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Numerical predictions of wave-induced motions

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Numerical predictions of wave-induced motions

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Abstract

Wave-induced motions of MV Estonia have been predicted in irregular seas at different headings and speeds by applying the strip method and the linear superposition principle. The numerical results have been compared to experimental data from model tests carried out by SSPA. Conclusions are based on the present estimate of the sea state, speed and heading at the time of the accident. The numerical results indicate that heavy bottom slams or incidents of green water on foredeck were unlikely during the last voyage of MV Estonia. Spray and smaller amounts of water came certainly to the deck and the vessel obtained flare impacts. The rigid body vertical accelerations of the vessel were before the accident near the passenger comfort limit which means that 10 to 20 % of the passengers may have been seasick (vomiting).

CONTENTS

1 INTRODUCTION

Wave-induced motions of MV Estonia have been predicted in irregular seas by applying the linear superposition principle. The superposition principle assumes that the ship responses in irregular seas may be determined by summing the ship responses to a large number of regular sinusoidal waves making up the irregular seaway. Response amplitude operators, or ship responses (heave, roll, pitch, vertical accelerations etc) in regular waves with unit amplitude have been determined by the SCORES-program (Raff, 1972) based on the strip theory.

In the strip theory, the hydrodynamic forces are first determined on two-dimensional ship sections and the total forces are obtained by integrating the sectional forces over the ship length. The method has been validated in numerous comparisons with model and full scale results. Numerical predictions have been made for different ship speeds, headings and wave periods to study their effect on the motions. The results are discussed from the point-of-view of passenger comfort, deck wetness and bottom slamming. The wave impact forces on the bow visor of MV Estonia have been determined by a time domain simulation method and are reported in the report VTT VALC106.

2 CONDITIONS

2.1 Sea states

Numerical predictions of wave-induced motions in long-crested irregular waves were made in four sea states using both the JONSWAP and the ISSC wave spectrum formula given in Appendix 4. The wave spectrum shows the wave energy distribution versus frequency. In the JONSWAP spectrum, the wave energy is concentrated over a narrower frequency band than in the ISSC spectrum. The significant wave height, H_S, was in all cases 4.0 m and the modal wave periods, T_0, or the periods corresponding to the spectrum peak were 7.0, 7.8, 8.5 and 9.5 s.

The present estimate of the sea state during the MV Estonia accident is 4 m significant height and 8 s modal period. Estimates of the modal period and the significant wave height were obtained from the Finnish, Swedish and German institutes of marine research, MTL, SMHI and DW, respectively. Table 2.1 gives their predictions determined by numerical models at the accident site at 02 Finnish time 28 September 1994, i.e. about one hour after the accident.

Table 2.1 Estimates of wave conditions at 02 28.9.1994 at the site of the accident.

Institute	H_S [m]	T_0 [s]	T_1 [s]	Mean dir. [deg.]
MTL, Finland	4.4	8.2		260
SMHI, Sweden	4.2	8.5	7.2	218 - 233
DW, Germany	4.3	8.3	7.0	218

In the table, T_1 is the mean wave period. SMHI gives both the wave direction corresponding to the peak frequency (first) and the direction of the shortest waves which is the same as the wind direction. MTL and SMHI have also made estimates of the wave conditions before and after the accident. A summary of these estimates is in Table 2.2.

Table 2.2 A summary of wave conditions before and after the accident.

Institute	Position	Time	H_S [m]	T_O [s]	Mean dir.
MTL	59 25, 22 35	27.9, 23.00	3	7	260
SMHI	59 27, 22 50	27.9, 23.00	2.5	6.7	250 - 185
MTL	Accident site	28.9, 01.00	4.0	7.8	260
MTL	Accident site	28.9, 01.30	4.2	8.0	260
MTL	Accident site	28.9, 08.00	5.0	8.7	270
SMHI	Accident site	28.9, 08.00	5.1	9.5	236 - 272

The estimates of the significant wave height by the different institutes agree remarkably well. The Finnish MTL has assumed in predicting the mean wave direction that the wind shift to south on the 27.9 did not last long enough to change the direction of the major wave components. This conclusion is based on their wave observations on the northern part of the Baltic. The experience of MTL is that the mean error in the predicted significant wave height is about 0.5 m, in the wave period about one second and in the wave direction about 10 degrees.

All the wave estimates are for deep water. Numerical predictions by MTL show that the significant wave height may increase significantly in shallow water due to wave focusing (Kahma et al. 1995). If waves with significant wave height 4 m and modal period 8 s enter an area were the waterdepth is around 20 m, the significant wave height may increase to 6 m while the period remains approximately constant. At the same time, statistics of the waves change so that a large part of the waves will have heights near the significant height. However, the maximum wave height will not increase respectively and remains approximately on the same level as with the original 4 m significant height.

The Finnish Lion, about 25 nautical miles west from the MV Estonia accident site, is an example of a shallow area were the significant wave height will increse in suitable weather conditions. The Finnish National Board of Navigation has analysed soundings in a sector reaching over 10 nautical miles east from the wreck of MV Estonia. The area covers the probable route of MV Estonia before the accident. The minimum waterdepth measured was 52 m which indicates that there cannot be sites shallower than about 40 m between the sounding lines. Thus, shallow waterdepth did not have an effect on the wave formation when the lockings of the bow visor of MV Estonia were broken. It may be assumed that the significant wave height was about 4 m and the modal period about 8 s at the time of the accident.

The following table shows a summary of the wave spectra in the numerical predictions and gives the relevant parameters used in forming the spectra.

Table 2.3 Summary of wave spectra.

Modal period T_O [s]	JONSWAP Wind speed [m/s]	ISSC Mean period T_1 [s]
7.0	38.1	5.40
7.8	22.2	6.01
8.5	14.4	6.55
9.5	8.3	7.33

The mean period of an ISSC spectrum is linked to the modal period by $T_1 = 0.771T_0$. The predictions at different wave periods show the effect of wave period on the wave-induced motions of MV Estonia. According to the linear superposition principle motions such as heave, pitch, vertical acceleration and vertical relative motion are directly proportional to the significant wave height at a fixed value of wave period. Thus, the predicted significant motion amplitudes, which are for H_s = 4.0 m, may easily be scaled for other values of significant wave height.

In addition to the predictions in long-crested seas, wave-induced motions were also computed in short-crested seas with a modal period of 7.8 s. The cosine-square spreading function was used.

Short-term wave statistics may be determined by applying the Rayleigh distribution in the same way as statistics of ship responses in a seaway. The probabilities of individual wave heights and ship response amplitudes exceeding certain levels are discussed in Section 3.

2.2 Speeds and headings

The numerical predictions were made for the vessel speeds of 7, 12, 15 and 17 knots. The present estimate of the forward speed of MV Estonia just before the accident is about 15 knots which is based on witness accounts. The wave-induced motions were determined at the headings to waves of 180^o (head seas), 150^o and 120^o. MV Estonia encountered the waves probably slightly to the port from direct head seas though there are estimates which indicate that the heading may have been closer to beam seas.

2.3 Definition of the vessel hull form

Figure 2.1 shows the body plan and lines of MV Estonia. In the numerical predictions, the vessel hull form was defined by 11 and 21 sections. The number of sections had an insignificant effect on the wave-induced motions. Lewis-forms were used in defining the section shapes. Table 2.4 presents a summary of the main particulars of MV Estonia.

Table 2.4 Main particulars of MV Estonia.

	Symbol	Dimension	Value
Length over all	L_{oa}	m	155.4
Waterline length	L_{wl}	m	144.8
Length betw. perp.	L_{pp}	m	137.4
Beam mld, A deck	B	m	24.2
Waterline beam	B_{wl}	m	23.6
Draught at aft. perp.	T_a	m	5.75
Draught at forw. perp.	T_f	m	5.25
Trim, positive by stern		m	0.50
Displacement	∇	m^3	12 243
Longitudinal CG from aft. perp.	LCG	m	63.7
Vertical CG	KG	m	10.50
Transverse metacentric height	GM_T	m	1.28
Roll radius of gyration	k_{xx}	m	8.96
Pitch radius of gyration	k_{yy}	m	36.2
Depth to stemhead	D	m	10.0

