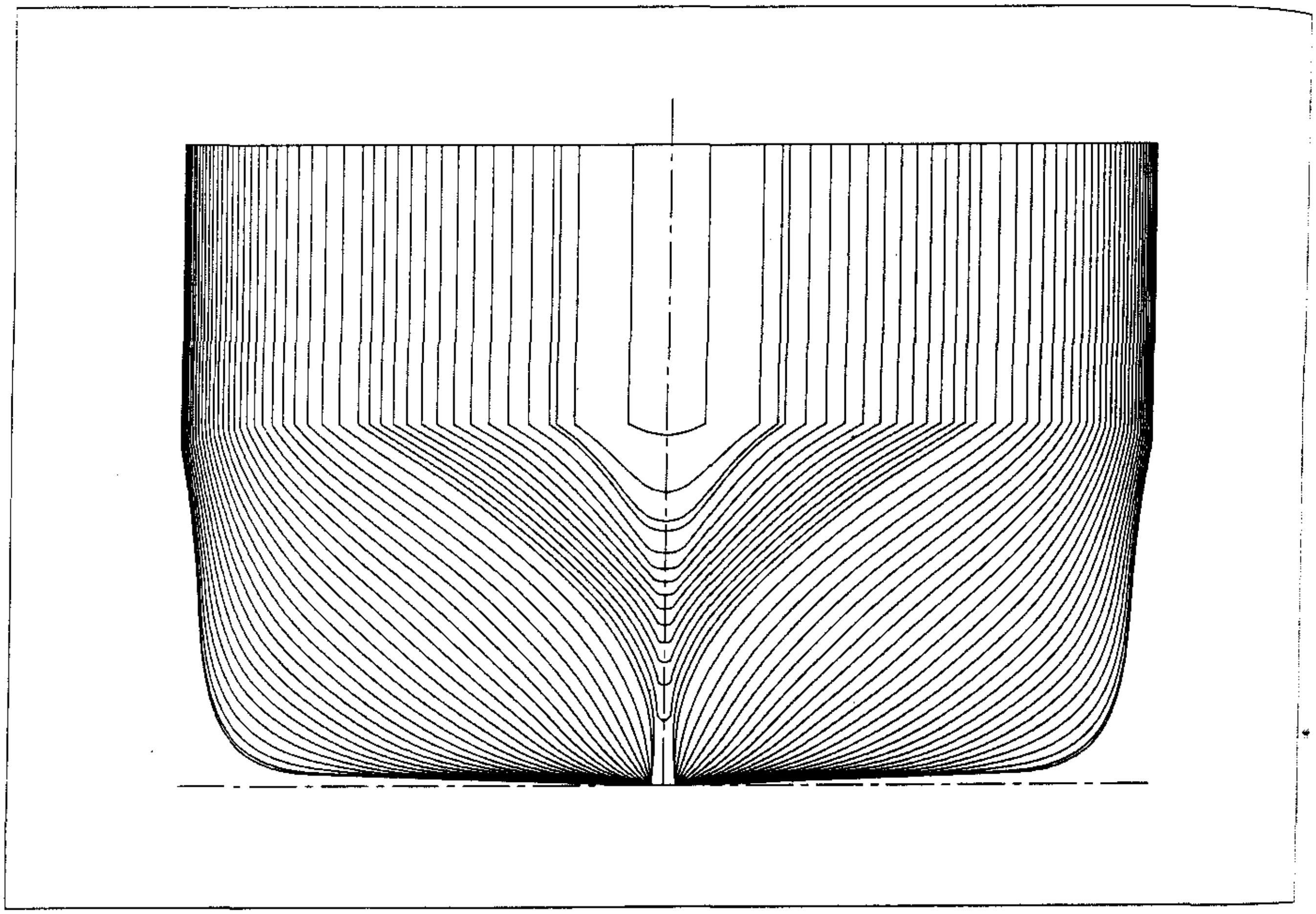


Figure 1. Body Plan, Simplified Ro-Ro Ferry

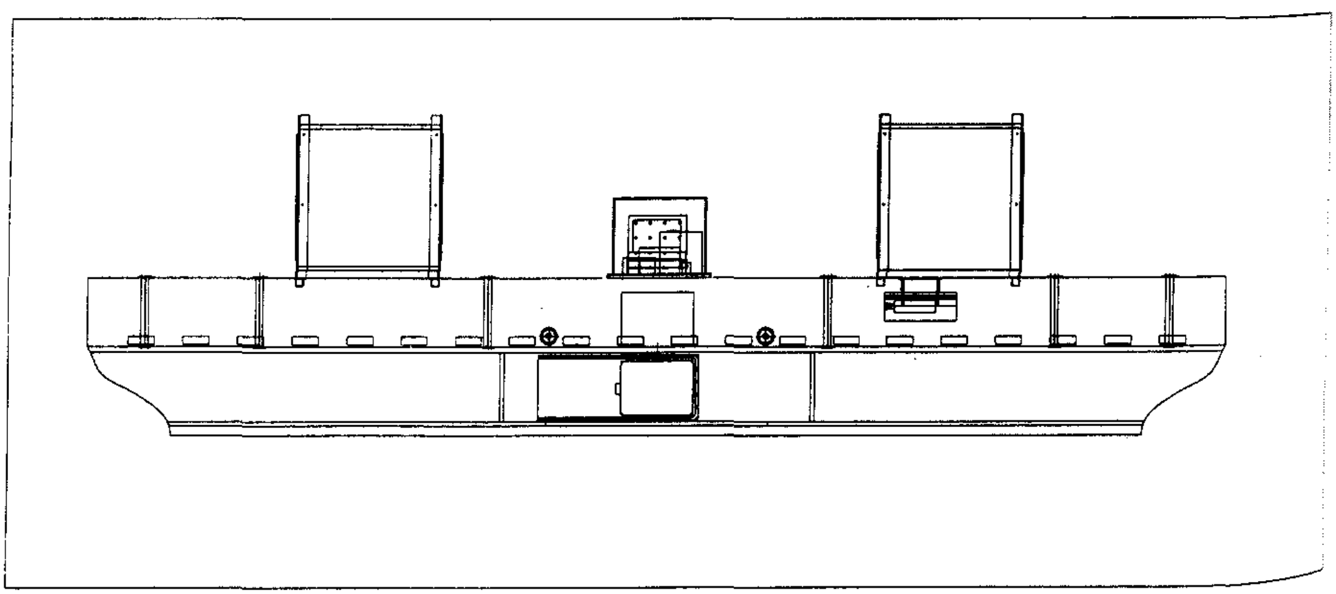


Figure 2. Profile, Simplified Ro-Ro Ferry

phase of the research should focus on a hull form closer to the shape of a real ship. Another factor in the selection of the ship dimensions was to ensure that the results of the research were applicable to the smaller ships in the Canadian fleet.

Other features such as area of freeing ports per unit length and location of the centreline casing were kept the same as the previous study. Since the earlier results had shown that permanently open freeing ports were of no benefit, the third phase only investigated flapped ports.

The major portion of the experiment program was to investigate the capsize survivability of the ferry model over a range of stability conditions related to the SOLAS 90 damage stability regulations. These regulations refer to three key variables and the minimum acceptable value of each. They are:

1) A minimum area under the GZ curve of 0.015 metre-radians,

2) A maximum righting arm (GZ) of at least 0.1 metres and

3) A minimum range of positive stability of at least 15 degrees

Length, O. A. m.	87.20
Length, W.L. m.	85.42
Beam, O. A. m.	18.48
Beam, W.L. m.	18.04
Draft, intact, m.	4.95
Depth, to car deck, m.	6.71
Volume of displacement, m^3.	4354.2

Table 1
Summary Particulars for Simplified RO-RO Ferry

The hull shape developed to meet the objectives discussed above had two planes of symmetry, one at the centreline and one at midships. A bodyplan and profile of the model are given in Figures 1 and 2 respectively. Summary particulars for the intact ship are given in Table 1.

For the hull form in question, it was not possible to obtain all the SOLAS parameters coincidentally, but the likelihood of this happening in real life is also very low. The positions of the vertical centre of gravity were picked to give each of these three parameters, for a total of four residual freeboards (0.2, 0.4, 0.8 and 1.2 metres). A summary of the test conditions is given in Table 2. A typical vertical centre of gravity for a ship of this size is approximately 7 metres.

It was felt that the minimum freeboard of 0.5 metres used in the previous study was too high so for this research a minimum value of 0.2 metres was used. The other freeboards were picked to cover the likely range of values for ships designed to SOLAS 90.

The effect of the number of freeing ports was studied at each test condition. Three levels of freeing ports were used. No ports open was equivalent to a fully enclosed deck.

Fb m	KG m	SOLAS 90 condition	GMf m	GMn
1.2	8.00	0.1 m GZ	0.373	3.47
1.2	7.59	0.015 m-radians	0.776	7.23
1.2	7.00	15 degree range	1.366	12.72
0.8	7.42	0.1 m GZ	0.930	9.52
0.8	7.22	0.015 m-radians	1.124	11.51
0.8	6.77	15 degree range	1.555	15.92
0.4	6.86	0.1 m GZ	1.537	17.20
0.4	6.36	0.015 m-radians	1.961	21.95
0.4	5.70	15 degree range	2.693	30.14
0.2	6.10	0.1 m GZ	2.174	25.40
0.2	5.51	0.015 m-radians	2.865	33.47

Table 2
Nominal Test Conditions and Measured GM for flooded hull

Six ports open per side, corresponded to the International Load Line Convention, with A/L of 0.08 and 20 ports open per side corresponded to A/L of 0.3 where A is the total area of open ports (per side) and L is the length of the deck. The freeing ports were fitted at the level of the car deck, and were 1.2 metres long by 0.6 metres high. Each port was fitted with a flap (opening outwards only) that could be locked shut, or