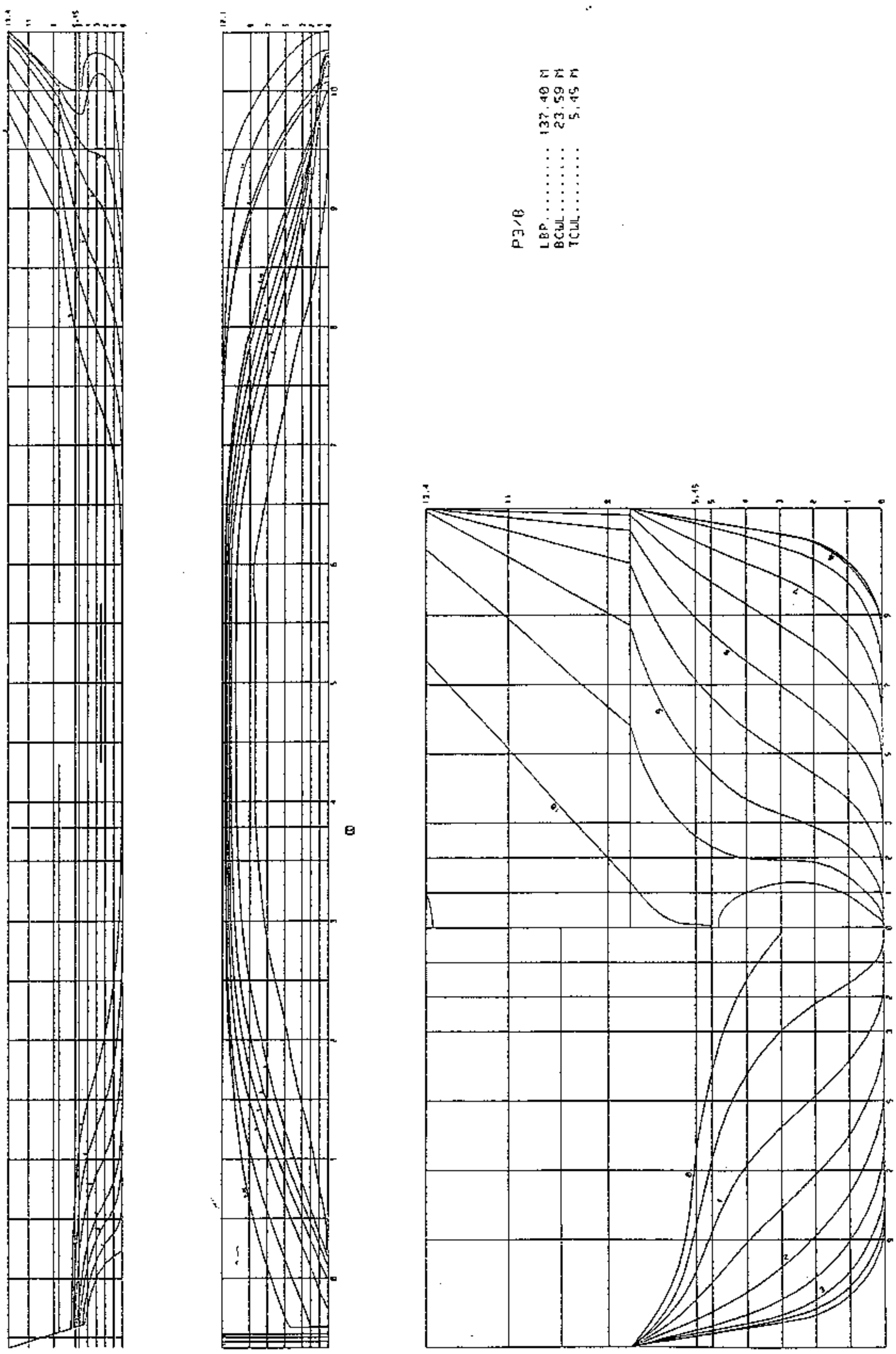

Fig. 2.1 Body and lines plan of MV Estonia.

The numerical predictions are for a vessel mean draught of 5.5 m and an aft trim of 0.5 m, i.e. the draft at the forward perpendicular was 5.25 m and at AP 5.75 m. The displacement of 12 365 tons at a water density of 1.01 tons/m^3 and the longitudinal centre of gravity were taken from hydrostatic calculations by the NAPA-program. After the predictions had been made, the load condition of MV Estonia during the accident trip was estimated as 12050 tons and 0.435 aft trim. The fore and aft draughts are respectively 5.172 m and 5.607 m. The difference between the actual and the assumed loading condition is so small that it has hardly any effect on the wave-induced motions.

Standard values of $0.25L_{wl}$ and $0.38B_{wl}$ were used for the longitudinal and transverse radius of gyration, respectively. The transverse metacentric height was set to 1.3 m while the actual value was 1.17m. All but one of the stations for which predictions were made are on the centre line. The roll motion and the transverse metacentric height have no effect on the results on the centre line. The roll motion of MV Estonia was small since the damping fins were out. However, the transverse metacentric height had an effect on the list of the vessel at later stages of the accident. Also the actual location of the centre of gravity differed a little from the assumed value. The final estimated values are: LCG = 63.85 m and KG = 10.62 m. A summary of the input data is given in Appendix 3.

2.4 Predicted responses

In addition to heave, pitch and roll, vertical acceleration has been determined at six stations: the stemhead on the Centre Line (CL), bow visor on the side, construction frame 8.5 (CL), bridge (CL), midship (CL) and aftship (CL). The vertical motion relative to wave surface has been predicted at the three foremost stations. The longitudinal and transverse coordinates of the six stations measured from the after perpendicular and the centre line, respectively, are given in the following table.

Table 2.5 Stations.

Station	Dist. from AP [m]	Dist. from CL [m]
Stemhead # 10 2/3	146.50	0
Bow visor # 10 1/4	140.84	6.08
# 8 1/2	116.79	0
Bridge	111.40	0
Midship	68.70	0
Aftship	10.00	0

Since only motions in the vertical plane were considered, the results apply on any deck at the specific station.

3 RESULTS

The results are given as significant amplitudes in tabular form in Appendix 1. The most important results are also shown in graphical form in Appendix 2.

The significant response amplitude, or the mean of the one third highest response amplitudes is given by:

Significant amplitude = 2(Root Mean Square value) = 2RMS while the mean of the one tenth of highest amplitudes is given by:

$$x_{1/10} = 2.55 \text{ RMS}$$

The significant wave height, respectively, is given by 2(significant amplitude) = 4RMS where RMS is the Root Mean Square value of the wave time history.

The probabilities of the response amplitude exceeding a specific value, z, in a short, a few hours long time interval may be estimated by the Rayleigh distribution:

$$P[x_o > z] = e^{-(\frac{z^2}{2RMS^2})}$$

For instance, the following exceedance probabilities are obtained.

Table 3.1 Exceedance probabilities according to the Rayleigh distribution.

Response amplitude	Probability of exceedance
RMS	0.6065
2RMS	0.135
2.55RMS	0.0387
4RMS	0.0003355

The table shows that there is a 13.5 % probability that the response amplitude will be larger than the significant amplitude. Thus, approximately one wave in ten waves is higher than the significant wave height. Approximately one response amplitude of 25 oscillations is larger than the mean of the one tenth highest amplitudes. As a rule of thumb is often used that the maximum amplitude during a few hours is twice the significant amplitude, or 4RMS which is exceeded approximately at a probability of 1/3000. The wave encounter period of MV Estonia during the accident night was 3.5 to 4.5 seconds so that MV Estonia encountered 3000 waves in 3 to 4 hours.

In every wave train including 3 000 individual waves with a significant height of 4 m, there is a good chance that one of the waves is higher than 8 m. At a probability of 1/3 000 the first or any other of the waves may be higher than 8 m. There are an infinite number of different wave trains which have the same significant height, spectrum and wave statistics.

The most probable extreme response amplitude in N oscillations, or wave encounters may be estimated by the formula:

$$X = RMS\sqrt{2\ln N}$$

The previous formula gives for instance the following results.

Table 3.2 Most probable extreme values.

Number of oscillations, N	Extreme value
100	3.035RMS
1 000	3.717RMS
3 000	4.002RMS
10 000	4.292RMS

The most probable extreme value in 3 000 oscillations, about 4RMS, agrees of course well with the probability of an individual response amplitude exceeding the value 4RMS. The probability of the extreme value exceeding the most probable value is quite high: 63.2 %. The most probable extreme value does not increase quickly with N, the number of oscillations, or wave encounters due to the logarithmic dependence on N. The statistics in Tables 3.1 and 3.2 explain quite well why 4RMS is often used as a rule of thumb for the maximum individual response or wave amplitude.

The results in the Appendices show in general that the modal wave period and the heading to waves have a stronger effect on the responses than the forward speed of the vessel within the wave periods and headings considered here. The significant motion amplitudes increase with increasing wave period and when the heading to waves changes from head seas towards beam seas. Respectively, the responses are larger in short-crested seas than in long-crested seas with the exception of the heading 120°. It seems thus that during the accident night in nearly head seas MV Estonia was more or less running through the waves. The situation was different if MV Estonia had a heading closer to beam seas. The results stress the importance of accurate estimates for the wave period, wave direction and the course of the vessel. The waves may have been quite confused and short-crested due to the wind shift during the day.

3.1 Comparison with numerical predictions and model tests by the SSPA

The significant amplitudes of the responses predicted by SSPA with a similar method as VTT agree very well with the Finnish results. The significant amplitudes at the highest value of modal wave period T_0 = 9.5 s are a little higher in the predictions by VTT when the results using the JONSWAP wave spectrum are compared to the VTT and SSPA results obtained by using the ISSC spectrum formula. The JONSWAP spectrum is narrower than the ISSC spectrum and close to resonance the vessel responses are larger when the energy in the waves is concentrated over a narrow band of frequencies near the resonance frequency. At the three shorter wave periods, the spectrum shape has little effect on the responses.