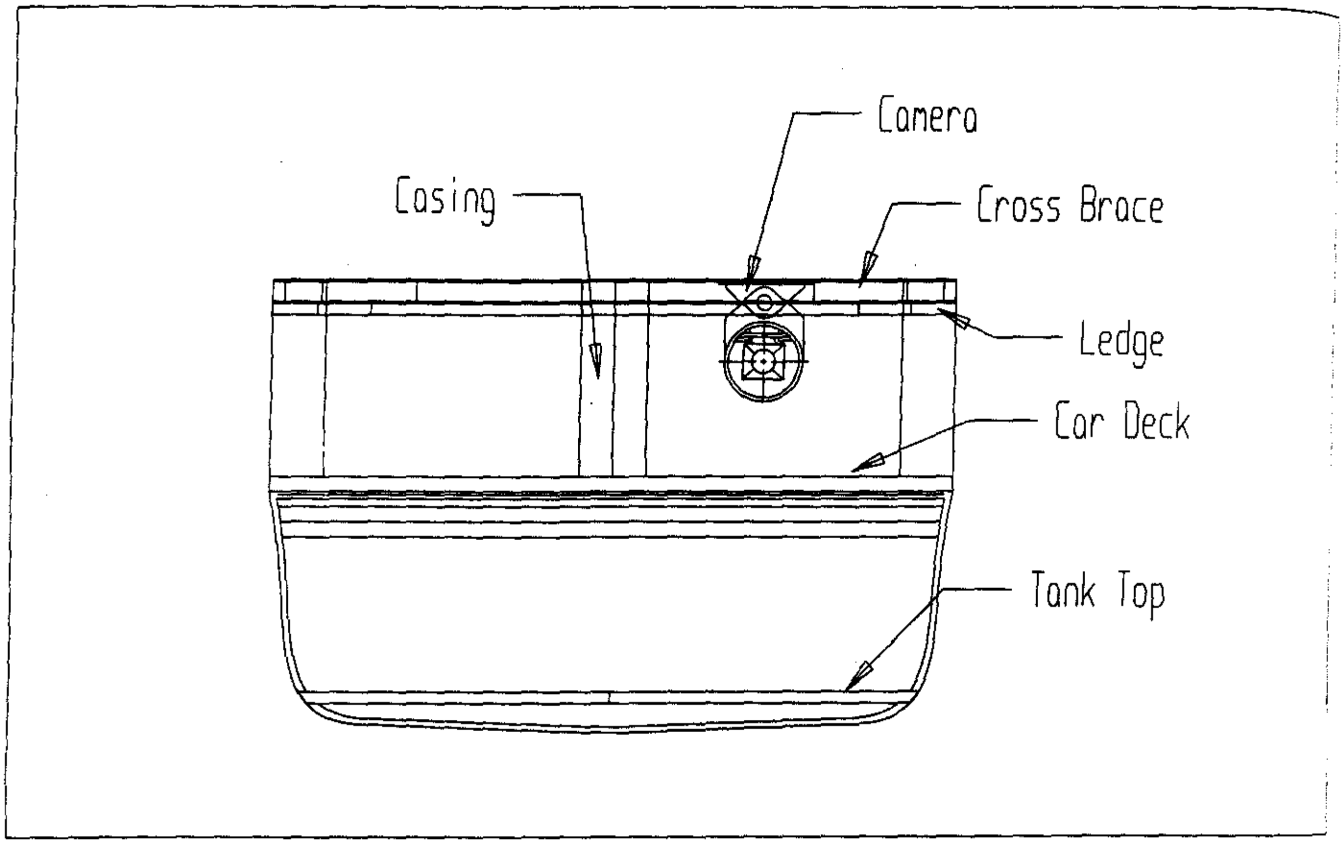


Figure 3. Mid Ship Cross-Section

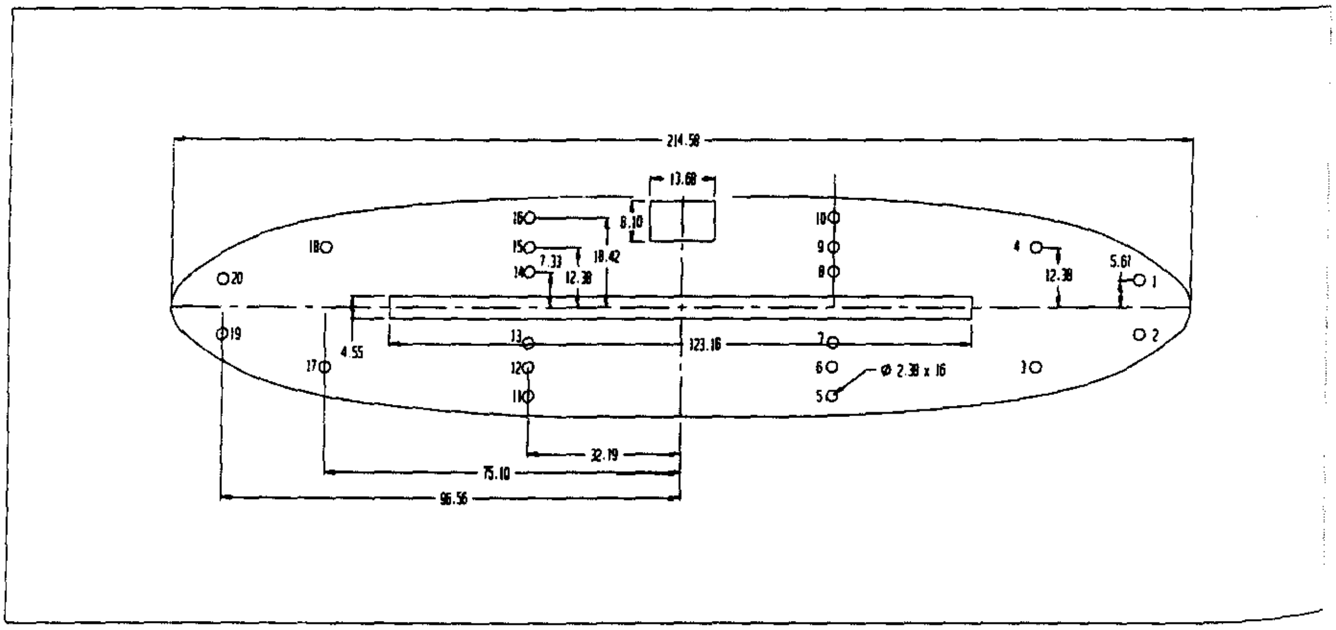


Figure 4. Deck Plan

allowed to flap open. Each condition was tested with and without the centreline casing to determine the difference in the results when the water was free to flow the full width of the model.

All of the experiments discussed in this section of the paper were carried out in a JONSWAP wave spectrum, with a peak enhancement factor of 3.3. The nominal waveheight and period relationships are given in Table 3. The wave height to period relationships were selected based on observations made in Canadian coastal waters. Also given are the calibrated values (based on a 40 minute repeat period) and the average of the values taken from the waveheight measurements made on the towing carriage, moving with the model.

In planning the third phase of this research project, it was important that the model construction, testing methods, data acquisition systems and analysis methods take advantage of the most recent developments in the area of damaged model testing. A summary of these developments is given by Molyneux [1996].

Hs m	Modal Period sec	Calibrated Hs (stationary) m	Average Hs (moving) m
1.0	5.5	1.04	1.32
1.5	6.0	1.60	1.73
2.0	6.5	1.98	2.24
3.0	7.0	2.92	3.22
4.0	7.5	3.92	4.06
5.0	8.0	4.86	4.85
6.0	8.5	5.91	6.08
7.0	9.0	6.61	6.59

Table 3
Nominal Significant Waveheights and Peak Periods

DESCRIPTION OF MODEL EXPERIMENTS

Model Construction

The model was constructed to 1:16 scale. This scale ensured that the model was as large as possible within the practical limitations of the testing facilities. Two identical half models of the hull and superstructure (bow and stern) were made from glass reinforced plastic using a female mold. A plywood double bottom concealing permanent lead ballast was then fitted and covered with glass fibre and resin. All void spaces in the double bottom were filled with closed cell foam. Transverse bulkheads, extending between the double bottom and the car deck, were constructed to define the limits of the available floodable length within the hull. The car deck was made from a single piece and included watertight hatches to permit access to the hull for fitting ballast in the void spaces and to permit the installation of foam inserts to vary the floodable length. The damage opening was fitted with a sliding door that was designed to be opened from the tow carriage. The model was also fitted with bilge keels, but no other appendages. A midships section drawing showing some details of the construction is shown in Figure 3.

The superstructure deck was made of plywood and clear lexan which permitted adequate ambient lighting for video records of water flow on the car deck. Foam buoyancy blocks were secured above the superstructure deck to ensure the model did not invert after a capsize. The exterior of the model was painted yellow from the baseline to the car deck and white from the car deck to the superstructure deck. The interior of the superstructure was also painted white.

An array of 20 capacitance probes fitted to the car deck as shown in Figure 4 was used to measure the level of accumulated water. Capacitance probes were also used to measure relative motion in way of the damage opening. A stationary capacitance wave probe located 60 metres from the wavemaker was used to measure the characteristics of the incident wave field. A second capacitance wave probe was fitted to the tow carriage to measure the wave conditions close to the model. A magnetic switch was used to detect the instant the door opened and the flooding started. Roll and pitch were measured using a 2-axis electro-mechanical gyro. Orthogonal linear accelerations were measured using uni-axial accelerometers fitted in a precision tri-axial mount.

All motion measurement instrumentation and the associated power supply, signal processing and data acquisition systems were installed in a waterproof box mounted on top of the superstructure amidships. Heat dissipation from this instrumentation box was ensured by using passive heat sinks. Electrical power for the

Casing	Deck Area (cu. m.)	Measured Volume (cu. m.)	Calculated Volume (cu. m.) Model static Mean	Model rolling Mean	Model rolling Std. dev.	Volume difference (cu. m.) Model static Mean	Model rolling Mean
In	1257.47	397.3	450.6	478.6	26.6	-53.3	-81.3
In	1257.47	94.2	92.9	92.6	12.5	1.3	1.6
In	1257.47	229.4	302.7	277.9	27.2	-73.3	-48.5
Out	1350.14	135.2	137.8	156.3	13.4	-2.6	-21.1
Out	1350.14	254.0	319.6	339.5	33.0	-65.6	-85.5
				Mean	22.5	-38.7	-47.0
				Std. dev.	9.1	35.5	37.7

Table 4
Results of volume of water on deck calibrations

ballast pumps, video camera, signal conditioning equipment and instrumentation was provided via a cable from the tow carriage. Data was transferred from the model to the tow carriage data acquisition system via an EtherNet link. Signals not collected on the model such as incident wave height and carriage speed were conditioned using a second signal conditioner. Time histories of each data channel were plotted for review at the end of each run. Video tapes were made of the side and end views of the model in waves, and a view of the water motion on the car deck.

Prior to commencing the test program, the empty model was weighed and the location of the centre of gravity, together with the radii of gyration in pitch and roll, were determined. All of the experiments were carried out in the Towing Tank at the Institute for Marine Dynamics in St. John's, Newfoundland. The tank is 200 m long, 12 m wide and 7 m deep.

Calibration of Volume of Water on Deck

During the first two phases of the project, it became clear that the volume of water on the deck was a key parameter effecting the capsize of the ship. For the hull form used in the third phase, it was expected that the volume required to capsize the ship would be smaller than the values obtained in the earlier phases. For this reason, special care was taken in determining the accuracy of the volume measurements. A number of experiments were carried out to assess the accuracy and sensitivity of the algorithm derived for computing the volume of water on the car deck from the water level data measured using the array of 20 level probes. The car deck was sealed and flooded with water. Tests were carried out for the following three conditions:

a) level upright (strapped to crane with a load cell to measure weight of water),
b) stationary, heeled,
c) dynamically excited by manually rolling the model.