The following two tables compare the significant motion amplitudes predicted by VTT to experimental results obtained by SSPA in head and bow seas at 15 kn speed. The results by SSPA are from the APPENDIX to the SSPA Report 7524, dated 1995-11-05. The significant motion amplitudes in tables 3.3 and 3.4 have been divided by the significant wave amplitude, $H_s/2$, to make it possible to compare tests at different values of significant wave height. The nominal value of modal wave period has been 8 s. For this particular value of modal period, the results of VTT have been determined by linear interpolation between the results for T_o = 7.8 and 8.5 s.

Table 3.3 A comparison of numerical and experimental motions in head seas with T_o = 8 s at 15 kn.

	SSPA towing tank		SSPA MDL	VTT strip theory
Sign. ampl./($H_s/2$)	H_s = 4 m	H_s = 5.5 m	H_s = 4 m	
Heave LCG	0.213	0.219	0.200	0.185
Pitch	0.546	0.609	0.410	0.484
Rel. motion #10	1,560	1.646	1.409	1.457
Rel. velocity #10	1.887	1.899	1.776	2.040
Vert. acc. visor	0.881	0.986	0.740	0.830
Vert. acc. L/2	0.306	0.325	0.260	0.238

Table 3.4 A comparison of numerical and experimental motions in bow seas with $T_o = 8$ s at 15 kn.

	SSPA MDL		VTT strip theory
Sign. ampl./(H_s/2)	$H_s = 4.3$ m	$H_s = 5.5$ m	
Heave LCG	0.310	0.310	0.238
Pitch	0.660	0.658	0.619
Rel. motion #10	1.819	1.851	1.645
Rel. velocity #10	2.002	2.038	2.096
Vert. acc. visor	1.111	1.137	1.059
Vert. acc. L/2	0.355	0.369	0.284

The numerical results show in general good correlation with the experimental results. In bow seas, the predictions by the strip theory are slightly below the test data with the exception of the relative vertical velocity which is about 5 % higher than in the tests. In particular, heave and the vertical acceleration at midship are underpredicted by the strip theory also in head seas where the other numerical results excluding the relative vertical velocity fall between the experiments in the towing tank and the Maritime Dynamics Laboratory (MDL).

The experimental results at different values of significant wave height confirm also in this case the validity of the linear superposition principle, i.e. the significant response amplitudes at the same wave period are linear with regard to the significant wave height.

3.2 Vertical accelerations

At the bow visor of MV Estonia, the significant amplitude of vertical acceleration was 2 - 2.5 m/s^2 and the largest amplitudes were about 0.4g just before the accident assuming that the heading to waves of the vessel was about 150 degrees, speed 15 knots, significant wave height about 4 m and the modal wave period 8 s. This acceleration level is roughly half of the level when masters of cargo vessels start to consider a manoeuvre to reduce the accelerations and about two thirds of the corresponding limit on Ro-Ro cargo vessels including the cross-channel car-ferry ms Roi Baudoin from the sixties (Karppinen, 1987).

Figure 3.1 compares the significant vertical accelerations on board MV Estonia to vertical accelerations masured on board some other vessels and to the ISO 2631/3 (1985) motion sickness standard which is based on the limiting Motion Sickness Incidence (MSI) of 10 % amongst the passengers. The corresponding limiting significant vertical acceleration level is 1.0 m/s^2. On the bridge and in the forward cabins of MV Estonia, the significant vertical acceleration was about 1.5 m/s^2 which is somewhat high from the point-of-view of passenger comfort. About 20 % of the passengers in the foremost cabins may have felt seasick. On the other hand, people tolerate higher vertical accelerations without getting seasick when they are laying in bed than when standing or sitting.

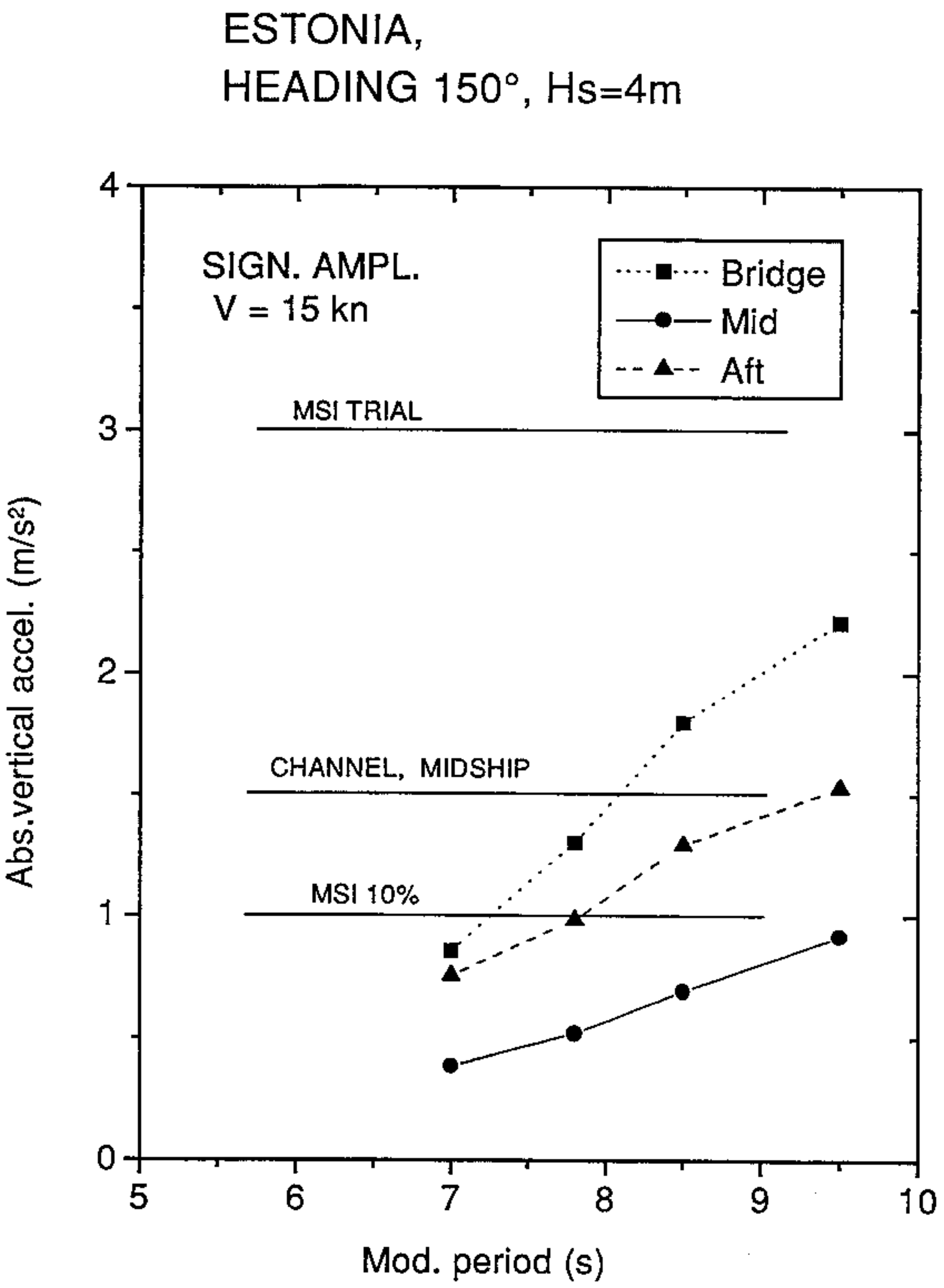

Fig. 3.1 Vertical accelerations on board MV Estonia compared to some other results.