The volume estimation procedure used linear interpolation between the waterlevel probes and assumed that the model had no appreciable trim. All tests were carried out at a residual freeboard of 0.8m and nominal vertical centre of gravity 7.42 metres above the keel, full scale. The experiments were carried out with and without the centreline casing in place. Results of these experiments are given in Table 4. Based on the standard deviation of the observed mean error and assuming it had a normal distribution, we determined that the calculated mean is within ± 75 cubic metres at 95% confidence. Another interesting observation is the standard deviation of the volume during the measurements. The average of this value is 22.5 cubic metres, and this gives an indication of the absolute accuracy of the algorithm, since the volume of water on the deck was constant over the time this value was computed.

The difference between the measured and computed volumes is primarily due to the accuracy of the measured depth of water on deck (estimated at +/- 3%) and the linear approximation used to compute volume of water on deck. During the calibration experiments, it was observed that water on deck accumulated at one end or other of the model, while the model (including the water) was being weighed. A detailed investigation revealed that this was especially true for calibration run numbers 1,3,5 (the runs with the highest difference between the measured and computed water volume). This resulted in an asymmetry between the depth of water in the bow and stern, which affected the results when the average depth of water is computed, especially if one end was dry. Checks on data taken during the experiments in waves did not show this longitudinal asymmetry and so we can assume that the errors in the calculated volumes from the experiments in waves are no greater than the values observed in the calibration.

Experiments in Irregular Waves

A typical test procedure started with the model being ballasted to the intact draft, trim and VCG. An inclining experiment was then carried out to verify that the condition was correct. The freeing port arrangement, centreline casing configuration, and floodable length for the desired residual freeboard were set. A roll decay test was carried out to determine the natural roll period of the flooded model.

The model was placed across the tank, with the damage facing the oncoming waves, approximately 20 metres from the wavemaker. The wavemaker was started and data acquisition began in the calm water period before the wave train reached the model. The model was kept in position (using ropes tied to the bow and stern) until the first few transient waves had passed. The hull damage door was opened using cables from the tow carriage and the model flooded down to its nominal residual freeboard.

The model was then permitted to drift down the tank under the natural action of the waves. The carriage operator, using the video image from the camera directed at the stern of the model, adjusted the carriage speed to preserve a constant distance between the carriage and the model (+/- 1 m). The model drifted down the tank in a very stable manner. The run was complete when the model capsized or a full scale time of approximately 40 minutes elapsed without capsize. At the end of the run, the model was righted using a pulley system on the tow carriage. It was then pumped dry and configured for the next experiment. The heel angle of the model was checked after each run, and if necessary the ballast was adjusted to ensure zero roll when the model was flooded. The model without the casing was very sensitive to the static heel of the model at the start of the experiment. A small change in static heel could change the waveheight to cause a capsize by the equivalent of several metres.

DISCUSSION OF RESULTS

Comparison of Experiment Results with SOLAS 90 Regulations

For the hull form in question, with its Centre of Gravity 7 metres above the keel (which is typical for a ship of this size) the strict compliance with all three parameters within SOLAS 90 occurred at a residual freeboard of 1.2 metres. The corresponding value of GMf was 1.37 m and the limiting constraint was the 15 degree range of positive GZ lever, and the two other limits were exceeded. In this condition the ship survived waves with a significant waveheight of 4 metres with the casing in place and 7 metre waves when the casing was removed. The IMO Panel of Experts noted that 99 percent of all collisions between ships had been observed in waves with a significant height under 4 metres.

Some other interesting observations were made. For the model with the casing removed, the survivability limit stayed at a significant height of 7 metres for all the conditions tested that met the 15 degree range requirement. For the conditions with the centreline casing in place however, when the residual freeboard was lowered to 0.8 metres, even though the centre of gravity was also lowered, the model only survived waves with a significant height of 2 metres. At a residual freeboard of 0.4 metres, the waveheight survived increased to 3 metres. Based on these observations, SOLAS 90 does not provide a uniform standard of survivability. Freeboard appears to have an effect on the waveheight survived, independently of its influence within the function of GZ against angle of heel.

If the SOLAS 90 standard was relaxed to the limiting constraints of 0.015 m-radians and 0.1m GZ, then the survivability of the model without the centreline casing was unchanged. For the model fitted with the centreline casing, the limiting significant waveheight for survivability was reduced to 1.5 metres at 0.4 metres of residual freeboard and 2.0 metres at 1.2 metres of residual freeboard. If the standard was relaxed further to the maximum GZ of 0.1m only, then limiting significant waveheight for survivability with the casing in place would be 1 metre or less, and with the casing removed would be between 1 metre and 6 metres. For operation in sheltered waters, where significant waveheights were typically under 2 metres, it would be possible to reduce the SOLAS 90 standard to 0.015 m-radians only, provided that the residual freeboard was greater than 0.8 metres.

The flapped freeing ports increased the survivability as a function of the number of ports open, ship stability and residual freeboard. The best effect of the freeing ports was seen at high freeboards, high stability and maximum number of ports, where the significant waveheight for survivability of the ship was increased by up to 3 metres. In the worst case, the freeing ports made no difference, and these cases had low residual freeboard, low stability and a small number of ports open. The performance of the freeing ports should be taken into account in any relaxation of the SOLAS 90 standards, provided that water cannot flow onto the deck through the openings.

Flooding the RO-RO deck

The results of the first phase of the research (Stubbs et al, 1996) gave some good indicators of the factors influencing the survivability of a damaged RO-RO vessel. The simplified flow chart shown in Figure 5 was derived from observations on the model's behavior during the experiments. The two critical points in the flooding and subsequent capsize process are shown as diamonds. The first one is critical because a capsize can be avoided if no water enters the car deck. The second point is critical because a capsize will not occur if the hull has sufficient stability to withstand the acquired volume of water on the deck. This process gives options for presenting the data with the objective of obtaining dimensionless limiting parameters to prevent the capsize of a damaged ferry.

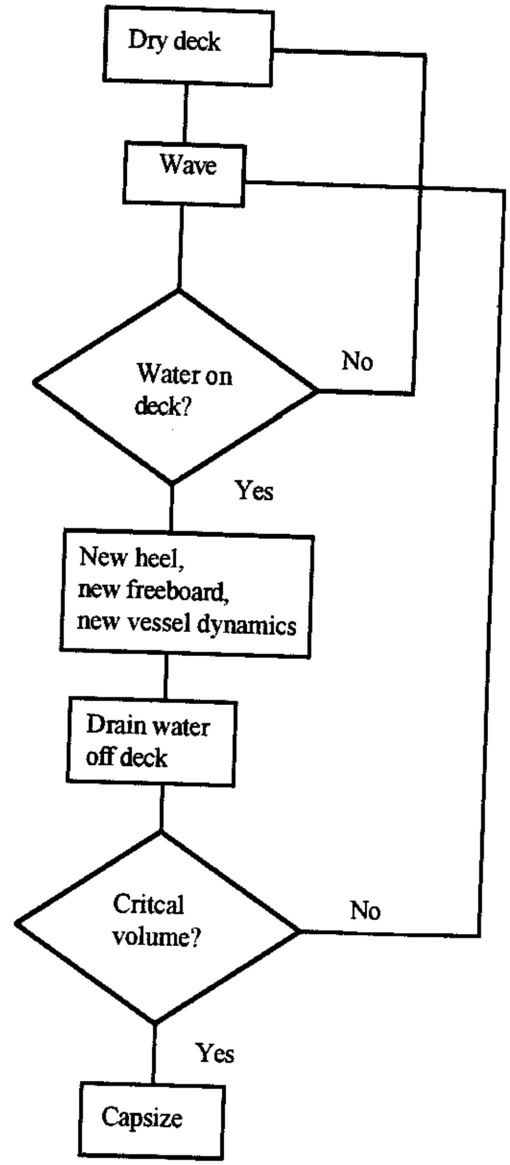
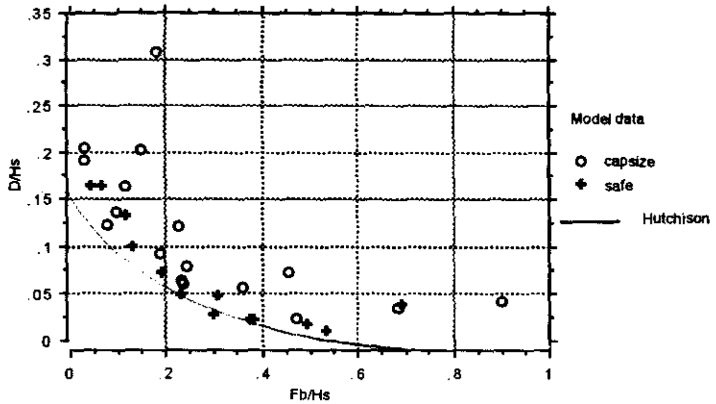


Figure 5, Simplified representation of the capsize process

The most obvious parameter to consider for limiting the volume of water on the deck is residual freeboard. Intuitively, a high freeboard in low waves will accumulate less water than a low freeboard in high waves. Hutchison et al [1996] suggested the non-dimensional parameter Fb/Hs as the independent variable that determined the amount of flooding on the car deck. The resulting depth of water on the deck was also non-dimensionalized by Hs, to give the parameter D/Hs.



igure 6, Non-dimensional depth of water on deck against non-dimensional freeboard, odel with casing and freeing ports closed.

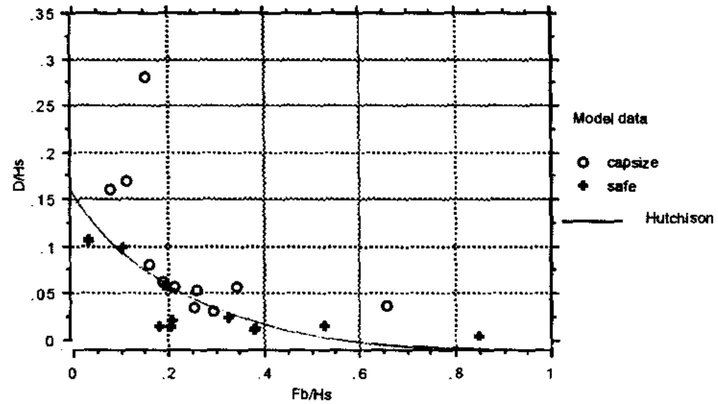


Figure 8, Non-dimensional depth of water on deck against non-dimensional freeboard, model with casing and six freeing ports open.