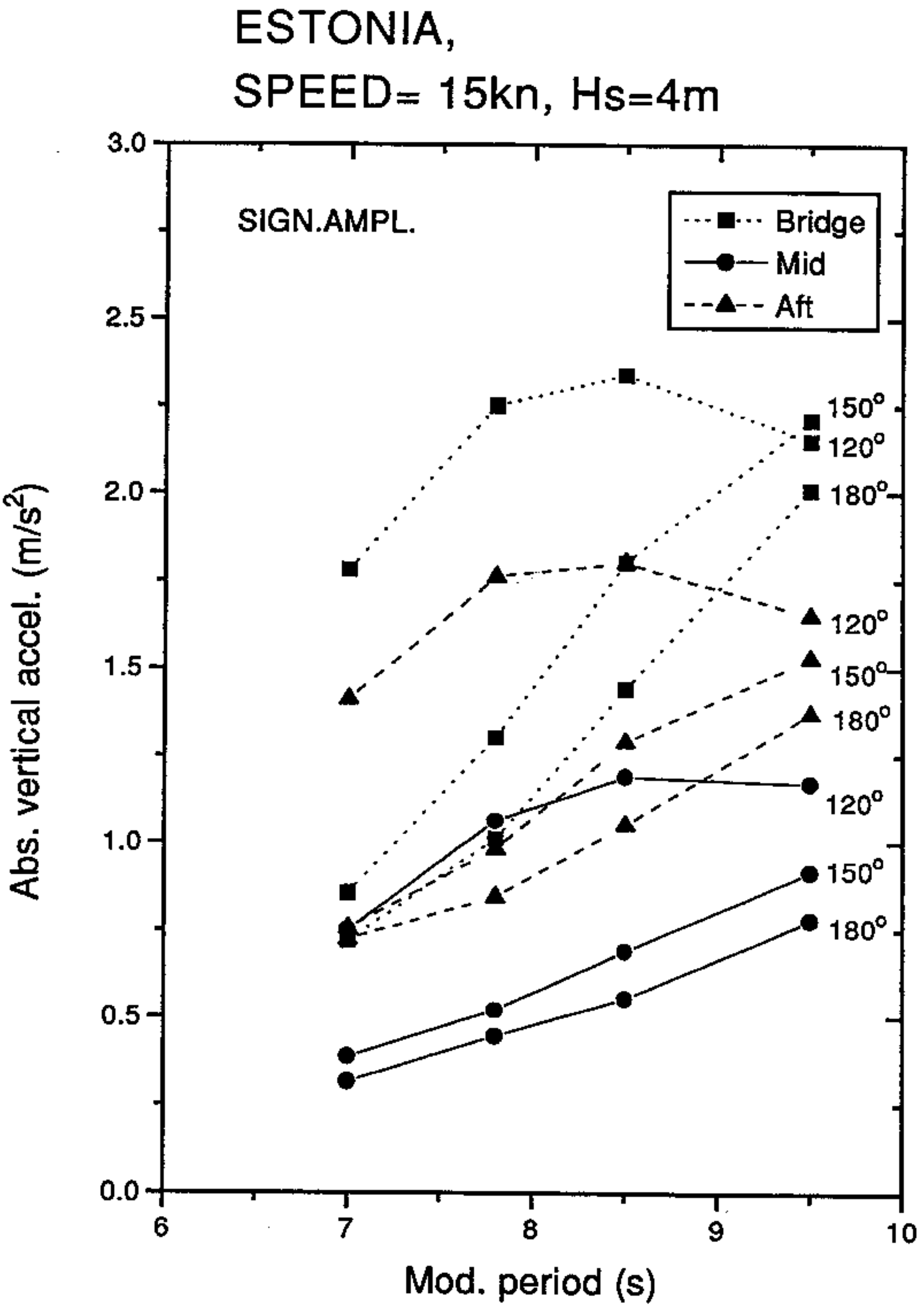

Fig. 3.2 The effect of heading on the vertical acceleration. JONSWAP spectrum.

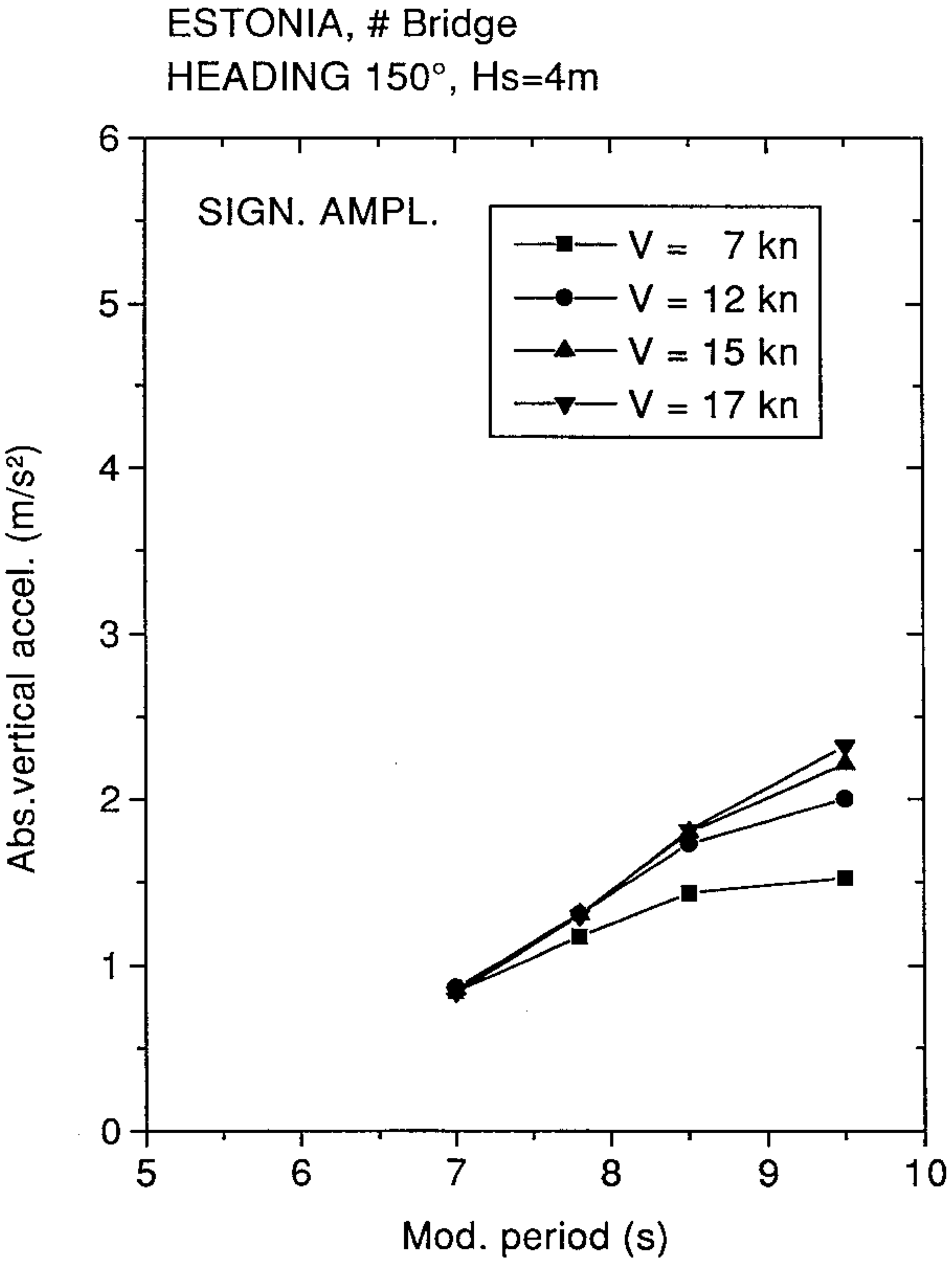

Fig. 3.3 The effect of speed on the vertical acceleration on the bridge in bow seas.

At midship, the acceleration level of about 0.7 m/s^2 significant amplitude was just perceptible and not many people should have felt symptoms of seasickness. At aftship in the cafeteria and restaurant spaces, the significant vertical acceleration was near the ISO 2631/3 limit of 1.0 m/s^2 when about 10 % of standing or sitting people unused to ship motion are seasick (vomiting) after an exposure of two hours. Thus, with regard to the passenger comfort the wave-induced motions of MV Estonia on the accident night after midnight Finnish time were near the comfort limit which is significantly below survival conditions. Before midnight, when the significant wave height was under 3 m, the vertical accelerations on board MV Estonia were at least 25 % lower than just before the accident.

Lawther and Griffin (1986) report on Channel crossings when the significant vertical acceleration at the centre of the ship has been 1.1 - 1.5 m/s^2 and 25 - 35 % of the passengers on board have been seasick (vomiting). Significant vertical acceleration amplitudes of 1.2 - 2.2 m/s^2 have been measured in the foreship on board ms Silja Symphony during a scheduled voyage from Helsinki to Stockholm in heavy bow seas (VTT Report VALC138 dated 12.9.1995). Ikeda and Shirazawa (1994) have observed MSI ratios of 20 to 40 % on board Japanese passenger/car ferries when the significant vertical acceleration has been 2 to 4 m/s^2.

During a seasickness trial on board a fast Norwegian passenger catamaran (Karppinen et al. 1993), the significant vertical acceleration amplitude in the passenger compartment was 3 m/s^2. Two trial runs were conducted with about 100 passengers on board on each trial. On both runs, about 20 % of the passengers were seasick (vomiting) after half an hour of exposure. The frequency of vertical motion during the tests was about 0.4 Hz which is higher than on board MV Estonia. People tolerate larger vertical accelerations without getting seasick at higher frequencies.

If MV Estonia was running in near head seas as assumed, a change of heading or reduction of forward speed would have had only a moderate effect on the vertical acceleration level (Figures 3.2 and 3.3). With a change of heading from bow seas towards beam seas, the accelerations would have increased while by dropping the speed to 7 knots the vertical acceleration level on the bridge would have decreased from about 1.5 m/s^2 to 1.3 m/s^2. In following seas, the vertical accelerations would of course have been significantly lower.