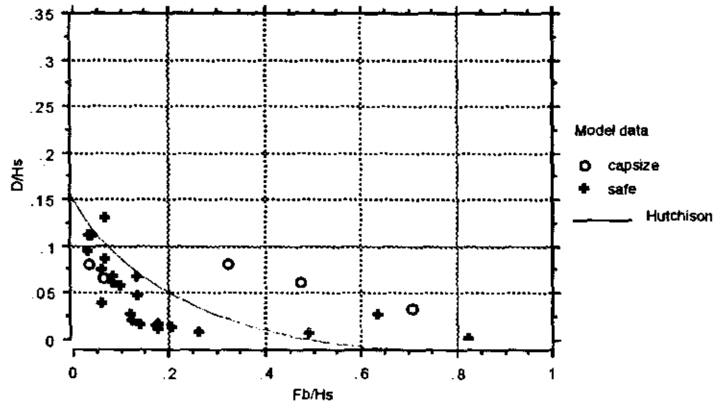


Figure 7, Non-dimensional depth of water on deck against non-dimensional freeboard, model without casing and freeing ports closed.

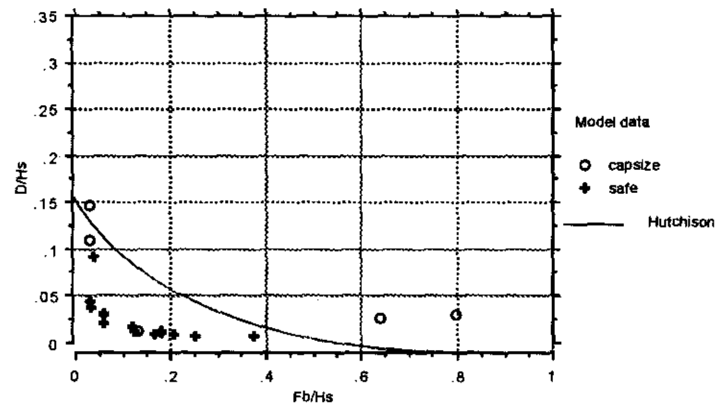


Figure 9, Non-dimensional depth of water on deck against non-dimensional freeboard, model with no casing and six freeing ports open.

For the experiments in irregular waves, the volume of water on deck was calculated from the measured depths of water. Average depth was calculated by dividing the volume by the area of the deck. For cases when the model did not capsize, the volume analyzed was the highest average volume of water. When the model did capsize, the value analyzed was that just prior to the rapid changes in observed roll, typical of a capsize. These data are plotted for the model with a centreline casing and no freeing ports open in Figure 6. The volumes from the cases when a capsize did not occur are a better indication of the limiting depth, since these conditions were ultimately stable and the mean steady volume of water was easy to determine. It can be seen that the line proposed by Hutchison et al is a reasonable indication of the limiting amount of water on the deck for the hull with the casing in place.

When the casing is removed (Figure 7) the observed values agree with the equivalent predictions at low freeboard to waveheight ratios, but as the freeboard increases, then the prediction is consistently higher than the observed values. The mechanism for this reduced depth of water on the RO-RO deck was due to the fact that when the casing was removed there was a general trend for the model to heel away from the waves. This increased the effective freeboard at the damage, and so in turn reduced the flooding rate, resulting in a lower depth of water on the deck.

This presentation is also effective for showing the influence of the freeing ports on the depth of water on the deck. Figures 8 and 9 show the effect of six freeing ports and Figures 10 and 11 show the effect of twenty freeing ports, with and without casing respectively. The freeing ports were most effective at medium values of Fb/Hs. At high values, there is very little water on the deck and the freeing ports are not needed. At low values of Fb/Hs, the external wave action works to keep the flapped ports shut, rendering them less effective. When the casing was removed, the freeing ports tended to be more effective, since the water could flow across the whole deck, allowing water to drain off both sides of the deck.

Volume of Water on Deck to Cause a Capsize

Stubbs et al [1996] showed that for the model used in the first phase of the research, the volume of water on deck to cause a capsize was a function of GMf and was independent of the number of freeing ports open or the arrangement of the deck (casing or no casing). A similar trend was also found within the data from the experiments carried out in the third phase.

D/Hs was used as a parameter to analyze the flooding of the deck and it can also be used as a parameter for non-dimensionalizing the volume of water on the deck. The other parameter required is a measure of stability, and as discussed above, GMf appeared to be a good indicator from the first two phases. However, a non-dimensional form is prefered. Spouge [1994] gives a non-dimensional GM, in the form

$$\mathrm{GMn} = \frac{\Delta\ \mathrm{GMf}}{1.025\ \mathrm{Lpp}\ \mathrm{B}^3} \tag{1}$$

This term allows for the change in righting moment of the hull with both GMf and the flooded volume of the hull, which changes with residual freeboard. Figure 12 shows D/Hs plotted against GMn for the model with the centreline casing for all the freeing port conditions. This figure shows a region where the model will definitely capsize and a region where it will definitely survive and a good demarcation between the two. Figure 13 shows the same data for the model with the casing removed. The results for this condition show much more scatter but the same transition line is drawn, since there was not sufficient evidence for producing a separate line.

Overall Survivability Function

If the depth of water on deck is not used in developing the stability criteria then an alternative presentation can be considered. Given both previous presentations show reasonably good demarcation between the ship remaining upright and the ship capsizing, this should also be true if we plot Fb/Hs against GMn. This is shown for the model with a casing and no freeing ports in Figure 14. This presentation is similar to those used by Dand [1991], Spouge [1994] and Vassalos [1996]. Clearly there is a limiting line for capsize safety, which is a smooth function of GMn.

When the same presentation is used for the model without the centreline casing (Figure 15), a similar survivability limit can be seen, but the

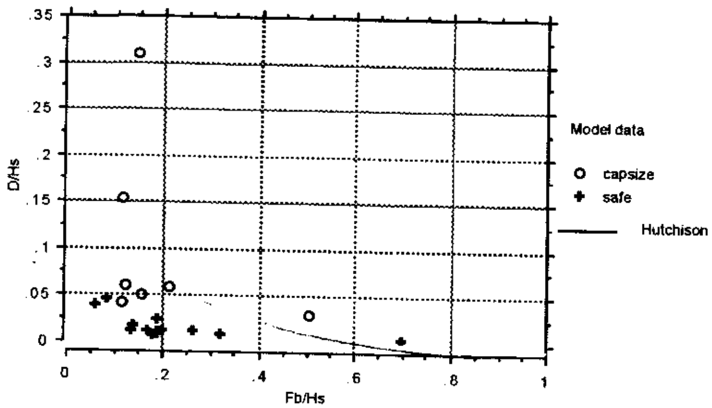


Figure 10, Non-dimensional depth of water on deck against non-dimensional freeboard, model with casing and twenty freeing ports open.

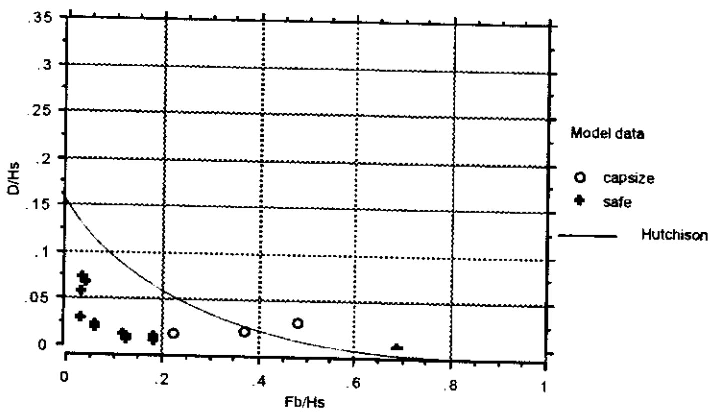


Figure 11, Non-dimensional depth of water on deck against non-dimensional freeboard, model with no casing and twenty freeing ports open.

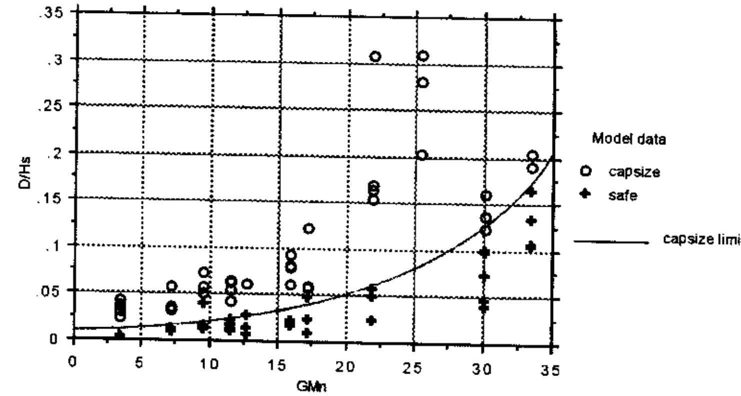


Figure 12, Non-dimensional depth of water on deck against non-dimensional metacentric height, model with casing.

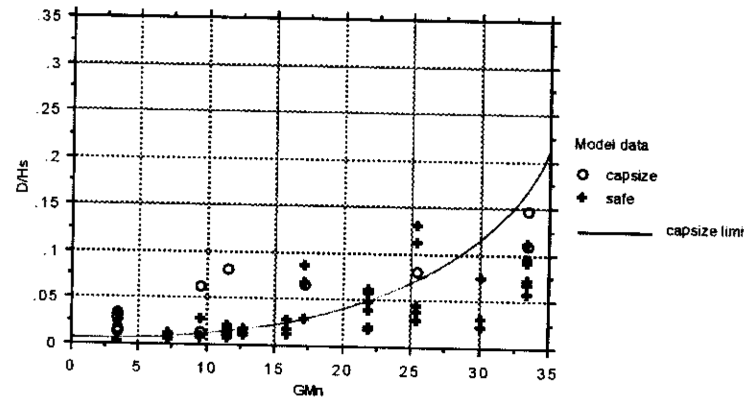


Figure 13, Non-dimensional depth of water on deck against non-dimensional metacentric height, model with no casing.

limit of survivability is more difficult to define. At low values of GMn (less than 10) the influence of the casing is negligible. At GMn values over 10 there is a clear increase in the waveheight that the model will survive for a given residual freeboard, although this influence reduces as the freeboard is increased.

This behaviour can be explained by the movement of the water on the deck, and the resulting heel angle. When the casing is fitted, it tends to trap the incoming water on the side of the damage. This results in a mean heel angle into the damage, which in turn accelerates the flooding process. All the capsizes observed for this model were with the damage side down.

The general benefit of removing the casing was to allow the water to flow across the full width of the deck. This tended to heel the model away from the damage, increase the effective residual freeboard, and increase the waveheight at which a capsize occurred. If the freeing ports were used, then there was the added advantage of being able to use the ports on both sides of the deck.

This trend was modified in certain circumstances. At low values of GMn there was a tendency for the model to heel into the damage as soon as the water came onto the deck. This negated the effects of heeling away from the damage, as discussed above. At the highest freeboards tested there was very little water on the deck, and so the casing had little effect, because the volume of water did not heel the model significantly.