3.3 Vertical relative motion at bow

The vertical relative motion is defined as the vertical ship motion relative to the vertical motion of the wave surface. The relative motion is obtained as the difference between the absolute rigid body vertical motion of the ship and the vertical motion of the undisturbed wave. If the amplitude of the vertical relative motion exceedes the freeboard at bow, there will be green water on deck.

The significant amplitude of the vertical relative motion at the bow visor of MV Estonia was according to the predictions 3 - 4 m. The freeboard to the car deck was about 2.0 m, to the upper edge of the ramp about 7.0 m and to the stemhead about 9.5 m (Figure 3.4). The stationary bow wave may be assumed to reduce these freeboards by 1 m though it is not clear whether the bow wave height should be taken into account.

The predicted vertical relative motion does not include the effect of dynamic swell-up which is difficult to estimate. The dynamic swell-up may increase the vertical relative motion by 30 to 50 %. In full scale, the dynamic swell-up gives rise to spray which by the action of wind comes to the foredeck. It is not well known what is the effect of dynamic swell-up on the green water on deck.

The following table gives probabilities of the water level exceeding certain heights at the bow. The exceeedance probabilities are given for both 3 m and 4m significant amplitude of relative motion. The freeboards include the effect of an one metre high bow wave.

Table 3.3 Probabilities of relative motion at bow exceeding certain levels.

Level and freeboard [m]	Exceedance prob. $r_S = 3.0$ m	Exceedance prob. $r_S = 4.0$ m
Car deck, FB = 1.0	0.801	0.882
Ramp, FB = 3.0	0.135	0.325
Ramp, FB = 4.5	0.0111	0.0796
Ramp upper edge, FB = 6.0	0.000335	0.0111
Stem, FB = 7.5	$3.7\ 10^{-6}$	0.000884
Stemhead, FB = 8.5		0.000120

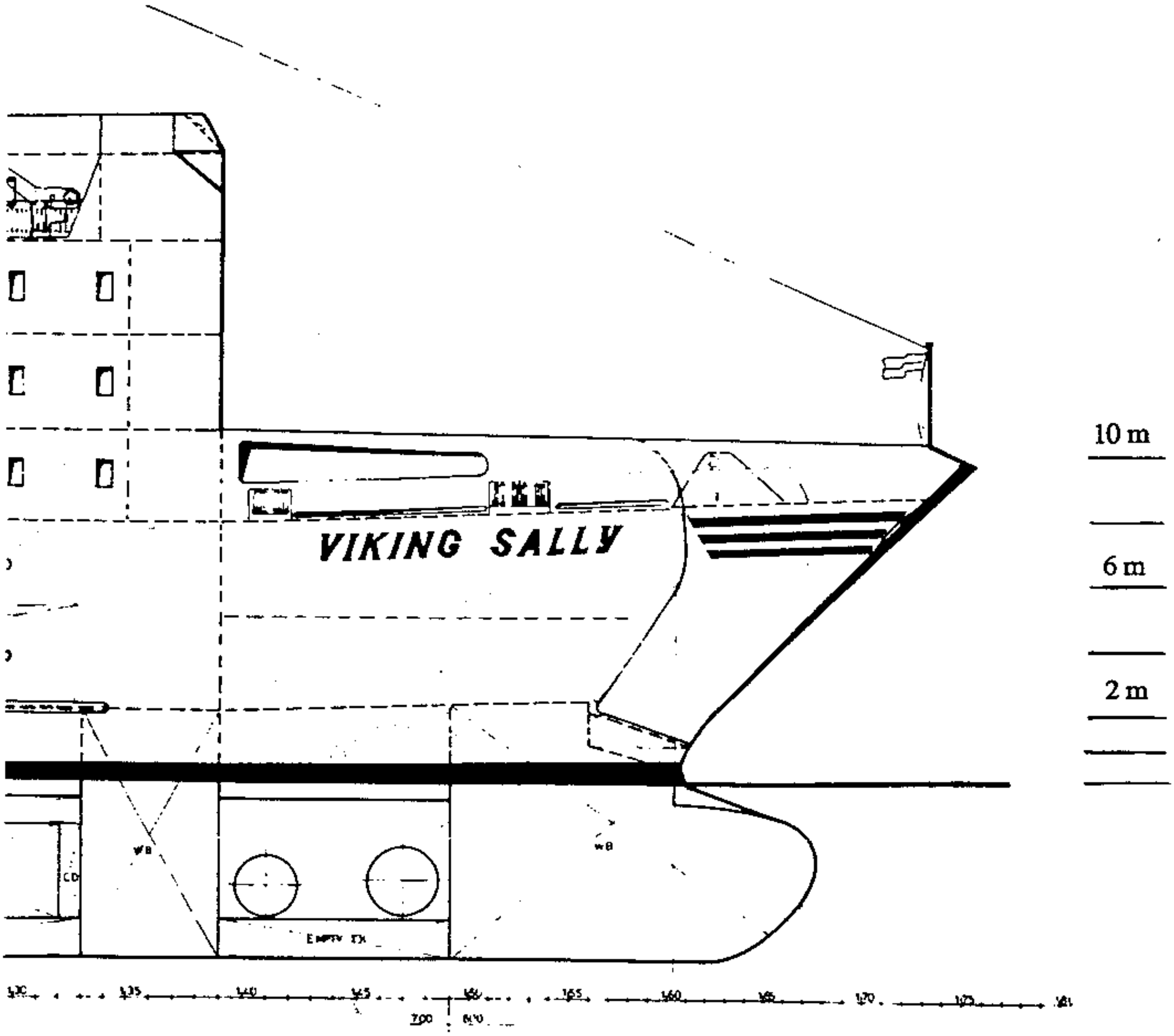

Fig. 3.4 Bow of MV Estonia.

The water level at bow rose in practice nearly at every wave encounter above the car deck level. One wave in hundred, or about once in five minutes the wave surface reached the level of the upper edge of the ramp opening from where there was still 2.5 m freeboard to the stemhead. With these waves, spray and some water came to the foredeck. The probability of relative motion exceeding the stemhead was about 1/10 000. Thus, it is possible that more water came to the foredeck a few times during the accident voyage.

The probability of ship bottom coming out of water at the station 8 1/2 was about 1/1 000 and the probability of a bottom slam about 1/2 000 using Ochi's formula for the critical re-entry velocity. Thus, MV Estonia may have obtained a bottom slam during the accident voyage. In general, the critical slamming probability when cargo ships reduce speed or change course seems to be over 0.01 (Karppinen & Aitta, 1986).

The probability of a flare impact during the accident voyage must have been significantly higher than the bottom slamming probability. The knuckle at the bow is about 2 m above the waterline and there the deadrise angles of the sections are small, about 20 degrees. If Ochis's critical re-entry velocity is applied with a freeboard of 2 m, a probability of about 0.1 is obtained for flare impacts. However, Ochi's formula gives in this case probably too low values for the re-entry velocity. The impact probability decreases quickly with increasing critical re-entry velocity.

3.4 Vertical relative velocity

The vertical relative velocity seems to be not so sensitive to changes in the modal wave period as the other responses. The significant amplitude at the bow visor of MV Estonia has been 4 to 4.5 m/s. The most probable extreme amplitude in 1 000 wave encounters has been about 8 m/s and in 10 000 near 10 m/s.

According to the drop tests by Yamamoto et al (1985) the maximum pressure on the flare part may be expressed as $k \ 0.5 \ \rho \ V^2$ where V is the vertical velocity and k a constant the value of which depends on the flare angle. MV Estonia had at the bow visor a flare angle of about 45^o for which roughly $k = 2$. This value with $V = 9$ m/s gives a maximum pressure of 8 ton/m^2 which is more than the design pressure but much less than the 50 ton/m^2 which has been reported in some cases. These very high pressures are local and may be explained by high, local water particle velocities in waves breaking nearly in the normal direction on the hull surface or being entrapped under an overhanging bow flare.

4 CONCLUSIONS

The rigid body vertical accelerations of MV Estonia during the accident voyage after midnight Finnish time were near the passenger comfort limit which corresponds to about 10 % of the passengers seasick (vomiting). From the point-of-view of passengers, the trip was uncomfortable. The conditions on board MV Estonia before the accident were probably similar to conditions which have been observed on board other passenger ferries in heavy weather in general. At the bow of MV Estonia, the vertical accelerations were about two thirds of the level when Ro-Ro cargo vessels decrease speed or change heading to reduce the wave-induced motions of the vessel. The bow of MV Estonia did not probably submerge to the waves, i.e. no events of green water on the foredeck, but certainly spray and smaller amounts of water came to the deck. There were not many heavy bottom slams but the number of flare impacts must have been significantly higher.