Comparisons with Published Survivability Limits

Spouge [1994] analyzed all the data available at that time, and presented a limiting survival condition in the form of Hn against GMn, where Hn represents the ratio of wave slope to roll angle required to cause flooding. Hn is defined as

$$Hn = \frac{\omega^2 \text{ Hs B C}}{4 \text{ g Fb}} \qquad (2)$$

where C is a constant with values of 1 when the damage is facing the oncoming waves and 0.5 for the damage away from the oncoming waves. Also given in this paper is a formula for the limiting waveheight. This is expressed as

$$GMn = -0.904Hn^2 + 11.4Hn - 0.885 \qquad (3)$$

This equation is compared with the IMD data in Figure 16 for the model with the casing and in Figure 17 for the model without the casing.

Spouge's limiting formula gives a good agreement for the model with the casing in place, but it under predicts the survivability of the ship when the casing is removed. This may be explained by the fact that at equivalent GMn values for the two deck arrangements, the behavior of the water on the deck is different, which in turn influences the survivability. GMn is not sufficient to define the differences between the hulls, since it does not include a parameter representing the effective floodable beam of the model, but only the overall beam.

Vassalos et al [1996] also discuss the problems associated with metacentric height as a predictor. As an alternative they propose a parameter based on the calculated static head of water on the car deck. The hull is assumed to be damaged below the waterline, but the car deck area remains intact. The volume of water on the deck required to heel the model to the angle corresponding value of maximum righting lever, GZ is calculated.

In this equilibrium position the maximum head of water h, inside the car deck above the calm water level is calculated. They then present a limiting equation relating this static head to significant waveheight, based on extensive simulations of several different RO-RO ferry types. The limiting equation is given as

$$Hs = \frac{h^{1/3}}{0.085} \qquad (4)$$

Values of h were calculated for our model and the corresponding values of Hs were determined using equation (4). Figure 18 shows the values of h against Hs for the Canadian data with the casing in place and with the casing removed in Figure 19. Also shown is the limiting line given in equation (4). In these figures, all the safe cases should be above the dividing line and all the capsize cases should be below the line. It can be seen that the condition with the casing has a reasonable agreement between the predictions and the observations, but for the condition with the casing removed the theory under predicts the observations.

Based on the data for the simplified model described in this paper, the published survivability limits appear to be reasonably

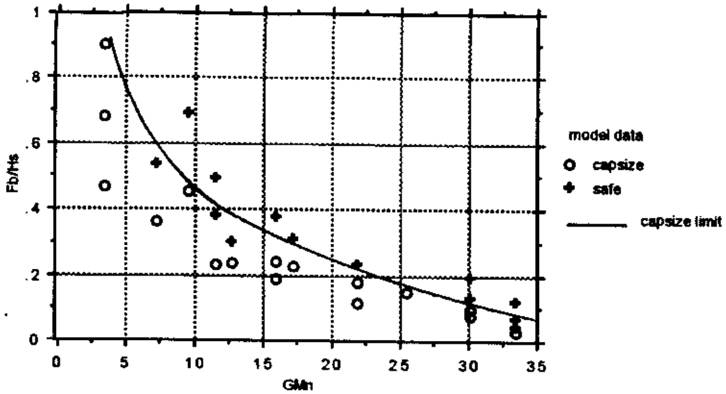


Figure 14, Non-dimensional residual freeboard against non-dimensional metacentric height, model with casing and freeing ports closed.

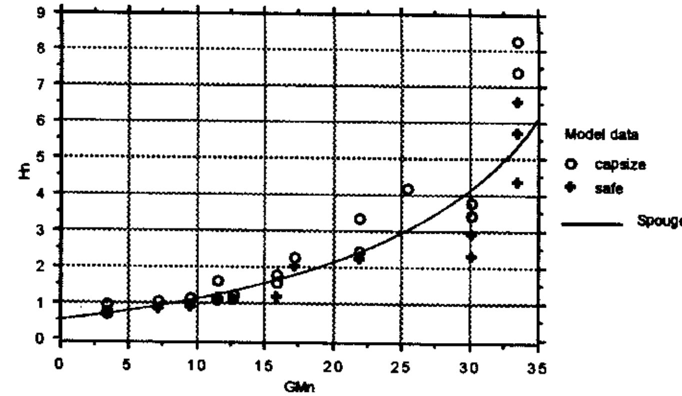


Figure 16, Non-dimensional waveheight against non-dimensional metacentric height, model with casing and freeing ports closed.

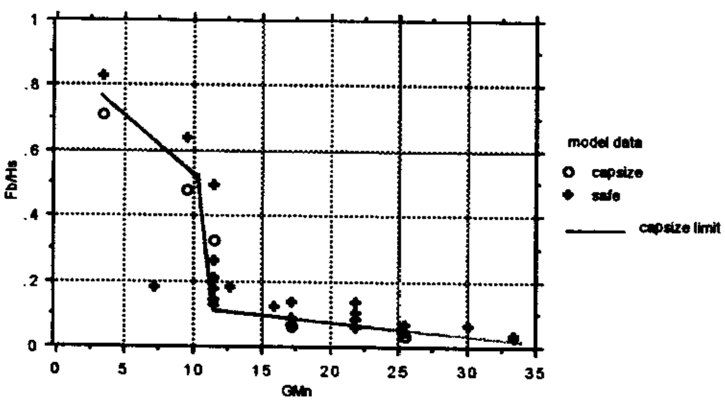


Figure 15, Non-dimensional residual freeboard against non-dimensional metacentric height, model with no casing and freeing ports closed.

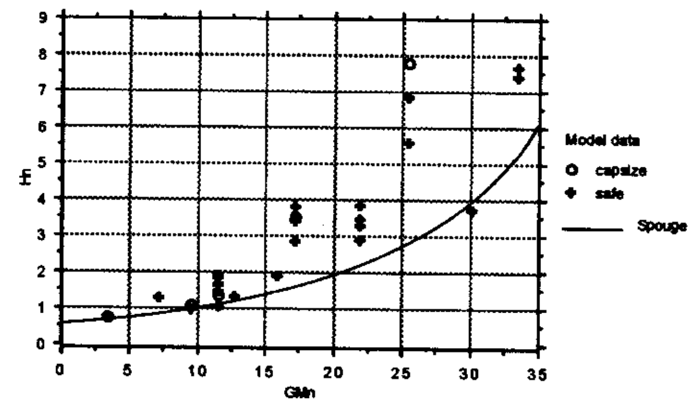


Figure 17, Non-dimensional waveheight against non-dimensional metacentric height, model with no casing and freeing ports closed.

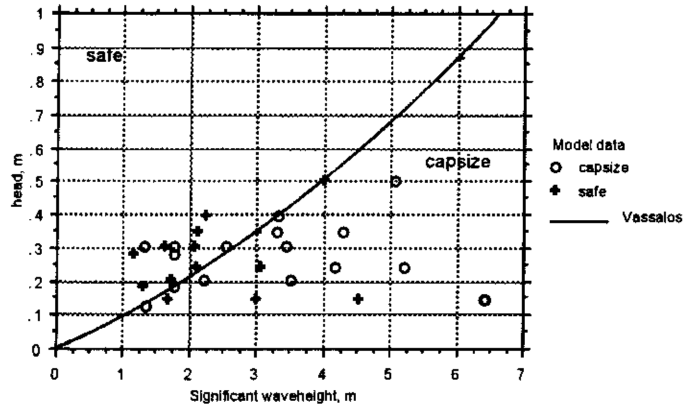


Figure 18, Comparison of limiting relationship between head and significant waveheight given by Vassalos et al and IMD data, model with casing and freeing ports closed

accurate for the fully enclosed cases with the centreline casing in place. The approaches used by Spouge [1994] and Vassalos [1996] are verified by the experimental data. However, both methods under predict the limiting waveheight for survivability when the centreline casing is removed. In Spouge's method, a multiplier for Hs, similar to that used for wave direction, would be a simple method of approaching the problem. This coefficient is not constant with GMn, as at low values of GMn there is very little influence of the casing. In these cases, the model tended to heel into the damage straight away, and so the limiting waveheight was unaffected by the casing. Based on the data in this paper the magnitude of this coefficient is given in Table 5. Care should be taken when using these values, since they are based on a small number of capsizes and only one hull form.

GMn	Hs multiplier
0	1.00
10	1.00
15	0.59
20	0.50
25	0.43

Table 5
Multiplier for Hs based on observed data when casing is removed

The method given by Vassalos recognizes the limitations of using GMf as a parameter and effectively uses maximum GZ instead. The problem for the hull described here is that the maximum GZ for the two methods is approximately equivalent, with and without the casing, but the observed survivability of the model is much improved when the casing is removed. The concept of using GZ should be effective in distinguishing large differences in GZ for the same GMf, such as would occur when comparing side casings with centreline casings. In the case of the model experiments described here, there are other factors which must also be considered.

The prediction of water on deck given by Hutchison et al [1996] is suprisingly good, considering that it is based on a stationary hull. It clearly gives a workable approximation for the amount of water that gets onto the deck and it has been expanded to include drainage effects. Again the predictions are best when the centreline casing is in place.

In addition to the results described in this paper, experiments were carried out to investigate the effect of peak period of the wave spectrum for a given significant waveheight. Other experiments studied the effect of bilge keels on survivability. Two combinations of residual freeboard and VCG were tested in coastal (JONSWAP) spectra and deep ocean (ITTC) spectra for the same nominal significant wave height. A comparison of the modal periods for the coastal spectra and the deep ocean spectra is given in Table 6.

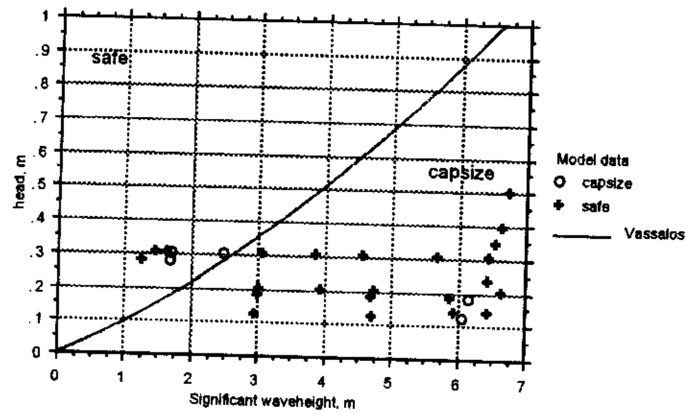


Figure 19, Comparison of limiting relationship between head and significant waveheight given by Vassalos et al and IMD data, model with no casing and freeing ports closed

Hs	Tm	Tm
	(coastal)	(deep ocean)
m	sec.	sec.
2.0	6.5	8.5
3.0	7.0	10.4
4.0	7.5	12.0
6.0	8.5	14.7
7.0	9.0	15.9

Table 6
Comparison of Model Periods,
Coastal Waves and Deep Ocean Waves

In each case, the effect of increasing the peak period improved the survivability of the ship. For the case with 15 degree range of positive GZ at 0.8 metres of residual freeboard the highest significant wave survived increased from 2 metres (coastal) to 4 metres (deep ocean). For the 15 degree range at 0.4 metres of residual freeboard, the highest significant waveheight survived increased from 3 metres to 7 metres. Waveheight alone is not the only parameter influencing survivability. Clearly wave steepness must also have an effect. This was recognized by Spouge in the definition of Hn.