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Appendix 1

Tables

Appendix 1 : Table A.1

JONSWAP, HEADING 180° Significant amplitudes

	SPEED	HEAVE	ROLL	PITCH	REL. VERTICAL MOTION			REL. VERTICAL VELOCITY			ABS.VERTICAL ACCEL.			ABS.VERTICAL ACCEL.		
	(kn)	(m)	(°)	(°)	(m)			(m/s)			(m/s^2)			(m/s^2)		
		LCG			10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	Bridge	Mid	Aft
To=7.0s	7	0.290	0	0.680	2.48	2.58	2.27	3.26	3.39	3.19	1.19	1.12	0.819	0.754	0.362	0.788
	12	0.216	0	0.562	2.28	2.37	2.27	3.71	3.83	3.82	1.18	1.10	0.802	0.737	0.331	0.750
	15	0.191	0	0.494	2.20	2.28	2.24	4.03	4.14	4.17	1.15	1.08	0.782	0.718	0.314	0.723
	17	0.179	0	0.452	2.16	2.23	2.21	4.25	4.35	4.40	1.12	1.05	0.765	0.702	0.305	0.709
To=7.8s	7	0.396	0	1.010	3.05	3.07	2.49	3.36	3.43	3.03	1.41	1.32	0.985	0.911	0.441	0.823
	12	0.339	0	0.921	2.82	2.86	2.55	3.71	3.80	3.63	1.56	1.46	1.090	1.000	0.443	0.839
	15	0.328	0	0.840	2.68	2.72	2.51	3.93	4.02	3.92	1.57	1.48	1.100	1.010	0.445	0.843
	17	0.326	0	0.785	2.60	2.64	2.47	4.09	4.17	4.11	1.56	1.47	1.090	1.010	0.449	0.849
To=7.8s	7	0.516	0.297	1.40	3.59	3.53	2.64	3.75	3.72	3.07	1.95	1.83	1.360	1.250	0.514	1.020
short	12	0.530	0.232	1.27	3.38	3.33	2.74	4.04	4.02	3.63	2.15	2.02	1.510	1.390	0.582	1.070
crested	15	0.542	0.204	1.17	3.21	3.17	2.72	4.18	4.17	3.89	2.17	2.04	1.530	1.410	0.616	1.100
	17	0.546	0.188	1.10	3.11	3.07	2.68	4.28	4.27	4.04	2.16	2.03	1.520	1.410	0.634	1.120
To=8.5s	7	0.440	0	1.48	3.83	3.75	2.75	3.73	3.71	3.01	1.83	1.72	1.260	1.160	0.441	0.953
	12	0.456	0	1.39	3.62	3.59	2.95	4.06	4.1	3.67	2.18	2.05	1.520	1.400	0.519	1.020
	15	0.474	0	1.29	3.40	3.40	2.92	4.18	4.23	3.94	2.24	2.11	1.570	1.440	0.553	1.050
	17	0.486	0	1.21	3.26	3.27	2.88	4.25	4.32	4.10	2.25	2.12	1.570	1.450	0.576	1.080
To=9.5s	7	0.555	0	2.08	4.72	4.46	2.84	4.11	3.95	2.80	2.19	2.06	1.500	1.370	0.447	1.130
	12	0.690	0	2.06	4.86	4.66	3.31	4.76	4.64	3.61	2.85	2.68	1.980	1.830	0.652	1.280
	15	0.771	0	1.97	4.76	4.59	3.45	4.98	4.89	4.00	3.11	2.93	2.180	2.010	0.777	1.370
	17	0.813	0	1.90	4.63	4.50	3.48	5.07	4.99	4.20	3.21	3.03	2.260	2.090	0.850	1.450

Appendix 1 : Table A.2

JONSWAP, HEADING 150° Significant amplitudes

	SPEED (kn)	HEAVE (m)	ROLL (°)	PITCH (°)	REL. VERTICAL MOTION (m)			REL. VERTICAL VELOCITY (m/s)			ABS.VERTICAL ACCEL. (m/s^2)			ABS.VERTICAL ACCEL. (m/s^2)		
	LCG				10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	Bridge	Mid	Aft
To=7.0s	7	0.327	0.288	0.811	2.73	2.70	2.36	3.34	3.34	3.14	1.30	1.21	0.909	0.841	0.413	0.774
	12	0.268	0.208	0.704	2.52	2.51	2.36	3.71	3.71	3.68	1.34	1.26	0.937	0.865	0.393	0.760
	15	0.253	0.174	0.631	2.42	2.41	2.32	3.96	3.96	3.98	1.33	1.25	0.925	0.854	0.385	0.754
	17	0.244	0.155	0.582	2.36	2.35	2.29	4.13	4.14	4.17	1.31	1.22	0.908	0.838	0.380	0.753
To=7.8s	7	0.412	0.289	1.330	3.56	3.48	2.71	3.71	3.66	3.13	1.83	1.72	1.270	1.170	0.457	0.926
	12	0.408	0.212	1.200	3.28	3.22	2.79	3.95	3.92	3.68	2.02	1.91	1.410	1.300	0.497	0.959
	15	0.417	0.180	1.090	3.08	3.03	2.73	4.07	4.05	3.92	2.02	1.91	1.410	1.300	0.518	0.981
	17	0.420	0.162	1.010	2.96	2.92	2.68	4.15	4.14	4.06	1.99	1.88	1.390	1.290	0.528	0.994
To=7.8s short	7	0.723	0.393	1.460	3.57	3.54	2.56	3.71	3.68	2.95	2.07	1.94	1.460	1.350	0.625	1.110
	12	0.748	0.344	1.340	3.40	3.38	2.67	3.99	3.97	3.47	2.27	2.14	1.610	1.500	0.705	1.170
	15	0.761	0.331	1.250	3.26	3.24	2.65	4.12	4.11	3.71	2.30	2.17	1.640	1.520	0.747	1.210
	17	0.765	0.328	1.180	3.16	3.15	2.63	4.20	4.20	3.86	2.29	2.16	1.640	1.520	0.769	1.230
To=8.5s	7	0.498	0.285	1.830	4.40	4.23	2.89	4.17	4.04	3.05	2.27	2.13	1.560	1.430	0.475	1.130
	12	0.583	0.211	1.730	4.27	4.13	3.17	4.55	4.45	3.73	2.70	2.55	1.880	1.730	0.620	1.220
	15	0.625	0.180	1.610	4.05	3.94	3.18	4.63	4.55	4.01	2.80	2.64	1.960	1.800	0.690	1.290
	17	0.641	0.162	1.570	3.88	3.78	3.15	4.66	4.59	4.15	2.81	2.65	1.960	1.810	0.724	1.340
To=9.5s	7	0.699	0.325	2.200	4.88	4.62	2.78	4.22	4.03	2.71	2.42	2.26	1.660	1.520	0.511	1.240
	12	0.864	0.240	2.280	5.15	4.91	3.27	4.93	4.74	3.49	3.10	2.91	2.160	2.000	0.756	1.410
	15	0.967	0.206	2.200	5.15	4.93	3.47	5.22	5.04	3.88	3.39	3.20	2.390	2.210	0.915	1.530
	17	1.020	0.186	2.130	5.08	4.87	3.53	5.35	5.18	4.10	3.53	3.33	2.500	2.320	1.010	1.620