Bilge keels also act to increase the survivability. A few experiments were carried out with the bilge keels removed. The significant waveheight survived was up to 1 metre higher when the bilge keels were present, compared to the same case without bilge keels. In some cases however, there was no increase. The benefit was seen most when the waveheights survived were high, and the roll angles were large. In cases where the roll angles were small, no increase in survivability was seen.

CONCLUSIONS

For the hull form tested, with a typical centre of gravity position of 7 metres above the keel and the resulting GMf value of 1.366 m, the SOLAS 90 regulations ensured that the ship survived waves with a significant height of 4 metres. Survivability of the ship was improved if the centreline casing was removed, and water was free to flow across the full width of the ship.

To meet the SOLAS 90 regulations with a realistic vertical centre of gravity, the hull form used for this study required a residual freeboard of 1.2 metres. If the residual freeboard was reduced and the vertical centre of gravity was also reduced to retain compliance with the SOLAS 90 regulations, then the waveheight that can be survived was also reduced. This implies that SOLAS 90 does not provide a uniform standard of safety (at least for the hull form used in this study) and residual freeboard is a parameter that should be included in any modifications to the regulations. Relaxing the SOLAS 90 regulations to a limitation of 0.015 m-radians, rather than the 15 degree range of positive GZ, reduces the survivability further and the waveheights that can be survived are between 1.5 and 2 metres.

The data in this paper, together with the data from the first phase of the research, showed that there are significant advantages to be gained by draining the deck of a damaged RO-RO ferry. Flow biased freeing ports can increase the survivability of the ship above the level of a ship with no freeing ports, provided that there is sufficient residual freeboard to allow effective drainage. The freeing ports prevent the volume of water on the car deck accumulating to the critical amount needed to induce a capsize.

The data given in this paper show good agreement with published methods of estimating the depth of water on the deck [Hutchison et al, 1996], the limiting GMf for a given waveheight and residual freeboard [Spouge, 1994] and limiting static head of water on the car deck [Vassalos et al, 1996], for the conditions when the centreline casing was in place. When the casing was removed, the published limitations tended to be pessimistic. This does add an extra factor of safety which may be an advantage when developing limiting criteria for survivability.

Whilst recognizing its limitations, GMf in its non-dimensional form, is a reasonable predictor of the survivability of damaged RO-RO ships, when combined with the ratio of residual freeboard to significant waveheight. However more work is required to define a consistent predictor which takes into account all the known factors affecting the behaviour of the ship, such as the width of the floodable deck in relation to the overall beam, the peak period of the wave spectrum and the presence of bilge keels on the ship. As it has been observed that the natural heave period in the damaged condition was practically the same as in the intact condition and was close to the peak of the wave spectrum, the focus of any future theoretical and experimental work should be directed towards exploring the relationship between heave, roll, relative motion at the damage opening, and deck flooding mechanism.

DISCLAIMER

The contents of this paper reflect the views of the authors and are not necessarily the official views or opinions of Transport Canada.

ACKNOWLEDGEMENTS

This research was funded by Transport Canada (Marine Safety Directorate), Transportation Development Centre, the Canadian Ferry Operators Association and the Institute for Marine Dynamics. The financial support and encouragment received from these organizations is gratefully acknowledged. We would also like to thank the staff of the Institute for Marine Dynamics and Polar Design Associates who worked on this project. The encouragement we received from Will Vickery, Canadian representative on the IMO Panel of experts and Bruce Hutchison, Chairman of the SNAME Ad Hoc Panel on RO-RO safetey was much appreciated.

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Discussion

Aage Damsgaard, Visitor, Danish Maritime Institute

We would like to thank the authors for this excellent and very systematic work. Their paper, which is easy to read, describes the results of the entire project clearly and with a good portion of details.

In the past 10 years DMI has built up a strong position in the field of model testing of damaged RO/RO ferries. Eleven models were built and tested to date. Some of them to support intensive government-funded research programs while others were commercial investigations for the approval in accordance with the Stockholm Agreement. Therefore, we understand the technical and practical problems, which the authors of this paper must have faced during all three phases of their project.

As regards the behavior of the damaged ferry and the understanding of the capsize process we would like to comment on two paragraphs from the paper.

Summarizing the results of Phase II, the authors say: "It was . . . observed that permanently open freeing ports were of no benefit to the survivability of the vessel, and in some cases they had a detrimental impact. The ability of the freeing ports to drain the deck is severely compromised by the water flooding the deck through the permanently open ports. Flapped ports, however, do not allow the ingress of water to the vehicle deck but do permit drainage. Their effect was to introduce a progressive increase in vessel survivability. . . ."

In 1996 we were in the process of constructing a model for an "approval test" in accordance with the "Stockholm Agreement." The model represented an open aft-deck ferry equipped with freeing ports with top-hinged gates. One of the problems we faced was how to model the dynamics and gravity of the model gates, which in a proper way would simulate the behavior of the gates in full-scale. We evaluated that leaving the freeing ports open would provide the most conservative approach, which is in good agreement with the conclusion of the authors.

However, our observations during testing of the above-mentioned model, and later of all other models equipped with open freeing ports, showed the excellent effectiveness of those devices which considerably improve draining of the vehicle deck. According to our observations, the flooding of water through the permanently open ports into the model reported by the authors is limited to short moments only, corresponding to the impacts of the highest waves of the irregular sea. The freeing port area of these ferries has typically been 0.08 × L and the minimum freeing port freeboard between 0.4 and 0.8 m.

The amount of water, which in this very short time passes the freeing port openings, is small compared with water which passes through the damage opening and, at frequent occasions, is thrown over a low side of the aft-ship. In some cases, during the following short period, the freeing ports might be slightly submerged at the increased angle of heel, but due to the fact that the head of the water accumulated on the vehicle deck is above the level of the surrounding area, the freeing ports contributed to the draining process. The models examined at DMI all represented SOLAS-90 ships and they survived all the required tests whereas they did not meet the Stockholm Agreement's requirements to freeing ports.

Later in the paper, the authors compare the behavior of their damaged model with and without a center casing on the vehicle deck, and they write: "The model without the (center) casing was very sensitive to the static heel of the model at the start of the experiment. A small change in static heel could change the wave height to cause capsize by the equivalent of several meters."

We fully agree with this formulation, as we do with the authors' description for the hydrodynamic mechanisms which are responsible for this behavior, which the authors bring in a later stage of the article. Based on the results of the research projects performed at DMI we have concluded that the small change in static heel can in some cases be equivalent to several meters of GM which is required to survive a given environmental condition. This is the reason why the test methods associated with the "Stockholm Agreement" demand at least 1 deg heel towards the damaged side of the model in the initial damaged condition. The same document would not accept the final heel of the model away from the damage after the end of each individual test away from the damage either.

A final comment on the analysis of the large amount of test data is that it would have been nice to see the data related to the Stockholm Agreement's specification of additional water elevation on the bulkhead deck as a function of residual freeboard and sea states.

This would have been particularly valuable since this specification is based on a fairly limited amount of data (additional reference) and has not to our knowledge been substantiated for other ship types and sizes.

Additional reference

DAMSGAARD, A., and SCHINDLER, M.S., "Model Tests for Determining Water Ingress and Accumulation," International Seminar on the Safety of Passenger RO/RO Vessels, RINA, London, June 1996.

Bruce L. Hutchison, Member

I would like to congratulate the authors on their continued excellent contributions to the technical literature regarding the safety of damaged vessels in waves. As noted in the paper, earlier similar work at IMD was contributed to the IMO Panel of Experts following the *Estonia* disaster, and those earlier test results also informed and inspired the analytical work of the SNAME Ad Hod RO/RO Safety Panel regarding the accumulation of water on deck.

The present work considers a hull form typical of North American RO/RO ferries and provides valuable data insight into the effects of casings and the benefits of freeing ports.

The experimental studies of the depth of water accumulation on deck are of special significance because the IMO Panel of Experts recommendations called for new stability regulations requiring RO/RO passenger vessels to meet SOLAS 90 residual stability criteria when burdened with water on deck, and the SNAME Ad Hoc RO/RO Safety Panel made similar recommendations.

Figures 6 through 11 of the present paper compare, for different freeing port and casing arrangements, experimental data for nondimensional depth of water on deck with the analytical curve determined by the SNAME Ad Hoc RO/RO Safety Panel. An often overlooked contribution of the SNAME Ad Hoc Panel was an analytical model for the depth of water on deck when the vessel is provided with flow biased freeing ports. Figures 20–23 herewith compare the predictions of the SNAME analytical model with the model tests. Only the "safe" points from the IMD tests are used for comparison. The agreement is fairly good, except perhaps at the very lowest values of f/H_s. In general the test data seem to indicate slightly better performance in terms of reduced depths of water on deck than the SNAME analytical model, which is therefore generally conservative.

The present paper makes it quite clear that casings increase the depth of water on deck and decrease survivability, and that flow biased freeing ports decrease the depth of water on deck

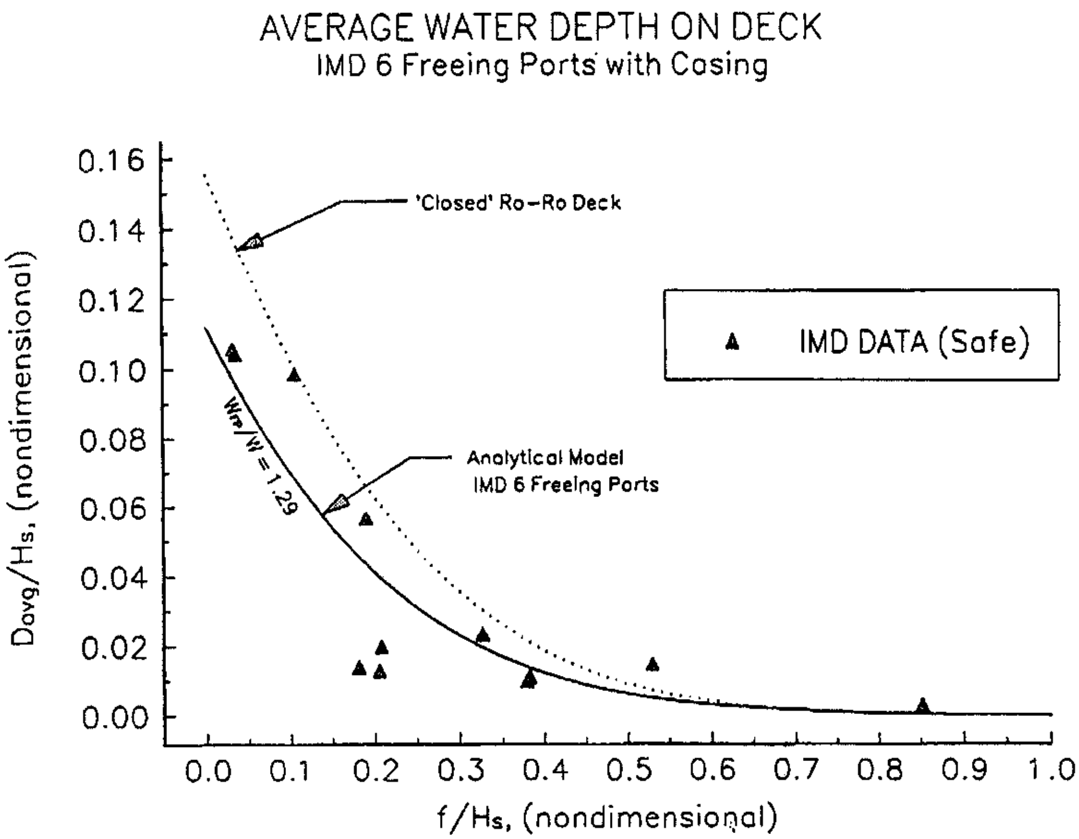

Fig. 20 SNAME analytical model compared with model test data with six freeing ports per side and a centerline casing.