Appendix 1 : Table A.3

JONSWAP, HEADING 120° Significant amplitudes

	SPEED	HEAVE	ROLL	PITCH	REL. VERTICAL MOTION			REL. VERTICAL VELOCITY			ABS.VERTICAL ACCEL.			ABS.VERTICAL ACCEL.		
	(kn)	(m)	(°)	(°)	(m)			(m/s)			(m/s^2)			(m/s^2)		
		LCG			10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	Bridge	Mid	Aft
To=7.0s	7	0.575	0.436	1.72	4.22	4.06	2.83	4.54	4.35	3.30	2.78	2.60	1.92	1.76	0.612	1.37
	12	0.623	0.348	1.49	3.93	3.77	2.89	4.64	4.44	3.69	2.82	2.64	1.96	1.81	0.715	1.40
	15	0.629	0.307	1.35	3.72	3.57	2.85	4.65	4.45	3.85	2.76	2.59	1.93	1.78	0.749	1.41
	17	0.624	0.284	1.26	3.58	3.44	2.81	4.65	4.46	3.94	2.70	2.54	1.89	1.75	0.761	1.41
To=7.8s	7	0.858	0.543	2.14	4.60	4.49	2.74	4.57	4.44	2.98	3.04	2.83	2.10	1.94	0.751	1.55
	12	0.969	0.438	1.99	4.62	4.50	3.01	4.95	4.81	3.50	3.34	3.13	2.36	2.18	0.962	1.68
	15	1.010	0.390	1.88	4.53	4.40	3.08	5.08	4.92	3.74	3.42	3.21	2.43	2.25	1.060	1.76
	17	1.020	0.362	1.80	4.44	4.31	3.10	5.13	4.97	3.88	3.44	3.23	2.45	2.27	1.110	1.81
To=7.8s	7	1.000	0.608	1.55	3.40	3.38	2.28	3.45	3.43	2.58	2.17	2.04	1.56	1.45	0.765	1.21
short	12	1.030	0.720	1.43	3.31	3.29	2.41	3.68	3.66	2.99	2.34	2.20	1.69	1.58	0.846	1.27
crested	15	1.040	0.946	1.35	3.22	3.20	2.42	3.77	3.76	3.18	2.36	2.23	1.72	1.61	0.889	1.31
	17	1.050	1.200	1.30	3.15	3.14	2.41	3.83	3.82	3.29	2.36	2.23	1.72	1.61	0.913	1.33
To=8.5s	7	1.070	0.639	2.27	4.40	4.32	2.48	4.16	4.06	2.60	2.89	2.68	2.01	1.86	0.796	1.53
	12	1.210	0.521	2.20	4.62	4.54	2.83	4.66	4.56	3.13	3.31	3.10	2.36	2.19	1.040	1.69
	15	1.280	0.467	2.12	4.66	4.58	2.98	4.89	4.78	3.41	3.50	3.28	2.51	2.34	1.190	1.80
	17	1.320	0.436	2.06	4.66	4.57	3.05	5.02	4.91	3.57	3.59	3.37	2.59	2.42	1.270	1.88
To=9.5s	7	1.310	0.775	2.24	3.86	3.80	2.10	3.49	3.41	2.15	2.53	2.35	1.79	1.65	0.792	1.40
	12	1.430	0.636	2.22	4.13	4.08	2.42	3.95	3.88	2.59	2.95	2.75	2.12	1.98	1.020	1.55
	15	1.520	0.577	2.18	4.25	4.20	2.59	4.20	4.13	2.84	3.16	2.96	2.30	2.15	1.170	1.65
	17	1.570	0.541	2.15	4.31	4.27	2.69	4.35	4.28	2.99	3.29	3.09	2.41	2.26	1.270	1.73

Appendix 1 : Table A.4

ISSC, Heading 180°

Significant amplitudes

	SPEED (kn) LCG	HEAVE (m)	ROLL (°)	PITCH (°)	REL. VERTICAL MOTION (m)			REL. VERTICAL VELOCITY (m/s)			ABS.VERTICAL ACCEL. (m/s²)			ABS.VERTICAL ACCEL. (m/s²)		
					10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	Bridge	Mid	Aft
To=7.0s	7	0.265	0	0.714	2.49	2.54	2.25	3.42	3.50	3.36	1.11	1.05	0.765	0.704	0.316	0.681
	12	0.218	0	0.623	2.34	2.39	2.26	4.01	4.09	4.07	1.16	1.10	0.803	0.739	0.310	0.662
	15	0.203	0	0.556	2.25	2.30	2.23	4.38	4.45	4.48	1.15	1.08	0.795	0.732	0.304	0.650
	17	0.196	0	0.512	2.20	2.25	2.21	4.64	4.70	4.74	1.13	1.07	0.781	0.719	0.301	0.646
To=7.8s	7	0.343	0	1.100	3.08	3.06	2.43	3.51	3.55	3.20	1.43	1.34	0.982	0.903	0.370	0.811
	12	0.342	0	1.030	2.96	2.96	2.54	4.03	4.08	3.88	1.65	1.55	1.140	1.050	0.410	0.834
	15	0.355	0	0.953	2.84	2.85	2.53	4.32	4.38	4.25	1.70	1.60	1.180	1.090	0.435	0.850
	17	0.363	0	0.899	2.76	2.77	2.51	4.52	4.57	4.48	1.71	1.61	1.200	1.100	0.452	0.866
To=7.8s	7	0.479	0.283	1.340	3.40	3.33	2.50	3.70	3.66	3.15	1.78	1.67	1.230	1.140	0.452	0.951
short	12	0.518	0.220	1.260	3.31	3.25	2.63	4.15	4.12	3.76	2.02	1.90	1.410	1.300	0.534	0.998
crested	15	0.545	0.193	1.180	3.20	3.15	2.63	4.38	4.36	4.08	2.08	1.96	1.460	1.350	0.583	1.030
	17	0.558	0.178	1.120	3.12	3.07	2.62	4.53	4.51	4.28	2.10	1.98	1.480	1.370	0.611	1.060
To=8.5s	7	0.426	0	1.420	3.57	3.47	2.54	3.63	3.62	3.05	1.66	1.56	1.140	1.040	0.403	0.908
	12	0.470	0	1.380	3.54	3.46	2.75	4.16	4.16	3.75	2.01	1.89	1.400	1.290	0.489	0.971
	15	0.511	0	1.310	3.44	3.39	2.79	4.42	4.43	4.10	2.14	2.02	1.500	1.380	0.548	1.010
	17	0.536	0	1.250	3.36	3.31	2.78	4.58	4.60	4.32	2.19	2.07	1.540	1.420	0.588	1.050
To=9.5s	7	0.724	0	2.290	4.06	3.86	2.60	3.72	3.63	2.83	1.86	1.75	1.280	1.170	0.433	1.000
	12	0.657	0	1.790	4.18	4.00	2.92	4.30	4.23	3.53	2.36	2.22	1.640	1.510	0.574	1.100
	15	0.731	0	1.740	4.15	4.00	3.03	4.57	4.51	3.89	2.57	2.43	1.810	1.670	0.675	1.180
	17	0.778	0	1.690	4.10	3.96	3.07	4.73	4.68	4.11	2.68	2.53	1.900	1.750	0.744	1.240

Appendix 1 : Table A.5

ISSC, HEADING 150° Significant amplitudes

	SPEED (kn)	HEAVE (m)	ROLL (°)	PITCH (°)	REL. VERTICAL MOTION (m)			REL. VERTICAL VELOCITY (m/s)			ABS.VERTICAL ACCEL. (m/s²)			ABS.VERTICAL ACCEL. (m/s²)		
	LCG				10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	Bridge	Mid	Aft
To=7.0s	7	0.290	0.238	0.909	2.80	2.75	2.35	3.51	3.50	3.31	1.35	1.26	0.929	0.855	0.351	0.745
	12	0.274	0.173	0.810	2.63	2.60	2.38	3.99	3.99	3.94	1.45	1.36	1.010	0.927	0.366	0.744
	15	0.274	0.145	0.733	2.52	2.49	2.35	4.28	4.28	4.28	1.45	1.36	1.010	0.929	0.374	0.749
	17	0.271	0.129	0.680	2.44	2.42	2.32	4.48	4.49	4.51	1.43	1.34	0.992	0.915	0.377	0.754
To=7.8s	7	0.394	0.264	1.320	3.43	3.33	2.53	3.69	3.64	3.17	1.70	1.60	1.170	1.080	0.408	0.899
	12	0.433	0.193	1.240	3.32	3.24	2.66	4.15	4.10	3.80	1.97	1.85	1.370	1.260	0.481	0.945
	15	0.463	0.163	1.160	3.21	3.13	2.67	4.38	4.34	4.12	2.04	1.92	1.420	1.320	0.528	0.981
	17	0.476	0.146	1.100	3.11	3.05	2.65	4.53	4.50	4.32	2.05	1.93	1.440	1.330	0.554	1.010
To=7.8s short crested	7	0.662	0.373	1.370	3.36	3.30	2.42	3.64	3.61	3.03	1.88	1.76	1.320	1.220	0.555	1.020
	12	0.698	0.326	1.290	3.28	3.24	2.55	4.04	4.02	3.59	2.09	1.97	1.480	1.370	0.637	1.070
	15	0.720	0.313	1.210	3.19	3.15	2.56	4.25	4.23	3.88	2.15	2.03	1.530	1.420	0.686	1.110
	17	0.731	0.310	1.160	3.12	3.09	2.55	4.39	4.37	4.06	2.17	2.04	1.550	1.440	0.715	1.140
To=8.5s	7	0.507	0.288	1.640	3.87	3.72	2.61	3.81	3.72	3.03	1.93	1.81	1.330	1.220	0.445	1.000
	12	0.585	0.212	1.580	3.86	3.73	2.84	4.30	4.22	3.67	2.31	2.17	1.610	1.490	0.567	1.090
	15	0.641	0.180	1.500	3.78	3.66	2.89	4.53	4.46	4.00	2.45	2.31	1.720	1.590	0.648	1.150
	17	0.670	0.162	1.440	3.70	3.59	2.90	4.66	4.59	4.19	2.50	2.36	1.760	1.630	0.697	1.190
To=9.5s	7	0.682	0.336	1.960	4.22	4.02	2.61	3.84	3.71	2.79	2.09	1.96	1.440	1.320	0.482	1.090
	12	0.792	0.248	1.940	4.36	4.17	2.94	4.40	4.27	3.45	2.59	2.43	1.810	1.670	0.652	1.210
	15	0.873	0.212	1.880	4.35	4.17	3.05	4.65	4.53	3.78	2.80	2.64	1.980	1.830	0.769	1.300
	17	0.922	0.191	1.830	4.31	4.15	3.09	4.79	4.67	3.97	2.90	2.74	2.060	1.910	0.844	1.360

Appendix 1 : Table A.6

ISSC, HEADING 120° Significant amplitudes

	SPEED	HEAVE	ROLL	PITCH	REL. VERTICAL MOTION			REL. VERTICAL VELOCITY			ABS.VERTICAL ACCEL.			ABS.VERTICAL ACCEL.		
	(kn)	(m)	(°)	(°)	(m)			(m/s)			(m/s^2)			(m/s^2)		
		LCG			10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	10 2/3	10 1/4	8 1/2	Bridge	Mid	Aft
To=7.0s	7	0.584	0.431	1.53	3.70	3.57	2.55	4.11	3.95	3.19	2.35	2.19	1.63	1.50	0.562	1.17
	12	0.647	0.343	1.39	3.57	3.45	2.63	4.36	4.20	3.60	2.46	2.30	1.75	1.59	0.679	1.22
	15	0.670	0.303	1.29	3.46	3.35	2.63	4.48	4.33	3.81	2.46	2.31	1.74	1.61	0.734	1.26
	17	0.676	0.280	1.23	3.38	3.27	2.62	4.56	4.41	3.94	2.45	2.30	1.74	1.61	0.762	1.28
To=7.8s	7	0.798	0.520	1.83	3.99	3.87	2.55	4.15	4.01	3.00	2.58	2.40	1.79	1.65	0.655	1.32
	12	0.889	0.419	1.71	3.96	3.85	2.71	4.45	4.31	3.43	2.79	2.61	1.97	1.82	0.819	1.41
	15	0.931	0.374	1.62	3.90	3.79	2.76	4.59	4.45	3.65	2.85	2.68	2.03	1.89	0.905	1.47
	17	0.952	0.348	1.56	3.84	3.74	2.77	4.67	4.53	3.78	2.88	2.70	2.06	1.91	0.955	1.51
To=7.8s short crested	7	0.913	0.579	1.40	3.15	3.12	2.18	3.35	3.33	2.66	1.96	1.84	1.40	1.31	0.689	1.10
	12	0.941	0.692	1.32	3.11	3.08	2.30	3.64	3.62	3.07	2.10	1.98	1.52	1.42	0.759	1.14
	15	0.957	0.930	1.25	3.05	3.03	2.32	3.79	3.77	3.29	2.14	2.02	1.56	1.45	0.801	1.17
	17	0.964	1.180	1.20	3.01	2.99	2.32	3.88	3.86	3.42	2.15	2.03	1.57	1.47	0.826	1.19
To=8.5s	7	0.971	0.605	1.99	4.04	3.94	2.47	4.04	3.92	2.79	2.64	2.45	1.84	1.69	0.706	1.37
	12	1.070	0.492	1.89	4.09	3.99	2.68	4.38	4.25	3.23	2.91	2.72	2.06	1.91	0.893	1.48
	15	1.130	0.442	1.81	4.07	3.97	2.76	4.54	4.41	3.45	3.01	2.82	2.16	2.01	0.999	1.56
	17	1.160	0.413	1.76	4.04	3.95	2.79	4.63	4.51	3.59	3.06	2.87	2.20	2.05	1.060	1.61
To=9.5s	7	1.180	0.734	2.08	3.89	3.81	2.28	3.74	3.64	2.47	2.55	2.37	1.79	1.65	0.737	1.36
	12	1.280	0.602	2.01	4.02	3.94	2.52	4.11	4.00	2.89	2.87	2.69	2.05	1.91	0.936	1.49
	15	1.350	0.545	1.96	4.05	3.97	2.63	4.29	4.18	3.11	3.01	2.83	2.17	2.03	1.050	1.57
	17	1.380	0.510	1.91	4.05	3.98	2.68	4.39	4.28	3.25	3.09	2.90	2.24	2.09	1.130	1.64

Appendix 2

Figures

SUPPLEMENT No. 413

Karppinen Tuomo :

MV ESTONIA Accident Investigation. Effect of speed on the visor loads.

Working paper.

29.10.1996

MV ESTONIA ACCIDENT INVESTIGATION

Effect of speed on the visor loads

The effect of forward speed on the visor loads in bow oblique seas (wave direction 150 degrees) is here analysed on the basis of the results of the model experiments and numerical simulations. Only the vertical force component is considered since the experiments show that the horizontal component was always very close to the vertical and the opening moment was proportional to the vertical force, i.e. a larger force indicates a larger opening moment.

The model experiments with Estonia, the extensive systematical series of experiments by SSPA and the simulations show that the vertical force on the visor in head and bow seas over a large speed range is approximately directly proportional to the forward speed. The dependence on speed may be a little weaker but it is hardly stronger. Thus, a linear relationship between the visor force and speed has been assumed. Two exceedance probabilities have been considered: 10^{-3} and 10^{-4} which correspond approximately to one hours and ten hours sailing time, respectively. The significant wave heights, H_s, have been assumed as 4 and 4.5 m.

The following table shows a summary of the vertical visor loads in bow oblique seas at different speeds according to the results of the numerical simulations (VTT Report VALC106, Table 5.1) and the assumption of linear dependence on speed.

Table 1. The vertical wave load on the visor in bow seas.

H_s [m]	Exc. prob.	Speed 7.5 kn	Speed 10 kn	Speed 12 kn	Speed 15 kn
4	10^{-3}	1375 kN	1830 kN	2200 kN	2750 kN
4	10^{-4}	1850 kN	2470 kN	2960 kN	3700 kN
4.5	10^{-3}	1950 kN	2600 kN	3120 kN	3900 kN
4.5	10^{-4}	2650 kN	3530 kN	4240 kN	5300 kN

The forces in the previous table include the effect of the weight of the visor which has been assumed as 589 kN (60 tons). The effect of wave height increase from 4 to 4.5 m is in agreement with the model tests.

To see better the trends with speed and since the load required to break the visor lockings is not exactly known, the load in the conditions where the lockings broke has been given the value of 100 and all the other force values have been scaled accordingly. Thus, the load 2750 kN which has an exceedance probability of 10^{-3} at 15 knots speed in seas with $H_s = 4$ m has been assigned the value of 100. The next table shows the results in this form.

Table 2. The relative vertical wave load on the visor in bow seas.

H_s [m]	Exc. prob.	Speed 7.5 kn	Speed 10 kn	Speed 12 kn	Speed 15 kn
4	10^{-3}	50	67	80	100
4	10^{-4}	67	90	108	135
4.5	10^{-3}	71	95	113	142
4.5	10^{-4}	96	128	154	193

When the lockings of the visor broke, the Estonia had been sailing about half an hour from the waypoint in increasing bow seas. Before the course change at the waypoint, the loads on the visor had been at least 25 % smaller than after the waypoint, i.e. about 75 using the same scale as in Table 2. Thus, it is reasonable to assume that the load which broke the attachments of the visor was not a very rare extreme load. On the other hand, the ultimate strength of the lockings could not have been below the level of about 75 since then the accident may have happened already before the waypoint. This, however, depends quite strongly on how quickly the significant wave height rose during the last half an hour before the accident. The ultimate strength of the locking system must have been a little smaller than the load which broke the lockings, perhaps about 90.

From the accident site, the Estonia had about 75 nautical miles to Söderarm. The significant wave height was increasing and there were on the way some areas of shallow water where the wave height would probably have been higher than in the surrounding deep water. At 15 kn speed it would have taken 5 hours and at 10 knots 7.5 hours to Söderarm. A large part of this time the significant wave height would have been about or larger than 4.5 m. At speeds more than 10 knots, the maximum loads would have been above the level of 95 according to Table 2. Thus, it can be concluded that at a speed of more than 10 knots in bow seas during the accident night after 01 Finnish time the Estonia had no chance of avoiding the breaking of the lockings.

At a speed of 7.5 knots, it would have taken about 10 hours to Söderarm. The maximum loads on the visor at this speed would most likely have exceeded the level which broke the lockings, if the Estonia had not changed significantly course. The Estonia may have survived in the prevailed bow seas without breaking the lockings at a speed of below 5 knots. The chances of survival would then have been of the same order as in playing the Russian Roulette.

If the lockings of the Estonia had been constructed according to the design calculations, the ultimate strength of the locking system would have been approximately twice the actual strength, or about 180 on the scale of Table 2. Then the Estonia would likely have survived at a speed of about 12 knots but not necessarily at 15 knots.

According to the IACS and BV Rules of 1982 the design load per attachement point for the visor of Estonia would have been about 200 tons instead of the original 100 tons. This means that the ultimate strength of the locking system would have been on the level of 360. The lockings of the visor of Mariella and the lockings of the bow doors of Silja Europa were probably on this or a little higher level. In spite of this, the bow doors of Silja Europa suffered damage during the accident night. The bow doors of Silja Symphony and Serenade were constructed according to even higher design loads and their strength was somewhere above the level of 500 if the same scale as used for Estonia is applicable.