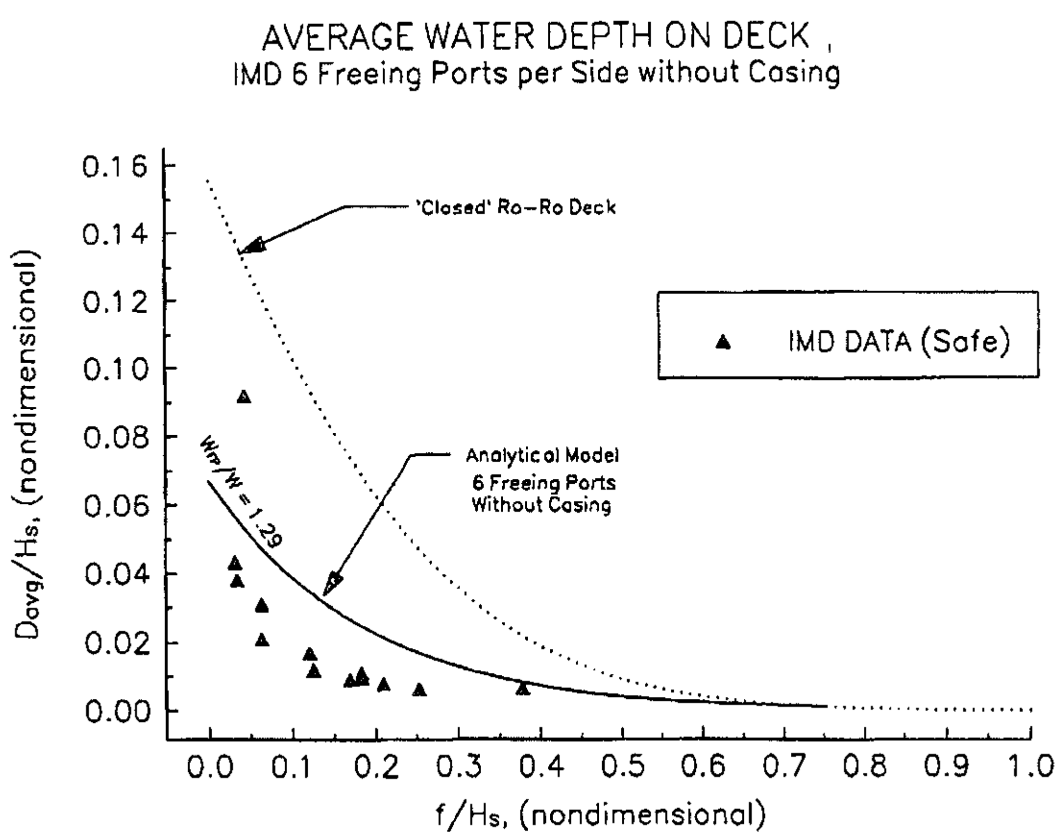

Fig. 21 SNAME analytical model compared with model test data with six freeing ports per side but no centerline casing.

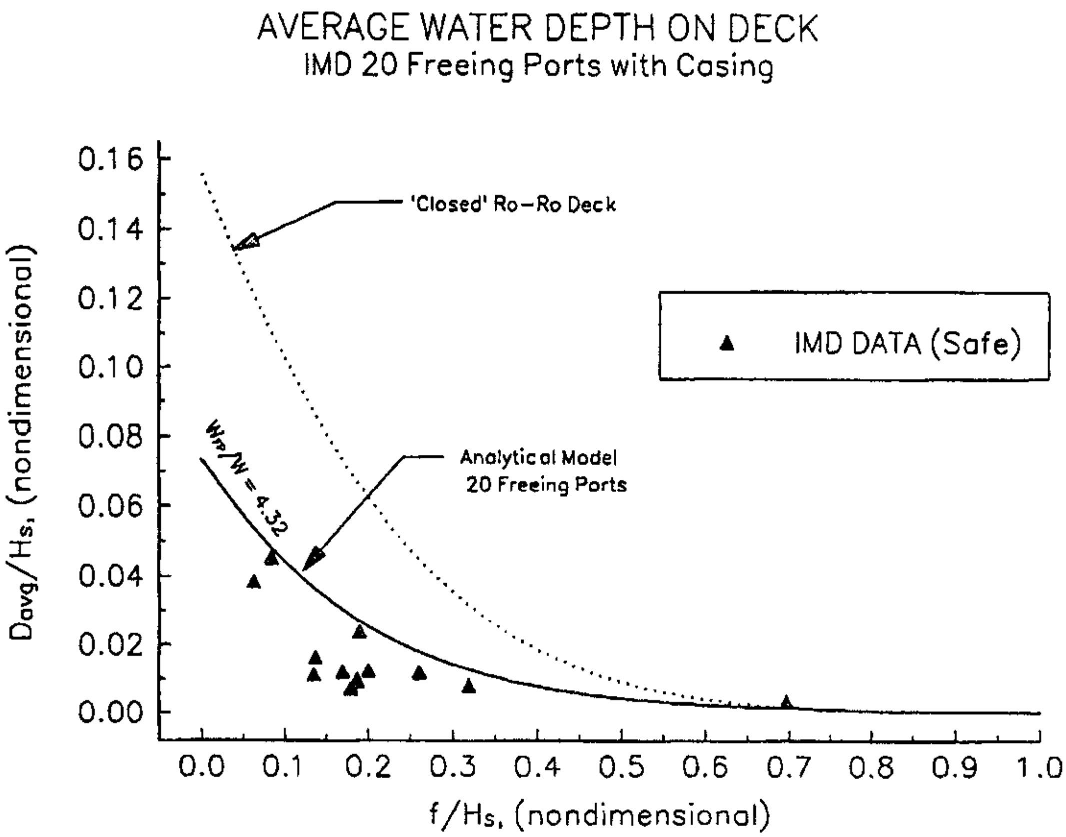

Fig. 22 SNAME analytical model compared with model test data with twenty freeing ports per side and a centerline casing.

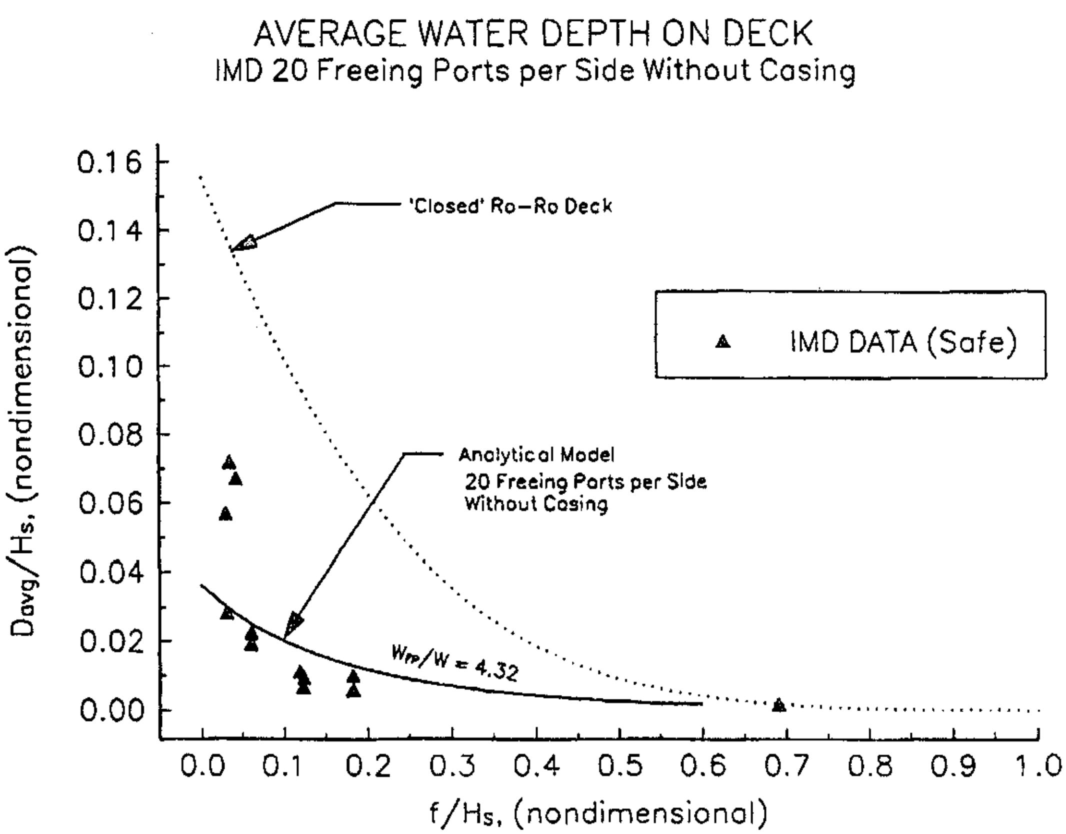

Fig. 23 SNAME analytical model compared with model test data with twenty freeing ports per side but no centerline casing.

and increase survivability. One of the recommendations of the SNAME Ad Hoc RO/RO Safety Panel was that new regulations provide appropriate credit for effective means of reducing the depth of water accumulation on deck, and the experiments reported here today certainly seem to establish flow biased freeing ports as one such effective means.

Finally, I would like to make some brief observations regarding the actual implementation of these concepts in the United States' newest large ocean and SOLAS certified RO/RO passenger vessel. The new Alaska Marine Highway System Ocean Class Vessel, now under construction by the Halter Marine Group, was designed to meet the damaged stability standards proposed by the IMO Panel of Experts, which called for satisfying the residual stability requirements of SOLAS 90, while burdened with a depth of water on deck corresponding to a conservative simplified version of the nondimensional line recommended by the SNAME Ad Hoc Panel. This high stability standard was achieved through the introduction of B/5 longitudinal bulkheads and cross flooding of wing tanks throughout the vessel.

The new Ocean Class Vessel has a centerline casing, but large water passes have been located at deck level throughout the casing to minimize the casing's effect of impeding flow to the opposite side of the vessel. The Ocean Class contract also originally called for flow based freeing ports but the shipyard was unable to identify a proven reliable and maintainable design and recommended deletion of that feature. If a suitable design is identified in the future, then freeing ports may be reintroduced as a retrofit.

I would like to conclude by encouraging the authors to continue their fine work and by also encouraging the marine profession to take note of some of these identified ways to enhance safety.

Robert F. Stanley, Member

Casings and vehicles, including cars, vans, and big trucks, intuitively would seem to have similar effects on blocking, restricting, and trapping water on the RO/RO deck. The different types of casings and the different types of vehicles would have a variety of details in affecting this free water. It would seem that distinctions based on casing arrangements should consider the vehicle load and its variability. Can the authors address this point, please?

H. Paul Cojeen, Member, and **Patrick Little,** Member

[The views expressed herein are those of the discussers and not necessarily those of the U.S. Coast Guard or the Department of Transportation.]

The authors are congratulated for their significant contribution towards the understanding of the physics of water accumulation on the deck of RO/RO ferries. To understand the significance of this work, it's important to look at how these model tests fit into the context of global maritime safety.

A new focus on RO/RO passenger ferry model testing began with the sinking of the *Herald of Free Enterprise* with the loss of 174 lives in 1987. A RO/RO passenger ferry, the *Herald of Free Enterprise* had left harbor with its bow doors open. Once clear of the breakwater, the waves caused water to enter the RO/RO deck, leading to a loss of stability and capsize. Following this sinking, there was a concerted effort at the International Maritime Organization (IMO) to prevent a similar occurrence in the future. The solution focused on two aspects of the casualty. Requirements for alarms and additional safety procedures were developed to ensure that these types of vessels would not leave port with the bow doors open. The second aspect involved the development of a damage stability standard for all passenger ships. Both aspects were included in a series of amendments to the International Convention on the Safety of Life at Sea (SOLAS), known collectively as SOLAS 90. The SOLAS damage stability standards were significantly upgraded by these amendments and were backed by an extensive set of studies sponsored by the United Kingdom.

After the amendments to SOLAS were adopted by IMO, many in the international maritime community felt the problem with water accumulation on the RO/RO deck had been solved. Fortunately, members of Transport Canada, led by Mr. Jim Archibold, had the foresight to realize that the understanding of the dynamics of capsize was limited. Transport Canada sponsored the model test program back in 1993 that ultimately resulted in the completion of this work.

The international maritime community was forced to rethink the effects of water on the RO/RO deck following the capsizing of the *Estonia* with the loss of over 900 lives in 1994. The work of SNAME in proactively addressing this problem is thoroughly discussed in the additional references at the end of this discussion, as well as the paper of Hutchison et al referenced in this paper. The following table lists the schedule and dates of SNAME's Ad Hoc Panel on RO/RO Ferry Safety, and illustrates how the Panel actively contributed to the RO/RO ferry safety discussions at IMO. The important point is that the first set of RO/RO ferry model tests had just been completed at the Institute for Marine Dynamics (IMD) at the time of the *Estonia* capsize. Throughout the ensuing debate at IMO, many of the participants tried to use the lack of model test data as a reason for not taking decisive action. The analytical work completed by the Ad Hoc Panel on RO/RO Ferry Safety, coupled with the physical model test data from IMD, prevented this stonewalling by providing a sound technical foundation for the decision-makers at IMO. Although the solution adopted by IMO was not perfect, the work completed at IMD was critical in achieving an incremental increase in damage stability standards.

Key Panel dates following loss of *Estonia* September 28, 1997

Date	Ad Hoc Panel Schedule	IMO Panel of Experts Schedule
10/21/94	Formation	
12/5/94		Formation
1/23/95	Position Paper	
1/30/95		Meeting
2/28/95	Position Paper	
3/9/95	Teleconference	
4/5/95		Stab Subgroup Meeting
4/5/95	Position Paper	
4/19/95		Preliminary Report
5/25/95	Teleconference	
9/1/95		Final Report & draft amendments
10/4/95	Position on Draft Amendments	
11/20/95		SOLAS Conference
2/28/96		Stockholm Agreement
10/2/96	Final Report Presented/Annual	

Additional references

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Authors' Closure

First, we would like to thank all the discussers for their valuable and insightful comments on our paper. We appreciate the time that they have taken to review our paper and prepare their discussions. We would also like to thank them for their kind words of encouragement.

Dr. Damsgaard provides some extra information on the flooding of the RO/RO deck through permanently open freeing ports. In reply to his questions over the effectiveness of permanently open freeing ports, we regret that we did not go into this in more detail in the formal presentation of this paper, since our objective was to focus on the third phase of the research, with the ship shaped model. The results of the experiments for the prismatic model with and without flaps on the freeing ports are given in detail in Molyneux et al (1997). This work showed that the effectiveness of the freeing ports varied with residual freeboard as well as the number of ports open. For a small number of freeing ports open (say A/L of 0.08, which was equivalent to the load line regulations), there was very little change from the fully enclosed case.

Increasing the area of the permanently open freeing ports above this level did not improve the survivability of the model. In a few cases there was a marginal improvement, but in many others the permanently open ports reduced the survivability significantly, when compared to the equivalent case with no freeing ports. This was in marked contrast to the flapped freeing ports, where there was a progressive improvement in the survivability as freeing port area was increased.

The permanently open freeing ports allowed the deck to flood more quickly than the equivalent condition with flapped ports, since water could enter the deck through the freeing ports as well as the damage opening. This heeled the model even further, reducing the freeboard, which accelerated the flooding process. Therefore, the larger the area of freeing port, the more water could flood the deck and so the easier it was to capsize the model. Flapped ports however, do not allow the ingress of water to the vehicle deck but do permit drainage. Their effect is to introduce a progressive benefit to the vessel in terms of survivability when freeing port area is increased.

In some cases, the smooth transition line between safe and capsize breaks down. This is because for a given value of GM after flooding, freeboard and freeing port area combine to prevent the ship capsizing. A small freeing port area at a high freeboard is much more effective at preventing a capsize than a large freeing port area at a low freeboard. In the case of the permanently open ports, the high freeboard reduces the possibility of flooding. With the flapped freeing ports, the external wave pressure at low freeboards tends to prevent the flaps from working effectively. All of these conclusions are based on the model with a centerline casing. For a model with no centerline casing, the flapped freeing ports are certainly more effective, and the permanently open ones are likely to be more effective. Also, for the prismatic model, all of the freeing ports are at the same distance from the centerline of the ship. On a ship shaped form, the flooding rate may be slightly lower, since the wave crest in a beam sea does not reach all the freeing ports at the same time.

In order to address Dr. Damsgaard's request for a comparison of our data with the depths of water on the deck for the Stockholm agreement, we have added an additional figure, Fig. 24, which shows the data from the IMD model experiments, for the ship shaped hull, with the centerline casing and all freeing ports closed. The line shown in the figure is the depth of water on deck, predicted by the Stockholm Agreement, and the points show the data from our experiments. We can see that the data fits the Stockholm agreement well for high residual freeboards, but less well at freeboards 0.4 meters and below.

We very much appreciate *Mr. Hutchison*'s valuable addition to our paper by adding a comparison between the measured data for different numbers of freeing ports and the analytical predictions. We agree with his comments on the comparisons between the results. The experiment data validate the SNAME method very well. We are also pleased that the results of the research are having a practical impact on new ship designs. It is encouraging to

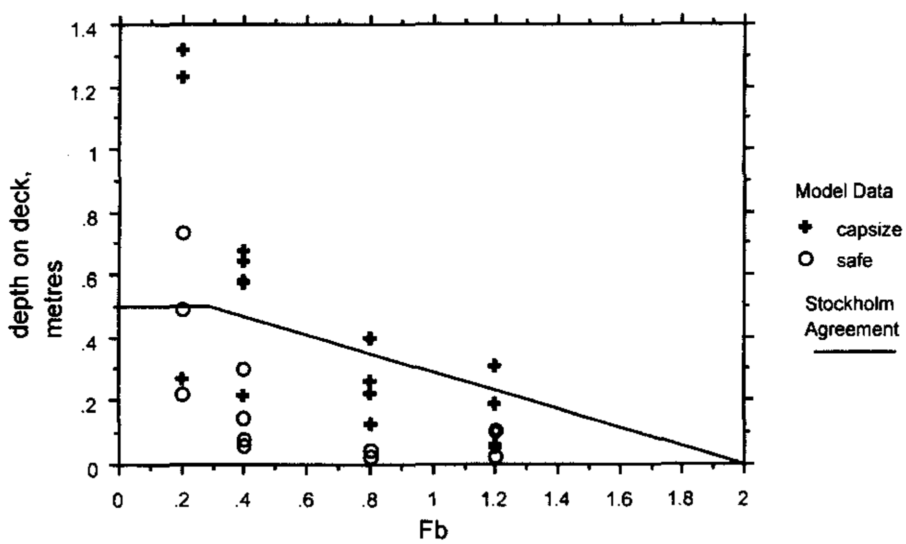

Fig. 24 Comparison of IMD data for water depth on deck with Stockholm Agreement, ship-shaped hull

see designers utilizing the results of the research, and going beyond the minimum required to satisfy regulatory requirements. Other work coming from Europe has confirmed that practical designs for new ships can be developed with sufficient stability to withstand the expected volumes of water on the car deck.

Mr. Stanley raises an interesting question with regard to the effect of cargo, in the form of cars and trucks on the RO/RO deck, and what this will do to the results. Most research in this field has assumed the simplified case of the car deck being empty. This is undoubtedly the simplest case to model, and there has been some argument that this is the worst case condition. Research work in Europe [Schindler & Velschou, 1994] has studied the effect of vehicles on deck on the ship's ability to withstand a capsize. The somewhat limited data indicated that the wave height to cause a capsize is not significantly different when cargo is on the deck, but the time taken for the ship to capsize is changed. However, from the point of view of understanding the hydrodynamics, it is desirable to include obstructions to the flow. We feel this is an area that would benefit from further research.

Mr. Cojeen and *Mr. Little* have kindly put the Transport Canada and IMD research in the perspective of the work carried out by the IMO and SNAME after the tragic sinking of the *Estonia*. The SNAME Ad Hoc Panel on RO/RO Safety helped to bring a different perspective to the work of the IMO, with a focus on vessels operating in sheltered water, where it is practical to use freeing ports to drain the deck, after flooding has occurred. We thank them for recognizing the contribution of Mr. Archibald, who instigated this work on behalf of Transport Canada, but who has since retired from that post.

Additional references

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